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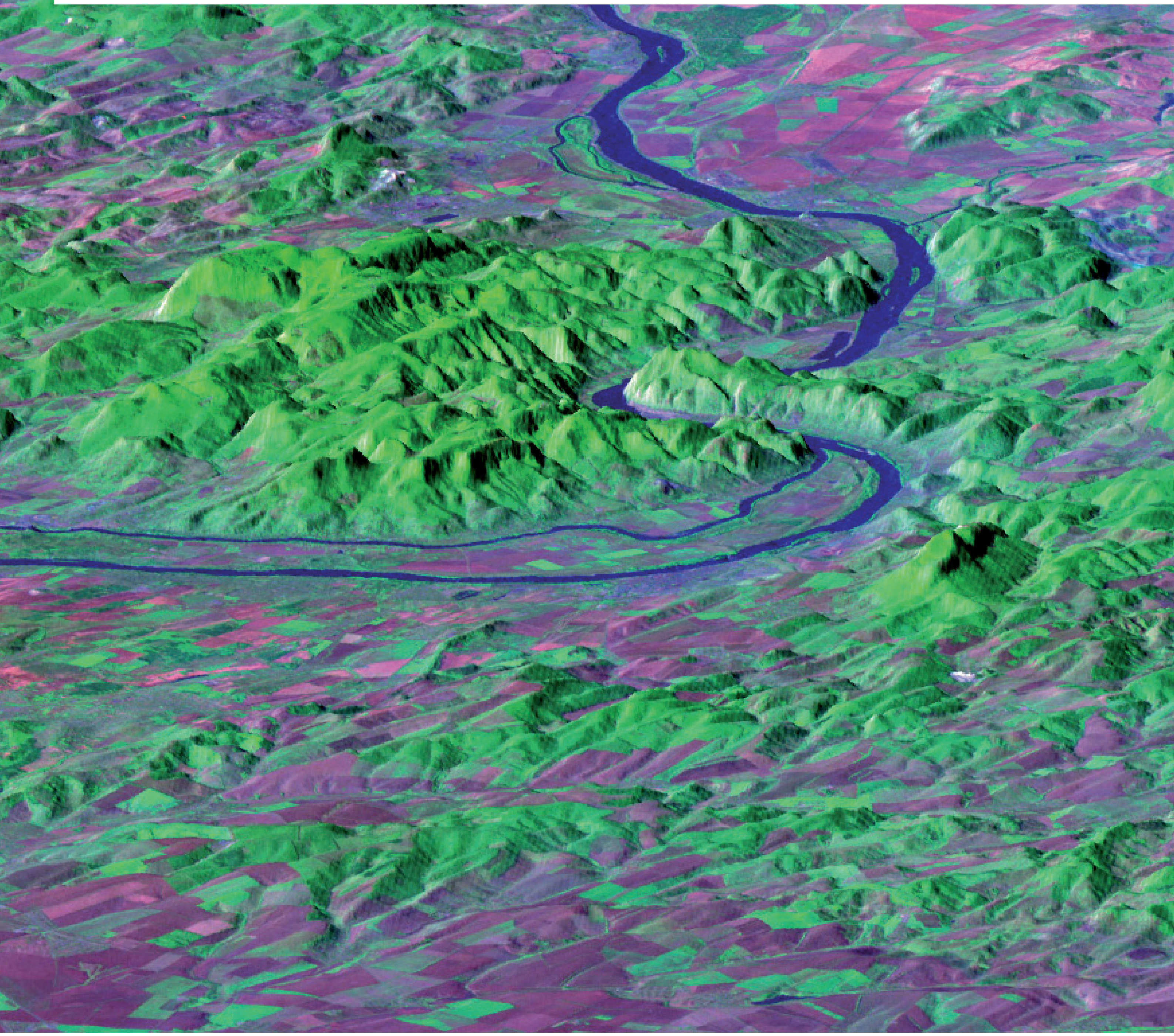
CSC Report 10

Challenges and possiblities in coupling climate, ecological, and socio-economic models:

overview and examples from two German research projects



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The cover image is showing the river Danube between the city of Györ (top center) and Budapest (lower left). The picture was generated from a Landsat satellite image draped over an elevation model produced by the Shuttle Radar Topography Mission (SRTM). The view uses a 3-times vertical exaggeration to enhance topographic expression. The false colors of the scene result from displaying Landsat bands 1, 4, and 7 in blue, green, and red, respectively. Band 1 is visible blue light, but bands 4 and 7 are reflected infrared light. This band combination maximizes color contrasts between the major land cover types, namely vegetation (green), bare ground (red), and water (blue). Shading of the elevation model was used to further highlight the topographic features.

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Citation:
Bowyer, P., Schaller, M., Keup-Thiel, E., Schwarze, R. (2012): Challenges and possibilities in coupling climate, ecological, and socio-economic models: overview and examples from two German research projects, CSC Report 10, Climate Service Center, Germany

Overview of Attempts Made at Coupling Climate, Ecological and Socio-Economic Models. Discussion of Problems of Coupling and Potential Solutions

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Foreword

Human activities have a major impact on the functioning of the earth system. However, in current environmental and earth system prediction models these activities are often either not represented, or are simply prescribed, and thus there is no two-way interaction between the different natural (physical, biological, chemical) and human (economic, political, social, and cultural) systems. For example, as changes in land cover and land use occur, the associated changes in land surface albedo, and in turn the effect this will have on atmospheric processes and climate, is not represented. To date, only one way coupling of different systems has been possible, and developing fully dynamic two-way interactivity between systems remains a considerable challenge for the research community. This document provides a summary of efforts that have been made in Germany at coupling climate, hydrological, ecological, and socio-economic models, using examples drawn from two research projects, GLOWA-Elbe and GLOWA-Danube. In addition, the document provides a discussion of the problems and challenges in developing fully integrated coupled modelling frameworks.

This report was written as part of the project: „Vernetzung von Klimaszenarien mit weiteren Szenarien aus dem ökologischen und gesellschaftlichen Bereich“, funded by the Federal Environmental Agency (UBA), and conducted by the Institute for Ecological Economy Research (IÖW) in Berlin, in cooperation with the Center for Environmental Research (UFZ, Halle), the Institute of Economic Structures Research (GWS, Osnabrück) and the Climate Service Center (CSC, Hamburg).

Bericht für das IÖW
Werkvertrag Nr.:2/74/09/UP-CSC

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List of Acronyms and Abbreviations

ACRE	Agro-eConomic model for agricultural pRoduction on rEgional level
ArcEGMO	ArcInfo basiertes gegliedertes hydrologisches Modellsystem
BOWAS	Bodenwasserhaushaltsmodell
CAPRI	Common Agricultural Policy Regionalised Impact analysis
GREAT-ER	Geography Referenced Regional Exposure Assessment Tool for European Rivers
HBV	Hydrologiska Byråns Vattenbalansavdelning
IPCC	Intergovernmnetal Panel on Climate Change
MODAM	Multi-Objective Decision support system for Agro-ecosystem Management
MODFLOW	Modular three-dimensional groundwater flow model
MONERIS	Modelling Nutrient Emissions in River Systems
MOVER2.2	Model for vegetation response in floodplains
PROMET	Processes of radiation, Mass and Energy Transport
RAUMIS	Regional Agricultural and Environmental Information System for Germany
SRES	Special Report on Emissions Scenarios
STABU	Statistisches Bundesamt
SWIM	Soil and Water Integrated model
VEGMOS	Vegetationsentwicklungsmodell
WABI	Wasserhaushaltsmodell
WaterGAP	Water – Global Assessment and Prognosis
WBalMo	Water Balance Model, also known as ArcGRM

1. Introduction

There is a growing recognition of the need for integrating models that describe the climate, ecological, hydrological, and socio-economic systems. Humans continuously interact with the climate and environment, through land transformation, management practices and economic activities, among others. These interactions between different earth system components constitute feedback mechanisms between all components, and in developing models for future scenarios, these interactions and feedbacks need to be taken into account in the modelling. This is not an easy task however, as it requires the fully dynamical coupling of a number of different environmental and economic models. To date, no such examples of integrated dynamical coupling of the climate, ecological, hydrological and socio-economic systems exist (Nobre *et al*. 2010). The current state of the art is the one way coupling of disparate models, whereby one model output is the input for another.

This document summarises those efforts that have been made in Germany at coupling climate, ecological, hydrological and socio-economic models. Examples are taken from two GLOWA projects, GLOWA-Elbe (Wechsung *et al*. 2008), and GLOWA-Danube (Ludwig *et al*. 2003, Barth *et al*. 2004). These two projects take different approaches to the integration, with GLOWA-Elbe using a more scenario based approach, whilst GLOWA-Danube develops an agent or actor based decision support system, DANUBIA, where decision making processes are simulated, given certain plans, actions, and decision rules. This approach is referred to as DeepActor within the GLOWA-Danube project, and is composed of six different actors, within which there are different actor types (Barthel *et al*. 2005, 2008).

This document consists of six sections, section 2 provides an overview of existing efforts at coupling climate, ecological, and socio-economic models, section 3 highlights and discusses the problems and challenges in developing coupled integrated modelling frameworks, whilst section 4 provides an overview of the environmental and economic models detailed in the text, as well as some examples of required climate model input parameters for selected ecological/hydrological models. The report finishes with a conclusion in section 5 and references are listed in section 6.

2. Coupling climate, ecological, and socio-economic models: existing efforts

Progress in the coupling and integration of climate, ecological, hydrological and socio-economic models has been advanced over the last few years in Germany, primarily (though not exclusively), through the efforts of two research projects: GLOWA-Elbe (Wechsung *et al*. 2008) and GLOWA- Danube (Ludwig *et al*. 2003, Barth *et al*. 2004). The development of integrated approaches is a highly demanding task, and requires a large investment of time, particularly in the collection and organisation of appropriate data sets necessary to construct socio-economic models.

Tables 1 and 2 provide an overview of the integrative work that can be found in the literature, relating to GLOWA-Elbe and GLOWA-Danube, respectively.

Whilst GLOWA-Elbe and GLOWA-Danube take different methodological approaches to the problem of integrative modelling (scientific models may be defined as being simplified representations of the structure and function of a particular system, and are thus abstract representations of reality (Heuvelink 1998)), they share similarities in their treatment of climate and socio-economic scenarios (a scenario being a plausible and often simplified description of how the future climate and socio-economic conditions may develop, based on a coherent and internally consistent set of assumptions). In order to aid understanding of the scenarios used and listed in tables 1 and 2, more details are provided below, in sections 2.1 and 2.2.

2.1 Climate scenarios

The climate scenarios that are used in the GLOWA-Elbe and GLOWA-Danube projects are given in tables 1 and 2 respectively. The purpose of this section is to provide a little more detail and context to the simulations that are used.

2.1.1 GLOWA-Elbe

In the GLOWA-Elbe project, regional climate scenarios are derived from STAR, a statistical downscaling model (Gerstengarbe and Werner 1997, 2008). 100 simulations are run with this model under an A1 IPCC SRES emissions scenario, such that the whole set is referred to as STAR100. In order to be able to establish which of these 100 might be more probable, they apply a frequency distribution fit on precipitation trend, in both the observed and simulated data sets. In so doing, simulation 32 of the 100 is determined to be the most likely, and is thus referred to as STAR32. The mean of the 100 simulations is best represented by simulation 54, which is thus referred to as STAR54. In the various studies detailed in table 1, some use all 100 simulations (STAR100), some the most probable (STAR32), whilst others use the mean conditions (STAR54).

2.1.2 GLOWA-Danube

In GLOWA-Danube, climate scenarios for the DANUBIA system are generated using a statistical downscaling tool called PROMET, which essentially uses the observed climate statistics together with a random number generator and trend in climate change, to produce simulations of future climate (Mauser and Bach 2009). The trends in climate change are calculated from various sources: the regional climate models REMO (Jacob 2001), and MM5 (Früh *et al*. 2006), regional trends from the IPCC report, and trends calculated from observed data (Barthel *et al*. 2010).

2.2 Socio-economic scenarios

The socio-economic scenarios used in both the GLOWA-Elbe and GLOWA-Danube projects, consist of a set of assumptions, which may or may not attempt to be consistent with a particular IPCC SRES scenario. These socio-economic scenarios are now described for each project in turn.

2.2.1 GLOWA-Elbe

In GLOWA-Elbe the following socio-economic scenarios were developed:

- **Reference 'Agenda2000'**: further development of the Common Agricultural Policy (CAP), where internal price support for agricultural products is maintained but cut back somewhat, and subsidies are increasingly decoupled from production (Gömann *et al*. 2008).
- **A1 'Liberalisation'**: Economic development is assumed to be consistent with the IPCC SRES A1 storyline. Describes the future as a very globalised and profit based world in which globalisation and the liberalisation of markets are of primary importance and environmental policy just acts in immediate response to emerging problems. For example, in the agricultural sector, this scenario assumed that the CAP would be liberalised, and there would be no price pegging for cereals, milk, and beef (Gömann *et al*. 2008).
- **B2 'Regionalisation'**: Economic development is assumed to be consistent with the IPCC SRES B2 storyline. This scenario sees the future as one of locally-based economies. Economic growth is less pronounced; political and social solutions are sought on local scales. Environmental policy is highly valued and generally implemented in accordance with the precautionary principle. A 200% nitrogen tax is associated with this scenario (Gömann *et al*. 2008).
- **$A1^{o}$**: the same as A1 above, but with less ambitious CO_2 reduction targets, so lignite mining continues (Grossmann *et al*. 2010).
- **$B2^{+}$**: the same as B2 above, but with more ambitious CO_2 reduction targets, so that CO_2 emission certificates become more expensive. Consequently, lignite mining is discontinued (Grossmann *et al*. 2010).
- **A1K**: This scenario is consistent with the A1 storyline above, but in addition uses climate simulation STAR54 (essentially the mean of the STAR100 simulations) (Klöcking and Sommer 2008). This means that scenario A1K includes both the socio-economic assumptions, as well as an increase in temperature.
- **Fen conservation management**: there are two management strategies for wetlands in the Spreewald. One is based on present day water management practices, whilst in the second strategy, use of fen sites is either discontinued (regeneration) or strongly extensified (maintenance of fens). The difference between these latter two options resides in the target water levels throughout the year. Under regeneration the target water level is 0.1m above ground level in winter, and 0.2m below ground level in summer, whilst under maintenance, the target water level is ground level in winter, and 0.3m below ground level in summer (Dietrich 2008).

2.2.2 GLOWA-Danube

In GLOWA-Danube, the DeepActor component of the DANUBIA system, requires that some assumptions about actor behaviour are made. To this end, three 'societal mega-trends' were identified and used as the socio-economic scenarios (Barthel *et al*. 2010). These trends determine the set of plans and actions that are available to the different actors, and thus the decision rules about how different actors might behave. The socio-economic scenarios were:

- **Business as usual**: actor behaviour is assumed to be the same as at present. For water supply companies (WSC), this meant respecting the environment, but still being economically oriented.
- **Liberalisation**: actor behaviour is geared towards the economic imperative. WSC act with disregard to the state of water resources and up to the technical capacities until all resources are used. No communication of the state of resources is provided to water users.
- **Sustainability**: actor behaviour is ecologically oriented. WSC react by reducing withdrawal and imposing restrictions on consumers.

3. Problems and possible solutions for coupling models in an integrated framework

Whilst various attempts have been made to couple climate, ecological, and socio-economic models in an integrated framework, there are three main issues that need to be overcome when trying to develop an integrated study. These are: process resolution, the temporal and spatial resolution of operation of the different models that are to be coupled, and data set availability, and the attendant effort involved in developing socio-economic models. Each of these issues will now be discussed in turn.

3.1 Process resolution

Because of the way in which the outputs of one model in an integrated system, depend on and relate to, the other model components in the system, together with the need for internal consistency, and the conservation of energy and mass between these components, process resolution is of major importance. Often, when developing an integrated framework, the integration involves coupling disparate groups of models that were never designed nor intended to be coupled together. As a result, combining these models in a consistent way can represent a major piece of work, often involving model calibration, and optimisation. For example, when coupling models that are philosophically different e.g. qualitative versus quantitative, dynamic versus static, or deterministic versus statistical models, one natural question that arises is: what is the required accuracy of the respective models? Also, when models are to be coupled what is to be done to resolve the fact that two different models might simulate one particular process in two different ways?

De Kok and Booij (2008), address the model philosophy issue with respect to coupling a deterministic rainfall-runoff model (HBV), to a statistical model of floodplain vegetation MOVER2.2, in the context of developing the Elbe Decision Support System (DSS). They develop a method whereby the accuracy required from the deterministic model can be derived from a functional relationship between the two. In this way unnecessary time spent on model optimisation can be avoided prior to coupling models, and ensures that a model of sufficient accuracy, but no more, is used. In other words, there is no point in supplying highly accurate inputs to one model, if that model itself cannot make similarly accurate simulations. This may have implications for the overall accuracy of the coupled system, and may involve generalisation of the kind of questions that can be asked, and/or the use to which the system can be put.

Another approach to circumvent this issue, is to ensure that you have a system that is developed with the intended purpose in mind, from the outset. This is the approach taken by Mauser and Bach (2009), who describe the PROMET system which is used to model the land surface energy and mass balance, meteorology, vegetation, snow and ice, soil hydraulics and temperature, groundwater, channel flow, and man-made hydraulic structures, in the DANUBIA DSS. This model is physically based, and as such does not require site specific calibration, and models all components of the land surface in one system.

3.2 Temporal and spatial resolution

The temporal and spatial resolution at which the different models that have to be coupled operate, also presents a difficult issue that needs to be addressed.

In developing an integrated method to analyse how global climate change, land use, and socio-economic development would affect water resources in the German Elbe basin, Hattermann *et al*. (2007, 2008), needed to link the Regional Agricultural and Environmental Information System (RAUMIS) model to the eco-hydrological model Soil and Water Integrated Model (SWIM) (Krysanova *et al*., 1998, 2005). RAUMIS is an agro-economic model and is used to calculate how changes in global crop market conditions will alter crop distribution, so that profit is maximised. These changes in crop distribution under future climate and socio-economic change, needed to be linked to the SWIM model. Owing to the fact that RAUMIS operates at the administrative level of counties, and SWIM at the hydrotope or hydrological response unit (HRUs) level, there was a spatial mismatch between the outputs of RAUMIS and the inputs to SWIM. To reconcile this spatial mismatch a crop generator was implemented in SWIM, which allowed the optimised crop distributions produced by RAUMIS at the county level, to be integrated into the spatial units of the SWIM model.

Berlekamp *et al*. (2007), also have a spatial resolution issue to address when coupling MONERIS and GREAT-ER in the Elbe DSS. MONERIS calculates nutrient inputs of phosphorous and nitrogen into river basins and operates at the catchment scale of ~1000 km^2. GREAT-ER, on the other hand, operates at the river reach scale of ~2 km in length, and calculates concentrations of hazardous substances released by point sources e.g. sewage treatment plants. As a consequence of the different scales, diffuse inputs from MONERIS have to be distributed to the river network of GREAT-ER. In order to achieve this distribution, and in the absence of a sufficiently detailed digital elevation model which would allow the calculation of the contributing areas of each river reach, Berlekamp *et al*. make the simplifying assumption that the relationship between reach length and contributing area doesn't change in a MONERIS sub-catchment i.e., the input to a reach (in GREAT-ER) is proportional to the length of the reach compared to the accumulated length of all reaches in the catchment.

Apfelbeck *et al*. (2007), also describe a method that is developed to overcome the problem of allocation of farm systems in the DANUBIA DSS. Farming systems within DANUBIA are represented by the DeepFarming actor model. Actors within the farming system have no economic knowledge of how to behave, so are issued a plan that is developed from yield information in the previous year obtained from the ACRE (Agro-eConomic model for agricultural pRoduction on rEgional level) database. The problem is that ACRE data are only provided at the district level, whereas the DANUBIA system operates on the basis of proxels (a process pixel, where model calculations are made), of 1 x 1 km. Apfelbeck *et al*. thus had to develop a farm system allocation tool, which took information from the ACRE database, and distributed farming systems spatially to the proxels, based on the most suitable farming system per proxel.

Klöcking *et al*. (2008), describe a system of linking a rainfall-runoff model ArcEGMO, and a groundwater model MODFLOW, that operate at different temporal resolutions, by letting each simulate conditions for a period of time, and then feeding back the processes between the two. Similar issues are encountered when coupling SWIM with the WBalMo model, which operate on daily and monthly time steps respectively (Hattermann *et al*. 2007).

3.3 Data set availability

Developing integrated frameworks that couple climate, ecological/hydrological, and socio-economic models, also places a big demand on, and can be constrained by, the availability of, and access to, suitable data sets.

In a study investigating the impact of low river flows on potential economic losses for water users in the Elbe basin, Grossmann *et al*. (2008, 2010) describe the major effort involved in collecting data sets, so that economic losses could be modelled, this is particularly the case with respect to non-market benefits. They collected and used an impressive array of data from a variety of sources, to construct the potential losses. These sources included *inter alia*: in the industry sector data from the

Statistisches Bundesamt (STABU), on the average revenue per employee; projected changes in population development were used in the public water supply utilities and waste water treatment and recreation sectors; primary data surveys of visitor behaviour were undertaken in the recreation sector to determine willingness to pay for services; projected changes in use levels of boating in the Müritz lakes region were also used. The collection of these disparate data sources clearly represents a huge investment of time and effort, whilst at the same time raises issues of data quality and data gaps. It is however, essential to collect these data sets if this kind of integrated approach is to be taken.

Barthel *et al*. (2005, 2008), describe the extensive lengths to which they went in order to populate and construct the WaterSupply actor model in the DANUBIA DSS. This effort involved obtaining information on all water supply companies (WSC) in the Upper Danube catchment, in order to construct the WSC database. This database needed populating with information related to supply e.g. number of customers, supply area, supplied population, extraction (e.g. number of extraction sites and amounts), and also water price and the costs of water supply. This was achieved using sources from government agencies, but there were issues around data protection and inconsistencies in data collection with data rarely being available even on a monthly time step, and often was spatially aggregated to a very high level at the community, district, or even state level. Barthel *et al*. (2005), also sent questionnaires to water companies to try and obtain further information on economic and technical details, but the response rate was only 10%. To try and arrive at a satisfactory resolution for the development of the database, they also made use of annual reports, and the internet, together with some educated guesses. They state that the development of this database alone, should be seen as a valuable outcome of the GLOWA-Danube project. Similar sentiments are shared by Grossmann *et al*. (2010).

In addition to the development of the WaterSupply actor model, the Household actor model was developed, based on the concept of lifestyles. This model used socio-demographic data from Sinus Sociovision (and in spatial form from a marketing company “Microm”), to generate household actor types. The data from Sinus Sociovision divides the German population up into ten so-called social milieus, which describe basic behaviour patterns and general values. These ten social milieus were then grouped into five clusters by Barthel *et al*. (2008): socially leading milieus, post-materialists, mainstream, traditional milieus, and hedonistic milieus, such that there were five actor types in the household model. Clearly, although these data are available, it is to be expected that they are not free to use, and thus have an associated potential cost, which may hinder progress in the development of integrated frameworks, where sufficient resources are not available.

4. Overview of ecological, hydrological, and socio-economic models used in GLOWA-Elbe and GLOWA-Danube

Table 3 provides a short summary of the different ecological, hydrological and socio-economic models that are either used in GLOWA-Elbe or GLOWA-Danube, or else are mentioned in the text. The various hydrological, and ecological models mentioned in the text, require some driving data, which, for simulating future time periods comes from climate model output. Table 4 provides a summary of some of these required inputs for some of the main models.

5. Conclusion

Progress has been made in the development of integrated modelling frameworks where climate, ecological, hydrological, and socio-economic models are coupled, but only as the result of a major effort, particularly on the part of the two projects GLOWA-Elbe, and GLOWA-Danube, which are summarised in tables 1 and 2 respectively.

A major impediment to coupling socio-economic models with climate and ecological/hydrological models it would seem, both in the current relatively straightforward one-way coupling, but also in developing dynamical coupling, is the establishment and creation of suitable socio-economic models, and their reliance on having access to, and availability of, suitable data sets with which models can be developed. It is crucial that this issue is addressed, if not, development of socio-economic models in integrated model coupling frameworks will be restricted to those projects/areas that have the funds and or infrastructure to pursue such activities, but more importantly, will continue to be a weakness in the modelling approach. It may be that new or different socio-economic models that are less data intense, also need to be developed, but this in turn would have implications for the kinds of questions that could be addressed.

The coupling of different ecological and hydrological models together, and with climate and socio-economic models also involves a major effort in terms of reconciling the process resolution issue. While the work to date has focused on one-way coupling, and the difficulties involved in doing so have been highlighted, the long term aim of developing dynamically coupled models in all aspects, represents an even greater challenge and attendant effort (Nobre *et al*. 2010). For example, Osborne *et al*. 2007, in dynamically coupling a crop growth model to a climate model, describe the nontrivial task involved and the associated difficulties and trade-offs made, and the implications this might have for model accuracy of particular phenomena e.g. modelling water deficit. The issue of process resolution is further complicated when differences in spatial and temporal resolution are considered.

The resolution of these issues of data availability, process resolution, and spatial and temporal resolution will have attendant implications for the kind of question that can be asked or investigated, in integrated frameworks. Clearly, if the integrated modelling is only as ‘good’ as the least accurate model, then there may be a generalisation in the modelling, such that it is only possible to ask more general questions, or that the question can’t be answered in the same way. The development of integrated frameworks where different models are coupled (either one-way or dynamic), will clearly involve trade-offs in the level of detail that can be considered, because of these issues. If further progress is to be made in coupling climate, ecological, hydrological, and socio-economic models, then much stronger and coordinated effort, needs to be made in the collection and monitoring of the required data, and making such data sets more easily accessible, and available. This is likely to require political coordination at a number of levels. There is still a long way to go before dynamically coupled integrated modelling frameworks can be developed, but progress is being made. It may be that coordination with associated efforts in further developing integrated assessment models would prove helpful (Füssell 2010), although that too may well involve resolving a scale issue.

Table 1. Overview of studies undertaken in the **GLOWA-Elbe** project, linking climate, ecological and socio-economic models. Supplementary text describing the various socio-economic and climate scenarios is provided in sections 2.1 and 2.2.

Study	**Aim**	**Climate data/scenarios**	**Socio-economic scenarios**	**Ecological, Hydrological, Economic Models used**	**Results**
Bangert *et al*. (2008)	To understand how vegetation might change under land use and climate change.	STAR 100 (ECHAM4-OPYC3, IPCC SRES A1).	Current management practices, and fen conservation with and without climate change.	WBalMo, VEGMOS, MODAM.	Almost one third of grasslands in strongly or very strongly seasonally moist hydrotopes will be lost under climate change.
Behrendt, H., *et al*. (2008)	To understand how climate change and intensity of agricultural use might affect nutrient inputs to rivers.	ECHAM4, HadCM3, IPCC SRES B2, time period 2025-2075, used as input to WaterGAP model. STAR32.	Reference (AGENDA2000), A1 liberalisation, B2 regionalisation, climate change scenario.	WaterGAP, RAUMIS, SWIM, MONERIS, WATSIM.	Potential changes in socio-economics or from measures aimed at reducing pollution are more influential in changing N emissions than climate. Small changes in N emissions as a result of altered discharge.
Gömann H., *et al*. (2008)	To investigate the impact of climate and land use change, on land cultivation.	STAR100 (ECHAM4-OPYC3, IPCC SRES A1), for the time period 2016-2025.	Reference scenario AGENDA2000, A1 liberalisation, B2 regionalisation and mineral nitrogen tax	WATSIM, RAUMIS, SWIM, MONERIS	General increase of fallow land under climate and economic change. Reduction in N balance on the land.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Grossmann, M., (2008)	To assess the economic value of wetlands under different management strategies and climate change.	STAR 100 (ECHAM4-OPYC3, IPCC SRES A1), time period 2003-2052.	Fen conservation with and without climate change. Use the concept of net benefit for the calculation of the effect of changes in water availability, on the different economic sectors in the Spreewald area.	WBalMo	Decline in net benefit, over the 2003-2052 period, with climate and socio-economic change (cessation of lignite mining). Water management strategies will need to take into account the need for greater volumes of water to maintain current economic value of services in this area.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Grossmann, M., *et al*. 2010	To investigate the implications of low river flows for meeting societal needs in a range of different economic sectors. Develop a method to integrate economic value of different sectors into the WBalMo model, in the form of economic loss functions.	STAR T2* (2 degrees warming for Elbe basin by 2050), T2f (wetter scenario), T2d (dryer scenario). *As far as it is possible to tell the STAR T2 scenarios are the same as STAR100, but are just given a different label in the literature.	A1° and B2+ Loss functions calculated for the following sectors: thermal power plants, hydropower, industry, public water supply utilities and waste water treatment, recreation in the Lusatian Lakes, boating in the Spreewald, boating in the Müritz Lakes, pond fisheries, irrigation of agricultural crops, and fen wetlands.	WBalMo, WABI	Agriculture the biggest loser, followed by hydropower, and wetlands. Climatic factors have more effect on economic losses than socio-economic ones. Biggest share of losses is observed at only a few sites in each sector. The effects of reduced water availability will be to exacerbate existing losses rather than create new ones.
Hattermann, F., *et al*. (2007)	To investigate climate and land use impacts on water resources, and quantify the uncertainty of water availability, for analysis of crop yield and distribution.	STAR100 (ECHAM5 IPCC SRES A2), time period 2000-2050, they use the median, min and max values from the 100 simulations from STAR.	Global crop market conditions from the IPCC SRES storyline, as represented by the agro-economic model CAPRI.	SWIM, RAUMIS, CAPRI, WBalMO	C4 plants higher biomass potential under climate change than C3 plants. Non-cropped land area increases by ~12%.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Hattermann, F., Krysanova, V., and Wechsung, F. (2008)	To investigate the impact of climate and land use change on agriculture.	STAR100 STAR32 (most probable scenario in STAR100), time period 2046-2055.	Reference scenario AGENDA2000, A1 liberalisation, B2 regionalisation: mineral N tax	STAR, SWIM, RAUMIS, MONERIS	Reduction in precipitation particularly in summer, as a result C3 yields fall strongly, C4 yields fall only slightly.
Kaltofen, *et al*. (2008)	To understand how water yield might change under land use and climate change.	STAR 100 (ECHAM4-OPYC3, IPCC SRES A1), time period 2003-2052.	Base (current management), Stable and climate change, lignite mining phased out.	WBalMo	Reduction in water yield. Reduction of water availability, will lead to exacerbation of current water availability problems.
Klöcking, B, Sommer, T., and Pfützner, B., (2008)	To investigate the impact of climatic and economic change scenarios on regional water and nitrogen budgets.	STAR54 (which represents mean conditions from STAR100, ECHAM4-OPYC3, IPCC SRES A1), time periods 2018-2022, and 2045-2055.	A1 liberalisation.	ArcEGMO, MODFLOW	Area becomes drier under climate change, and precipitation more heterogeneous. Groundwater not recharged as much, but there is no reduction in N loads from agriculture.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Lorenz *et al*. (2008)	To understand how soil-water balance, fen degradation, and grassland productivity might change under land use and climate change, in the Spreewald region.	STAR 100 (ECHAM4-OPYC3,IPCC SRES A1), time period 2003-2052.	Current management strategy, and fen conservation management with and without climate change.	WBalMO, BOWAS, VEGMOS, MODAM	Water availability declines. 5% reduction in grassland productivity. Peat loss was 20% higher under climate change and current management scenario, than the scenario with no climate change. The fen conservation strategy is seen to reduce these 20% losses by less than 5%, at the sites studied. Cumulative CO_2 emissions from fen sites are 10% higher under the climate change scenario, than the no climate change scenario. Implementing fen conservation strategies would only reduce these increased emissions by ~2.5%.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Maier, U., (2008)	To investigate the effects of changes in land use, cropping patterns and adapted fertilisation strategies have on farm enterprises.	STAR100 (ECHAM4-OPYC3, IPCC SRES A1), time period 2046-2055. STAR54.	Reference (AGENDA2000), A1 liberalisation, A1K, B2 regionalisation.	SWIM for agricultural yields	All land use scenarios result in a reduction in profits, 5% in A1, 12% in B2, A1K loses 11.5%.
Messner, F., *et al*., (2008)	To develop economic valuation and transfer functions and integrate them into WBalMo, to quantify the economic value of wetlands and their services, as a result of changes in surface water availability.	STAR 100 (ECHAM4-OPYC3, IPCC SRES A1), time period 2003-2052.	A1 liberalisation, and B2 regionalisation, with and without climate change. Five different water management strategies considered also.	WBalMo	Water management strategy in the Spree-Havel is currently sub-optimal, and that increased welfare for society could be achieved through the use of water transfer policies. Profits of fisheries in the region of the Upper Spree could halve as a result of climate and socio-economic change.

Table 2. Overview of studies undertaken in the **GLOWA-Danube** project, linking climate, ecological and economic models. Supplementary text describing the various socio-economic and climate scenarios is provided in sections 2.1 and 2.2.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Barthel, R., *et al*. (2008)	Use DANUBIA to investigate the impact of changes in climate and consumer and water supply company behaviour on domestic water consumption and drinking water supply infrastructure.	MM5 IPCC B2 scenario, downscaled with observed records, and bias correction is the **business as usual** scenario. Modern day 1970-2003 as an **optimistic** scenario **Pessimistic** scenario of the 5 hottest and driest months in 1970-2003. Simulation period out to the year 2039.	Business as usual, liberalisation, sustainability.	DANUBIA (16 different natural and social science models).	Over the time period, and under the business as usual climate scenario, drinking water demand decreases as a result of changes in behaviour of customers, but also improvements in technology and water use.

Study	Aim	Climate data/scenarios	Socio-economic scenarios	Ecological, Hydrological, Economic Models used	Results
Barthel, R., *et al*. (2010)	Concept and implementation of the WaterSupply model in DEEPACTOR, a multi-actor based model of the water supply sector with a focus on water resource utilisation, and distribution of individual water supply companies. W*aterSupply* represents the link between water supply and demand, and has a focus on public drinking water supply. Use flags from DANUBIA to indicate changes in *groundwaterQuantity* and *drinkingwaterQuantity*.	Hourly climate data for the period 2011-2060, come from a stochastic weather generator in PROMET, adding a temperature and precipitation trend from the IPCC A1B scenario. To represent uncertainty they make three different assumptions about the future trend in temperature and precipitation in the Upper Danube. For each general trend they develop four subsets which contain 'critical' events, to give 12 resulting climate scenarios. Three climate trends are: IPCC regional trend, ECHAM4/REMO trend, measurements 1960-2006. The four climate variants are: baseline (average conditions), five warm winters, five hot summers, five dry years all consecutive.	Business as usual, liberalisation, sustainability.	DANUBIA (16 different natural and social science models).	Under the IPCC and 5 dry summers scenario, groundwater resource quality deteriorates appreciably. Socio-economics play a part in the decline also, although the effect of climate is greater. Drinking water quantity declines strongly under a sustainability scenario, much more so than a liberalisation scenario, where drinking water quantity remains good or very good throughout the region and time period of the study. Baseline conditions sees a moderate degradation in drinking water quantity. Increase in the number of communities that received notice of drinking water quantity deterioration increased for lower quality flags and decreased for higher quality flags.

Table 3. Summary of the various ecological, hydrological, and socio-economic models used in GLOWA-Elbe and GLOWA-Danube, either listed in table 1 or 2, or mentioned in the text. Also some other models that are mentioned in the text that weren't specifically used in the two GLOWA projects are described.

Model	Description	Reference
ACRE (Agro-eConomic model for agricultural pRoduction on rEgional level)	ACRE is a comparative static partial equilibrium model which optimises agricultural production by maximising agricultural total gross margin, and operates at the district level. Changes in policies affecting agriculture can be investigated.	Henseler *et al*., 2005
ArcEGMO (ArcInfo basiertes gegliedertes hydrologisches Modellsystem)	Model for distributed hydrological modelling, at the river basin scale, at various spatial disaggregation levels. The model is suitable for application at the meso- to macroscale, and is integrated into ArcInfo or ArcView, allowing the use of additional data sets to be easily integrated.	Becker *et al*. (2002),
BOWAS (Bodenwasserhaushaltsmodell)	A soil vegetation atmosphere model.	Wessolek *et al*. (1987)
CAPRI (Common Agricultural Policy Regionalised Impact analysis)	CAPRI is used to assess the effect of the Common Agricultural Policy (CAP) and trade policies on production, income, markets, trade, and the environment, from the global to regional scale.	http://www.capri-model.org/index.htm http://www.ilr1.uni-bonn.de/agpo/rsrch/capri/capri-documentation.pdf

Model	Description	Reference
DANUBIA	A decision support system, consisting of 16 different simulation models all integrated and coupled in the DANUBIA DSS. There are five different components in DANUBIA: atmosphere, land surface, river network, groundwater and actor.	Barthel *et al*. (2008)
GREAT-ER (Geography referenced Regional Exposure Assessment Tool for European Rivers)	A water quality model that calculates concentrations of hazardous substances released by point sources (e.g. sewage treatment plants, households), and operates at the river reach level.	Matthies *et al*. (2001)
HBV (Hydrologiska Byråns Vattenbalansavdelning)	The HBV model is a rainfall-runoff model from the Swedish Meteorological and Hydrological Institute, which calculates river discharge and water pollution, and operates at the basin and sub-basin scales.	Bergström, S. (1992)
MODAM (Multi-Objective Decision support system for Agro-ecosystem Management)	Designed for analysis of different nature protection strategies in farming.	Zander and Kächele (1999)
MODFLOW (Modular three-dimensional groundwater flow model)	MODFLOW is a three-dimensional finite difference groundwater model that was developed by the US Geological Survey. It simulates the steady and non-steady groundwater flow in an irregularly shaped flow system.	McDonald, M.G., and Harbaugh, A.W., 1988

Model	Description	Reference
MONERIS (Modelling Nutrient Emissions in River Systems)	A water quality model, which estimates nutrient emissions into river basins from point sources and diffuse pathways (7 different pathways considered), and operates at the sub-catchment scale.	Behrendt *et al*. (2000)
MOVER2.2(Model for vegetation response in floodplains)	A rule based vegetation model for the investigation of vegetation development in floodplains.	Fuchs *et al*. (2002)
PROMET (Processes of radiation, Mass and Energy Transport)	An integrative tool that models fluxes of energy and matter (water, carbon, nitrogen), at a range of spatial scales from fields to mesoscale river catchments. It consists of eight components: meteorology, land surface energy and mass balance, vegetation, snow and ice, soil hydraulic and soil temperature, groundwater, channel flow, and man-made hydraulic structures.	Mauser and Bach (2009)
RAUMIS (Regional Agricultural and Environmental Information System for Germany)	Allows regionally differentiated ex post analyses of the agricultural sector on the basis of various consolidated agricultural data sources. Ex ante policy impact analysis of medium and long term effects of changes in framework conditions e.g. agri-environmental policies, prices.	Weingarten (1995), Henrichsmeyer *et al*. (1996)

Model	Description	Reference
SWIM (Soil and Water Integrated Model)	An eco-hydrological model , which integrates hydrological processes, vegetation (crop growth), nutrients (nitrogen and phosphorous), and sediment transport at the river basin scale.	Krysanova, *et al*. (2005)
VEGMOS (Vegetationsentwicklungsmodell)	A rule based vegetation development model developed for the Spreewald in Germany. The model predicts potential vegetation on the basis of pedo-geological association, water level, land use and initial land cover.	Vater *et al*. (2002)
WABI (Wasserhaushaltsmodell)	Designed for water balance calculations for fenland areas, with regulation of groundwater. WABI calculates the water demand or the water drainage considering the precipitation-evapotranspiration balance with regard to groundwater level, soil type, and land use, and on the operation of weirs.	Dietrich *et al*. (1996)
WaterGAP (Water – Global Assessment and Prognosis)	This model is used to investigate current and future world-wide water availability, and water use, and eventually water quality. Consists of a water use model and a hydrological model.	Alcamo *et al*. (2003)

Model	Description	Reference
WBalMo (Water Balance Model, also known as ArcGRM)	Calculates the water balance between natural discharges and water use in large river basins. Includes processes of water withdrawal and release, water transfers from one region to another, and also the management of reservoirs.	Kaden *et al*. (2004)

Table 4. Climatic input parameters required for some of the main models cited in this report. Many other models mentioned in the text and in table 3, rely on outputs from the models listed below.

Model	**Input data**
HBV	Precipitation, air temperature, and potential evapotranspiration (PET). Required at a daily time step, but PET can be provided at a monthly time step.
PROMET	Hourly air temperature, precipitation, air humidity, wind speed, incident short and long-wave radiation flux (calculated from relationships with cloud cover and temperature).
SWIM	Daily precipitation, mean, minimum and maximum air temperature, solar radiation, rainfall intensity parameters.
WaterGAP	Monthly air temperature, precipitation, number of wet days, cloud cover and sunshine hours.

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