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Integrated hydro-economic modelling: Approaches, key issues and future research directions

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ABSTRACT

Integrated hydro-economic models aim to capture the complexity of interactions between water and the economy. Three main approaches are distinguished: modular, holistic and computable general equilibrium models. The latter top-down models counterbalance the traditional emphasis on bottom-up water engineering approaches. Key issues and future research directions in integrated hydro-economic modelling are discussed and illustrated through a variety of case study applications worldwide. Although the interaction works both ways, feedback effects of water changes on the economy and changes in the economy on the water system are often missing in practice. The link between water and ecology is another important future research direction.

1. Integrated modelling and water management

Water is more and more considered an economic good due to competing water use resulting in resource scarcity (e.g. Briscoe, 2005; Young, 2005). Policy demand for information about the economic value of water and the economic consequences of water management has increased correspondingly. The complexity of interactions between water and the economy can be captured through formal, mathematical models linking relevant hydrological and biogeochemical processes to economic 'laws' of supply and demand underlying the provision of scarce water services. Historically, these models have been developed by hydrologists and civil engineers, focusing on single and multiple objective decision-making and trade-offs (e.g. Dudley, 1972; Braat and Lierop, 1987; McKinney and Cai, 1997; Andreu et al., 1996; Rosegrant et al., 2000; Cai et al., 2003). Being the largest freshwater consumer in the world (FAO AquaStat, 2007), agriculture has been the prime focus of many of these models, going back to the 1960s when resource economists developed the first optimal control groundwater models for demand management in irrigated agriculture (Burt, 1964, 1966). These models often include a detailed hydrological module – and in some cases also hydraulic and biogeochemical modules — to control for the hydro-geological heterogeneity in a basin area. Node networks are typically used as graphical delineations of water flows and stocks in a watershed or river basin into different (water quantity and/or quality) balance and monitoring stations linked to specific water demand and supply. For each node, a water demand and supply function is estimated based on the geographical unit's hydro-geological and biogeochemical characteristics. In the case of agriculture, the demand and supply functions are for example based on an agronomic model, such as a crop yield function, which depends on factors like soil, crop acreage, rainfall, crop evapotranspiration and irrigation system characteristics. Economic behaviour is usually included through a profit maximization objective function, where fixed and variable production costs are subtracted from the yield benefits subject to the natural resource constraints of land and water availability. The latter is dependent on the hydro-geological conditions involved, including water supply and water quality constraints. Recent examples of engineering approaches to integrated hydro-economic modelling are found in the special issue about economic-engineering of water resources in the Journal of

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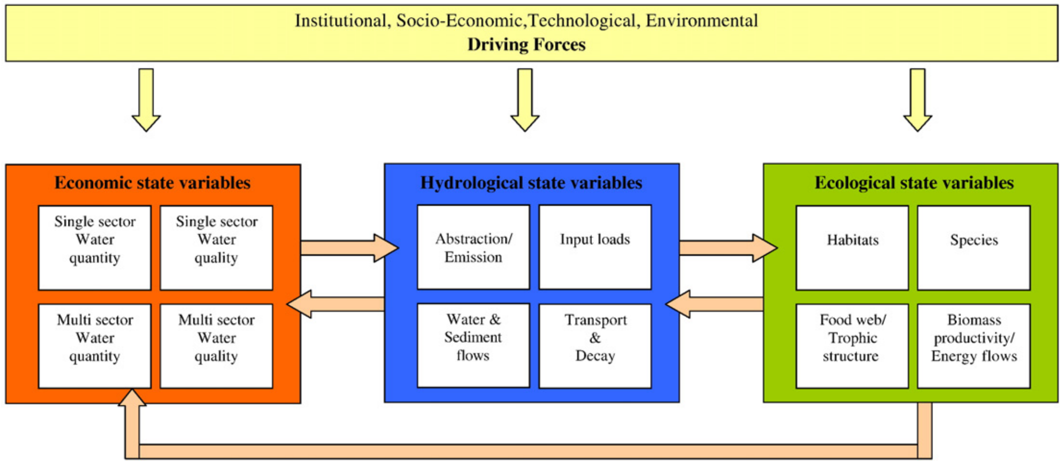

Fig. 1 – Disciplinary dimensions underlying integrated hydro-economic modelling.

Water Resources Planning and Management published in November 2006 (Lund et al., 2006).

The key to integrated hydro-economic modelling is that water systems perform economic functions, they can be used as a source and a sink for socio-economic activity, and hence have economic value. Usually after some degree of transformation, water can be used as a source for economic consumption like drinking and recreation, and in economic production as an input factor in crop and food production, energy, paper, or metal production. At the same time, water is also used as a sink for the negative by-products of economic production and consumption processes resulting in the emission of polluting substances into surface and groundwater bodies. The interaction between the hydrological and economic realm works both ways: water is transformed for economic use and the impact of economic use on water availability and quality consequently has implications in both the short and long term for the transformation process to modify water for economic use.

2. Approaches to integrated hydro-economic modelling

In the literature, a distinction is made between two different approaches to integrated hydro-economic model development, i.e. (1) models which allow for an effective transfer of information from one component to the other: the compartment or modular approach and (2) the holistic approach based on one integrated model (Braat and Lierop, 1987). In the modular approach a connection is built between the hydrological and economic model, and output data from one module usually provides the necessary input for the other.[1] In principle, the modules operate independently of each other and systems of equations are solved in an exogenous way (input variables from one model into the other are exogenous). In holistic models, variables that are exogenous in a modular approach are solved endogenously in a system of equations (Cai and Wang, 2006).

Under the modular approach, a loose connection exists between the different hydrologic and economic components. The various sub-models can be very complex and the main problem is to find the right transformation of data and information between sub-models. In the holistic approach there is one single unit with both the hydrologic and economic component tightly interwoven in a consistent endogenous model. In order to be able to solve the complexity of simultaneous equations, the different components have to be represented in a simple way (McKinney et al., 1999). So, whereas information transfer between the various compartments or sub-models is one of the most important technical obstacles in the modular approach, the most important issue in the holistic approach is to find one single solver for the variable quantities and represent both the simplified hydrological and economic component in a meaningful way.

In practice, most hydro-economic models are based on a simple economic optimization algorithm subject to detailed surface and groundwater flow processes and their impact on one or multiple economic sectors, i.e. starting from the middle hydrology block in Fig. 1 where the arrow points to the left to the economics block. Although they are driven by certain institutional and/or economic forces, their main focus is on the water system and the effect of for example water allocation problems on economic sectors. They are based on detailed node networks of water and substance balances throughout the river basin, linked to an economic activity through a demand function. This demand function often depends on fixed (exogenous) technical input–output parameters of the economic production process involved (e.g. irrigation demand from agriculture), and reflects at best a partial economic equilibrium system of demand and supply equations.

Few integrated hydro-economic models exist which are primarily driven by economic conditions and trade-offs and their impact on water system variables through water extraction and/or emissions to surface and groundwater

[1] We use the term hydrological here throughout this paper to mean both water quantity flow models and biogeophysical water quality and water allocation models.

bodies, i.e. starting from the left-hand side economics block in Fig. 1. These models are based on economic demand (consumption) and supply (production) functions, which are related to different forms of water use where water is an essential input in consumption and production processes. Examples include input–output models of direct and indirect water use (e.g. Velázquez, 2006; Okadera et al., 2006).

Even less models exist which focus on the effect of changes in eco-hydrology state variables on economic starting point conditions and economic adaptation and mitigation processes, i.e. the feedback arrow from hydrology and ecology to the economic system in Fig. 1. These models incorporate changes in the water system and their effect on the economic system. Most of these types of models are partial economic equilibrium models, based on production function approaches, where water is one of the input factors and changes in the availability or quality of water in the production process at hand is assessed through physical dose–effect relationships, which are related to market prices in order to arrive at a marginal value of water use.

Finally, 'meta-models' are distinguished as a separate class of modelling tools, used to develop and construct general frames around specific problems analyzed with the help of a variety of data, expert judgments and models. Meta-models integrate simulation results from sub-models (e.g. an economic optimization and a water quality simulation model) in a cause–effect framework. They are called meta-models because they include the results of different models, where underlying model response surfaces are summarised for example in conditional probability distributions. They lie somewhere between the holistic and modular approach. The biogeophysical and economic components are linked, but the model is usually not solved simultaneously.

3. Main objective and overview special issue

In this special issue we selected a variety of papers to represent the different methodological approaches in integrated hydro-economic modelling in modern academic research in developed and developing countries. Three groups of papers are presented based on (i) holistic, (ii) modular and (iii) Computable General Equilibrium (CGE) models (Table 1). Contrary to most holistic and modular model types, CGE models start the integration procedure from the economic system and attempt to link economic relationships to the hydrological system. We consider the use of CGE models a distinctive new approach to integrated hydro-economic modelling. The special issue aims to provide an overview of some of the key conceptual and methodological issues in integrated hydro-economic modelling, and illustrate the use

Table 1 – Special issue general overview

Paper	Water type	Water management problem	Country	Model type	Scale	Sector	Methodological focus
1. Ward and Pulido-Velázquez (2008)	SW and GW	Water supply and pollution	US	Holistic	Rio Grande River Basin	Urban drinking water	—Quantity–quality link —Water pricing
2. Cai et al. (2008)	SW	Water scarcity and allocation	Chile	Holistic	Maipo River Basin	Agriculture	—Water substitution —Upscaling to river basin
3. Pulido-Velázquez et al. (2008)	SW and GW	Water scarcity and allocation	Spain	Holistic	Adra River Basin	Urban-agricultural water demand	—Conjunctive modelling SW–GW —Scarcity value of water
4. Volk et al. (2008)	SW	Water pollution and ecology	Germany	Modular	Upper Ems River Basin	Agriculture	—GIS based data tool —Geographical scales
5. Jonkman et al. (2008)	SW	Flooding and flood damage	Netherlands	Modular	National, coast and river basin	Economy-wide	—GIS based data tool —Indirect effects —Mortality
6. Barton et al. (2008)	SW	Water pollution and quality	Norway	Modular	Morsa catchment	Water recreation	—Bayesian Belief Network
7. van Heerden et al. (2008)	SW	Water scarcity and allocation	South-Africa	CGE	National	Forestry and agriculture	—Economy-wide effects —Water taxation —Triple dividend
8. Strzepek et al. (2008)	SW	Water scarcity and allocation	Egypt	CGE	Nile River Basin	Economy-wide (agriculture, transport, tourism, power)	—Economy-wide effects —Risk premiums
9. Brouwer et al. (2008)	SW	Water pollution	Netherlands	CGE	National river basins	Economy-wide	—Economy-wide effects —Downscaling to river basin —Emission permit market

Explanatory notes: SW: Surface Water; GW: Ground Water.
CGE: Computable General Equilibrium.

and usefulness of hydro-economic models in policy and decision-making. Attention is also paid to the underlying mathematical formulation of the models, but the discussion of the simulation and optimization software and IT hardware used to run the models is beyond the scope of the special issue.

The implementation of the 2000 European Water Framework Directive (2000/60/EC) has been an important driving force behind the development and evaluation of integrated hydro-economic models in a number of European Member States (for an overview, see Brouwer et al., 2007). Some of the integrated models presented in this special issue are closely related to this new piece of European water policy legislation, such as the papers by Volk and co-authors, Pulido-Velázquez and co-authors, Barton and co-authors, and Brouwer and co-authors. However, the papers in this special issue address water management challenges facing water managers worldwide: water scarcity and water supply across different competing water use(r)s, water quality and ecology, and flooding[2]. All three holistic models focus on river basin wide water scarcity and water supply in arid regions in Spain (Pulido-Velázquez and co-authors), Chile (Cai and co-authors) and the United States (Ward and Pulido-Velázquez combine water supply with water pollution in their US example). Two of the three CGE models examine the economy-wide impacts of temporal water supply variability and water use restrictions in Egypt (Strzepek and co-authors) and South-Africa (Van Heerden and co-authors). The third CGE example by Brouwer and his co-authors shows how economic activities are linked to water pollution flows (emissions) in the Netherlands, and how national economy-wide impacts of different emission reduction scenarios run through a CGE can be disaggregated to the level of river basins.

The three modular approaches to integrated hydro-economic modelling presented in this special issue are applied to typical North-European water management problems. Two of them look at water pollution, in a watershed in Norway (Barton and co-authors) and a river basin in Germany (Volk and co-authors), and one at flooding in the Netherlands (Jonkman and co-authors). The latter two modular approaches make use of geo-referenced data in GIS as a basis for the appraisal of alternative land use change and flood scenarios, allowing variation in the scale at which the scenarios and their outcomes are evaluated and presented. The meta-model presented by Barton and co-authors is based on a Bayesian Belief Network, which implies that the appraisal includes probability distributions attached to different (expected) outcomes. Joint uncertainty of the components is calculated in one and the same model and in that sense more holistic than modular.

[2] Due to lack of space examples from Australia and Asia are missing in the special issue. Interesting hydro-economic modelling work is ongoing in Australia related to water allocation problems, including environmental demand for water and the introduction of new water trade systems (see, for example, Kirby et al. (2006) for the largest river basin in Australia, the Murray-Darling). An example of an integrated hydro-economic model in Asia is given in Ringler and Cai (2006).

An attempt was made to incorporate both groundwater and surface water models, but most papers in the special issue focus on surface water only. Only two papers (Ward and Pulido-Velázquez and Pulido-Velázquez and co-authors) focus explicitly on the conjunctive modelling of connected ground and surface water flows. Although water use in agriculture has always been one of the most important focal points in integrated hydro-economic modelling, also in many of the papers presented in this special issue, we managed to find a wider variety of sector applications including urban water supply (Ward and Pulido-Velázquez) and water-based recreation (Barton and co-authors). The latter paper also establishes important links between water pollution and ecology, as does the paper by Volk and his co-authors.

Finally, the institutional-economic aspects of integrated water management are captured in the presented models through the baseline and policy scenarios related to for example water allocation rights, the introduction of new water trade systems and the modification of existing economic instruments like water bills (Ward and Pulido-Velázquez), water taxes (Van Heerden and co-authors), water fees (Cai and co-authors), and water pollution permits (Brouwer and co-authors).

4. Key issues and future research directions in integrated hydro-economic modelling

Linking hydrological and economic systems through holistic, modular or CGE models raises a number of important methodological and operational (programming-technical) issues and challenges. McKinney et al. (1999) identify the following limitations to integrated hydro-economic modelling:

- Hydrological models are often based on simulation techniques, whereas economic models usually use optimization techniques.
- Water bodies, watersheds and basins usually are the geographical unit in hydrological models, while economic models often refer to administrative boundaries of a region (county, province, state) or a country as a whole.
- Time scales in hydrological models often refer to days, months or seasons (summer and winter), while in economic models the time scales (intervals and horizon) are usually longer than that (years).

These challenges also play an important role in this special issue, especially different spatial scales. Volk and co-authors show how a common definition of landscape units in GIS, based on the European land use database CORINE, enables them to analyze the impacts of land use change scenarios on micro, meso and macro scale using the same set of transferable hydrological indicators as a basis for the economic and ecologic impact assessment procedure. The use of geo-referenced flood and flood damage data in GIS, also partly based on land use information, allows Jonkman and his co-authors to simulate and predict the potential physical and financial damage due to catastrophic flooding in a consistent way at local, regional and national level. Cai and co-authors estimate – based on local agricultural surveys – crop production functions including water for different locations throughout the river basin. Given the hydrologic and agronomic heterogeneity found within the river basin, a single generic micro production function for the whole basin does not exist. The empirical analysis shows that the parameter estimates for the same quadratic production function differ per location. Cai and his co-authors hence use different crop production functions for the eight agricultural zones distinguished in their hydro-economic river basin model. Brouwer and co-authors apply a disaggregation procedure for the macro-economic effects of water policy scenarios estimated with the help of a CGE model to different river basins based on an integrated national and river basin accounting system.

The lack of an appropriate economic system model behind much of the integrated hydro-economic modelling work so far is another key issue addressed in this special issue. Three papers try to counterbalance the traditional emphasis in integrated hydro-economic modelling on the comprehensive modelling of surface and groundwater flow processes by showing how an economic CGE model can be extended to assess the economy-wide impacts of water policy. CGE models take into account the various inter-linkages between economic sectors and are particularly useful for the evaluation of water pricing policies. CGE approaches model economy-wide effects, but fail to capture the more detailed hydrological and biogeochemical processes involved. Hence, the trade-off is that interest in the economy-wide impacts of water policy is at the expense of the level of hydrological detail.

Van Heerden and his colleagues apply a comparative-static CGE approach to model water demand in two of the most water-intensive sectors in the South African economy: irrigated crop production and forestry. Water is included in the model through sector specific water demand functions and the introduction of a water use tax. The authors justify the application of the CGE approach by pointing out how the model is able to capture the economic mechanisms at work when a tax on water use increases crop prices, reduces crop demand and in turn water use, and provides farmers at the same time with an incentive to look for substitution possibilities, which also has an effect on water use demand and the price of other inputs.

In the paper by Strzepek and his co-authors, a comparative-static CGE is used to evaluate the economy-wide impacts of the Aswan dam in the Nile river basin. Although the dam appears to have very little effect on the economy as a whole, the use of a CGE model is useful because of the fact that the dam has an impact on multiple sectors, each competing for the same water: agriculture, commercial shipping, power generation and tourism. Water is included in a nested CES production function as a fixed land-water technology production factor. Also van Heerden and co-authors link water to land use in their model. Contrary to the two other CGE models presented in this special issue, a distinction is made by Strzepek and co-authors between seasonal water stocks and flows to account for the hydrological cycle (winter and summer) and water supply variability within one year.

Like Van Heerden and co-authors, Brouwer and his co-authors use a comparative-static CGE model to assess the economy-wide impacts of a new economic instrument to price water, i.e. the introduction of an emission permit system to reduce the emission of water polluting substances in the context of new European water quality legislation. At the same time the model is used to get a better indication of the direct and indirect economic impacts of large-scale water policy interventions. Emissions to water are in this model included as input factors in the production function of the different economic sectors, and not linked to land use.

The inclusion of water markets and the use of economic instruments is another important key issue in both the holistic and CGE models. Pulido-Velázquez and his co-authors use a holistic hydro-economic model to signal seasonal peaks in marginal values of water supply and discuss the consequences of these peaks for water pricing policy. Ward and Pulido-Velázquez investigate the impact of a two-tiered pricing system on urban drinking water demand using a dynamic non-linear programming optimization model. The two-tiered price system implies that a price is charged to urban households higher than the average cost price above subsistence levels of demand, accounting for the environmental costs of water use. The revenues of the excess price are used to subsidize the politically set level of subsistence water use. In their holistic river basin model, Cai and co-authors vary water input fees in irrigated agriculture to assess the impact of price increases on the rate of substitution between agricultural input factors.

An important difference between the holistic and CGE approaches to model water pricing is the absence of inter-sectoral linkages in most holistic models. The effect of water pricing on the general price level in the economy, and corresponding adjustments in inter-sectoral supply and demand, falls outside the scope of the analysis. The impact of changing price levels is examined for each sector separately, contrary to the modelling of demand and supply equations in the CGE models.

The reciprocal effect of changes in the water system on the economic system and vice versa the effect of changes in the economic system on the water system is one of the most important challenges in integrated hydro-economic modelling. One could argue that economic adaptation processes are implicitly part of the holistic models developed for example for water scarcity problems. Hydrological conditions and constraints determine water demand in different sectors (e.g. agriculture), and sets of hydrological supply and economic demand equations are solved simultaneously through (non-)linear programming optimization procedures. Cai and co-authors focus, for example, on water input substitutability based on imposed water use constraints. Systematic feedback mechanisms are usually missing, however, in modular and CGE approaches to integrated hydro-economic modelling. The direction of influence is usually one-way in these cases. Brouwer and co-authors show, for example, how the adoption of technical measures in economic activities have an impact on emission levels and hence water quality, but the corresponding change of water quality on these economic activities through changes in productivity, avoided damage and treatment costs or the human welfare implications of the environmental benefits involved are not accounted for. In a similar way the flood damage model presented by Jonkman and co-authors investigates the impact of climate change and flood scenarios on economic activities and corresponding damage costs, but the model does not account for changes in economic behaviour as a result of the stochastic shocks faced by the economic system. Adaptation and resilience to new circumstances based on socio-economic learning processes are expected to play an important role and may significantly mitigate the longer-term economic effects of environmental change. Except for the inclusion of endogenous rates of technological change in dynamic CGE models these learning experiences are usually not or not fully captured in integrated hydro-economic models.

Risk and uncertainty receive special attention in this special issue too. Although two distinct concepts, they are often treated as one and the same problem. Uncertainty is made 'manageable' by converting it into a risk, i.e. attaching probabilities to certain outcomes. This is for example the case in the paper by Barton and his co-authors, where uncertainties in chemical and ecological processes and model outcomes are translated into probability density functions based on empirical data and expert judgment, which are subsequently linked to water quality outcomes and economic costs and benefits related to these water quality outcomes.

Uncertainty may manifest itself in different ways in integrated hydro-economic modelling and differ fundamentally between different disciplinary realms (economics, hydrology, ecology), in terms of their underlying sources, characteristics and size. The key question here is how these fundamentally different types of uncertainty in input data, model structure, parameter values, and model results are integrated in a consistent way in the different approaches to integrated hydro-economic modelling. Scenario and sensitivity analysis are the two most common approaches, also in this special issue. For instance, Jonkman and his co-authors explicitly address the issue of uncertainty inherent to stochastic environmental shocks through the use of different flood scenarios. Risk obviously plays an important role in integrated hydrodynamic-economic modelling of flood events, linking damage assessments to the likelihood that these damages actually occur. Finally, Strzepek and co-authors present an interesting analysis of risk premiums for water security based on national income estimations from their CGE model under different risk behaviour and water supply scenarios.

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REFERENCES

Andreu, J., Capilla, J., Sanchís, E., 1996. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. Journal of Hydrology 177 (3–4), 269–291.

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management; pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecological Economics Special Issue Integrated Hydro-Economic Modelling: Approaches, Key Issues and Future Research Directions.

Braat, L.C., Lierop, W.F.J., 1987. Integrated economic-ecological modelling. In: Braat, L.C., Lierop, W.F.J. (Eds.), Integrated economic-ecological modelling. Amsterdam, North-Holland.

Briscoe, J., 2005. Water as an economic good. In: Brouwer, R., Pearce, D.W. (Eds.), Cost-Benefit Analysis and Water Resources Management. Edward Elgar, Cheltenham, UK.

Brouwer, R., Barton, D., Oosterhuis, F., 2007. Economic Methods, Models and Instruments for the Water Framework Directive. International Water Association (IWA) Catchmod Series. (Publication No.).

Brouwer, R., Hofkes, M., Linderhof, V., 2008. general equilibrium modelling of the direct and indirect economic impacts of water quality improvements in the Netherlands at national and river basin scale. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Burt, O.R., 1964. Optimal resource use over time with an application to groundwater. Management Science 11, 80–93.

Burt, O.R., 1966. Economic control of ground water reserves. Journal of Farm Economics 48, 632–647.

Cai, X., Wang, D., 2006. Calibrating holistic water resources — economic models. Journal of Water Resources Planning and Management 132 (6), 414–423.

Cai, X., McKinney, D.C., Lasdon, L.S., 2003. An integrated hydrologic–agronomic–economic model for river basin management. Journal of Water Resources Planning and Management 129 (1), 4–17.

Cai, X., Ringler, C., You, J., 2008. Substitution between water and other agricultural inputs: a holistic hydro-economic modelling analysis and implications for water conservation in a river basin context. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Dudley, N.J., 1972. Irrigation planning, 4, optimal interseasonal water allocation. Water Resources Research 8 (3), 586–594.

Kirby, M., Qureshi, M.E., Mainuddin, M., Dyack, B., 2006. Catchment behaviour and counter-cyclical water trade: an integrated model. Natural Resource Modeling 19 (4), 483–510.

Jonkman, S.N., Bočkarjova, M., Kok, M., Bernardini, P., 2008. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Lund, J.R., Cai, X., Characklis, G.W., 2006. Economic engineering of environmental and water resource systems. Journal of Water Resources Planning and Management 132 (6), 399–402.

McKinney, D.C., Cai, X., 1997. Multiobjective optimization model for water allocation in the Aral Sea basin. Second American Institute of Hydrology (AIH) and Tashkent Institute of Engineers for Irrigation (IHE) Conjunct Conference on the Aral Sea Basin Water resources problem. Tashkent, Uzbekistan. Model for Negotiations in Regional Water Resources Allocation. ASCE Water Resources Planning Management Division, 1997 Annual Conference, Houston, Texas.

McKinney, D., Cai, X., Rosegrant, M.W., Ringler, C., Scott, C.A., 1999. Modeling Water Resources Management at the Basin Level: Review and Future Directions. International Water management Institute, Colombo. (SWIM Paper 6, 71 pp.).

Okadera, T., Watanabe, M., Xu, K., 2006. Analysis of water demand and water pollutant discharge using a regional input–output table: an application to the City of Chongqing, upstream of the Three Gorges Dam in China. Ecological Economics 58, 221–237.

Pulido-Velázquez, M., Andreu, J., Sahuquillo, A., Pulido-Velázquez, D., 2008. Hydro-economic river basin modelling: the application of a holistic surface-groundwater model to assess opportunity costs of water use in Spain. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Ringler, C., Cai, X., 2006. Valuing fisheries and wetlands using integrated economic–hydrologic modelling — Mekong river basin. Journal of Water Resources Planning and Management 132 (6), 480–487.

Rosegrant, M., Ringler, C., McKinney, D.C., Cai, X., Keller, A., Donoso, G., 2000. Integrated economic–hydrologic water modelling at the basin scale: the Maipo River Basin. Journal of Agricultural Economics 24 (1), 33–46.

Strzepek, K.M., Yohe, G.W., Tol, R.S.J., Rosegrant, M.R., 2008. General equilibrium modelling of the value of the high Aswan dam to the Egyptian economy. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

van Heerden, J., Horridge, M., Blignaut, J.N., 2008. Integrated general equilibrium modelling of the impacts of water market instruments on the South African economy. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Velázquez, E., 2006. An input–output model of water consumption: analysing intersectoral water relationships in Andalusia. Ecological Economics 56, 226–240.

Volk, M., Hirschfeld, J., Dehnhardt, A., Schmidt, G., Bohn, C., Liersch, S., Gassman, P.W., 2008. Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems river basin. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Ward, F.A., Pulido-Velázquez, M., 2008. Efficiency, equity, and sustainability in a holistic water quantity — quality optimization model in the Rio Grande basin. Ecological Economics Special Issue Integrated Hydro-Economic Modelling.

Young, R.A., 2005. Determining the economic value of water. Concepts and methods. Resources for the Future, Washington DC, USA.