IWMI Working Paper

167

Review of Hydro-economic Models to Address River Basin Management Problems: Structure, Applications and Research Gaps

Maksud Bekchanov, Aditya Sood and Marc Jeuland

1985 2015

International Water Management Institute

Duke SANFORD SCHOOL OF PUBLIC POLICY

CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

Working Papers

The publications in this series record the work and thinking of IWMI researchers, and knowledge that the Institute's scientific management feels is worthy of documenting. This series will ensure that scientific data and other information gathered or prepared as a part of the research work of the Institute are recorded and referenced. Working Papers could include project reports, case studies, conference or workshop proceedings, discussion papers or reports on progress of research, country-specific research reports, monographs, etc. Working Papers may be copublished, by IWMI and partner organizations.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to *provide evidence-based solutions to sustainably manage water and land resources for food security, people's livelihoods and the environment.* IWMI works in partnership with governments, civil society and the private sector to develop scalable agricultural water management solutions that have a tangible impact on poverty reduction, food security and ecosystem health.

IWMI Working Paper 167

Review of Hydro-economic Models to Address River Basin Management Problems: Structure, Applications and Research Gaps

Maksud Bekchanov, Aditya Sood and Marc Jeuland

International Water Management Institute

The authors: Maksud Bekchanov is a Postdoctoral Fellow - Economics/Hydro-Economics at the International Water Management Institute (IWMI), Colombo, Sri Lanka; Aditya Sood is Senior Researcher – Integrated Hydrological Modeling at IWMI, Colombo, Sri Lanka; and Marc Jeuland is an Assistant Professor at the Sanford School of Public Policy, Duke University, Durham, NC, USA.

Bekchanov, M.; Sood, A.; Jeuland, M. 2015. *Review of hydro-economic models to address river basin management problems: structure, applications and research gaps*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 60p. (IWMI Working Paper 167). doi: 10.5337/2015.218

/ river basin management / hydrology / economic impact / models / water demand / water power / water resources / water management / water quality / water use / water supply / water allocation / water footprint / virtual water / international waters / groundwater recharge / reservoir storage / catchment areas / environmental flows / ecosystem services / indicators / climate change / dam construction / food security / institutions /

ISSN 2012-5763
e-ISSN 2478-1134
ISBN 978-92-9090-826-5

Please direct inquiries and comments to: *IWMI-Publications@cgiar.org*

A free copy of this publication can be downloaded at
www.iwmi.org/Publications/Working_Papers/index.aspx

Acknowledgements

The authors would like to thank Prasanna Sambandamurthy (consultant, IWMI, Sri Lanka) for her help in searching for hydro-economic modeling studies from bibliographic databases, and Yamuna Udumalagala (IWMI, Sri Lanka) for making the required papers available for reviewing. The authors are also grateful to Robyn Johnston (IWMI, Sri Lanka) and Claudia Ringler (International Food Policy Research Institute [IFPRI], USA) for their helpful recommendations, and to Joseph Perera for his valuable editorial assistance.

Project

This study was carried out under the project titled 'Basin-scale hydro-economic modeling of water-food-energy-environment nexus'.

Collaborators

This research study was a collaboration of the following organizations:

International Water Management Institute (IWMI)

Sanford School of Public Policy, Duke University, Durham, NC, USA

Donors

This work has been undertaken as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE). IWMI is a member of the CGIAR Consortium and leads this program.

Contents

Summary vii
1. Introduction 1
2. Representation of Water and Economic Systems with HEMs 2
   2.1 Categories of HEMs 3
   2.2 Basic Structure of Node-based River Basin Models 4
   2.3 Basic Structure of Economy-wide Models 6
3. Advantages and Limitations of HEMs 7
   3.1 Node-based River Basin Management Models: Simulation and Optimization 7
   3.2 Economy-wide Hydro-economic Models: IOMs and CGE Models 9
4. Review of HEM Applications 10
   4.1 Selection of Papers for Review 11
   4.2 Review of Applications of HEMs 12
   4.3 Systematic Comparison of HEMs 21
   4.4 Notable Research Clusters Engaged in Work with HEMs 37
5. Challenges and Perspectives for Future Research 40
   5.1 Issues Related to the Resolution of HEMs 40
   5.2 The Production Function Relationships in HEMs 41
   5.3 Data Challenges 41
   5.4 Visualization and Presentation of Results 41
   5.5 A Research Agenda for Extending the Utility of HEMs 42
6. Conclusion 44
References 45

Summary

Across the globe, the prospect of increasing water demands coupled with the potential for reduced water availability is calling for implementation of a range of technological, institutional, and economic instruments to address growing water scarcity. Hydro-economic models (HEMs), which integrate the complex hydrologic and economic interrelationships inherent in most water resources systems, provide an effective means of diagnosing and devising solutions to water-related problems across varied spatial and temporal scales. HEMs are powerful tools for examining potential future changes in water resources systems, and can be used to test the effects of infrastructural and policy responses developed to cope with water management problems. This study reviews recent advances in hydro-economic modeling and characterizes the types of issues that are typically explored in the hydro-economic modeling literature. HEMs are broadly classified into two categories on the basis of their structure: node-based river basin (simulation or optimization) models and economy-wide (input-output or Computable General Equilibrium) models that account for processes linked to water resources. The review highlights the primary differences in the applications and interpretations obtained using these approaches, analyzes the distribution of questions that HEMs have been used to answer, and discusses previous work and efforts to integrate across model types. Our findings suggest that additional efforts are needed to more realistically account for the range and complexity of interlinkages between water systems and society, particularly with regards to ecology and water quality, and the food and energy sectors. Additionally, the forces that depend on water and operate on the broader economy, for example in interregional trade should be investigated further. Moreover, effects on the distribution of income within countries, and on migration should be considered in basin management modeling studies. In effect, because of the inherent complexity in the economic dynamics underlying many water systems, we argue that such tools can challenge intuition and generate critical insights that are relevant to more effective management of transboundary water resources.

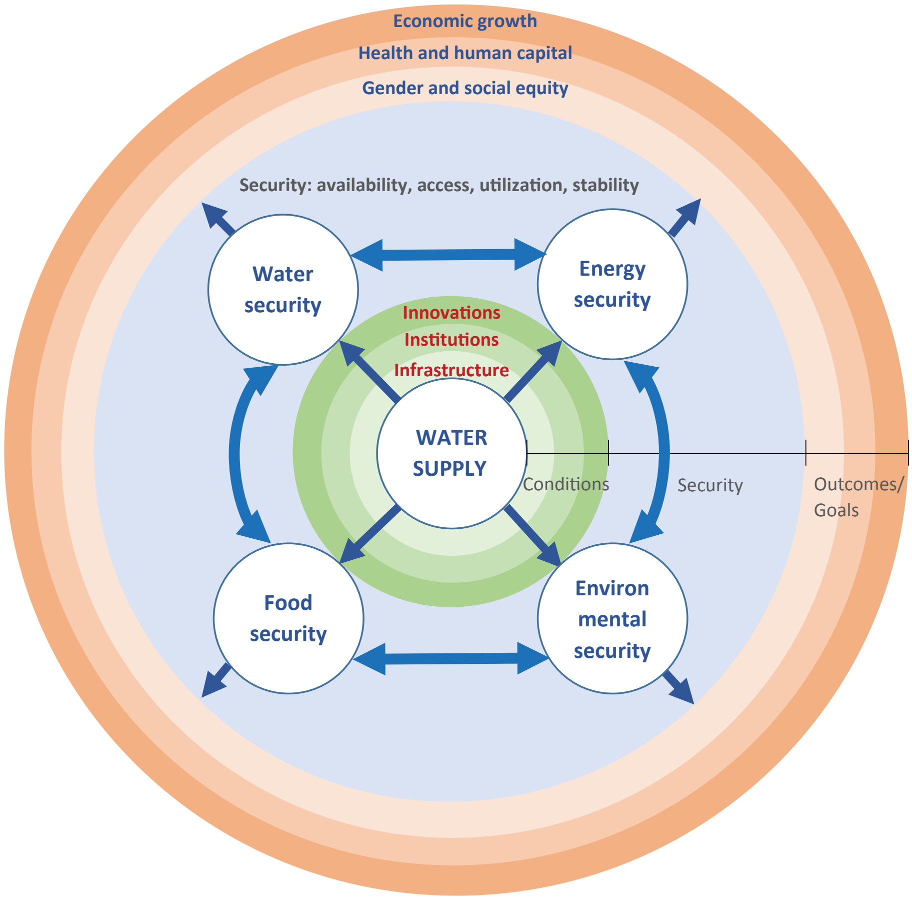
1. INTRODUCTION

The safeguarding of sustainable access to natural resources such as water at acceptable quality is a key challenge across the globe (Grey and Sadoff 2007). Population growth, increased demand for food and energy, urbanization, and industrial development exacerbate pressure on scarce fresh water resources (Vörösmarty et al. 2000; Rosegrant et al. 2002; Molden and de Fraiture 2010). As options for supply augmentation have become increasingly limited and expensive to address water scarcity, policies for water demand management have also become more common (Randall 1981; Harou et al. 2009; Rosegrant et al. 2014). Yet, efficiently managing water uses requires a careful balance of tradeoffs across a multitude of sectors such as food production, energy supply, and ecosystem services, and across space and time.

From an economic perspective, such a complex balancing of sectoral water demands requires use of a holistic approach to planning that adequately accounts for the value of integrity of the environment in water resource systems. This holistic approach should consider all interlinkages between water, energy, food production, and ecosystem services sectors (Howells et al. 2013; Bazilian et al. 2011). Furthermore, it should take a broader view of water security as it is constrained by institutions and the political economy of water utilization (e.g., efforts to maintain affordability and accessibility in local markets over time). Adding to the complexity of water systems in particular, these interlinkages relate to both economic production (for food, energy, and ecosystem services) and welfare-improving consumption (by households for various purposes, as well as natural systems), and thus to broader goals of economic growth, improvement of health and nutrition, and social equality (Figure 1). While water resources are at the core of many different production systems, these production sectors are also mutually interdependent. For example, the energy sector delivers electricity and fuel to agriculture, where it may be used for the pumping of water. In turn, the agriculture sector may produce biofuels that are then used as fuel. Agriculture and ecosystems are also closely interconnected since all agricultural activities occur within the agro-ecosystem. Soil fertility, temperature, solar radiation, rainfall, and groundwater levels determine agricultural productivity, and these environmental parameters are in turn influenced by irrigation return flows and land use change. Moreover, options for the use of water and other intermediate inputs to production are dependent on infrastructure, institutions, and technological resources.

Hydro-economic models (HEMs) are one type of decision tool that allows for an integrated analysis of the complex economic and environmental dynamics of such water resource systems (Harou et al. 2009). HEMs are typically built around a river basin, which is generally accepted as the most appropriate unit for integrated analysis since water-dependent production and environmental systems are strongly interconnected within river basins (Keller and Keller 1995; Keller et al. 1996; Ringler et al. 2004). The main components of HEMs are mathematical representations of the hydrologic relationships in the water system and the water demand and production relationships of different water-using sectors (e.g., agriculture, industry, municipal sector, and hydropower production). Early applications used a relatively simple model structure to examine a limited set of sectors and water allocation problems (f.e., Ward and Lynch 1996). As modeling techniques have progressed, however, increasingly complex and sophisticated processes, such as detailed agronomic and groundwater relationships (Cai et al. 2002), and various representations of environmental flow requirements (benefits) are now routinely included in such models (Jenkins et al. 2004; Ringler et al. 2006). This makes HEMs as effective tools to analyze river basin water use problems. In particular, such analysis sheds light on increased competition for water across economic sectors and environmental systems (Ringler 2001), potential interdependence across water users within a river basin (Wu et al. 2013), and effective and efficient water resource management to deal with issues of flooding and droughts, of impacts of dam constructions on downstream water availability.

FIGURE 1. Interlinkages between water use, economic and environmental security, and social welfare (growth, health, income and gender equity).



This study reviews the main approaches to hydro-economic modeling, and provides a systematic assessment of recent applications that leads to identification of key research gaps. The review starts with general categories and a brief description of the underlying structure of most HEMs (Section 2), which is followed by a section on more detailed description of the main approaches to hydro-economic modeling and their (dis)advantages (Section 3). Section 4 then reviews applications and trends, based on a literature survey of recent peer-reviewed publications related to the implementation of HEMs. Section 5 summarizes our findings, and describes the main research gaps that should perhaps be more thoroughly investigated and considered in future hydro-economic modeling studies. The last section describes concluding remarks.

2. REPRESENTATION OF WATER AND ECONOMIC SYSTEMS WITH HEMs

Different types of HEMs have been applied to solve various water management issues across the river basins and sub-catchments across the world. Although some problems such as increasing competition for water among economic sectors are likely common for many water resource systems, each basin also has unique features that may generate specific problems, which are different from the problems of other basins. For instance, drought is perhaps the most significant issue in the river basins in California, USA, while competition for water between irrigation and energy production is a major problem in the Aral Sea Basin. In many Australian rivers, however, the most important tradeoffs are from irrigation to the municipal and industrial sector. As for river basins throughout Brazil changes in land use (deforestation) due to increased biofuel production and livestock rearing, and its impact on water systems, is a particular issue. By converting particular river basin structures and problems into abstract modeling representations, HEMs can advance understanding of these issues and inform the development of more effective solutions that can be discussed and interpreted by different stakeholders in the decision-making process. Based on the focus of the study and considered research questions the structure of these models may substantially differ from each other. This section provides a short explanation of HEM categories before discussing the general structure of each model type.

2.1 Categories of HEMs

HEMs can be categorized into two general types. The first type are node-based river basin management models that include both simulation and optimization models (SIMOPT). The second are economy-wide models that include Input-Output models (IOM) and Computable General Equilibrium (CGE) models. Although simulation and optimization models are often considered as distinct in other reviews (Harou et al. 2009), much of the underlying structure of such models can be considered to be similar. We, therefore, group them together under the larger heading of node-based river management models. Within this group, simulation models are built and calibrated to reproduce the behavior of real water systems. Following this calibration, simulation HEMs can be used to assess different scenarios of physical or management-induced change. Optimization models, on the other hand, aim to determine a hypothetical best case (as determined by the objective function of the model) for a particular river basin – the optimal outcome may pertain to efficiency in water use, identify an optimal infrastructure development pathway, or minimize the costs of water allocation. With few changes in equations, simulation models can often be readily converted into optimization models, so long as the objective function is specified. Similarly, optimization models can easily be converted into simulation models, e.g. by removing an objective function and including the requisite model equations for specifying water distribution. Hydro-economic simulation and optimization models can also be combined to allow for more thorough testing of the sensitivity of optimal solutions than would be possible with optimization approaches alone.

Economy-wide models differ substantially from these node-based river basin models, in that they allow assessment not only of impacts in primary markets using water as an input to production. Instead, these approaches produce estimates of impacts on the broader economy (that are transmitted through secondary markets). Thus, they require a structure and data pertaining to the use of factors of production including water and intermediate goods, and provide the basis for analyzing effects on income and its distribution to different economic sectors and agents. These models, however, do not thoroughly consider water systems since restricted by high-scale spatial and temporal aggregation of variables representing the water system.

Prior to discussing the structure of each of these two model types in more detail, a brief mention of econometric models, which are widely applied in resource economics (Kaimovitz and

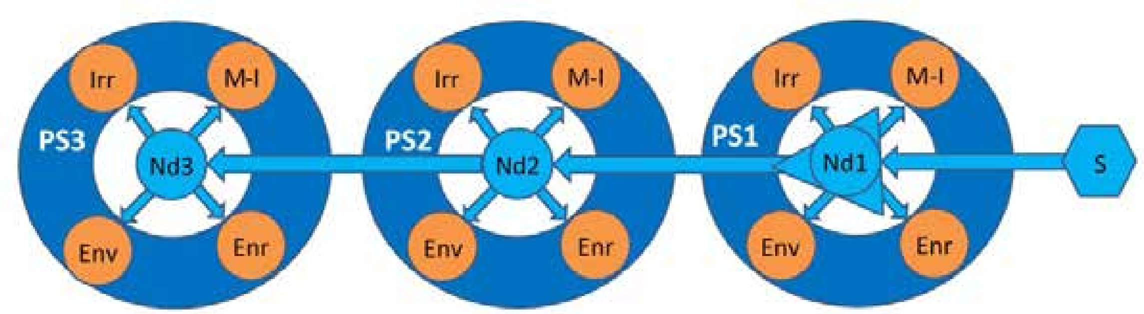
Angelsen 1998) but have thus far been sparsely used for understanding river basin management patterns is important. Indeed, such models have mainly been applied to specific problems, for example, in establishing water demand functions for different economic sectors and regions (Booker and Young 1994; Dalhuisen et al. 2003; Bekchanov et al. 2015), and for valuation of water ecosystem services (Carson and Hanemann 2005; Loomis et al. 2000). Such work can and should be integrated into river basin HEMs, but it does not provide a meaningful alternative to these at this time. This is perhaps because of the diversity of sectors involved, and the mismatch between water resources planning problems and the scale and coverage at which econometric data are typically collected. Maximum entropy econometric techniques have nonetheless been implemented to precisely calibrate complex multi-input and multi-output production functions in river basin models using a minimal amount of data (Howitt et al. 2012). In basin management modeling, econometric models could perhaps be more widely applied to characterize the statistical correlates of specific phenomena common to many river basins, e.g., extent of ecological degradation, and the relative balance of agricultural and other production. Econometric models could then be used to analyze scenarios of parameter change due to policy or other drivers, using simulation methods. In fact, improvements in data collection and analysis are expected to enhance application of econometric approaches in basin-wide water management modeling.

2.2 Basic Structure of Node-based River Basin Models

River basins or sub-catchments as modeled in HEMs usually comprise a main river and its tributaries, and their drainage areas span over different types of zones that may range from highlands (e.g., more sparsely populated mountainous and forested zones that also often receive disproportionately large amounts of a catchment's precipitation) to lowlands (that typically include greater human population and economic activity), as well as deltas (Figure 2; Table 1). Human interventions that depend on water influence and transform the natural landscape within basins, creating irrigation sites, rural/urban settlements, exploiting fisheries and recreation sites, and constructing water treatment plants, dams, and hydropower stations. These interventions may, in turn, also affect the hydrological behavior of the water resources on which they depend. Moreover, water production and consumption activities are connected to an extensive set of commodity markets and economic systems that may extend well beyond a river basin via production and market infrastructure. Water resource systems themselves may also cross political or other institutional boundaries that influence patterns of settlement and development interventions.

In water resources systems, users can be categorized into four main types: food production, municipal / industrial (M/I) sector, energy production, and environmental systems. In many systems, food production via irrigated agriculture is the most important consumer of water, especially in lower income countries. The energy sector may use water flow for hydropower production (a nonconsumptive use), irrigating biofuel crops, or cooling thermal or other power plants. Industrial and municipal users, generally, do not consume as much water but M/I water demand has been increasing in parallel with the economic development, and population and industrial growth. Environmental systems comprise a variety of ecosystems including wetlands, river banks, and lakes that depend on instream flows or seasonal inundation. Though the ecosystem services produced in these environmental systems may have low direct monetary benefits, their long-term, indirect, and nonmonetary benefits can be significant.

FIGURE 2. River node structure (a simplified example) for node-based modeling.



Notes: S – Water supply (river runoff); PS1, PS2, PS3 are production sites; Nd1 (reservoir), Nd2, Nd3 are river nodes; Irr – Irrigation; M-I – Municipal and industrial sector; Enr – Energy production including hydropower production; Env – Environmental system

TABLE 1. River basins characteristics and their representation in node-based models.

Real world characteristic or feature	**Node-based model representation**	**Mathematical formulation**
Catchment inflows (glacier melting, precipitation runoff)	Inflow nodes	Water flow input parameters
River and major tributaries	River flow nodes	River water flow (mass balance) relationships
Water users (e.g., irrigation; municipal/industrial (M/I) demand; hydropower; ecosystems; recreation and navigation)	Water withdrawal (irrigation, M/I demand sites) or nonconsumptive demand nodes	Water use-production functions or water demand constraints
Natural and man-made water control structures (lakes, surface and underground water reservoirs, dams, and dykes)	Surface water and groundwater reservoir nodes	Water balance and reservoir storage-elevation relationships
Return flows	Arrow linking water user site with drainage or river node	Return flow constraints
Groundwater recharge	Arrow linking water user site, surface water reservoir and river node with groundwater reservoir	Groundwater recharge/ discharge relationships
Production and market infrastructure	Interregional transportation routes	Commodity demand functions; export/import taxes and transport/trading costs
Political borders and water management institutions	Allocation rules, if relevant	Water or benefit allocation constraints, sectoral or regional prioritizations in water allocation

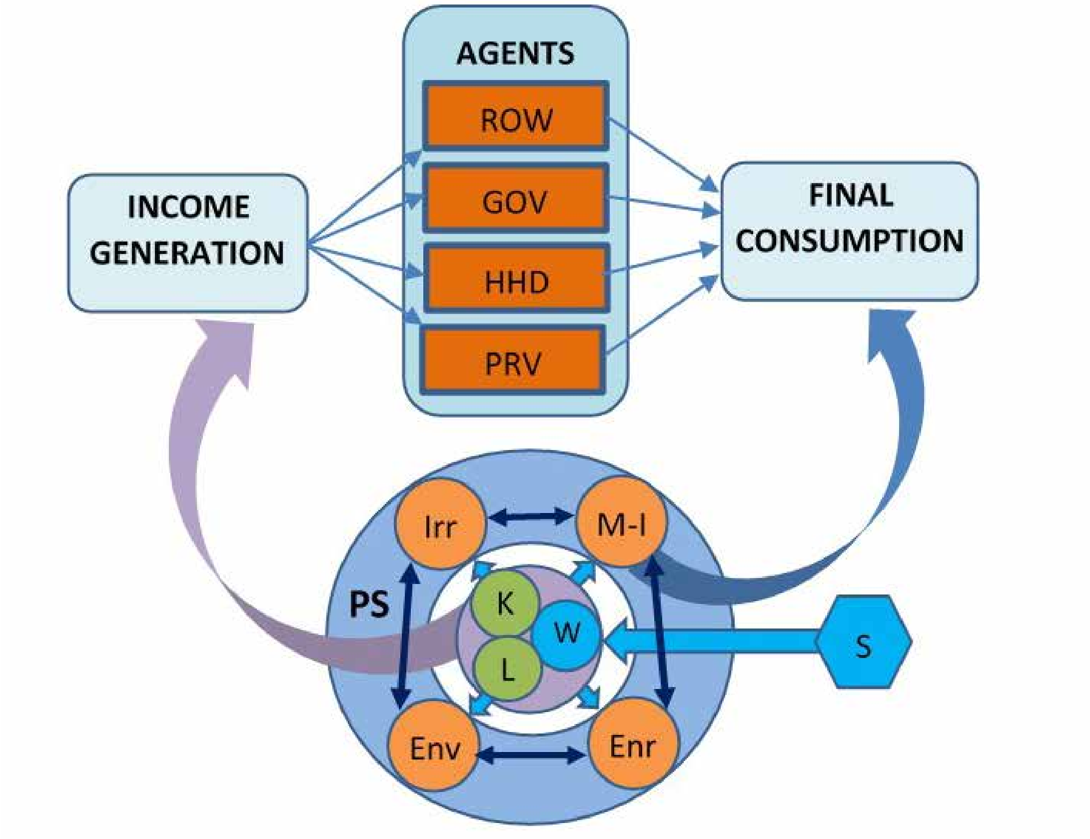
Due to the interconnectivities within water resource systems, local changes affecting a specific river reach or process may result in a dynamic set of water balance adjustments that percolate through the system. For instance, increased water supply in tributaries may cause floods that cascade downstream and affect reservoir operations. In contrast, reduced water supply in source nodes may cause droughts and demand shortfalls for downstream users, leading to reduced production. Dams or other artificial control structures can be added to a system to regulate river flows and help smooth temporal anomalies in water supply. However, upstream reservoirs can also be managed unilaterally, for instance, with the primary aim of increasing hydropower production benefits while neglecting downstream irrigation water needs. Node-based HEMs can, therefore, be used descriptively to better quantify and understand the consequences of current institutions and management practices, by asking 'what if' questions and testing their responses to different stressors or potential changes in management. Node-based HEMs can also be used to analyze the economic trade-offs among different water users, or can be used to identify efficient or more equitable water allocations (e.g., by relaxing water sharing rules and institutions, or testing the implications of institutions that aim to enhance equity). Node-based models also allow forecasting and assessment of the magnitude of various water management problems such as flooding, droughts, or competition for water (e.g., upstream and downstream users, environmental water needs versus demand for production processes, or construction of new dams or irrigation projects that have adverse environmental impacts), and provide a framework for understanding how different solutions and interventions may serve to reduce them and mitigate conflicts.

2.3 Basic Structure of Economy-wide Models

In contrast to node-based models, economy-wide models consider simplified water use relationships by including water as one factor of production in addition to capital and labor resources (Figure 3). River basins or sub-catchments are considered as single-nodes that can supply water to any economic sector that utilize it. Such models typically emphasize economic relationships, intermediate uses, and sectoral interlinkages and usually devote less attention to the spatial and temporal dynamics of water systems. Sectors (for example, industrial) are typically disaggregated to include detailed accounts. When comparing IOM and CGE models, IOMs tend to be more descriptive tools that explain static conditions, while CGE models tend to be more useful for simulating and predicting the effects of economic perturbations or input/resource-based shocks. IOMs thus usually include relationships between water uses, economic outputs, and final consumption. CGE models additionally consider price-commodity demand relationships, production functions and income generation/distribution relationships.

Incomes generated from the use of capital and labor are distributed among private enterprises and households. The government imposes taxes on production, trade, and resources, and as a main supplier of water resources may collect payments for water. The 'rest of the world' agent supplies imported goods to domestic markets and exports national commodities if the world prices are sufficiently higher than national prices. When they are linked to broader economic models, hydro-economic research questions can be extended to consider the broader socioeconomic impacts of changes in water system structure and management. For instance, analysts can use these tools to better understand the impacts of drought or infrastructural improvements (e.g., dams) on income among different types of households, or to consider the role of introducing improved irrigation technologies on poverty alleviation.

FIGURE 3. Water use and production relationships in economy-wide models.



Notes: S – Water supply (river runoff); PS – Production site; Irr – Irrigation; M-I – Municipal and industrial sector; Enr – Energy production including hydropower production; Env – Environmental system; W – Water; K – Capital resources; L – Labor resources; PRV – Private sector (enterprises); HHD – Households; GOV – Government; ROW – Rest of the world (exports/imports)

3. ADVANTAGES AND LIMITATIONS OF HEMs

In this section, uses and (dis)advantages of node-based and economy-wide HEMs are briefly described.

3.1 Node-based River Basin Management Models: Simulation and Optimization

As discussed above, simulation and optimization methods are the most widely used approaches in hydro-economic modeling. Both types of HEMs include mathematical equations that maintain hydrological mass balance and define flows along the river and to different water users, reservoirs, and consider consumption or production relationships at river nodes (e.g., water use and crop yield relationships) (Rosegrant et al. 2000).

Simulation models, in particular, are well suited to asking and evaluating 'what if' questions that are related to specific types of changes that can affect the economics of water resource systems (Harou et al. 2009). As such, they are commonly used to assess future changes in water demand, for example, based on observed population growth and irrigation expansion or stricter demand management, and to evaluate new investments in supply augmentation or physical efficiency, including technological and infrastructural improvements (de Fraiture et al. 2001; Rosegrant et al. 2005). Perhaps the most important shortcoming of simulation HEMs is the potentially infinite number of model scenarios that can arise within the often large and multi-dimensional systems being considered, which can impede identification of a best policy option in a short duration of time. This shortcoming can be reduced considerably by integrating simulation-based analysis with optimization models that answer questions about 'what is the best'. In addition, this shortcoming is somewhat balanced by the lower computational requirement of most simulation models relative to optimization, which allows much more rapid solution and generation of model output, as well as expanded possibility for considering small time steps and/or a long time horizon of implications.

Optimization HEMs are also widely used for river basin management studies (Harou et al. 2009). Such models include an objective function that is either maximized or minimized subject to the variety of economic and biophysical (mass balance or other) constraints that comprise the set of model equations described above. The form of the objective function varies substantially in the literature; many models seek to maximize the economic benefits of a particular set of water uses (Ringler et al. 2004), while others minimize the costs of agricultural production subject to some expected level of output or the marginal costs of water supply (Jenkins et al. 2004). Multi-objective functions may further combine several economic objectives together. For example, Cai et al. (2003b) proposed a multi-objective formulation that balances profit maximization with reduced inequality in water distribution across irrigation sites and maintenance of ecological sustainability. Optimization models can also be differentiated based on the stochasticity of parameters used. If fixed values of parameters are used, the models are considered as deterministic, whereas if probabilistic parameters are used, the models are considered stochastic. Many parameters in water systems, e.g. water availability, future crop prices, climate (temperature and precipitation) are, however, random variables that vary over time. When the statistical properties (mean value, standard error, variation, etc.) of such parameters are considered, the stochastic optimization HEMs provide additional information on uncertainty of the model results and policy implications.

In practice, the main approaches to optimization are normative and positive mathematical programing. Normative modeling aims to identify an ideal (optimum) that is rarely achievable but helps to define a production frontier against which the relative efficiency of various water allocation options can be compared. In contrast, positive mathematical programing is based on a calibration of the model to observed levels of water use and production. To achieve calibration that is consistent with economic theory, the model then imposes equality of marginal values of inputs across production sectors (Howitt 1995), which accounts for feedback across sectors (Howitt et al. 2012). Because of its greater relative simplicity, normative modeling is more widely used than positive programing.

Despite their widespread use in policy modeling, as optimization HEMs are considerably more difficult to solve than simulation models, they are often applied to a single representative (or for extreme circumstances in sensitivity analysis) year with a monthly time-step. This leads to critiques that optimization HEMs may fail to adequately consider the long-term dynamics of policies that are optimal in the short-term, and particularly their effects on environmental sustainability (Cai et al. 2003a). Optimization HEMs are also sometimes criticized for assuming that an optimal basin-wide solution could be implemented by an omniscient social planner. There are two potential problems with this assumption. First, important aspects of the problem may be ignored by the social planner (i.e., the model), for example, aspects related to uncertainty in river flows, water demands, or ecosystem dynamics. Second, in transboundary river basins different parties have different interests and power, and may not accept the globally optimal solution. However, it is worth noting that institutional water sharing rules can be imposed by the modeler.

There are also ways to account for interests of multiple water stakeholders instead of assuming an omniscient decision maker for the entire basin. Game theoretic approaches using optimization HEMs can accommodate the strategic interests and behavior of individual riparian countries or stakeholders (Dinar and Wolf 1997; Teasley and McKinney 2011). In cooperative games, different combinations of coalitions can be considered by changing the weights for individual country benefits in the objective function (Teasley and McKinney 2011). Upstream prioritized water distribution can be also modeled through sequential optimization of water uses that begins with maximization of economic benefits by water users located furthest upstream, followed by optimization by the next set of users in response to the first set of upstream releases, and sequential movement to the downstream (Jeuland et al. 2014). Related to this idea, an elegant approach of modeling 'use it or lose it' water distribution that favors upstream water user's interests has been recommended based on Multiple Optimization Problem with Equilibrium Constraints (MOPEC) (Kuhn et al. 2014). Other optimization approaches aimed at decentralized water management seek to calibrate actual water allocations that in reality lie somewhere along the continuum between fully uncoordinated interests that favor upstream users and basin-wide economic efficiency (Yang et al. 2012). Of course, modeling large numbers of potential coalitions and weighted interests, or the implications of sequential decisions, increases computational burden, and poses challenges for interpreting results.

3.2 Economy-wide Hydro-economic Models: IOMs and CGE Models

While simulation and optimization HEMs are well-adapted to understanding economic dynamics related to river flow and efficient allocation of water from a basin across space and time, they do not readily provide understanding of the role of water in generating indirect (forward) linkages that affect macroeconomic indicators, the distribution of income, and commodity trade. Such issues are better handled using economy-wide water management models such as IOMs and CGE models. IOMs, in particular, are used to analyze the movement and contribution of water along the commodity supply chain, as it is embedded in intermediate inputs and consumptive goods. CGEs are extended economy-wide models that additionally allow for complex adjustments in utilization of factors and production due to relationships between (endogenous) prices and production processes.

IOMs were originally developed to analyze interlinkages between primary inputs, economic production of intermediate goods, and final demand (consisting of private consumption, governmental demand, investment demand, and net exports) (Leontief 1936). Input-output models incorporating environmental (e.g., water use) accounts have been applied to estimate the water footprint of different commodities as an alternative to bottom-up approaches (e.g., Life-Cycle Analysis (LCA)) that usually only consider virtual water content at the first stage of production (Lenzen and Foran 2001; Lenzen 2003, 2009). In most IOM-based studies of the water footprint, the agricultural sector has been highly aggregated into a small number of agricultural production sectors such as crops, livestock, and forestry. Greater disaggregation into individual crops can thus allow for comparing water use footprints within agricultural sector and along different agricultural supply chains (Bekchanov et al. 2014). For a detailed analysis of supply chains of some commodities that are accounted in aggregated accounts in IOMs, hybrid IOMs that combine LCA with IOM have also been implemented (Treolar 1997; Lenzen 2002; Suh et al. 2004; Suh and Huppes 2002). Using IOM-like models such as the Ghosh model, the economy-wide impacts of reduced water supplies have been traced through the affected production (and value-added) sectors (González 2011), albeit at an aggregated and national level that does not easily lend itself to the temporally variable nature of water resource dynamics.

A particularly common application of national and international multi-regional IOMs to water issues has been for analysis of international trade of virtual water that is embedded in commodities traded across borders (Duarte et al. 2002; Velázquez 2006; Dietzenbacher and Velázquez 2007; Feng et al. 2011a). This virtual water content is estimated using data on water use intensity of commodities in either the importing or exporting country (Feng et al. 2011a). The former approach is based on an assumption that virtual water embedded in imported commodities is equivalent to that in domestically produced commodities (Lenzen 2009; Bekchanov et al. 2014), while the latter determines virtual water content based on the water use practices in exporting countries (Feng et al. 2011a). Such IOMs are then most commonly used to recommend design of policies that would encourage water saving through importing of high virtual water content commodities to water-scarce regions (Lenzen et al. 2013). Despite the advantages of IOMs in evaluating intersectoral and interregional virtual water flows, they are often overly simple, for example, as shown by the assumption of linearity in the relationship between water use and economic output, or the lack of accounting for substitution possibilities across inputs (e.g., capital, labor and water).

Some of these shortcomings can be overcome using CGE models. CGE models include a detailed accounting of economic relationships in a country or on a global scale. They allow for consideration of income generation and distribution relationships in addition to intersectoral intermediate input use interlinkages (Robinson et al. 2012). CGE models also allow for complex adjustments due to relationships between (endogenous) prices and production. In the relatively small number of applications of CGE models to problems that include water, the water input is included as one of several substitutable production factors, along with labor and capital, using a constant elasticity of substitution (CES) or Cobb-Douglas production technology. The most typical applications of these models are for the analysis of agricultural water use policies, which usually requires disaggregation of the agricultural sector account in standard CGE models (Bekchanov et al. 2012).

Currently, a majority of economy-wide models are developed at the national level and neglect the economic and physical differences across regions within a country. In contrast to node-based models, economy-wide models usually assume a single node for the entire basin or subbasin that provides water for all economic sectors. Thus, river flow and reservoir water balance relationships are largely ignored by most of the economy-wide models. Multi-regional CGE models can be used to consider the spatial aspects of water allocation in some detail, and to consider the interregional resource distribution impacts of economic policies in the water sector (Diao et al. 2004, 2008). Nonetheless, the disconnect in temporal and spatial scales between water resource systems and the political boundaries of economy-wide models continues to pose significant challenges to constructing useful economy-wide HEMs.

4. REVIEW OF HEM APPLICATIONS

As discussed, each of the model types described above have strengths and weaknesses that inform the set of specific research and policy questions to which they are routinely applied. For instance, among river basin HEMs, simulation models are most useful for scenario-based analysis and forecasting of water supply, demand, and allocation over time under specific technological, socioeconomic, demographic changes. Optimization HEMs, on the other hand, provide greater insight on tradeoffs and efficiency gains from reallocation of water among competing sectors.

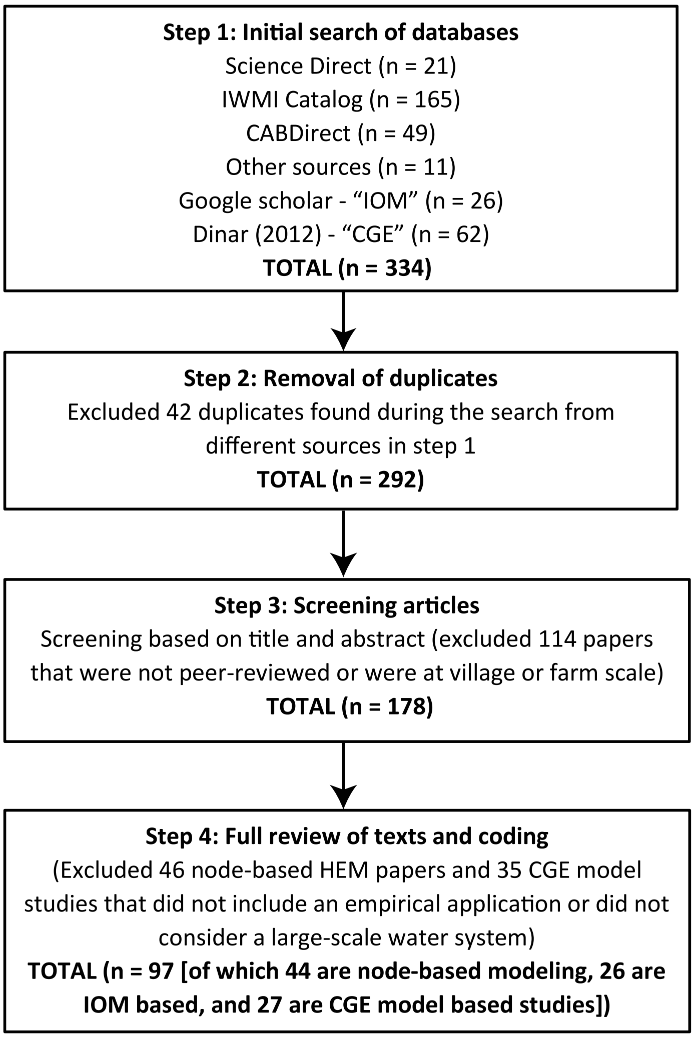
Economy-wide HEMs such as IOMs are helpful for assessing water footprint and virtual water flows embedded in products and traded commodities. CGE models can be used to analyze economy-wide and distributional effects of various water management policies or changes in water supply, e.g., due to climate change. In this section, we carry out a systematic review of applications of each of these approaches in the literature, to highlight the specific types of questions that have been most often considered using the particular modeling approach.

4.1 Selection of Papers for Review

For analyzing applications of HEMs in the literature, various search techniques were combined. This was followed by initial screening of papers prior to a detailed review. Working from the general classification of model types described in the previous section, we conducted separate searches for papers of each type. Within the category of river basin management HEMs (which includes both simulation and optimization models), papers were searched and selected from several bibliographic databases such as the International Water Management Institute (IWMI) Library Catalog, Science Direct Database, and CABDirect (Figure 4). These bibliographic searches yielded 235 papers. Within the category of economy-wide models, separate searches were conducted for papers written based on IOM and CGE models. A few highly-cited IOM studies were selected using a search in google scholar; a review of these and other more narrow searches yielded a set of additional papers that specifically address virtual water and intersectoral linkages. Thus, a total of 26 papers on IOM applications on water system analysis was included for further review. For CGE models related to water, we began from a recent paper (Dinar 2012) that reviewed 57 papers on CGE models, which also included water accounts. A few additional papers (n = 5) known to the authors were added to these studies.

After removal of 42 duplicates from different bibliographic sources 292 papers were included for further review. These papers were screened based on title and abstract and 114 papers were removed if they were not peer-reviewed or were implemented at village or farm-level. During the full review process of the selected process additional papers that do not include empirical findings, which are not at large scale (basin, subbasin and country), or are purely the analysis of hydrological system without economic assessment were excluded. Consequently, 44 papers on node-based models, 26 on IOM, and 27 on CGE models were selected for a more detailed analysis.

FIGURE 4. Selection of papers for review of river basin HEMs.



4.2 Review of Applications of HEMs

4.2.1 Node-based River Basin HEMs

River basin HEMs have been used extensively to explore various water management issues in basins throughout the world (Table 2). Intersectoral allocation of water resources is a task that is challenged by the particular economics and property rights governing water use dynamics, and the multitude of water users and interests whose collective demand contributes to growing scarcity (Hanemann 2006). Future expectations about patterns of climate change and socioeconomic factors such as population growth and economic development influence real and perceived scarcity in river basins. These in turn influence the value of adaptation strategies such as reservoir expansion and adoption of efficiency-improving technologies.

Though cost-benefit analysis and thinking about the consumer surplus benefits of public hydrological structures and operating schemes was first conducted by French engineers such as Charles Navier and Jules Dupuit as early as in 1800s, development of integrated HEMs largely grew out of the work of the Harvard Water Program that began in the 1960s. A group of academics affiliated

TABLE 2. List of node-based basin management studies analyzing water allocation problems.

#	Papers	Study area (Basin and/or region)	Research focus (objective)
1	Cai et al. 2002	Syr Darya Basin (Central Asia)	Trade-offs between the benefits of current and future generations
2	Cai et al. 2003a	Syr Darya Basin (Central Asia)	Modeling interrelationships between hydrologic, agronomic and economic components
3	Cai et al. 2003b	Syr Darya Basin (Central Asia)	A sustainable balance between irrigation management and environmental preservation
4	Teasley and McKinney 2011	Syr Darya Basin (Central Asia)	Assess the potential benefits for the riparian countries under various arrangements of cooperation
5	Gurluk and Ward 2009	Nilufer River Basin (Turkey)	Climate change impact
6	Karimi and Ardakanian 2010	Hypothetical Iranian Basin	Water demand and supply modeling
7	Ringler et al. 2004	Mekong River Basin (China, Vietnam, Thailand, Cambodia, Laos)	Water allocation trade-offs for instream and offstream uses
8	Ringler et al. 2006	Dong Nai River Basin (Vietnam)	Water market, dam construction, trade liberalization
9	Ringler and Cai 2006	Mekong River Basin (China, Vietnam, Thailand, Cambodia, Laos)	Valuing fisheries and wetlands
10	Divakar et al. 2011	Lhao Phraya River Basin (Thailand)	Different set of sectoral water allocation prioritizations
11	Yang et al. 2012	Yellow River Basin (China)	Decentralized optimization
12	George et al. 2011a, 2011b	Musi River Basin (India)	Assess different water development strategies
13	Wu et al. 2013	Ganges River Basin (India)	Dam construction and flooding control
14	Jeuland et al. 2013	Ganges River Basin (India)	Climate change and infrastructure development
15	Pande et al. 2011	Gujarat and Rajasthan (India)	Comparing optimization and autarkic water allocation
16	Y.C.E. Yang et al. 2013	Indus Basin (Pakistan)	Climate change impact
17	Mullick et al. 2013	Teesta River Basin (Bangladesh)	Trade-offs between economic efficiency and environmental protection
18	Mainuddin et al. 2007	Murray River Basin (Australia)	Compare administrative and market-based approaches of reallocating water to the environmental needs
19	Qureshi et al. 2007	Murray River Basin (Australia)	Comparing administrative and market-based acquisition of water to environmental needs
20	Connor et al. 2009	Murray River Basin (Australia)	Climate change impact
21	Grafton and Jiang 2011	Murray-Darling River Basin (Australia)	Water acquisition to environmental needs
22	Tisdell 2010	Murrumbidge Catchment (Australia)	Water acquisition to environmental needs
23	Akter et al. 2014	Macquarie Marshes (Murray-Darling River Basin, Australia)	Incorporating nonuse environmental values in HEM
24	Chatterjee et al. 1998	Central California (USA)	Trade-offs of water uses between agricultural and hydropower production sectors

Continued

TABLE 2. List of node-based basin management studies analyzing water allocation problems. (Continued)

#	Papers	Study area (Basin and/or region)	Research focus (objective)
25	Jenkins et al. 2004	California (USA)	Water scarcity costs under intra- and inter-state water markets
26	Pulido-Velázquez et al. 2004	Southern California (USA)	Conjunctive water use and water markets
27	Medellín-Azuara et al. 2008	California (USA)	Climate change adaptation
28	Howitt et al. 2012	California (USA)	Drought
29	Ward and Lynch 1996	Rio Chama River Basin (New Mexico, USA)	Trade-offs between water uses for hydropower production and instream recreation
30	Ward and Booker 2003	Rio Grand River Basin (New Mexico, USA)	Instream flow protection for endangered species
31	Ward and Pulido-Velázquez 2008	Upper Rio Grand Basin (USA)	Impact of water conservation on water withdrawals
32	Pulido- Velázquez et al. 2008	Adra River Basin (Spain)	Combined surface water and groundwater use
33	Gutižrrez et al. 2013	Middle Guadiana Basin (Spain)	Water allocation between ecosystems and agriculture
34	Hirt et al. 2012	Weser River Basin (Germany)	Nitrogen use impact
35	Rosegrant et al. 2000	Maipo River Basin (Chile)	Water rights trading
36	Cai and Rosegrant 2004	Maipo River Basin (Chile)	Technology choice
37	Maneta et al. 2009	San Fransisco River Basin (Brazil)	Drought impact analysis
38	Torres et al. 2012	San Francisco River Basin (Brazil)	Drought impact and bioethanol demand increase analysis
39	de Moraes et al. 2011	Pirapama River Basin (Brazil)	Water quality management
40	Ahrends et al. 2008	Atankwidi Catchment (Sudan)	The impact of reservoir volume/outflow restrictions
41	Jeuland 2010	Nile River Basin (Egypt)	Interlinkages among climate change, hydrology, and economy
42	Barbier 2003	Hadejia-Jama (Northern Nigeria)	Impact of upstream dam construction on downstream irrigation and agriculture
43	Kuhn et al. 2014	Lake Naivasha Basin (Kenya)	Multiple optimization problem with equi librium constraints
44	Welsch et al. 2014	Mauritius	Biofuel production futures

with the program and having engineering, economics, and law backgrounds collaborated to create a set of new and innovative integrated water resources planning and management tools. Node-based HEMs, in particular, combined engineering techniques and principles with economic theory (Maass et al. 1962). This work also introduced important ideas from stochastic hydrology, game theory, and operations research (Dorfman 1965; Rogers 1969; Fiering and Jackson 1971). Building on such contributions, hydro-economic modeling techniques spread across a variety of other academic departments in engineering and policy schools (Revelle et al. 1969; Cohon and Marks 1973; Moy et al. 1986). An important contribution to the literature was the integration of agronomic, hydrologic, and economic components within a unified modeling framework (Cai et al. 2003a). Such integrated hydro-economic models allowed for more realistic analysis of water allocation trade-offs across different uses, as opposed to relying on assumptions about the transferability of demand functions for water that had been parameterized for specific locations and at a particular point in time. As with many of the first applications of HEMs, these new integrated models were mostly applied to problems of crop production, hydropower generation, and municipal and industrial demand (Ringler et al. 2004; Divakar et al. 2011). Water use trade-offs between agricultural and hydropower production, in particular, have also been analyzed using dynamic models that seek to account for changes in supply and demand over time (Chatterjee et al. 1998). Some researchers also choose to preserve the detail of separate hydrological, energy production planning, and land use change models rather than combining them into a single integrated model, instead linking them together, e.g., for analysis of interrelationships among the water, food, and energy sectors (Bazilian et al. 2011; Howells et al. 2013; Welsch et al. 2014).

A second set of newer applications considers the potential for water transfers (using water market mechanisms) from lower-value agriculture to higher-value urban and industrial demands (Rosegrant et al. 2000). Ringler et al. (2006), for example, analyze policy scenarios that include water rights trading, dam construction, and trade liberalization to achieve more efficient water allocation among agriculture, hydropower production and industrial water uses (Ringler et al. 2006). Potential for intra- and inter-state water markets under drought have also been analyzed extensively in California (Jenkins et al. 2004; Draper et al. 2003; Newlin et al. 2002). These efforts have coincided with the implementation of water markets in several river basins and countries (Hearne and Easter 1997; Grafton et al. 2012).

A third domain of analysis using HEMs considers water use trade-offs between agricultural production and environmental systems (Mullick et al. 2013; Cai et al. 2003b; Cai et al. 2002; Gutižrrez et al. 2013). One common application in this domain is to understand the impact of changes in reservoir releases on outcomes such as instream recreation (Ward and Lynch 1996) and protection of endangered fish species (Ward and Booker 2003). Some studies frame the latter problem as one of economic losses to downstream agriculture and ecosystems, which is attributed to the construction of dams upstream (Barbier 2003) and reservoir water release regulations (Ahrends et al. 2008). Some others, however, consider the value of dam construction for reducing downstream flooding (Wu et al. 2013; Jeuland et al. 2013). In Australia, there has been extensive analysis of the socioeconomic and environmental implications of increasing environmental flows under alternative allocation regimes, e.g., administrative versus market-based water allocation (Mainuddin et al. 2007; Qureshi et al. 2007; Tisdell 2010; Grafton and Jiang 2011). Most of these studies only consider the economic effects of imposing minimum environmental flows. A much smaller body of work considers functional relationships between water flow and the production of environmental benefits, as in Ringler and Cai's (2006) work on fishery and wetland services in the Mekong River Basin. More precise estimation of environmental flow and benefit relationships was conducted using extensive surveys in the Macquarie Marshes in Australia (Akter et al. 2014).

Fourth, another fairly recent set of applications considers the conversion of agricultural land to production of crops for use as biofuels, and sensitivity to fluctuations in water availability (e.g., drought). Particularly, the impact of the expected increase of world market prices for biofuel commodities on sugarcane production and profits of small and large farms (Torres et al. 2012) and soybean land use changes under drier conditions (Maneta et al. 2009) has been studied. Unsurprisingly owing to the growing interest in biofuels in Brazil and the US, much of this work focuses on these and similar regions (Torres et al. 2012; Maneta et al. 2009).

Fifth, there is an increasing interest and modeling of the effects of climate change on the economic benefits derived from water resources systems. Many of these studies focus on sensitivities to changes in water supply, via its impact on physical hydrology, crop production, food prices, and farm income. For example, in the Indus Basin (Y.C.E. Yang et al. 2013), Murray

River Basin (Connor et al. 2009), Nilufer Basin (Gurluck and Ward 2009), and Nile Basin. Others have considered how the benefits of planned water infrastructures (e.g., dams) might be affected by the effects of climate change (Jeuland 2010; Jeuland et al. 2013). Under this broad umbrella of climate change applications of HEMs, many applications consider the economic value of adaptation strategies to cope with perturbation of water supplies, via responses that include conjunctive use of surface water and groundwater (Pulido-Velázquez et al. 2004, 2006, 2008), adoption of more efficient irrigation technology (Ward and Pulido-Velázquez 2008; Cai and Rosegrant 2004), and new dam construction (George et al. 2011a, 2011b).

It is noteworthy that very few HEMs have been used to consider the quality aspects of water allocation decisions. In this domain, the effects of nitrogen discharge taxes on groundwater contamination and riverine water quality has been assessed for the Weser River Basin in Germany (Hirt et al. 2012). Water and salt salinity impacts on crop growth, groundwater quality, and surface water quality have likewise been analyzed for the Syr Darya Basin (Cai et al. 2003a). More advanced analysis of interrelationships between agricultural, industrial water uses and water contamination has been conducted for the Pirapama Basin in Brazil (de Moraes et al. 2011).

4.2.2 IOMs

As discussed briefly above, application of IOMs to problems in the water sector has mostly analyzed the virtual water content of products and water footprints of economic sectors or nations. Virtual water is defined as the amount of water required to produce products while the water footprint is defined as the virtual water embedded in final consumption of a commodity (H. Yang et al. 2013). Virtual water trade has been proposed as an option to reduce water scarcity in arid areas, which would then import crops or products with high water footprints as an alternative to domestic production (Allan 1997; Hoekstra and Hung 2005). Initially, virtual water content and water footprint analysis of food crops were mainly conducted based on bottom-up approaches such as Life Cycle Assessment (LCA). International virtual water flows have been analyzed to assess water saving potential through changing international trade patterns (Chapagain et al. 2006). At river basin scale, the virtual water content of different agricultural products and virtual water trade balances have been estimated for systems in the European Union (EU), to explore the potential for water saving (Vanham 2013). For example, an analysis of the Guadalquivur River Basin (Spain) explored the sectoral water reallocation in relation to the virtual water content of agricultural commodities that could be efficiently moved across space (Montesinos et al. 2011). In the same basin, the dynamics of surface water and groundwater content of commodities has been analyzed to assess the potential for improved efficiency through conjunctive use of water resources (Dumont et al. 2013).

The addition of detailed environmental accounts to the IOM framework has also facilitated the integrated assessment of water footprints for a set of economic commodities extending beyond the agriculture sector (UN, Eurostat, IMF, OECD and World Bank 1993; Feng et al. 2011a; H. Yang et al. 2013; Table 3). Using this integrated framework, researchers have estimated the water footprint of commodities (both direct and indirect water uses) produced by different economic sectors in many countries and regions, including Australia (Lenzen 2003), Andalusia in Spain (Velázquez 2006), China (Zhao et al. 2009) and Uzbekistan (Bekchanov et al. 2014). One of the major research objectives of such studies has been to identify sectors with low virtual water requirements and high economic potential in water scarce zones (Duarte et al. 2002; Lenzen 2003; Bekchanov et al. 2014). This work is complemented by the estimation of national virtual water trade balances in many of the same regions, e.g., Andalusia in Spain (Dietzenbacher and Velázquez 2007), Australia (Lenzen and Foran 2001), China (Zhao et al. 2009) and Uzbekistan (Rudenko et al. 2013). Another set of studies consider more explicitly issues of intersectoral water flows and virtual water multipliers[1] (Velázquez 2006; Wang et al. 2009). Water footprint analysts have also made a case for differentiating blue and green water sources, since blue water resources figure more prominently in water reallocation and saving policies (Antonelli et al. 2012). Relatively few studies have considered the dynamics of virtual water uses over time (Zhang et al. 2012).

Except water footprint analysis, IOM-based studies have also considered the effects that policies or interventions might have on economic production and water consumption. For example, Llop (2008) assess the effect of introducing a water tax and improving water use efficiency on water consumption and production levels. The change in income multipliers due to dam construction has also been considered in the case of the Bakra Dam in India using a Social Accounting Matrix simulation model (Malik 2007). The Ghosh model has been used to project the impact of reduced water supplies on economic output and value added across sectors (Gonzales 2011).

Since water availability and allocation is spatially and temporally heterogeneous within countries, national IOMs cannot easily consider virtual water flows and policies to reduce water scarcity at regionally-relevant scales. Multi-regional IOMs help to address at least the spatial limitations of these country models (Zhang et al. 2011a, 2011b), for example, in the UK, where multi-regional IOMs have been used to estimate water use intensities and to identify sectors with higher than average backward and forward linkages (Yu et al. 2010). Multi-regional IOMs have also been applied to estimate interregional virtual water trade flows in Australia (Lenzen 2009), and to analyze water footprints in China (Wang and Wang 2009; Zhang et al. 2011a). Wang and Wang (2009) analyze the dynamics of virtual water trade flows, while Zhang et al. (2011a) addressed internal and external (across provinces) water footprints, for Beijing. Other studies consider the impact of virtual water trading on water scarcity and ecosystem damages (Feng et al. 2014), and the virtual water export and pollution effects of commodity trade between North and South China (Guan and Hubacek 2007). Multi-regional IOMs have been also implemented to analyze virtual water trades at basin scale, e.g., for the Yellow River Basin (Feng et al. 2011b; Okadera et al. 2014), as well as across a larger set of regions, e.g., considering 30 provinces of China (Feng et al. 2014; Zhang and Anadon 2014).

TABLE 3. List of IOM studies analyzing virtual water and water footprint problems**.**

#	Papers	Study area	Research focus (objective)
1	Lenzen and Foran 2001	Australia	Water footprint and virtual water trade
2	Lenzen 2003	Australia	Key sectoral interlinkages
3	Lenzen 2009	Australia	Inter-regional virtual water trade flows
4	Bekchanov et al. 2014	Uzbekistan	Sustainable sectoral transformation
5	Rudenko et al. 2013	Uzbekistan	Cotton value chain development
6	Malik 2007	Punjab (India)	Dam construction impact on income multipliers
7	Guan and Hubacek 2007	China	Virtual water export and pollution effects of commodity trade
8	Wang et al. 2009	Zhangye city (China)	Water footprint, intersectoral virtual water flows, virtual water trade
9	Wang and Wang 2009	China	Analysis of dynamics of virtual water trade

Continued

TABLE 3. List of IOM studies analyzing virtual water and water footprint problems.(Continued)

#	Papers	Study area	Research focus (objective)
10	Zhao et al. 2009	China	National water footprint intensity
11	Feng et al. 2011b	China	Water footprint and interregional virtual water trade flows
12	Zhang et al. 2011a	Beijing (China)	Internal and external water footprints
13	Zhang et al. 2011b	China	International trade impact on water resources
14	Zhang et al. 2012	Beijing (China)	Internal and external water footprints
15	Feng et al. 2014	China	Virtual scarce water flows and their impact on ecosystems
16	Okadera et al. 2014	China	Water footprint assessment based on closed and open economy models
17	Zhang and Anadon 2014	China	Water footprint and interregional virtual water trade flows
18	Duarte et al. 2002	Spain	Key sector analysis based on Hypothetical Extraction Method
19	Llop 2008	Spain	Taxing water use
20	Velázquez 2006	Andalusia (Spain)	Intersectoral virtual water flows
21	Dietzenbacher and Velázquez 2007	Andalusia (Spain)	Water footprint and virtual water trade
22	Gonzales 2011	Catalonia (Spain)	Economy-wide impact of reduced water supply
23	Antonelli et al. 2012	Mediterranean region	Direct and indirect water consumption differentiated by green and blue components
24	Yu et al. 2010	UK	Regional and global water footprints
25	Chen et al. 2012	Global	Virtual water content of commodities across the globe
26	Lenzen et al. 2013	Global	International virtual water trade flows

Finally, at a global scale, virtual water flows embedded in international commodity trade have been assessed using a global multi-regional IOM (Chen et al. 2012). Lenzen et al. (2013) conduct a similar analysis but use a more consistent and disaggregated IOM to determine the virtual water content of consumption across countries, and to evaluate its impact on water availability for environmental systems in exporting countries (Lenzen et al. 2013).

4.2.3 CGE Models

As discussed above, IOMs have been used for very limited types of analyses. In contrast, CGE models are more powerful tools that can be used to assess a broader set of policy questions. In fact, these models have been widely used for analyzing the impact of water supply reduction, changes in water pricing, and infrastructure improvements on sectoral water uses, economic output, income distribution, final consumption, prices, and foreign trade (Table 4). For example, studies have considered the effects of water pricing reform on water use by different sectors, sectoral incomes and economic outputs in Morocco (Diao and Roe 2000, 2003) and South Africa (van Heerden et al. 2008; Letsoalo et al. 2007). Similarly, the economic gains of introducing water rights trading has been discussed for Morocco (Diao et al. 2004), South Africa (Hassan and Thurlow 2011), and Australia (Peterson et al. 2005; Smajgl et al. 2006, 2009).

CGE models may also enhance assessment of the economics of virtual water trade, which is the most common water-related application of IOM-based analyses. Berrittella et al. (2007) use CGE models to explore how virtual water dynamics respond to changing water supply conditions and trade policies. Unlike the global multi-regional IOMs that assume a linear relationship between water use and economic output, such models more flexibly account for substitution across factors.

Unlike the IOMs that also typically focus on static conditions, CGE models can be used to quantify the economic impacts of reduced water supplies (due to climate change or other causes) on economic outputs and water allocation. Applications span locations such as Australia (Smajgl 2006; Dixon et al. 2011; Horridge et al. 2005), and the US (Rose and Liao 2005). CGE models also better allow analysis of the economy-wide impacts of infrastructure or technology improvements that relate to physical efficiency, e.g., in aquaculture (Kaliba et al. 2007), or relate to new dam construction (Strzepek et al. 2008). In an effort to predict future economic changes that relate to water systems, several CGE model studies consider multiple scenarios. For instance, Robinson et al. (2012) analyzed a package of climate change adaptation options including infrastructural improvements and construction of water storage facilities under conditions of reduced water availability in Ethiopia. Qureshi et al. (2012) analyzed the effects of water rights trading and desalination investment on water use, employment, sectoral economic output and interregional migration, in the context of growing water demand in Australia. The effects of a variety of changes in policy (including water taxation, liberalization of international trade, and irrigation efficiency improvement) and water supply on income, water use, virtual water flow, and welfare have been addressed by Berrittella et al. (2007, 2008a, 2008b) and Calzadilla et al. (2010, 2011a, 2011b) using global multi-regional CGE models (GTAP-W). Recently, Liu et al. (2014) combined a more detailed partial equilibrium model – IMPACT-WATER – with the GTAP-BIO-W CGE model to analyze the impact of reduced irrigation on crop production, international trade, and welfare levels.

TABLE 4. List of economy-wide CGE studies analyzing water allocation and trade issues.

#	Papers	Study area	Research focus (objective)
1	Horridge et al. 2005	Australia	Drought impact
2	Peterson et al. 2005	Murray-Darling River Basin (Australia)	Irrigation water rights trading
3	Smajgl 2006	Great Barrier Reef (Australia)	Relationships between water use reduction, fertilizer application, ecological habitat, and touristic benefits
4	Smajgl et al. 2006	Northeast Queensland (Australia)	Trade-offs between sugarcane production and environmental flows
5	Smajgl et al. 2009	Great Barrier Reef (Australia)	Multi-agent framework to analyze the impact of water policies on water uses, outputs, and erosion across farms
6	Dixon et al. 2011	Murray-Darling River Basin (Australia)	Environmental flow acquisition

Continued

TABLE 4. List of economy-wide CGE studies analyzing water allocation and trade issues. (Continued)

#	Papers	Study area	Research focus (objective)
7	Qureshi et al. 2012	Australia	Income and employment impacts of water rights trading and establishing desalination plants
8	Seung et al. 2000	Nevada (US)	Water transfer for recreation purposes
9	Goodman 2000	Arkansas Basin (US)	Comparing reservoir expansion and rural to urban water transfer
10	Rose and Liao 2005	Portland Metropolitan Water System	Economy-wide effects of earthquake and water distribution system disruptions
11	Gómez et al. 2004	Balearic Islands	Comparing water rights trading, water desalination, and rural to urban water transfer
12	Diao and Roe 2003	Morocco	Linkages between trade liberalization and water market policies
13	Diao et al. 2004	Morocco	Economy-wide impact of water markets
14	Roe et al. 2005	Morocco farm-level policies	Feedback links between economy-wide and
15	Kaliba et al. 2007	Ghana, Kenya, Tanzania	Aquaculture expansion and poverty reduction
16	Strzepek et al. 2008	Egypt	Dam construction impact
17	Letsoalo et al. 2007	South Africa	Water pricing
18	van Heerden et al. 2008	South Africa	Taxes on water demand by forestry and irrigation
19	Hassan and Thurlow 2011	South Africa	Intra- and inter-regional water rights trading
20	Robinson et al. 2012	Ethiopia	Climate change adaption measures
21	Berritella et al. 2007	Global	Virtual water trade flows
22	Berritella et al. 2008a	Global	Trade liberalization and water uses
23	Berritella et al. 2008b	Global	Water pricing
24	Calzadilla et al. 2010	Global	Green and blue water uses and international trade
25	Calzadilla et al. 2011a	Global	Climate change and trade liberalization policies
26	Calzadilla et al. 2011b	Global	Irrigation management improvements and international trade
27	Liu et al. 2014	Global	International trade impact of reduced water supply

Source: Authors' elaboration based on previous review (Dinar 2012) and cited papers.

Although the core of the CGE model is often similar across studies, applications to water problems often require additional components to produce accurate representations of the behavior and responses of hydrological and biological systems. One of the most common linkages is to farm production models, which allows a more detailed and realistic analysis of the agricultural production sector, and its relationships with macroeconomic outcomes, interregional production and trade (Diao and Roe 2000, 2003; Diao et al. 2004; Robinson et al. 2012). Several studies have combined CGE models with food web models (Smajgl 2006), hydro-economic models (Dixon et al. 2011; Smajgl 2006), multi-agent based models (Smajgl et al. 2009), and surface water and groundwater balance models (Smajgl et al. 2006), to analyze the complex relationships between agricultural production and water systems ecology. Other efforts have led to consideration of water use tradeoffs between the forestry and other production sectors (van Heerden et al. 2008), between recreation and irrigation (Smajgl et al. 2006; Seung et al. 2000), as well as those induced by expansion of aquaculture production (Kaliba et al. 2007). Poverty reduction (Kaliba et al. 2007) and interregional migration (Qureshi et al. 2012) due to change in water availability and water policies have also been addressed within the CGE framework.

4.3 Systematic Comparison of HEMs

Following selection of the papers and summarization of their contents as discussed above, the HEM applications in each category and model type (e.g., node-based vs. economy-wide models) were systematically reviewed according to a set of specific comparison criteria. The criteria included:

a) main themes studied (these include intersectoral water allocation; sectoral adjustment (expansion or contraction); virtual water content/water footprint; virtual water trade; change in environmental flows; climate change/change in water supply; dam/reservoir impacts; water use efficiency: water markets and other price instruments; water use efficiency: non-price instruments; water-energy-food nexus; trade liberalization; sustainable groundwater abstraction; and water quality and ecosystem services);

b) frequency of specific scenarios analyzed under those main themes (specifically, scenarios of: water supply change [climate change, drought, change in water supply]; water allocation options; storage infrastructure change [dam construction, reservoir capacity expansion, water release regimes], water supply enhancements [desalination, waste water reuse, etc.], efficiency technology and infrastructure [conveyance, irrigation efficiency improvement, infrastructural investments], extent of water rights trading, water pricing rates, environmental flow requirements, increased water demand [aquaculture, biofuel expansion], non-price instruments limiting water use/pollution, market distortions [e.g., subsidies, trade barriers], taxation of water uses/pollution);

c) key indicators of impact (specifically: i. economic impacts, on overall and sectoral value added; employment; equivalent variation of welfare/income multipliers; consumption; ii. price effects through water shadow price [marginal value], returns to land, capital, and labor; iii. trade impacts through exports/imports/trade balance; iv. water allocation impacts, to irrigation; to urban users; from groundwater; v. intersectoral linkage impacts through virtual water export/import/net export; direct, indirect and total water consumption coefficients; national water footprint and intersectoral virtual water flows; forward and backward linkage indexes and vi. other outcomes, such as on ecological indicators [e.g., water quality/salt discharge/external costs of salinity, ecological habitat]; agricultural cropping area; water saving and water use efficiency);

d) sectors (agriculture; hydropower; municipal and industrial; services; fisheries/aquaculture; recreation; and livestock);

e) water use sources considered in the model (surface water, groundwater, precipitation, return flow reuse, desalination);

f) production function relationships (Linear, Cobb-Douglas, logarithmic, CES, etc.);

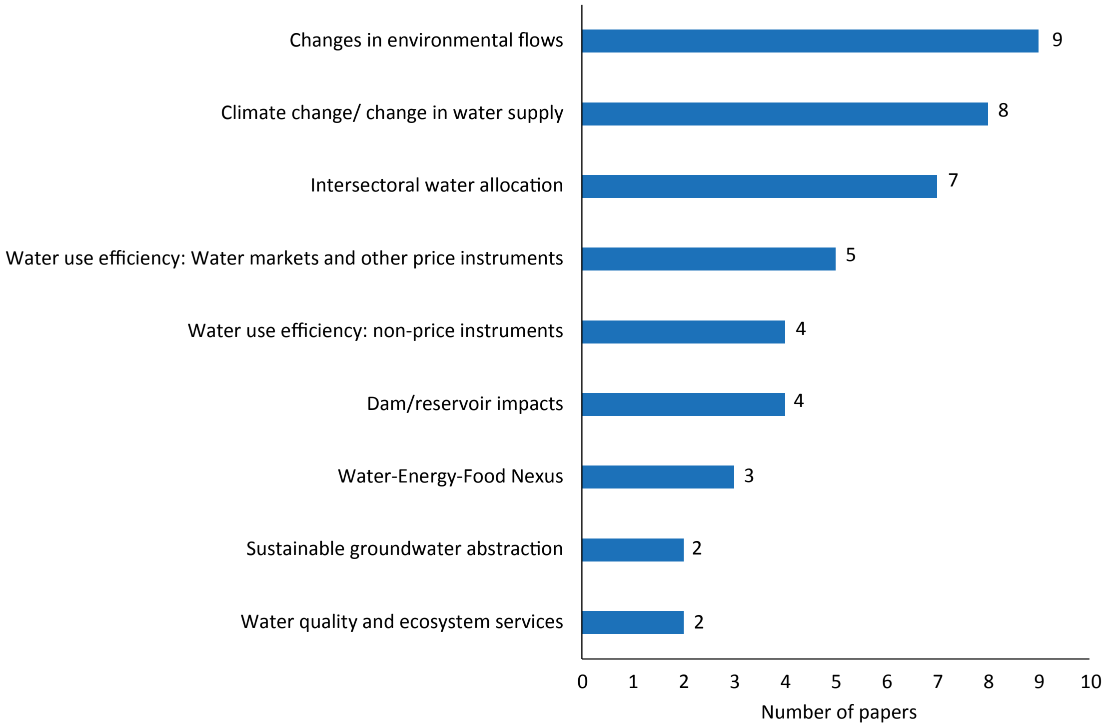
g) model structure (static *vs* dynamic, deterministic *vs* stochastic, etc.); and

h) geographic domain (basins, sub-catchments, and countries considered).

4.3.1 Main Themes

Summarizing the set of applications reviewed in this paper, we find that the majority of node-based HEM applications have been focused on the economic implications of increased environmental flows in water-scarce environments (Figure 5). A large number of studies have also considered water system impacts of, and adaptation to, climate change, as well as intersectoral water allocation problems, including some consideration of allocation institutions (e.g., administrative vs market-based). Several studies focus on price (including water markets) and non-price instruments of improving water use efficiency and the impact of dams and reservoir releases on downstream water availability and ecosystems. Much rarer are studies that: a) address the interlinkages between the water, energy, and food sectors; b) consider conjunctive use of both surface water and groundwater resources and sustainable groundwater abstraction in dry areas; and c) focus on water quality management problems.

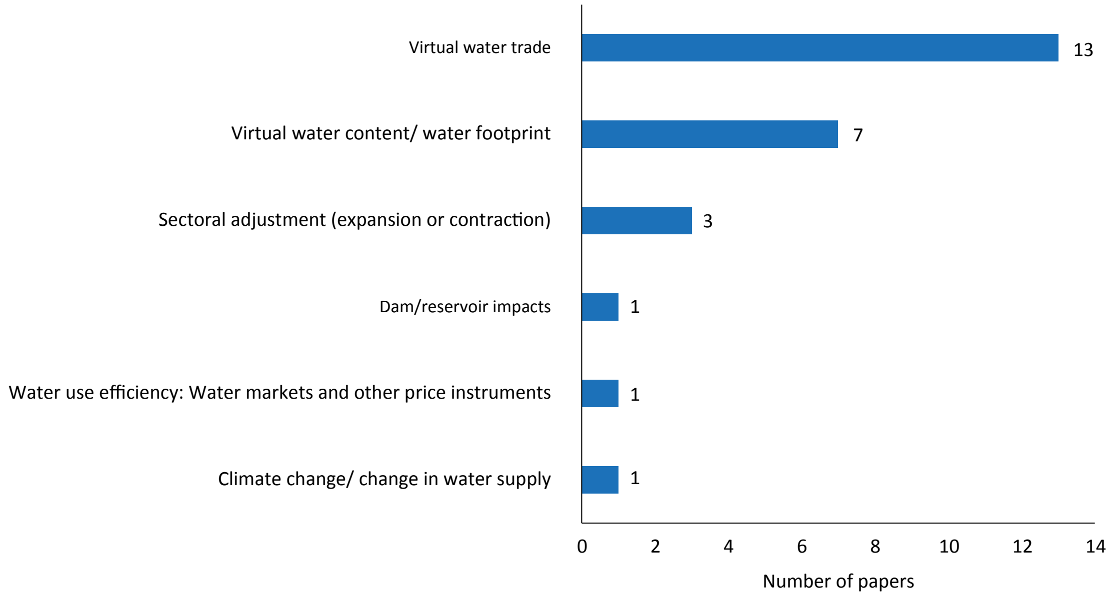
FIGURE 5. Main themes in node-based modeling papers considered in this review.



Note: A total of 44 papers are included above.

Analyzing input-output modeling studies, we note that 13 out of 26 studies focused on virtual water trade relationships (Figure 6). IOMs are also often used for virtual water content and water footprint analysis. Very few studies have used IOMs as simulation tools to estimate the effects of water pricing policies, dam construction or water supply disruptions (e.g., drought) on incomes, ecosystems area losses, and pollution. Since IOMs consider linear relationships between economic output and final consumption, researchers must consider the results of IOM-based simulation models with caution. Nevertheless, the input-output tables provide essential and very useful database for more sophisticated models such as CGE models.

FIGURE 6. Main themes in IOM studies.

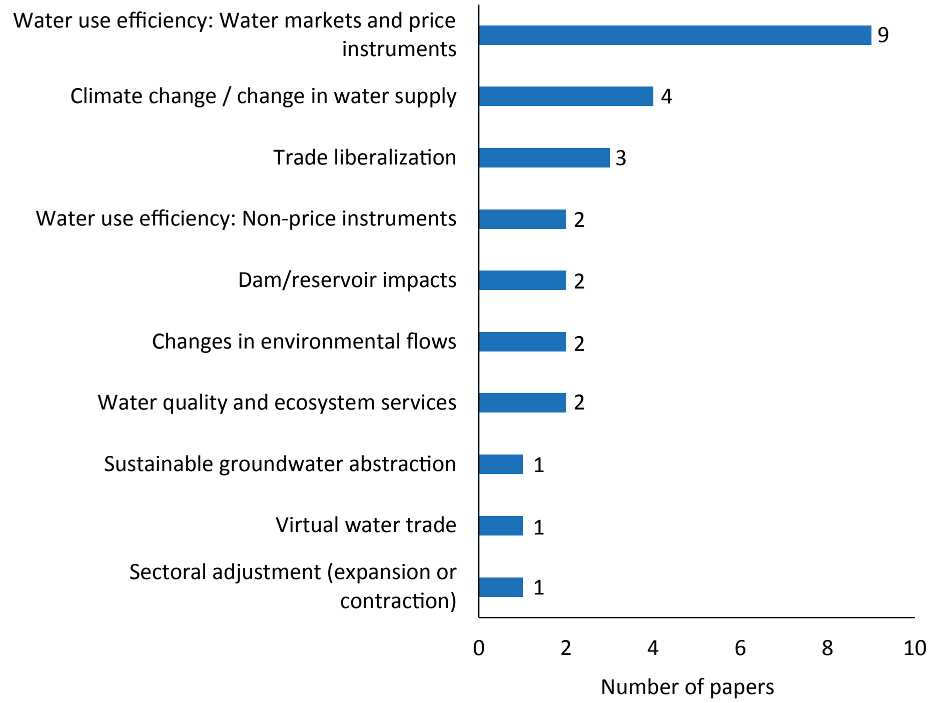


Note: A total of 26 papers are included above.

Analysis of the CGE modeling studies indicates that the majority of these papers focus on water rights trading and pricing mechanisms for improving water use efficiency (Figure 7). Reduced water availability due to climate change or droughts has also been frequently considered. Several studies have addressed technical options for water supply enhancement, e.g., through dam construction or water quality improvement, or non-price instruments for improved water use efficiency, particularly in irrigation. A very few CGE modeling studies explore conjunctive use of different water sources, sectoral expansion (e.g., of aquaculture), and virtual water trade. In the future, CGE models will likely be more heavily used in virtual water analyses instead of IOMs, given that the latter oversimplify essential relationships between non-water factors and production levels, and neglect diminishing returns of increased input.

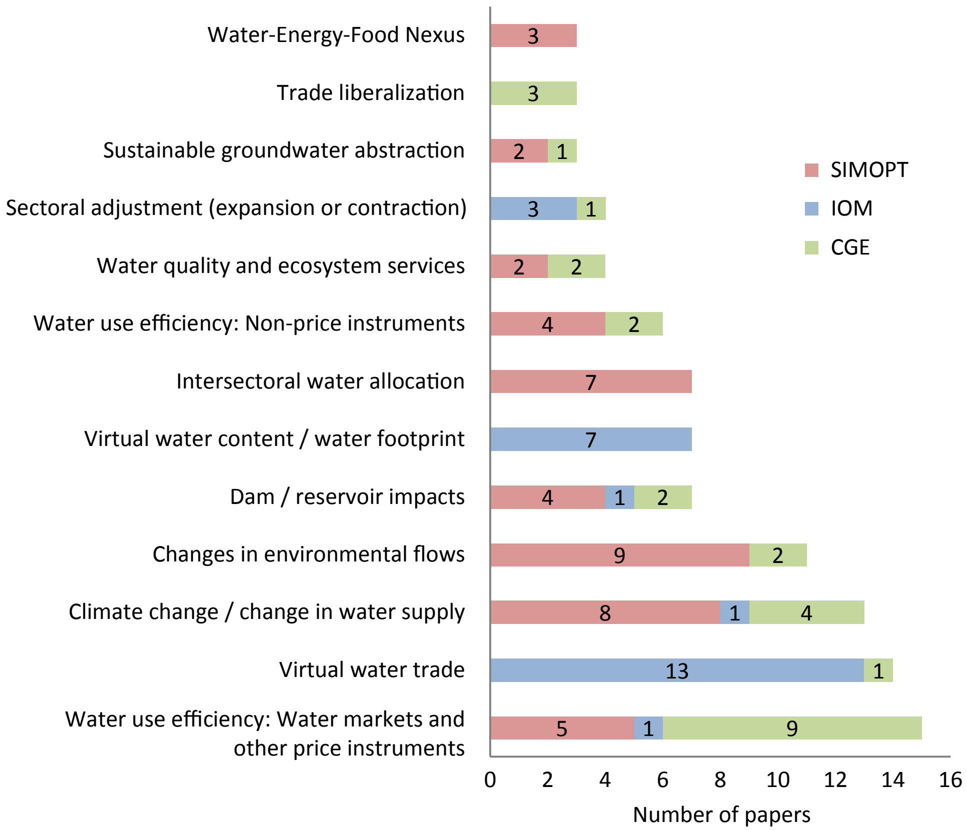
Comparing the three types of HEM studies based on these major themes, we observe that the node-based models are favored for analysis of intersectoral water allocation, analyses of changes in environmental flows, and issues related to the water-energy-food nexus (Figure 8). As expected, input-output models are exclusively implemented to analyze virtual water trade, water footprint, and expansion or contraction of water-intensive sectors. CGE models have been more predominantly used to analyze trade liberalization, water pricing and virtual water trade issues. About two-thirds of papers on topics of reduced water supply, dam construction, non-price instruments of increasing water use efficiency and sustainable groundwater use, utilize node-based modeling, while the remaining papers on these topics are based on CGE models.

FIGURE 7. Main themes in CGE modeling studies.



Note: A total of 27 papers are included above.

FIGURE 8. Comparison of different modeling studies according to their main research theme.



As CGE models increasingly become integrated with hydro-economic and ecological models, we may expect to see more analyses of many of these issues across modeling frameworks, rather than within the node-based framework alone. Such integration could be particularly helpful for considering intersectoral linkages and dependencies among the water, food, and energy sectors. Nonetheless, CGE models with components focused on water (CGE-Water) and energy production (CGE-Energy) mostly remain separate at this time and, as such, a focus on developing a new generation of CGE models that combine their respective advantages would be helpful. In the future, progress in conducting detailed analysis of hydrological and crop or energy production systems within a single framework will depend on more effective integration of such tools.

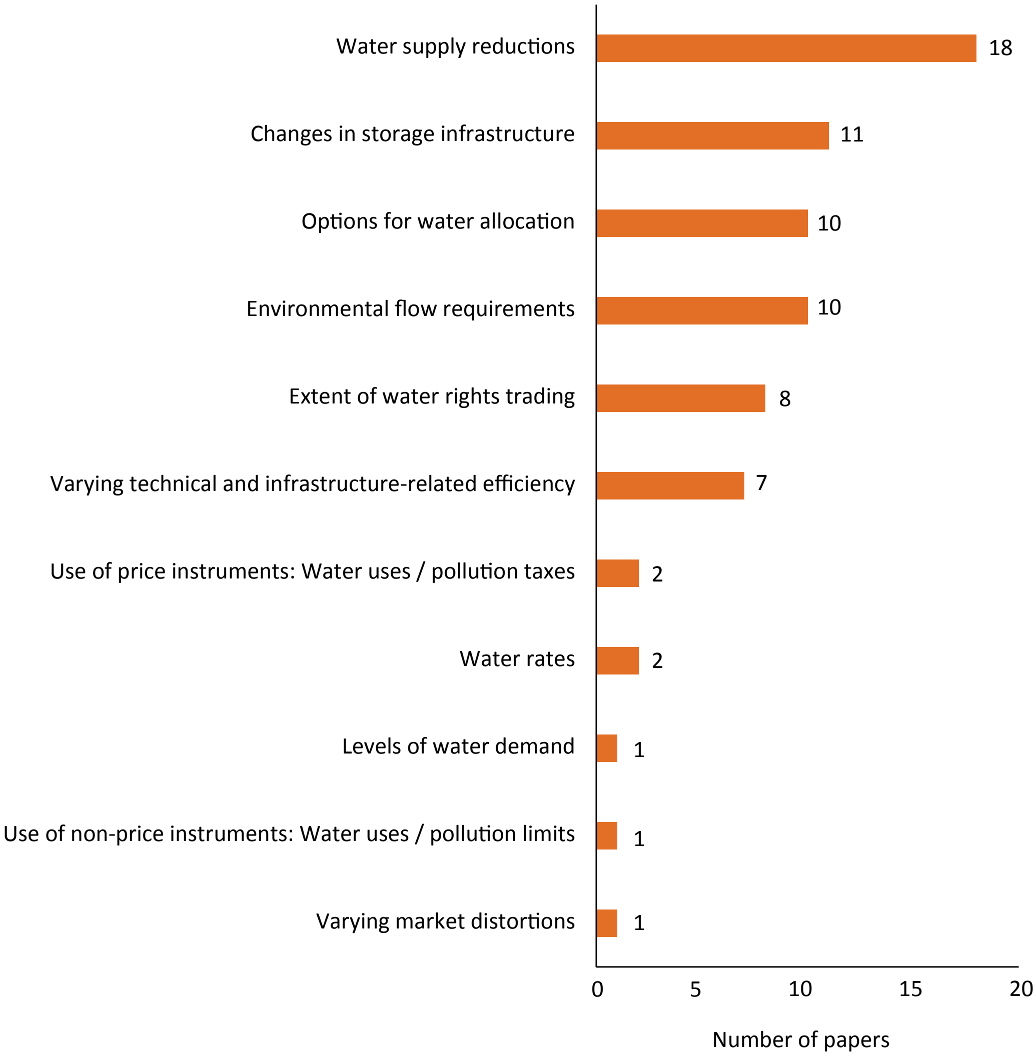
4.3.2 Scenarios

Under the broad umbrella of themes shown in Figure 8, we can categorize the specific analytical or policy scenarios considered across HEM studies. Nearly half of the reviewed node-based modeling studies consider scenarios related to changes in water supply, due to drought or climate change (Figure 9). In particular, it is notable that many studies that do not have drought or climate change as their main focus, nonetheless, consider scenarios with such changes; this may be due to the influence of the technical hydrology and civil engineering literatures, which lend consistent and considerable attention to risks of disruptions in water availability due to stochastic flows and long-term hydrological uncertainty. Studies that include scenarios related to water allocation options (including for environmental flows) and the benefits of infrastructure and water rights trading are also common. In contrast, studies that include scenarios related to price instruments for pollution control (e.g., taxing salt discharge), liberalizing commodity prices, and increasing water demands (e.g., for irrigation expansion or biofuel production), are less common.

In the case of input-output modeling studies there are relatively few studies that conduct scenario-based analysis. This is logical since IOMs are widely used for descriptive analysis rather than simulation analysis, largely because they include very restrictive linear production functions. The few analyses that consider alternative scenarios aim to explore the influence of dam construction, water pricing and water availability reductions impact on production and incomes.

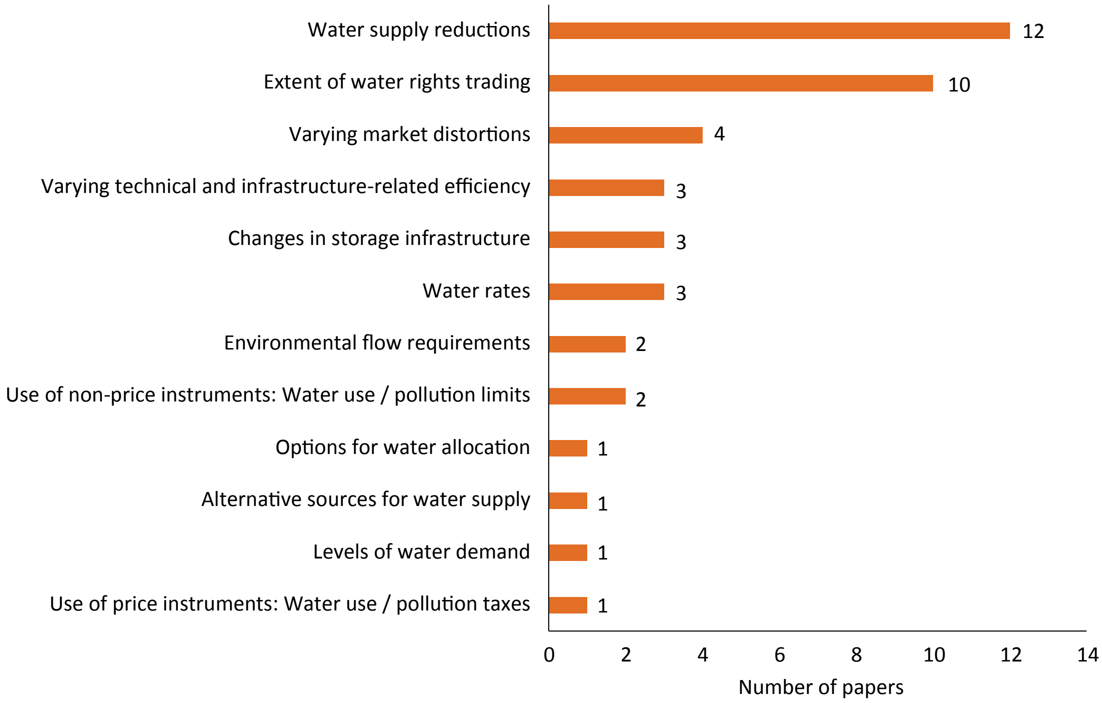
Similarly to the node-based models, many CGE water studies have considered scenarios related to climate change and supply disruptions (Figure 10). A considerable number of studies have also addressed different levels of water rights trading, as well as decreases in market distortions through reduced subsidies or tariffs. Perhaps unsurprisingly given the fact that the value of water quality is difficult to measure, very few studies incorporate questions related to water supply enhancement through desalination and taxation of water pollution. Because of the lack of geographical specificity in most CGE models, it has also proven difficult to test different water allocation scenarios that have a spatial component within the CGE modeling framework.

FIGURE 9. Main scenarios examined using the hydro-economic river basin models.



Note: A total of 44 papers are included above. The categories are not mutually exclusive, so one paper may address several scenarios.

FIGURE 10. Main scenarios examined using the water use CGE models.



Note: A total of 27 papers are included above. The totals exceed the number of studies, since one paper may address multiple scenarios.

Comparison of model types according to the scenarios considered indicates that use of node-based models dominates for scenarios related to water allocation options, environmental flow requirements, storage infrastructure changes, and taxation of water pollution (Figure 11). Although there are very few studies on desalination and restricting fertilizer application and water pollution most of them are based on CGE modeling analysis. Studies that consider scenarios related to water supply reduction and water rights trading are roughly equally considered in node-based and CGE HEMs.

4.3.3 Indicators

When presenting results, authors of studies based on HEMs have to choose which indicators of impact they will track. The majority of node-based modeling studies report on agricultural production levels, benefits, and water uses by sectors (Figure 12). A large number of studies also consider impacts on power production levels and benefits, cropping area, and the shadow value of water uses. Much less frequent are analyses that track water or environmental quality indicators (e.g., ecological habitat, wetland sustainability), effects on labor/employment, and infrastructure costs. No HEM applications were found that consider impacts on migration, which would nonetheless seem important for analyses of new dams. Transaction costs of policy changes were also never reported.

FIGURE 11. Comparison of different modeling studies according to the considered scenarios.

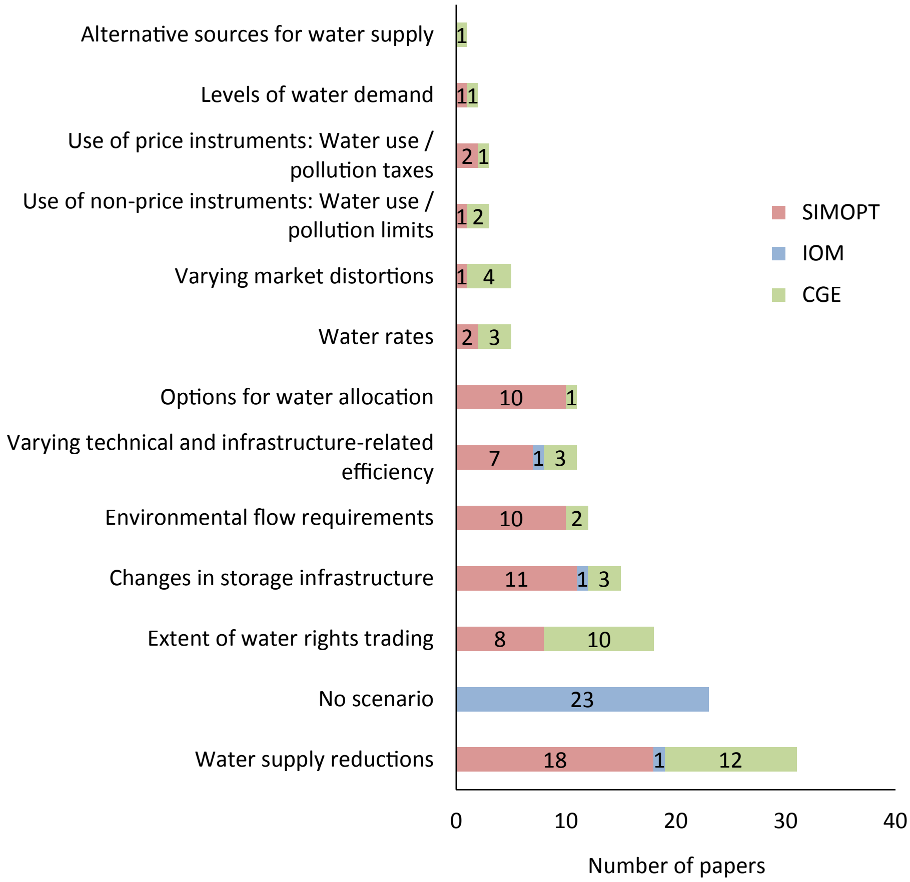
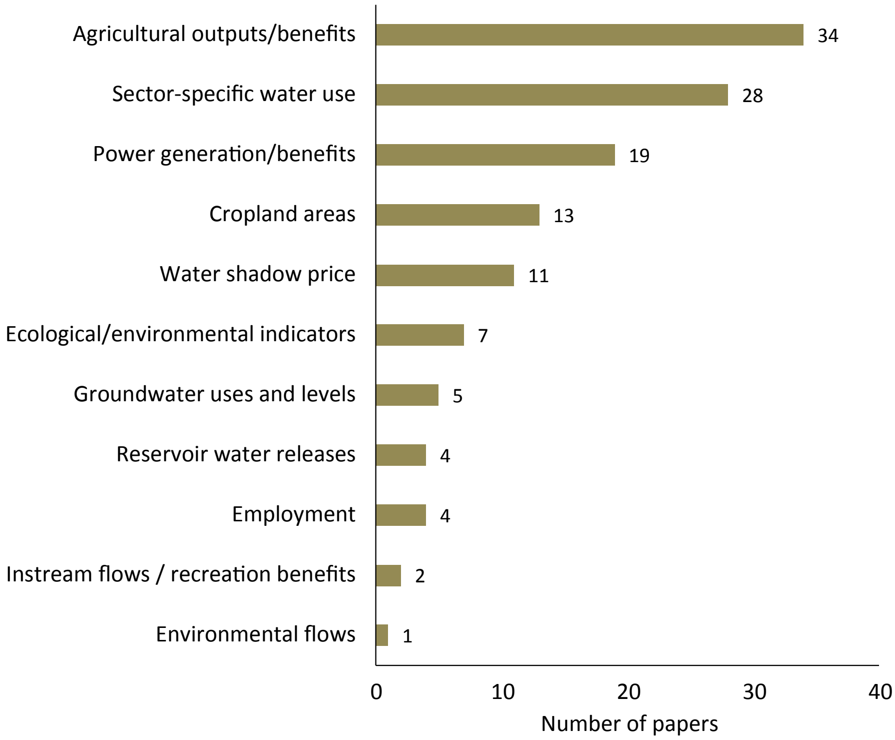


FIGURE 12. Analyzed indicators impacted by the scenario changes in the reviewed node-based modeling studies.

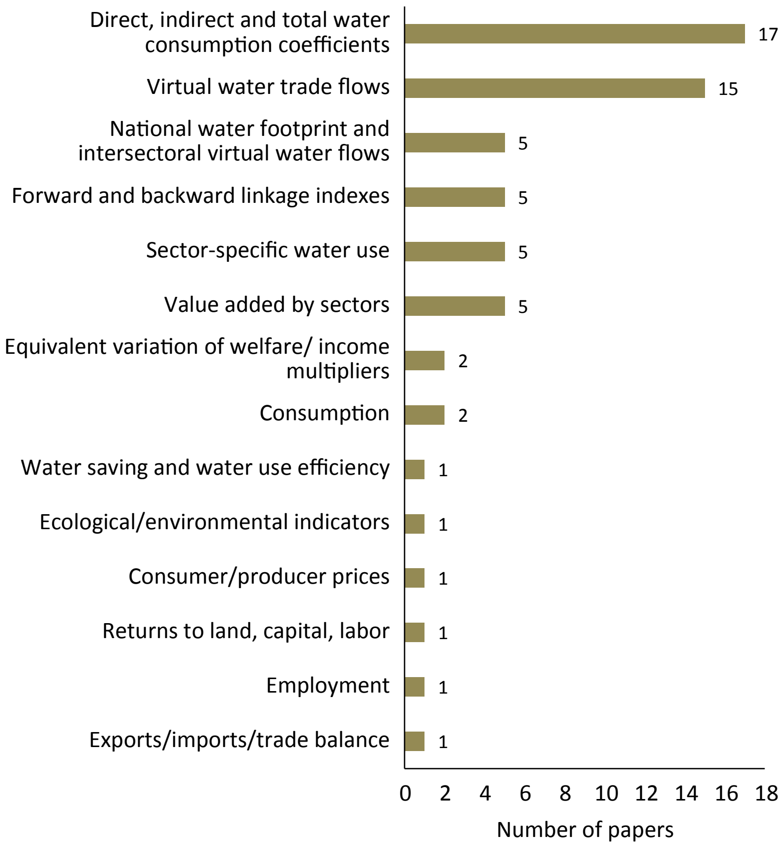


Note: A total of 44 papers are included above. The totals exceed the number of studies, since one paper may report multiple indicators.

Analysis of the indicators considered in IOM-based studies indicates that the majority of the studies present direct and indirect water consumption coefficients and virtual water exports and imports (Figure 13). A considerable number of studies analyze intersectoral virtual water flows, backward and forward linkage indexes, water uses by sectors, and value added by sectors. Equivalent welfare variation, consumption, water use efficiency, ecological indicators, consumer and producer prices, returns to production factors, employment, and exports and imports are rarely considered.

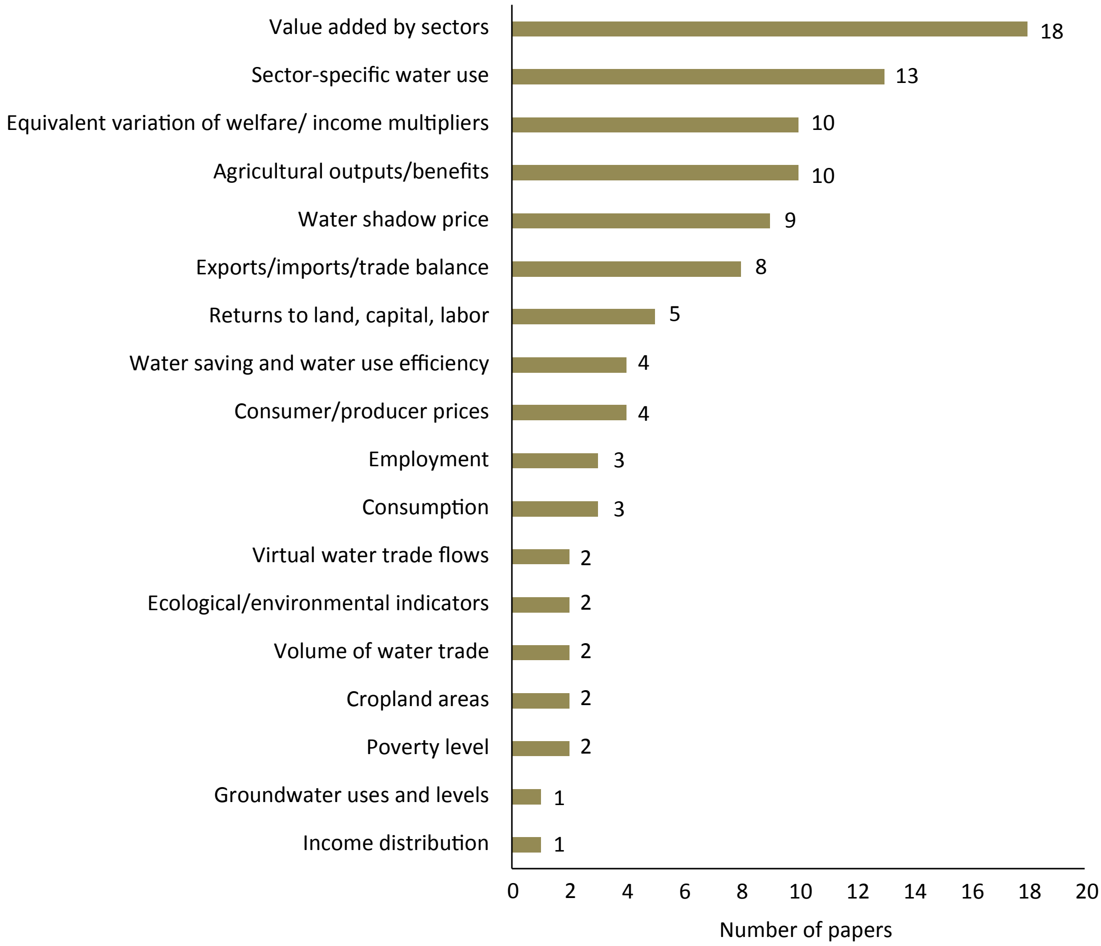
The indicators most frequently considered in node-based based modeling studies also roughly overlap with typical CGE model outcomes (Figure 14). A large number of studies also address agricultural production benefits, equivalent variation in welfare, shadow price of water, and foreign trade indicators. These studies more rarely focus on other common CGE indicators such as changes in employment, consumption, income distribution and poverty alleviation, or even water-specific outcomes such as the virtual water trade, water quality and groundwater uses.

FIGURE 13. Analyzed indicators in the reviewed IOM studies.



Note: A total of 26 papers are included above. The totals exceed the number of studies, since one paper may report multiple indicators.

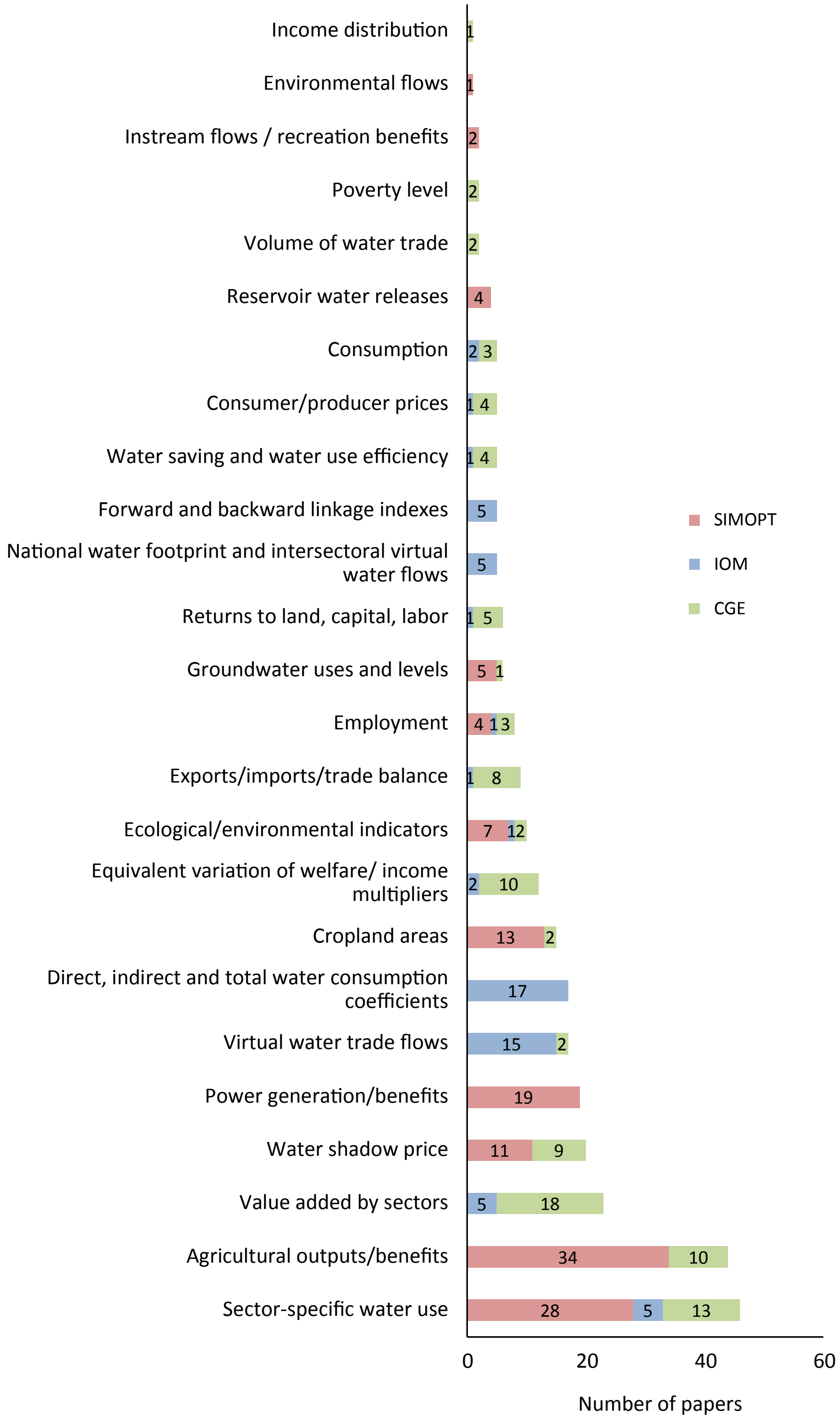
FIGURE 14. Main performance indicators assessed using the water use CGE models.



Note: A total of 27 papers are included above. The totals exceed the number of studies, since one paper may report multiple indicators

The comparison of outcome indicators reveals that these vary considerably across model types (Figure 15). Node-based models predominantly consider the indicators such as agricultural outputs, power generation benefits, cropland areas, groundwater uses and levels, reservoir water releases, instream flow/recreation benefits, and environmental flows. IOM-based modeling studies instead tend to focus on virtual water trade flows, direct and indirect water consumption coefficients, intersectoral virtual water flows, and backward and forward linkage indexes. CGE-based studies are dominant in addressing indicators such as value added by sectors, equivalent variation in welfare, exports and imports, returns to production factors, and consumer and producer prices. Volume of water trade, poverty level, and income distribution are considered by only a few CGE modeling studies.

FIGURE 15. Comparison of modeling types according to the indicators they considered.



4.3.4 Sectors

In terms of sectors covered, nearly all node-based HEM studies consider the agriculture (crop production) sector; this is perhaps not surprising since irrigation is the primary consumer of water resources in many regions (Table 5). A large percentage of studies also include hydropower production, and the municipal and industrial sectors. A countable number of studies consider other sectors such as fisheries, recreation, and livestock as well. Given the importance of the livestock and fishery sectors for food security, and their relation with the larger agriculture sector, further node-based hydro-economic modeling studies should perhaps consider improving representation of these sectors. IOMs and CGE models consider all economic sectors yet only some models consider agriculture and crop production at a disaggregated level. Hydropower production can usually be included in the energy production sector, while the industrial and services sectors are typically more highly disaggregated. Very few models consider ecosystem services.

TABLE 5. Sectors included in node-based HEMs considered in this review.

Sectors	SIMOPT	IOM	CGE
Crop production	42	26	27
Livestock	2	26	27
Hydropower	20	0	0
Energy production	1	26	27
Municipal and industrial sector	18	26	27
Services	0	26	27
Recreation	3	0	1
Environmental flow, ecosystem services	17	0	0

4.3.5 Water Uses

The HEMs reviewed in this study include water from a variety of different sources (Table 6). Most of the node-based modeling studies consider surface water flows explicitly in the models. A large number of studies also included groundwater and precipitation (the latter requires some conversion of precipitation to surface water runoff, groundwater recharge, or harvested water). Relatively few models focus specifically on options for reuse of return flows or augmentation of supplies using desalination. IOM- and CGE-based studies usually consider only surface water consumption by sectors. Some few CGE-based studies may additionally consider precipitation and groundwater uses. It should be also noted that the spatial aspects of water flows and availability are not explicit in almost all CGE modeling papers.

TABLE 6. Water source types considered in node-based HEMs considered in this review.

	SIMOPT	IOM	CGE
Surface water	41	26	26
Precipitation	19	2	8
Groundwater	22	1	9
Reuse of return flow	4	0	0
Desalination	1	0	3

4.3.6 Functional Relationships

There is great diversity in the specific functional relationships between water input and production outputs across the reviewed papers (Table 7). For the 42 node-based modeling studies (out of 44 studies in total) that include agriculture, eight are based on model changes in yields as a function of water input using the well-known methodology by the Food and Agriculture Organization of the United Nations (FAO 1992; Allen et al. 1998). Seven studies are based on an assumption of fixed profits per unit of water use, while six consider the relationship between water input and production to be quadratic. A more flexible relationship that is commonly used in economy-wide models is based on a CES function; this approach is implemented in seven studies of the US California, and the San Francisco River Basin in Brazil. A variety of other functional relationships appear much more rarely in the literature, as shown in Table 7.

TABLE 7. Functional relationships between water use and outputs across the sectors.

Functional forms	SIMOPT							IOM	CGE
	Crop	Livestock	Hydropower	Municipal-industrial water use	Fishery/ aquaculture	Recreation	Environmental flow		
Minimum requirement	0	0	0	1	0	0	12	0	0
Fixed water use per hectare	2	0	0	0	0	0	0	0	0
Linear or fixed value per unit of water	7	0	1	2	0	2	2	25	0
Piece-wise linear	1	0	0	3	0	0	0	0	0
Revenue as a linear function of the ratio of actual evapotranspiration	1	0	0	0	0	0	0	0	0
(ET) to potential ET	1	0	0	0	0	0	0	0	0
Based on FAO56 report	8	0	0	0	0	0	0	0	0
Quadratic	6	0	0	3	0	0	3	0	0
Inverse demand function	1	0	1	8	0	0	0	0	0
Logarithmic	1	0	0	0	0	0	0	0	0
Exponential	1	0	0	0	0	0	0	0	0
Trigonometric	0	0	0	0	1	0	0	0	0
Cobb-Douglas	0	0	0	0	0	1	0	1	2
CES	7	0	0	0	0	0	0	0	25
Standard HP production formula*	0	0	18	0	0	0	0	0	0
Otherwise or not mentioned	7	2	0	1	2	0	0	0	0
	42	2	20	18	3	3	17	26	27

Notes: *Hydropower production is calculated as a multiplication of river flow, reservoir height, production efficiency.

From an economic point of view, the use of CES production functions allows for the most flexible representation of production functions. The biological dependence of yields on water availability at the most critical moments for crop growth, however, mandates consideration of the timing of water consumption as well as total allocation. Further studies should work to better integrate these approaches to obtain both economically and agronomically consistent crop production functions. Implementation of linear functions for the relationships between water uses and profits on the other hand tends to contradict both economic (and agronomic) theory, since these theories are based on diminishing returns (and nonlinear changes in yields) with increasing resource use. Linear functions may only prove useful approximations in problems that do not consider radical changes in water allocation. Thus, researchers should be cautious in using linear crop production functions and relying on fixed water use assumptions in modeling studies.

For hydropower production, the typical approach is to model energy production as a multiplicative (nonlinear) function of hydropower production plant efficiency (usually assumed for simplicity to be constant), average monthly water levels in the reservoir, and monthly water releases. To approximate the effects of changes in efficiency over a range of operation, a few models use relationships based instead on linear regression or inverse relationships between flow and production. Municipal and industrial benefits have mostly been assessed to be dependent on water through an inverse demand relationship (e.g., marginal benefits declining as a function of quantity consumed by the sector). Quadratic or linear relationships between water use and total benefits occasionally being used. Environmental flows and benefits are mostly considered based on minimum requirement thresholds (constraints), rather than as dependent on the quantities of water delivered.

Almost all of IOM studies consider fixed water consumption per unit of economic output. Only a few studies use Cobb-Douglas production functions. CGE modeling studies are usually based on CES production functions though a few include Cobb-Douglas production relationships.

4.3.7 Model Structure

Based on the literature survey model structure was also analyzed (Table 8). More than 80% of node-based models and all CGE models considered in the reviewed papers are nonlinear models. Only one paper out of ten considered uncertainty in parameters and estimated variables. More than one third of the papers related to node-based or CGE modeling conducted dynamic analysis but only one tenth of the papers related to IOMs carried out dynamic analysis. Although node-based models are usually spatially disaggregated only one third of the IOM or CGE model based studies considered multiple regions in their analysis.

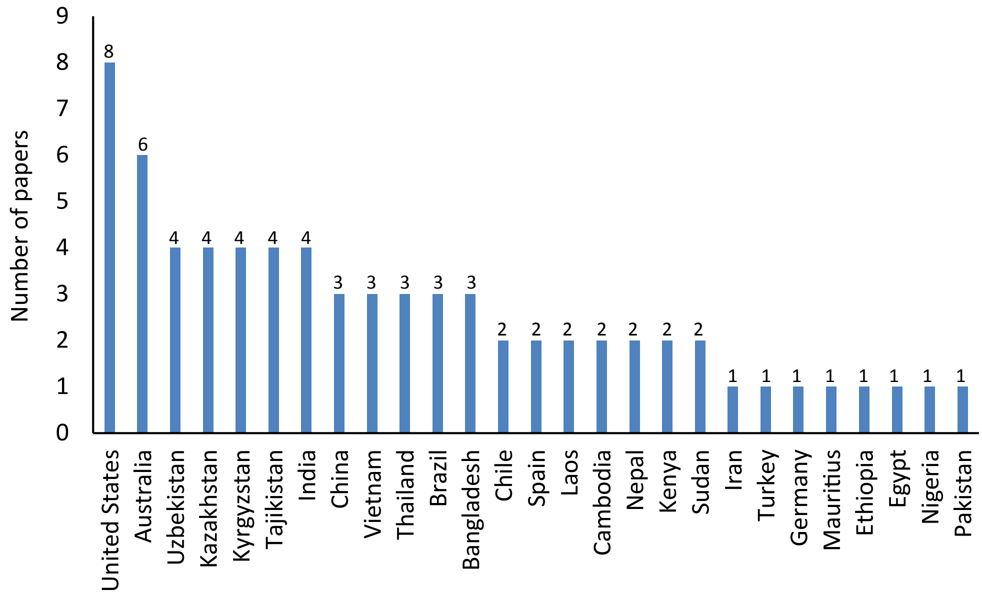
4.3.8 Study Areas

In terms of geographic scope and coverage, we found that node-based HEMs have been applied to basins all over the world. The countries with the most applications are the US (where the most work has been done in California) and Australia (mainly for the Murray-Darling River Basin) (Figure 16). Many models have also been applied to the Indus and Ganges river basins of South Asia, and the Syr Darya Basin of Central Asia. Only one study was found for the cases of Nigeria, Turkey, Iran, Germany, Mauritius, Ethiopia, Egypt, Kenya, Sudan, and Pakistan.

TABLE 8. Classification of the reviewed studies according to model structure.

		Number of papers				Share of mode types (%)				Share by structure (%)			
Model structure	**Category**	**SIMOPT**	**IOM**	**CGE**	**Total**	**SIMOPT**	**IOM**	**CGE**	**Total**	**SIMOPT**	**IOM**	**CGE**	**Total**
Linearity	Linear model	8	25	0	33	24	76	0	100	18	96	0	34
	Non-linear model	36	1	27	64	56	2	42	100	82	4	100	66
Stochasticity	Stochastic	6	0	2	8	75	0	25	100	14	0	7	8
	Deterministic	38	26	25	89	43	29	28	100	86	100	93	92
Dynamics	Static	28	24	17	69	41	35	25	100	64	92	63	71
	Dynamic	16	2	10	28	57	7	36	100	36	8	37	29
Time step	Annual	7	0	26	33	21	0	79	100	16	0	96	34
	Monthly	37	0	1	38	97	0	3	100	84	0	4	39
Spatial dimension	Single region	0	16	18	34	0	47	53	100	0	62	67	35
	Multi-regional	44	10	9	63	70	16	14	100	100	38	33	65
Spatial scale	Global	0	2	7	9	0	22	78	100	0	8	26	9
	Basin-wide	39	2	4	45	87	4	9	100	89	8	15	46
	Nationwide	1	17	12	30	3	57	40	100	2	65	44	31
	City, catchment	4	5	3	12	33	42	25	100	9	19	11	12

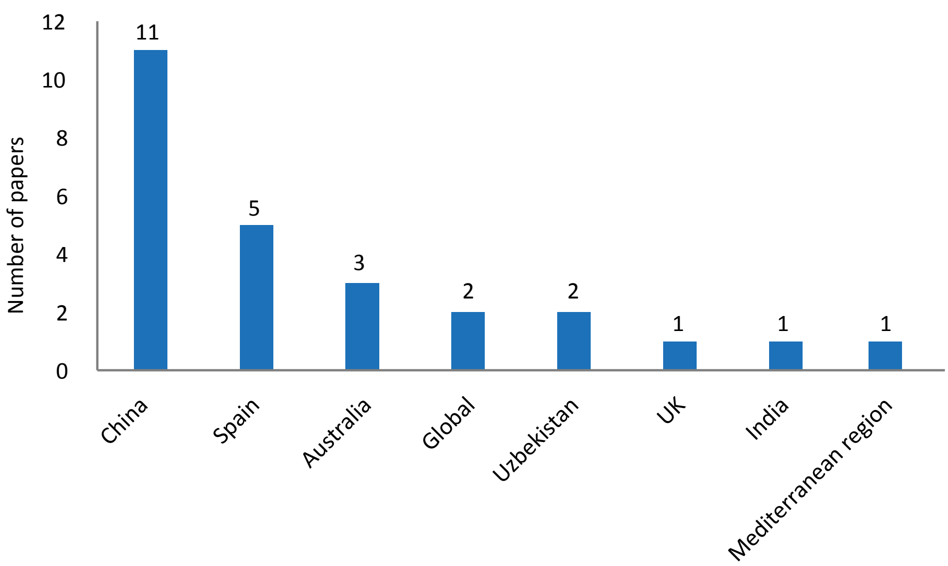
FIGURE 16. Countries and regions considered in node-based HEMs included in this review.



Note: A total of 44 papers are included above. The totals exceed the number of studies, since one paper may address a basin spanning multiple countries. For the Nile River Basin study only four biggest countries (Egypt, Sudan, Ethiopia, and Kenya) out of ten in the basin are included.

IOMs have been applied to analyze water resource problems in a very small set of countries. A surprisingly large number of these studies are in China (Figure 17), though several studies consider Spain and Australia. Other countries with water-related IOM studies are India, Uzbekistan, and the UK. Global IOM applications in this domain remain rare.

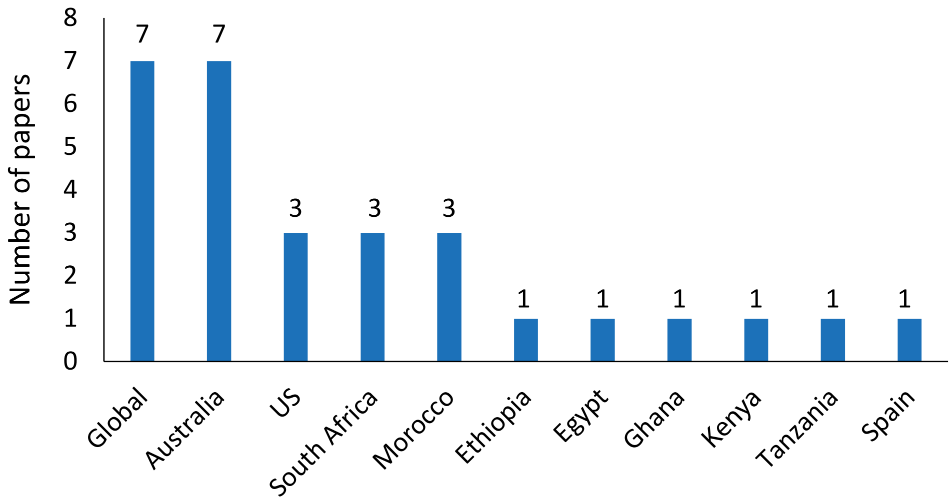
FIGURE 17. Study areas considered in IOM studies.



Note: A total of 26 papers are included above.

The CGE modeling studies that address water issues and are included in this review have primarily been global or focused on Australia (Figure 18). Other countries or regions with multiple studies include the US, South Africa and Morocco. A single study was found that considered each of Ethiopia, Egypt, Ghana, Kenya, Tanzania, China, and Spain.

FIGURE 18. Study areas considered in water use CGE modeling studies.



Note: A total of 27 papers are included above. The totals exceed the number of studies, since there is a paper which addressed the cases of Ethiopia, Kenya and Tanzania together.

4.4 Notable Research Clusters Engaged in Work with HEMs

Many groups at different research institutions, centers, and universities have been involved in the development and use of HEMs to address water management issues. Based on the reviewed papers, we can, however, identify a set of notable research clusters that have published extensively in this domain over a long period of time (Table 9). Although the researchers involved may be based in other locations or may have changed their affiliations over time, some attempt has been made to identify the institution where the cluster seemed to be anchored. The groups discussed here do not appear in any specific order, except in being categorized primarily as using a) node-based HEMs, or b) economy-wide HEMs (IOMs or CGE models).

4.4.1 River Basin HEM Clusters

The first notable cluster is within the International Food Policy Research Institute (IFPRI). Work by IFPRI researchers has been widely cited in the literature, and different versions of the IFPRI river basin optimization HEM (a normative optimization model) have been used to analyze water problems spanning river basins from around the world, such as the Maipo River Basin (Rosegrant et al. 2000), Syr Darya Basin (Cai et al. 2002, 2003a, 2003b), Mekong River Basin (Ringler et al. 2004), and Dong Nai River Basin (Ringler et al. 2006). The basic model, which operates on a monthly time step, considers water allocation across different economic sectors such as irrigation, industry, hydropower production, fishery, and environmental systems. Hydrological relationships exist for river flow, groundwater dynamics, and evapotranspiration processes. Economic profits are based on fixed prices that can be further improved by considering supply

TABLE 9. Major research groups engaged in hydro-economic modeling according to the review.

Group	Main questions addressed	Model type	Case study area
Node-based HEMs			
IFPRI	Trade-offs in water use across sectors, water rights trading	Hydro-economic optimization	Mekong, Maipo, Syr Darya, Dong Nai
UC Davis	Economic impact of drought	Hydro-economic optimization (CALVIN)	California
World Bank	Dam construction impact, flood management, robustness analysis	Hydro-economic optimization	Ganges, Nile
University of New Mexico	Water markets	Hydro-economic optimization	Rio Grande (New Mexico, USA)
SEI, Sweden	Water-energy nexus	Simulation (WEAP) and optimization (LEAP)	Mauritius
UC Riverside, World Bank	Institutions, transboundary water management	Game theory models	General framework
IFPRI	Economy-wide impacts of dam construction	Economy-wide HEMs CGE combined with hydro-economic model	Indus (Pakistan)
World Bank/IFPRI	Water pricing; top-down and bottom-up policy simulations	Multi-regional CGE with hydrological model	Morocco
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Economic impacts on ecological habitat	CGE with water and ecological component	Australia
University of Palermo, Italy	Trade liberalization and water supply change effect on trade and virtual water flows	Global CGE (GTAP-W)	World
University of Hamburg, Germany	Trade liberalization and water supply change effect on water reallocation and incomes	Global CGE (GTAP-W)	World
University of Sydney, Australia	Analysis of water footprint and virtual water trade	National and international single and multi-regional IOMs	Australia, Brazil, Global

and price relationships. Ecosystem values and fishery production functions are represented by stylized functions and warrant further study.

A similar optimization HEM with detailed hydrological accounts that uses positive programing was developed by the researchers of the University of California, Davis, to analyze drought impacts in California. Price and supply relationships as well as nonlinear production costs functions are considered in the model. The basic model has also been adapted for application to the San Francisco River Basin in Brazil (Maneta et al. 2009; Torres et al. 2012). It includes separate production functions for irrigated and rain-fed crops, and does accommodate substitution among capital, labor, and water use inputs, using a CES formulation.

A set of related optimization and simulation HEMs have been developed and used by researchers associated with the World Bank to analyze the economic and flood reduction potentials of planned infrastructure projects in the Nile and Ganges river basins, and to analyze the economic benefits of cooperation (Whittington et al. 2005; Wu and Whittington 2006; Wu et al. 2013). Some of this work explores the sensitivity of economic outcomes to climate change

(Jeuland 2010; Jeuland et al. 2013). In addition, it includes a robustness analysis of different hydropower dam alternatives optimized for energy production under status quo conditions. The model uses repeated simulation to better understand infrastructure performance under uncertainty about water availability, and a range of biophysical and economic parameters that affect net benefits (Jeuland et al. 2014).

Also within the World Bank, other researchers have worked extensively on strategic behavior of riparian water users within river basins (Dinar et al. 2007; Dinar and Wolf 1997) integrated game theoretic concepts with hydro-economic modeling. While their HEM is considerably simpler than the optimization models developed by those used by the clusters described above, they are important for taking account of individual stakeholder interests and the strategic power of different coalitions of riparians.

Finally, researchers at Stockholm Environment Institute (SEI) have developed a simulation HEM called the Water Evaluation and Planning (WEAP) system, that can be linked to an energy production planning model (Long-range Energy Alternatives Planning [LEAP] system). WEAP is a river basin hydro-economic model that includes a user-friendly interface for mapping water inputs, infrastructures, and uses. LEAP allows to determine an optimal portfolio of energy production options (solar, wind, fossil fuel, and hydropower) under different scenarios of energy demand, capacity and costs of energy production by plant and fuel type.

4.4.2 Economy-wide HEM Clusters

IFPRI researchers headed by Robinson et al. (2012) recently combined a river basin model (WEAP) with a CGE model to analyze potential water demand management measures to cope with reduced water supply in Ethiopia. The outputs from an optimization basin management model such as crop yields, hydropower generation and investment under different scenarios of climate change was used to calibrate the initial conditions of the CGE model. Next, economy-wide effects of climate change were estimated using the CGE model.

IFPRI has also been involved in collaborative work with researchers at the World Bank, who combined a farm sector production model with CGE models to consider interdependencies in water use and economic production (Diao et al. 2008). The model allows for simultaneous consideration of macroeconomic policies and water pricing reform impacts on water uses and farm-level outcomes. The crop production sector is highly disaggregated, and multiple agricultural production regions can be included in the model, allowing for important variation in the spatial pattern of crop production, and water availability and use.

In a different effort, researchers at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia have integrated CGE models with ecological models, water use models and Multi-Agent Based systems (Smajgl et al. 2006, 2009). These integrated models allow analysis of the impacts of production decisions on ecological systems. The work has also been extended to include model subcomponents dealing with labor use and trade, which can be used for analysis of the impacts of water and economic policies on interregional migration and the flow of goods (Qureshi et al. 2012).

The final significant research group in economy-wide work with water modeling is at the Center of Integrated Sustainability Analysis (ISA) at Sydney University in Australia. ISA researchers developed global multi-regional input-output tables that include water use accounts. These can be used to analyze international virtual water flows embedded in export and import goods and services (Lenzen et al. 2013). Their IOM allows for estimation of virtual water balances of different countries, and tracking of the destinations of the water content (direct and indirect) of different consumer goods. According to the authors, the results also shed light on the water intensity of products, and may help to suggest pathways for coping with growing water scarcity and/or degraded environmental conditions.

5. CHALLENGES AND PERSPECTIVES FOR FUTURE RESEARCH

Our review of hydro-economic modeling studies points to a range of potential improvements that might enhance the value of HEMs, as well as a number of research questions that should perhaps receive greater attention from researchers using such models in future work. We focus on issues of model resolution, better specification of production functions, data and visualization or presentation of results. This section closes with some perspectives on important topics for future research using HEMs.

5.1 Issues Related to the Resolution of HEMs

An important challenge in using HEMs (and especially economy-wide models such as IOMs and CGEs) is their limited spatial and temporal resolution. Hydrological systems respond on a variety of scales: many important processes (environmental and peak flow dynamics that are relevant for ecosystem service production and floods or droughts) play out at very short time scales of minutes to hours, while others occur on a daily to weekly timeframe (e.g., water delivery to irrigated agriculture), or on much longer monthly, annual, or even decadal scales (e.g., reservoir storage, seasonal or interannual variability in river flows, and climate change) (Islam and Susskind 2012). Similarly, physical processes such as river flow and groundwater recharge do not fit cleanly with the political boundaries that correspond to many water management national or regional institutions.

With their node-link specification, river basin HEMs are well tailored to represent surface water systems, but face challenges when extended to include groundwater dynamics or processes of land use change that affect the generation of runoff at the sub-catchment scale (Wu et al. 2013). In contrast, economy-wide models need to be integrated with more spatially-resolved water balance models, and regional or spatial disaggregation of economic data, to adequately represent such dynamics (Bekchanov et al. 2012). When using optimization models (e.g., node-based models), linking of economic and hydrological sub-models that operate at different spatial scales is a challenge and require additional adjustments. In all HEMs, detailed spatial consideration of water, land use, and crop production relationships is important since it allows to address possible varying effects of the aggregate (nation-wide or basin-wide) changes across environments with different hydrological, institutional, and socioeconomic characteristics.

Similarly, the temporal resolution of most HEMs is monthly or perhaps biweekly (for node-based models), or annual (for economy-wide models). This makes them well-suited for use as long-term planning tools, e.g., for assessment of the economics of infrastructure investments and long-lived policies. They are, however, less well tailored to understanding the economics of processes that operate on short timescales, for example, calculating the benefits of flood control. This partly explains why the latter objective is sometimes reflected through a model's constraint set (Jeuland et al. 2014), and why other similarly temporally resolved processes are infrequently included in HEMs. Future work to include such aspects would perhaps be beneficial for increasing uptake and confidence that HEMs represent more economically-relevant aspects of water resources.

5.2 The Production Function Relationships in HEMs

HEMs were largely developed for the purpose of assessing the economic tradeoffs of water allocation to the agriculture, hydropower, and municipal and industrial sectors; as such, they are well adapted to the analysis of problems focusing on those sectors. Even so, the appropriate functional form for the demand curves and for relevant production relationships is debatable. Linear production functions (or assumptions of constant marginal net benefits) are common, but these ignore diminishing marginal returns, e.g., the fact that the marginal product of water is decreasing in the number of units used. A CES function for agricultural production that incorporates seasonal water scarcity can be acceptable from both an economic and agronomic perspective. In economy-wide models, technological changes such as drip or sprinkler irrigation cannot be modeled explicitly but require assumptions about implied changes in Total Factor Productivity (TFP) or inclusion of shift parameters of production functions.

Other water uses – for livestock, fisheries, and nonmarket ecosystem services – tend to be rarely included in HEMs, and are also much less well understood. In economy-wide analysis, such nonmarket aspects are nearly always ignored. Hence, there is a great need for multi-disciplinary research involving economists, ecologists, and fishery and livestock science specialists, on the relationship between water quantities and production in these domains. Because nonmarket aspects are very significant for water (Hanemann 2006), incorporation of such aspects seems critical for correct and full understanding of hydro-economic tradeoffs, and of their distributional implications.

5.3 Data Challenges

Complementary to production functions is the challenge of data, as required for calibration and specification of those relationships. There is relatively limited econometric research that estimates the marginal product of water, especially in the difficult domains – livestock, fisheries, and nonmarket ecosystem services – described above. Furthermore, river basin- or national-scale data collection in such domains is uncommon, because they do not appear in national accounts. With economy-wide models, this is a particular problem because such models require a very large amount of data. Moreover, the methods of nonmarket valuation that are required for such assessment, require detailed survey data collection, and can be impractical or financially infeasible to be conducted at national or river basin scale. Even in the more traditionally-recognized sectors that require water (i.e., agriculture, hydropower, and municipal/industrial), a significant challenge relates to the projection of future prices and production efficiency.

Finally, integration of economic values from partial equilibrium models with the normalized and static numeraire prices in CGE models complicates the process of integrating node-based and spatially-explicit HEMs with aggregated economy-wide models. Thus, the theoretical consistency of CGE models does not always match with more realistic analyses using empirical models (Scrieciu 2007).

5.4 Visualization and Presentation of Results

Yet another difficulty concerns the interpretation of results from HEMs. Aggregate outcomes, whether at national or basin-scale, offer little insight on the distribution of the outcomes from policies or changes being analyzed. These distributional aspects are often of paramount importance to decision makers, as is evidenced by work on the strategic behavior surrounding water resources.

More widespread use of Geographic Information System (GIS) to present results would perhaps help to communicate results and inform water negotiations, and might also motivate innovation in data collection and modeling at the scales most relevant to the parties and regions affected by reallocation of water. Similarly, an ability to open the 'black-box' of economy-wide models would be of great help for understanding their policy relevance.

In addition, inclusion of scientists from disciplines other than economics and engineering in data collection and in the interpretation of results would increase the utility and realism of HEMs. This communication should also extend to include stakeholders such as water managers or agricultural producers in order to validate model results. Communication between scientists and decision makers and stakeholders is also needed to identify critical policy questions and inform appropriate model development.

5.5 A Research Agenda for Extending the Utility of HEMs

This review identified themes and problems that appear in many HEM applications, and highlighted a number of areas that have received scant attention. There is some consistency in the findings across basin-scale and economy-wide HEMs, although a number of important differences also emerged from the analysis in Section 4. The most critical research gaps are identified below:

1. **Integrated analysis of issues related to the water-energy nexus**: While most HEMs include the energy sector insofar as surface water resources are used for hydropower generation, the unified analysis of interlinkages between energy and water systems is relatively rare. Besides simple analysis of tradeoffs across sectors, such analysis would also include such issues as: a) Dual energy and water inputs in some domains (e.g., agriculture irrigated with groundwater or surface water that must be pumped to users, or use of desalinated water), and b) consumptive and nonconsumptive water input needs of the energy sector (e.g., for cooling of power plants, or for biofuels production). It is important to better understand how these systems interact and affect the marginal product of water and value of energy, input use and consumption and economic well-being. In particular, integration of CGE models with sufficiently detailed water and energy accounts would allow for more insightful analyses of water, energy, and food production relationships.
2. **Economic assessment and consistent inclusion of nonmarket ecosystem services and water quality aspects**: The extent to which ecosystem services production depends on water flows that vary in time and space is poorly understood, especially for nonmarket goods. More study is needed to characterize the nature of the relationship between water flows and aspects such as fisheries productivity, soil fertility, subsistence livelihoods of various types, benefit functions related to wetlands or other unique ecosystems, and nonuse ecosystem values. Tourist and recreation benefits generated from improved environmental quality should also be integrated into HEM studies. Hydro-economic models should also consider long-term linkages between the economy and ecological systems, since short-term environmental impacts are usually modest while long-term impacts can be substantial and irreversible. In addition to water quantity issues, such work should also endeavor to improve the linkages between water quality and economic benefits in HEMs, where progress remains limited and slow due to the complexity underlying the dynamics of water quality. In fact, with the possible exception of salinization in irrigated areas, this review noted very few HEM-based studies that include water quality concerns.

3. **Development of better tools for calculating the effects of water allocation on economic welfare**: Node-based HEMs are very well suited for assessment of water-use trade-offs across sectors and economic impacts of changes in water supply or infrastructure development. Yet in most cases, these are partial equilibrium models that cannot explain the distribution of impacts. Given the high dependence of irrigated agriculture on water supply and the presence of market imperfections in the global food system, it is conceivable that significant reallocation of water could affect national prices of agricultural commodities, with complex implications for the distribution of economic impacts. CGE models are well suited for such assessments, but require inputs from disaggregated analyses that accurately predict the local effects of reallocation policies on production. New hybrid models that integrate the strengths of node-based and economy-wide HEMs should be developed to further shed light on indirect and distributional impacts. Data permitting (with detailed social accounting matrices, for example), these could be especially useful for assessing the effects of various water sector policies and interventions on poverty, female labor participation, and interregional migration and trade. Integration of river basin optimization models with CGE models can perhaps be facilitated using the Mixed Complementarity Programming (MCP) framework (Rutherford 1995; Lofgren and Robinson 1997).
4. **Water footprint analysis that is more consistent with economic theory**: As discussed in Section 4, input-output models (IOMs) have been widely used to conduct water footprint and virtual water analyses. These are useful descriptive tools for indicating water use intensity of produced and traded commodities across regions facing different water resource endowments and environmental pressures (Daniels et al. 2011). Such IOM-based results have, however, been heavily criticized since they do not consider opportunity costs, fail to incorporate the theory of comparative advantage, and neglect dependence of production on the factors except water (Wichelns 2004, 2010a, 2010b). Integrating node-based optimization HEMs with IOMs could help alleviate such concerns, assuming the former allow for flexible substitution across inputs used in production. Global level CGE models should also be increasingly used for virtual water trade and comparative advantage analysis, rather than IOMs which necessitate a range of restrictive assumptions.
5. **Analysis and understanding of the costs of institutional constraints**: Except in rare instances, water is not allocated using market mechanisms but rather through a variety of government and other institutions. Water allocation is also affected by physical and political asymmetries that may lead to variation in the marginal value of water across space and time. Interactions between different political units within a basin, and calculation of the benefits of cooperation (or the losses associated with non-cooperation and mistrust) should be analyzed further, and analysts should develop tools to easily convey the costs of these lost opportunities to decision-makers (for example, as in Jeuland et al. 2014). Assessment of the role of institutional barriers in inhibiting development opportunities and advancement of nonmarket objectives (issue 2 above) could be particularly fruitful areas for future research. Similarly, more work could be done to evaluate how transaction costs reduce potential economic benefits. Moreover, rather than assuming that an omniscient decision maker guides basin-wide optimization, multi-agent models that consider interactions among different water stakeholders with different interests should continue to be developed.

6. **Continued progress on tools and structuring results presentation to aid decision-making under uncertainty**: Uncertainty has always been an important issue in water resources planning, largely because many infrastructure planning decisions are nearly irreversible and very long-lived. To be sure, societal preferences and objectives shift over time, as is evidenced by today's debates over decommissioning of dams in many developed countries (Stanley and Doyle 2003). Meanwhile, water demand projections are challenging and often overestimated by risk averse planners who above all seek to protect against supply shortfalls (Gleick 2003). Climate change adds an additional layer of uncertainty to this complex problem (Jeuland 2010). To deal with these issues, researchers have used well-developed stochastic simulation and optimization methods and are contributing to continued innovation around issues of robustness and flexibility (Groves and Lempert 2007; Jeuland and Whittington 2014). Nonetheless, the presentation of results from such work remains challenging, and its effects on decision-making are thus unclear at this time.

6. CONCLUSION

Hydro-economic models have been recognized as an effective tool of analyzing the impact of natural (e.g., climate change, drought, and flooding), technical (e.g., dam construction, irrigation technology adoption), and institutional (e.g., water markets and formation of coalitions) changes on water and production system. Particularly, hydro-economic basin management models have been mainly used for assessing water use and economic output linkages and analyzing trade-offs of water use across the economic sectors while economy-wide water management models have been implemented to estimate economy-wide (final consumption and income distribution) effects of various water and agricultural policies. Our review of hydro-economic modeling studies indicates that the policy relevance of HEM studies increases with the further inclusion of economically sound analysis of water-energy-food production and consumption interlinkages, water quality aspects of water management, environmental impact (wetlands, lakes, forests, and other ecosystems) of water uses, interests of multiple stakeholders (transboundary management), effects on employment (male and female) and migration due to infrastructural constructions, and environmental and economic risks.

Since each model type has both its advantages and shortcomings, in general, and also in addressing particular research questions, no prioritization of any model type is possible. Because for the different structure, and spatial and temporal scales of different model types integrating them or building a universal model is a complicated task. However, implementation of various modeling tools for analyzing the particular water system and systematical synthesis of the results of these various models, while considering their assumptions, seems a more viable option for deriving consistent policy recommendations. Further improvement of model databases and making the model formulation and results easily interpretable into policy actions enhances cooperation among the modelers and water managers.

REFERENCES

Ahrends, H.; Mast, M.; Rodgers, C.; Kunstmann, H. 2008. Coupled hydrological - economic modelling for optimised irrigated cultivation in a semi-arid catchment of West Africa. *Environmental Modelling and Software* 23(4): 385-395.

Akter, S.; Grafton, R.Q.; Merritt, W.S. 2014. Integrated hydro-ecological and economic modeling of environmental flows: Macquarie Marshes, Australia. *Agricultural Water Management* 145: 98-109.

Allan, J.A. 1997. *`Virtual water': A long term solution for water short Middle Eastern economies?* Paper presented at the 1997 British Association Festival of Science, Roger Stevens Lecture Theatre, University of Leeds, Water and Development Session, TUE.51, 14.45, 1997.

Allen, R.; Pereira, L.; Raes, D.; Smith, M. 1998. *Crop evapotranspiration - Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56. Rome: Food and Agriculture Organization of the United Nations (FAO).

Antonelli, M.; Roson, R.; Sartori, M. 2012. Systemic input-output computation of green and blue virtual water 'flows' with an illustration for the Mediterranean region. *Water Resources Management* 26(14): 4133-4146.

Barbier, E.B. 2003. Upstream dams and downstream water allocation: The case of the Hadejia- Jama'are floodplain, northern Nigeria. *Water Resources Research* 39(11): WES 1.1 – WES 1.9.

Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; Yumkella, K.K. 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39(12): 7896-7906.

Bekchanov, M.; *Müller*, M.; Lamers, J.P.A. 2012. A computable general equilibrium analysis of agricultural development reforms: national and regional perspective. In: *Cotton, water, salts and soums - economic and ecological restructuring in Khorezm, Uzbekistan*, eds., Martius, C.; Rudenko, I.; Lamers, J.P.A.; Vlek, P.L.G. Springer: Dordrecht/Heidelberg/London/New York. Pp. 347-370.

Bekchanov, M.; Bhaduri, A.; Lenzen, M.; Lamers, J.P.A. 2014. Integrating input-output modeling with multi-criteria analysis to assess options for sustainable economic transformation: The case of Uzbekistan. In: *The global water system in the Anthropocene: Challenges for science and governance*, eds., Bhaduri, A.; Bogardi, J.; Leentvaar, J.; Marx, S. Springer: Dordecht/Heidelberg/London/New York. Pp. 229-245.

Bekchanov, M.; Bhaduri, A.; Ringler, C. 2015. Potential gains from water rights trading in the Aral Sea Basin. *Agricultural Water Management* 152: 41-56.

Berrittella, M.; Hoekstra, A.Y.; Rehdanz, K.; Roson, R.; Tol. R.S.J. 2007. The economic impact of restricted water supply: A computable general equilibrium analysis. *Water Research* 41: 1799-1813.

Berrittella, M.; Rehdanz, K.; Tol, R.S.J.; Zhang, J. 2008a. The impact of trade liberalization on water use: A computable general equilibrium analysis. *Journal of Economic Integration* 23(3): 631-655.

Berrittella, M.; Rehdanz, K.; Roson, R.; Tol, R.S.J. 2008b. The economic impact of water taxes: A computable general equilibrium analysis with an international data set. *Water Policy* 10(3): 259-271.

Böhringer, C.; Löschel, A. 2006. Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. *Ecological Economics* 60: 49-64.

Booker, J.F.; Young, R.A. 1994. Modeling intrastate and interstate markets for Colorado river water resources. *Journal of Environmental Economics and Management* 26(1): 66-87.

Cai, X.; McKinney, D.C.; Lasdon, L.S. 2002. A framework for sustainability analysis in water resources management and application to the Syr Darya Basin. *Water Resources Research* 38(6): 21.1-21.14.

Cai, X.; McKinney, D.C.; Lasdon, L.S. 2003a. Integrated hydrologic-agronomic-economic model for river basin management. *Journal of Water Resources Planning* 129(1): 4-17.

Cai, X.; McKinney, D.C.; Rosegrant M.W. 2003b. Sustainability analysis for irrigation water management in the Aral Sea region. *Agricultural Systems* 76: 1043-1066.

Cai, X.; Rosegrant, M.W. 2004. Irrigation technology choices under hydrologic uncertainty: A case study from Maipo River Basin, Chile. Water Resources Research 40: 10.

Calzadilla, A.; Rehdanz, K.; Tol, R.S.J. 2010. The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *Journal of Hydrology* 384: 292-305.

Calzadilla, A.; Rehdanz, K.; Tol, R.S.J. 2011a. Trade liberalization and climate change: A computable general equilibrium analysis of the impacts on global agriculture. *Water* 3: 526-550.

Calzadilla, A.; Rehdanz, K.; Tol, R.S.J. 2011b. Water scarcity and the impact of improved irrigation management: A computable general equilibrium analysis. *Agricultural Economics* 42(3): 305-323.

Carson, R.T.; Hanemann, W.M. 2005. Contingent Valuation. In: *Handbook of Environmental Economics: Valuation of Environmental Changes, Vol . 2,* eds., Maler, K.G.; Vincent, J.R. Amsterdam: North-Holland. Pp 821-936.

Chapagain, A.K.; Hoekstra, A.Y.; Savenije, H.G. 2006. Water saving through international trade of agricultural products. *Hydrology and Earth System Sciences* 10: 455-468.

Chatterjee, B.; Howitt, R.E.; Sexton, R.J. 1998. The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management* 36(3): 295-313.

Chen, Zh.; Chen, G.; Xia, X.; Xu, Sh. 2012. Global network of embodied water flow by systems input-output simulation. *Frontiers of Earth Science* 6(3): 331-344.

Cohon, J.L.; Marks, D.H. 1973. Multi-objective screening models and water resource investment. *Water Resources Research* 9(4): 826-836.

Connor, J.; Schwabe, K.; King, D.; Kaczan, D.; Kirby, M. 2009. Impacts of climate change on lower Murray irrigation. *Australian Journal of Agricultural and Resource Economics* 53: 437-456.

Dalhuisen, J.M.; Florax, R.; de Groot, H.; Nijkamp, P. 2003. Price and income elasticities of residential water demand: A meta-analysis. *Land Economics* 79(2): 292-308.

Daniels, P.L.; Lenzen, M.; Kenway, S.J. 2011. The ins and outs of water use – a review of multi-region input–output analysis and water footprints for regional sustainability analysis and policy. *Economic Systems Research* 23(4): 353-370.

de Fraiture, C.; Molden, D.; Amarasinghe, U.; Makin, I. 2001. PODIUM: Projecting water supply and demand for food production in 2025. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 26(11—12): 869-876.

de Moraes, M.M.G.A.; Cai, X.; Ringler, C.; Albuquerque, B.E.; Vieira da Rocha, S.P.; Amorim, C.A. 2011. Joint water quantity-quality management in a biofuel production area-integrated economic-hydrologic modeling analysis. *Journal of Water Resources Planning and Management* 136(4): 502-511.

Diao, X.; Roe, T. 2000. The win-win effect of joint water market and trade reform on interest groups in irrigated agriculture in Morocco. In: *The political economy of water pricing reforms*, ed., Dinar, A. New York: Oxford University Press. Pp. 141-165.

Diao, X.; Roe, T. 2003. Can a water market avert the “double whammy” of trade reform and lead to a “win-win” outcome? *Journal of Environmental Economics and Management* 45(3): 708-723.

Diao, X.; Roe, T.; Doukkali, R. 2004. Economy-wide gains from the decentralized water allocation in a spatially heterogeneous agricultural economy. *Journal of Environment and Development Economics* 13(4): 371-399.

Diao, X.; Dinar, A.; Roe, T.; Tsur, Y. 2008. A general equilibrium analysis of conjunctive ground and surface water use with an application to Morocco. *Agricultural Economics* 38: 117-135.

Dietzenbacher, E.; Velázquez, E. 2007. Analyzing Andalusian virtual water trade in an input-output framework. *Regional Studies* 41(2): 185-196.

Dinar, A. 2012. *Economy-wide implications of direct and indirect policy interventions in the water sector lessons from recent work and future research needs*. Policy Research Working Paper. Washington, DC: World Bank.

Dinar, A.; Wolf, A. 1997. Economic and political considerations in regional cooperation models. *Agricultural and Resource Economics Review*. 26(1): 7-22.

Dinar, A.; Dinar, S.; McCaffrey, S.; McKinney, D. 2007. *Bridges over water: Understanding transboundary water conflict, negotiation and cooperation*. World Scientific on Energy and Resource Economics. Vol. 3. World Scientific Publishing Co. Ptc. Ltd.

Divakar, L.; Babel, M.S.; Perret, S.R.; Das Gupta, A. 2011. Optimal allocation of bulk water supplies to competing use sectors based on economic criterion: An application to the Chao Phraya River Basin, Thailand. *Journal of Hydrology* 401(1-2): 22-35.

Dixon, P.B.; Rimmer, M.T.; Wittwer, G. 2011. Saving the southern Murray Darling basin: The economic effects of a buyback of irrigation water. *Economic Record* 87(276): 153-168.

Dorfman, R. 1965. Formal models in the design of water resource systems. *Water Resources Research* 1(3): 329-336.

Draper, A.J.; Jenkins, M.W.; Kirby, K.W.; Lund, J.R.; Howitt, R.E. 2003. Economic-engineering optimization for California water management. *Journal of Water Resources Planning and Management* 129(3): 155-164.

Duarte, R.; Sánchez-Chóliz, J.; Bielsa, J. 2002. Water use in the Spanish economy: An input output approach, *Ecological Economics* 43(1): 71-85.

Dumont, A.; Salmoral, G.; Llamas, M.R. 2013. The water footprint of a river basin with a special focus on groundwater: The case of Guadalquivir basin (Spain). *Water Resources and Industry* 1-2: 60-76.

FAO (Food and Agriculture Organization of the United Nations). 1992. CROPWAT: a computer program for irrigation planning and management. Irrigation and Drainage Paper 46. Rome: FAO.

Feng, K.; Chapagain, A.; Suh, S.; Pfister, S.; Hubacek, K. 2011a. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Economic Systems Research* 23(4): 371-385.

Feng, K.; Siu, Y.L.; Guan, D.; Hubacek, K. 2011b. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption-based approach. *Applied Geography* 32: 691-701.

Feng, K.; Hubacek, K.; Pfister, S.; Yu, Y.; Sun, L. 2014. Virtual scarce water in China. *Environmental Science and Technology* 48(14): 7704-7713.

Fiering, M.; Jackson, B. 1971. *Synthetic streamflows*. Water Resources Monograph Series. Washington, DC: American Geophysical Union.

George, B.; Malano, H.; Davidson, B.; Hellegers, P.; Bharati, B.; Massuel, S. 2011a. An integrated hydro-economic modelling framework to evaluate water allocation strategies I: Model development. *Agricultural Water Management* 98(5): 733-746.

George, B.; Malano, H.; Davidson, B.; Hellegers, P.; Bharati, B.; Massuel, S. 2011b. An integrated hydro-economic modelling framework to evaluate water allocation strategies II: Scenario assessment. *Agricultural Water Management* 98(5): 747-758.

Gleick, P. 2003. Water use. *Annual Review of Environment and Resources* 28: 275-314.

Gómez, C.M.; Tirado, D.; Rey-Maquieira, J. 2004. Water exchanges versus water works: Insights from a computable general equilibrium model for the Balearic Islands. *Water Resources Research* 40: W10502. doi:10.1029/2004WR003235

González, J.F. 2011. Assessing the macroeconomic impact of water supply restrictions through an input–output analysis. *Water Resources Management* 25: 2335-2347.

Goodman, D.J. 2000. More reservoirs or transfers? A computable general equilibrium analysis of projected water shortages in the Arkansas River basin. *Journal of Agricultural and Resource Economics* 25(2): 698-713.

Grafton, R.Q.; Jiang, Q. 2011. Economic effects of water recovery on irrigated agriculture in the Murray-Darling Basin. *Australian Journal of Agricultural and Resource Economics* 55(4): 487-499.

Grafton, R.Q.; Libecap, D.; Edwards, E.C.; O'Brien, R.J.; Landry, C. 2012. Comparative assessment of water markets: Insights from the Murray-Darling Basin of Australia and the Western USA. *Water Policy* 14: 175-193.

Grey, D.; Sadoff, C.W. 2007. Sink or swim? Water security for growth and development. *Water Policy* 9 (6): 545-571.

Groves, D.G.; Lempert, R.J. 2007. A new analytic method for finding policy-relevant scenarios. *Global Environmental Change: Human and Policy dimensions* 17(1): 78-85.

Guan, D.; Hubacek, K. 2007. Assessment of regional trade and virtual water flows in China. *Ecological Economics* 61: 159-170.

Gurluk, S.; Ward, F. 2009. Integrated basin management: Water and food policy options for Turkey. *Ecological Economics* 68(10): 2666-2678.

Gutižrrez, I.B.; Varela-Ortega, C.; Purkey, D.R. 2013. Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. *Journal of Environmental Management* 128: 144-160.

Hanemann, W.M. 2006. The economic conception of water. In: *Water crisis: Myth or reality*, eds., Rogers, P.; Llamas, M.R.; Cortina, L.M. London, UK: CRC Press.

Harou, J.J.; Pulido-Velázquez, M.; Rosenberg, D.E.; Medellín-Azuara, J.; Lund, J.R.; Howitt, R.E. 2009. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology* 375: 627-643.

Hassan, R.; Thurlow, J. 2011 Macro-micro feedback links of water management in South Africa: CGE analyses of selected policy regimes. *Agricultural Economics* 42(2): 235-247.

Hearne R.; Easter, H. 1997. The economic and financial gains from water markets in Chile. *Agricultural Economics* 15(3): 187-199.

Hirt, U.; Kreins, P.; Kuhn, U.; Mahnkopf, J.; Venohr, M.; Wendland, F. 2012. Management options to reduce future nitrogen emissions into rivers: A case study of the Weser River basin, Germany. *Agricultural Water Management* 115: 118-131.

Hoekstra, P.Q.; Hung, A.Y. 2005. Globalisation of water resources: International virtual water flows in relation to crop trade. *Global Environmental Change* 15: 45-56.

Horridge, M.; Madden, J.; Wittwer, G. 2005. The impact of the 2002–2003 drought on Australia. *Journal of Policy Modelling* 27(3): 285-303.

Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerstroem, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fisher, G.; van Velthuizen, H.; Wiberg, D.; Young, C.; Roehrl, A.; Mueller, A.; Steduto, P.; Ramma, I. 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change* 3(7): 621-626.

Howitt, R.E. 1995. A calibration method for agricultural economic production models. *Journal of Agricultural Economics* 46(2): 147-159.

Howitt, R.E.; *Medellín-Azuara*, J.; *MacEwan*, D.; *Lund*, J.R. 2012. Calibrating disaggregate economic models of agricultural production and water management. *Environmental Modeling and Software* 38: 244-258.

Islam, S.; Susskind, L. 2012. Understanding and characterizing complex water management problems. In: *Water diplomacy: A negotiated approach to managing water networks*. New York: RFF Press. Pp. 41-52.

Jenkins, M.W.; Lund, J.R.; Howitt, R.E.; Draper, A.J.; Msangi, S.M.; Tanaka, S.K.; Ritzema, R.S.; Marques, G.F. 2004. Optimization of California's water system: Results and insights. *Journal of Water Resources Planning and Management* 130(4): 271-280.

Jeuland, M. *2010. Economic implications of climate change for infrastructure planning in transboundary water systems: An example from the Blue Nile*. *Water Resources Research* 46(11): W11556.

Jeuland, M.; Harshadeep, N.; Escurra, J.; Blackmore, D.; Sadoff, C. *2013. Implications of climate change for water resources development in the Ganges* Basin. *Water Policy* 15(Suppl.1): 26-50.

Jeuland, M.; Baker, J.; Bartlett, R.; Lacombe, G. 2014. The costs of uncoordinated infrastructure management in multi-reservoir river basins. *Environmental Research Letters* 9(10): 105006-105006.

Jeuland, M.; Whittington, D. 2014. Water resources planning under climate change: Assessing the robustness of real options for the Blue Nile. *Water Resources Research* 50(3): 2086-2107.

Kaimovitz, D.; Angelsen, A. 1998. *Economic models of tropical deforestation: A review*. Jakarta: Centre for International Forestry Research.

Kaliba, A.R.; Ngugi, C.C.; Mackambo, J.M.; Osewe, K.O.; Senkondo, E.; Mnembuka, B.V.; Amisah, S. 2007. Potential effect of aquaculture promotion on poverty reduction in sub-Saharan Africa. *Aquaculture International* 15: 445-459.

Karimi, A.; Ardakanian, R. 2010. Development of a dynamic long-term water allocation model for agriculture and industry water demands. *Water Resources Management* 24(9): 1717-1746.

Keller, A.; Keller, J. 1995. *Effective efficiency: A water use efficiency concept for allocating freshwater resources.* Water Resources and Irrigation Division Discussion Paper 22. Arlington, Virginia, USA: Winrock International.

Keller, A.; Keller, J.; Seckler, D. 1996. *Integrated water resource systems: Theory and policy implications.* Colombo, Sri Lanka: International Irrigation Management Institute (IIMI). 18p. (IIMI Research Report 3).

Kuhn, A.; Britz, W.; Willy, D.K.; van Oel, P. 2014. Simulating the viability of water institutions under volatile rainfall conditions – The case of the Lake Naivasha Basin. *Environmental Modelling & Software.* doi:10.1016/j.envsoft.2014.08.021 (in press).

Lenzen, M. 2002. A guide for computing inventories in hybrid life-cycle assessment: Some Australian results. *Journal of Clean Production* 10: 545-572.

Lenzen, M. 2003. Environmentally important paths, linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics* 14(1): 1-34.

Lenzen, M. 2009. Understanding virtual water flows: A multi-region input-output case study of Victoria. *Water Resources Research* 45: W09416. doi:10.1029/2008wr007649

Lenzen, M.; Foran, B. 2001. An input–output analysis of Australian water usage. *Water Policy* 3: 321-340.

Lenzen, M.; Moran, D.; Bhaduri, A.; Kanemoto, K.; Bekchanov, M.; Geshcke, A.; Foran, B. 2013. International trade of scarce water. *Ecological Economics* 94: 78-85.

Leontief, W. 1936. Quantitative input–output relations in the economic system of the United States. *The Review of Economic Statistics* 18: 105-125.

Letsoalo, A.; Blignaut, J.; de Wet, T.; de Wit, M.; Hess, S.; Tol, R.S.J.; van Heerden, J. 2007. Triple dividends of water consumption charges in South Africa. *Water Resources Research* 43: W05412.

Liu, J.; Herte, T.W.; Taheripour, F.; Zhu, T.; Ringler, C. 2014. International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change* 29: 22-31.

Llop, M. 2008. Economic impact of alternative water policy scenarios in the Spanish production system: An input-output analysis. *Ecological Economics* 68: 288-294.

Lofgren, H.; Robinson, S. 1997. *The mixed-complementarity approach to agricultural supply in computable general equilibrium models*. TMD Discussion Paper No. 20. Washington, DC: International Food Policy Research Institute (IFPRI).

Loomis, J.B.; Kent, P.; Strange, L.; Fausch, K.; Covich, A. 2000. Measuring total economic value of restoring ecosystem services in an impaired river basin: Results from a contingent valuation survey. *Ecological Economics* 33(1): 103-117.

Maass, A.; Hufschmidt, M.; Dorfman, R.; Thomas, H.; Marglin, S.; Fair, G. 1962. *Design of Water-Resources Systems*. Cambridge, Massachusetts: Harvard University Press.

Mainuddin, M.; Kirby, M.; Qureshi, E. 2007. Integrated hydrologic-economic modelling for analyzing water acquisition strategies in the Murray River basin. *Agricultural Water Management* 93(3): 123-135.

Malik, R.P.S. 2007. Do dams help reduce poverty? *Journal of the Indian Society of Agricultural Statistics* 61(2): 199-207.

Maneta, M.P.; Torres, M.O.; Wallender, W.W.; Vosti, S.; Howitt, R.; Rodrigues, L.; Bassoi, L.H.; Panday, S. 2009. A spatially distributed hydro-economic model to assess the effects of drought on land use, farm profits, and agricultural employment. *Water Resources Research* 45: W11412.

Medellin-Azuara, J.; Harou, J.J.; Olivares, M.A.; Madani-Larijani, K.; Lund, J.R.; Howitt, R.E.; Tanaka, S.K.; Jenkins, M.W.; Zhu, T. 2008. Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change* 87(1): S75-S90.

Molden, D.; de Fraiture, C. 2010. Comprehensive assessment of water management in agriculture. *Agricultural Water Management* 97(4): 493-578.

Montesinos, P.; Camacho, E.; Campos, B.; Rodríguez-Díaz, J.A. 2011. Analysis of virtual irrigation water. Application to water resources management in a Mediterranean river basin. *Water Resources Management* 25: 1635-1651.

Moy, W.S.; Cohon, J.L.; ReVelle, C.S. 1986. A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir. *Water Resources Research* 22(4): 489-498.

Mullick, R.A.; Babel, M.S.; Perret, S.R. 2013. Marginal benefit-based optimal water allocation: Case of Teesta River, Bangladesh. *Water Policy* 15: 126-146.

Newlin, B.D.; Jenkins, M.W.; Lund, J.R.; Howitt, R.E. 2002. Southern California water markets: Potential and limitations. *Journal of Water Resources Planning and Management* 128(1): 21-32.

Okadera, T.; Okamoto, N.; Watanabe, M.; Chontanawat, J. 2014. Regional water footprints of the Yangtze River: An interregional input–output approach. *Economic Systems Research* 26(4): 444-462.

Pande, S.; van den Boom, B.; Savenije, H.H.G.; Gosain, A.K. 2011. Water valuation at basin scale with application to western India. *Ecological Economics* 70(12): 2416-2428.

Peterson, D.; Dwyer, G.; Appels, D.; Fry, J. 2005. Water trade in the southern Murray-Darling Basin. *Economic Record* 81(255): S115-S127.

Pulido-Velázquez, M.; Jenkins, M.W.; Lund, J.R. 2004. Economic values for conjunctive use and water banking in southern California. *Water Resources Research* 40(3): W03401.

Pulido-Velázquez, M.; Andreu, J.; Sahuquillo, A. 2006. Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *Journal of Water Resources Planning and Management* 132(6): 454-467.

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* 66(1): 51-65.

Qureshi, M.E.; Connor, J.; Kirby, M.; Mainuddin, M. 2007. Economic assessment of environmental flows in the Murray Basin. *Australian Journal of Agricultural and Resources Economics* 513: 283-303.

Qureshi, M.E.; Proctor, W.; Young, M.D.; Wittwer, G. 2012. The economic impact of increased water demand in Australia: A computable general equilibrium analysis. *Economic Papers: A journal of applied economics and policy* 31: 87-102.

Randall, A. 1981. Property entitlements and pricing policies for a maturing water economy. *Australian Journal of Agricultural Economics* 25: 195-212.

Revelle, C.; Joeres, E.; Kirby, W. 1969. The linear decision rule in reservoir management and design: 1, development of the stochastic model. *Water Resources Research* 5(4): 767-777.

Ringler, C. 2001. *Optimal allocation and use of water resources in the Mekong River Basin: Multi-country and intersectoral analyses.* PhD Thesis. Frankfurt, Germany: Peter Lang.

Ringler, C.; Von Braun, J.; Rosegrant, M.W. 2004. Water policy analysis for the Mekong River basin. *Water International* 29(1): 30-42.

Ringler, C.; Cai, X. 2006. Valuing fisheries and wetlands using integrated economic-hydrologic modeling—Mekong River basin. *Journal of Water Resources Planning and Management* 132(6): 480-487.

Ringler, C.; Huy, N.V.; Msangi, S. 2006. Water allocation policy modeling for the Dong Nai River basin: An integrated perspective. *Journal of American Water Resources Association* 42: 1465-1482.

Robinson, S.; Willenbockel, D.; Strzepek, K. 2012. A dynamic general equilibrium analysis of adaptation to climate change in Ethiopia. *Review of Development Economics* 16: 489-502.

Roe, T.L.; Dinar, A.; Tsur,Y.; Diao, X. 2005. Feedback links between economywide and farm-level policies: With application to irrigation water management in Morocco. *Journal of Policy Modelling* 27(8): 905-928.

Rogers, P. 1969. A game theory approach to the problems of international river basins. *Water Resources Research* 5(4): 749-760.

Rose, A.; Liao, S.Y. 2005. Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions. *Journal of Regional Science* 45(1): 75-112.

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

Rosegrant, M.W.; Cai, X.; Cline, S.A. 2002. *World water and food to 2025: Dealing with scarcity*. Washington, DC: International Food Policy Research Institute (IFPRI).

Rosegrant, M.W.; Sulser, T.B.; Ringler, C.; Cline, S.A.; Msangi, S. 2005. *International Mmodel for Ppolicy Aanalysis of Aagricultural Ccommodities and Ttrade (IMPACT): Distributed Vversion 1.0*. IFPRI: Washington, D.C: International Food Policy Research Institute (IFPRI).

Rosegrant, M.W.; Koo, J.; Cenacchi, N.; Ringler, C.; Robertson, R.; Fisher, M.; Cox, C.; Garrett, K.; Perez, N.; Sabbagh, P. 2014. *Food security in a world of natural resource scarcity: The role of agricultural technologies*. Washington, DC: International Food Policy Research Institute (IFPRI).

Rudenko, I.; Bekchanov, M.; Djanibekov, U.; Lamers, J.P.A. 2013. The added value of a water footprint approach: Micro- and macroeconomic analysis of cotton production, processing and export in water bound Uzbekistan. *Global Planetary Change* 110: 143-151.

Rutherford, T.F. 1995. Extension of GAMS for complementarity problems arising in applied economic analysis. *Journal of Economic Dynamics and Control* 19(8): 1299-1324.

Scrieciu, S.S. 2007. The inherent dangers of using computable general equilibrium models as a single integrated modelling framework for sustainability impact assessment. A critical note on Böhringer and Löschel (2006). *Ecological Economics* 60(4): 678-684.

Seung, C.K.; Harris, T.R.; Englin, J.E.; Netusil, N.R. 2000. Impacts of water reallocation: A combined computable general equilibrium and recreation demand model approach. *Annals of Regional Science* 34: 473-487.

Smajgl, A. 2006. Quantitative evaluation of water use benefits—an integrative modeling approach for the Great Barrier Reef region. *Natural Resource Modeling* 19(4): 511-538.

Smajgl, A.; Greiner, R.; Mayocchi, C. 2006. Estimating the implications of water reform for irrigators in a sugar growing region. *Environmental Modeling and Software* 21(9): 1360-1367.

Smajgl, A.; Morris, S.; Heckbert, S. 2009. Water policy impact assessment—combining modeling techniques in the Great Barrier Reef region. *Water Policy* 11: 191-202.

Stanley, E.H.; Doyle, M.W. 2003. Trading off: The ecological effects of dam removal. *Frontiers in Ecology and the Environment* 1: 15-22.

Strzepek, K.M.; Gary, W.Y.; Tol, R.S.J.; Rosegrant, M.W. 2008. The value of the high Aswan Dam to the Egyptian economy. *Ecological Economics* 66: 117-126.

Suh, S.; Huppes, G. 2002. Missing inventory estimation tool suing extended input-output analysis. *International Journal of Life Cycle Assessment* 7: 134-140.

Suh, S.; Lenzen, M.; Treolar, G.J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguhi, Y.; Munksgaard, J.; Norris, G. 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Sciences &Technology* 38: 657-664.

Teasley, R.; McKinney, D. *2011. Calculating the* benefits of transboundary river basin cooperation: Syr Darya Basin. *Journal of Water Resources Planning and Management* 137(6): 481-490.

Tisdell, J.G. 2010. Acquiring water for environmental use in Australia: An analysis of policy options. *Water Resources Management* 24: 1515-1530.

Torres, M.O.; Maneta, M.; Howitt, R.; Vosti, S.A.; Wallender, W.W.; Bassoi, L.H.; Rogrigues, L.N. 2012. Economic impacts of regional water scarcity in the Sao Francisco River basin, Brazil: An application of a linked hydro-economic model. *Environment and Development Economics* 17(2): 227-248.

Treolar, G.J. 1997. Extracting embodied energy paths from input-output tables: Towards input-output based hybrid energy analysis method. *Economic Systems Research* 9: 375-391.

UN (United Nations); Eurostat (Commission of the European Communities); IMF (International Monetary Fund); OECD (Organisation for Economic Co-operation and Development); World Bank. 1993. *System of National Accounts. Series F, 2.* New York: United Nations.

Vanham, D. 2013. An assessment of the virtual water balance for agricultural products in EU river basins. *Water Resources and Industry* 1-2: 49-59.

van Heerden, J.H.; Blignaut, J.; Horridge, M. 2008. Integrated water and economic modeling of the impacts of water market instruments on the South African economy. *Ecological Economics* 66(1): 105-116.

Velázquez, E. 2006. An input-output model of water consumption: Analysing intersectoral water relationships in Andalusia. *Ecological Econ*omics 56: 226-240.

Vörösmarty, C.J.; Green, P.; Salisbury, J.; Lammers, R.B. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289(5477): 284-288.

Wang, H.; Wang, Y. 2009. An input–output analysis of virtual water uses of the three economic sectors in Beijing. *Water International* 34(4): 451-467.

Wang, Y.; Xiao, H.L.; Lu, M.F. 2009. Analysis of water consumption using a regional input-output model: Model development and application to Zhangye City, northwestern China. *Journal of Arid Environments* 73: 894-900.

Ward, F.A.; Lynch, T.P. 1996. Integrated river basin optimization: Modeling economic and hydrologic interdependence. *Water Resources Bulletin* 32(6): 1127-1138.

Ward, F.A.; Booker, J.F. 2003. Economic costs and benefits of instream flow protection for endangered species in an international basin. *Journal of the American Water Resources Association* 39(2): 427-440.

Ward, F.A.; Pulido-Velázquez, M. 2008. Water conservation in irrigation can increase water use. *PNAS* 105(47): 18215-18220.

Welsch, M.; Hermann, S.; Howells, M.; Rogner, H.H.; Young, C.; Ramma, I.; Bazilian, M.; Fischer, G.; Alfstad, T.; Gielen, D.; Le Blanc, D.; *Röhrl,* A.; Steduto, P.; Müller, A. 2014. Adding value with CLEWS – modelling the energy system and its interdependencies for Mauritius. *Applied Energy* 113: 1434-1445.

Whittington, D.; Wu, X.; Sadoff, C. 2005. Water resources management in the Nile Basin: The economic value of cooperation. *Water Policy* 7(3): 227-252.

Wichelns, D. 2004. The policy relevance of virtual water can be enhanced by considering comparative advantages. *Agricultural Water Management* 66(1): 49-63.

Wichelns, D. 2010a. Virtual water: A helpful perspective, but not a sufficient policy criterion. *Water Resources Management* 24(10): 2203-2219.

Wichelns, D. 2010b. Virtual water and water footprints: Policy relevant or simply descriptive? *International Journal of Water Resources Development* 26(4): 689-695.

Wu, X.; Whittington, D. 2006. Incentive compatibility and conflict resolution in international river basins: A case study of the Nile Basin. *Water Resources Research* 42: W02417.

Wu, X.; Jeuland, M.; Sadoff, C.; Whittington, D. 2013. Interdependence in water resource development in the Ganges: An economic analysis. *Water Policy* 15: 89-108.

Yang, H.; Pfister, S.; Bhaduri, A. 2013. Accounting for a scarce resource: Virtual water and water footprint in the global water system. *Current Opinion in Environmental Sustainability* 5(6): 599-606.

Yang, Y.C.E.; Zhao, J.; Cai, X. 2012. A decentralized method for water allocation management in the Yellow River basin. *Journal of Water Resources Planning and Management-ASCE* 138(4): 313-325.

Yang, Y.C.E.; Brown, C.M.; Yu, W.H.; Savitsky, A. 2013. An introduction to the IBMR, a hydro-economic model for climate change impact assessment in Pakistan's Indus River basin. *Water International* 38(5): 632-650.

Yu, Y.; Hubacek, K.; Feng, K.; Guan, D. 2010. Assessing regional and global water footprints for the UK. *Ecological Economics* 69: 1140-1147.

Zhang, Z.Y.; Shi, M.J.; Yang, H. 2011a. Analyses of water footprint of Beijing in an interregional input-output framework. *Ecological Economics* 70: 2494-2502.

Zhang, Z.Y.; Yang, H.; Shi, M.; Zehnder, A.J.B.; Abbaspour, K.C. 2011b. Analyses of impacts of China's international trade on its water resources and uses. *Hydrology and Earth System Sciences* 15: 2871-2880.

Zhang, Z.Y.; Yang, H.; Shi, M.J. 2012. Understanding Beijing's water challenge: A decomposition analysis of changes in Beijing's water footprint between 1997 and 2007. *Environmental Science & Technology* 46(22): 12373-12380.

Zhang, C.; Anadon, L.D. 2014. A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. *Ecological Economics* 100: 159-172.

Zhao, X.; Chen, B.; Yang, Z.F. 2009. National water footprint in an input-output framework: A case study of China 2002. *Ecological Modeling* 220(2): 245-253.

IWMI Working Papers

167 *Review of Hydro-economic Models to Address River Basin Management Problems: Structure, Applications and Research Gaps*. Maksud Bekchanov, Aditya Sood and Marc Jeuland. 2015.

166 *Water Resources Assessment of the Volta River Basin*. Marloes Mul, Emmanuel Obuobie, Richard Appoh, Kwabena Kankam-Yeboah, Emmanuel Bekoe-Obeng, Barnabas Amisigo, Frederick Yaw Logah, Benjamin Ghansah and Matthew McCartney. 2015. (Also available in French)

165 *Baseline Review and Ecosystem Services Assessment of the Tana River Basin, Kenya.* Tracy Baker, Jeremiah Kiptala, Lydia Olaka, Naomi Oates, Asghar Hussain and Matthew McCartney. 2015.

164 *Consumer Perceptions of Fruit and Vegetable Quality: Certification and Other Options for Safeguarding Public Health in West Africa*. Bernard Keraita and Pay Drechsel. 2015.

163 C*haracteristics of Urban and Peri-urban Agriculture in West Africa: Results of an Exploratory Survey Conducted in Tamale (Ghana) and Ouagadougou (Burkina Faso).* Imogen Bellwood-Howard, Volker Häring, Hanna Karg, Regina Roessler, Johannes Schlesinger and Martina Shakya. 2015.

162 *Review Paper on 'Garden Kits' in Africa: Lessons Learned and the Potential of Improved Water Management.* Douglas J. Merrey and Simon Langan. 2014.

161 *Extent of Arsenic Contamination and Its Impact on the Food Chain and Human Health in the Eastern Ganges Basin: A Review.* N. Rajmohan and S. A. Prathapar. 2014.

160 *Revitalizing Canal Irrigation: Towards Improving Cost Recovery.* Ravinder P. S. Malik, S. A. Prathapar and Madhavi Marwah. 2014.

159 *A Framework to Understand Gender and Structural Vulnerability to Climate Change in the Ganges River Basin: Lessons from Bangladesh, India and Nepal.* Fraser Sugden, Sanjiv de Silva, Floriane Clement, Niki Maskey-Amatya, Vidya Ramesh, Anil Philip and Luna Bharati. 2014.

158 *Review of Literature on Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka.* Andrew Noble, Priyanie Amerasinghe, Herath Manthrithilake and Sutharsiny Arasalingam. 2014.

157 *Hydrogeology of the Eastern Ganges Basin: An Overview.* N. Rajmohan and S. A. Prathapar. 2013.

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

International Water Management Institute

IWMI is a member of the CGIAR Consortium and leads the:

CGIAR RESEARCH PROGRAM ON Water, Land and Ecosystems

ISSN: 2012-5763
e-ISSN: 2478-1134
ISBN: 978-92-9090-826-5