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Hydro-Economic Modeling of Water Resources Management Challenges: Current Applications and Future Directions

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Hydro-economic modeling (HEM) addresses research and policy questions from socio-economic and biophysical perspectives under a broad range of water-related topics. Applications of HEM include economic evaluations of existing and new water projects, alternative water management actions or policies, risk assessments from hydro-climatic

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uncertainty (e.g., climate change), and the costs and benefits of mitigation and/or adaptation to such events. This paper reviews applications of HEM in five different categories: (1) climate change impacts and adaptation, (2) water–food–energy–ecosystems nexus management, (3) capability to link to other models, (4) innovative water management options, and (5) the ability to address and integrate uncertainty. We find that (i) the increasing complexity and heterogeneity of water resource management problems due to the growing demand and competition for water across economic sectors, (ii) limited availability and high costs of developing additional supplies, and (iii) emerging recognition and consideration of environmental water demands and value, have inspired new integrated hydro-economic problems and models to address issues of water–food–energy nexus sustainability, resilience, reliability through water (re)allocation based on the relative "value" of water uses. In the past decade, the field of HEM has improved the integration of ecosystem needs, but their representation is still insufficient and mostly ineffective. HEM studies address how to sustainably manage water resources, including groundwater which has become an area of particular interest in climate change adaptation. The current most used spatial and temporal resolutions (basin-scale and yearly time-step) are appropriate for planning but not for operational decisions and could be underestimating impacts from extreme events (e.g., flood risk) captured only by sub-monthly time scales. In addition, HEM primarily focuses on biophysical and economic indicators but often overlooks preferences and perspectives of stakeholders. Lastly, HEM has been widely used to analyze transboundary cooperation, showing benefits for increasing water security and economic development, particularly as climate change develops. We conclude that the field of HEM would benefit from developing more operational models and enhancing the integration of commonly neglected variables, such as social equity components, ecosystem requirements, and water quality.

Keywords: Hydro-economic modeling; water policy; global climate change; water–food–energy–ecosystems nexus.

1. Introduction

Climate change threatens the water–food–energy–ecosystems nexus by fundamentally transforming seasonality, location, and intensity of hydro-climatic events (Hoegh-Guldberg *et al.* 2018). These hydro-climatic changes combined with anthropogenic activities, such as unsustainable living styles, economic growth, and water demands, require efficient and resilient water management strategies to overcome various and compounding future challenges (Burek *et al.* 2016). To achieve this, decision-makers and researchers must consider hydrologic and socioeconomic dynamics, linkages, and feedbacks. Hydro-economic modeling (HEM) combines temporal and spatial variability of biophysical elements with socioeconomic dynamics to inform water management decisions (Harou *et al.* 2009). As a result, HEM has become a valuable tool for analyzing water-human systems, forecasting water management scenarios, developing water policy, and optimizing operations of water-related infrastructure (Bekchanov *et al.* 2017).

Harou *et al.* (2009) conducted a comprehensive review on HEM in 2009. Other review papers related to HEM since then have focused on specific elements such as integration and representation of the environmental variables (Momblanch *et al.* 2016), forested watershed management decisions (Ovando and Brouwer 2019), identification of other river management challenges and gaps (Bekchanov *et al.* 2017 2016), and integration of climate variables to inform adaptation plans (Ward 2021). Gaps identified include a link to biodiversity, water quality, and social aspects such as health and equity. The need to incorporate the evaluation of uncertain futures and assumptions has also become a core element in model development (Herman *et al.* 2015). HEM has limitations, some of which produce unreliable predictions on water demands, profitability, depletion of resources, or resilience to climate change (Harou *et al.* 2009).

This review updates and expands contributions by Harou *et al.* (2009) based on the literature published since then, given that water-related issues have worsened. This aggravation in water issues has brought challenges to water policymakers and researchers worldwide; however, these challenges have motivated innovations in HEM and the development of better-informed models to address an uncertain future and there have been computational improvements and conceptual advancements in research (Morales-Hernández *et al.* 2020). The overarching objectives of this review are: (a) to identify how existing hydro-economic models (HEMs) have innovated in integrating sectoral models such as climate, hydrological, energy, agricultural, environmental, and economy-wide models; and (b) to assess the scope of the impact and water policy issues that HEMs have addressed. The rest of Section 1 gives a background on HEM. Section 2 describes the methodology to select and review peer-reviewed studies and their classification into five categories based on HEM applications. Section 3 presents the results, including the most common modeling techniques and applications, temporal and spatial resolutions, and findings within each of the five categories: (i) climate change impacts and adaptation, (ii) water–food–energy–ecosystems nexus management, (iii) capability to link to other models, (iv) innovative water management options, and (v) the ability to address and integrate uncertainty. Finally, Secs. 4 and 5 discuss the limitations of the general use of HEMs and the review conclusions.

1.1. *Fundamentals of hydro-economic modeling*

Water is essential for maintaining societies and ecosystems and serves as input for producing and processing goods and services. Precipitation, evaporation, and runoff determine water availability in the natural environment at different spatial scales and in different periods (day-to-day, month-to-month, seasons-to-season, or inter-annual). Water uses derive from human processes and variables, involving projections and plausible development paths of population and consumption growth, economy, and technological developments, among other factors. Water resources modeling includes different details of biophysical processes at various spatial and temporal resolutions and human water objectives under available resources and infrastructure. Therefore, hydro-economic models (HEMs) combine these biophysical, technological, and economic representations of the water resources systems to create tools for informing and increasing knowledge in water resources planning (Bekchanov *et al.* 2017; Harou *et al.* 2009).

In its beginnings, water research and development answered questions of adding additional water supplies and facilities mainly with engineering solutions, for example, by creating infrastructure projects (Booker *et al.* 2012; Expósito *et al.* 2020). These efforts can be characterized primarily as an expansionary water economy where the benefits of developing new supplies exceed the cost (Randall 1981). Without computational capacities, cost-benefit analyses dominated the economic analysis of water management systems and projects (Kneese 2011), in which the benefits must exceed costs. Advancements in computer technologies and computational algorithms stimulated the development of more integrated HEMs combining elements of hydrologic uncertainty with water infrastructure systems and multiple water users applying mathematical programming, simulations, and decision theory (Maass *et al.* 1962; Reuss Martin 2003). Today we define water resources management problems within a framework, incorporating complex systems and concepts including economic and engineering principles, and formulation of goals and constraints within resources limits and quality norms.

Since about the 1970s, the problem of water management and HEM has been increasingly felt as not only the problem of a water infrastructure evaluation for water supply increase but also of emergent cases of water scarcity, impacts of floods and droughts, and increasing water demand by often competing water users. New challenges widen the focus from water supply to water demand management, including the design of water pricing mechanisms and water markets to regulate and, in many cases, limit water demand (Randall 1981). The role of economics in water management and policy analysis expanded from cost and benefit analysis of proposed single-use infrastructure development projects (Booker *et al.* 2005; Booker and Young 1994; Cai *et al.* 2003; Kahil *et al.* 2015; Noel and Howitt 1982) to the analysis of optimal water (re)allocation across multiple water uses and water sources over larger hydrologic regions (Essenfelder and Giupponi 2020). For example, Inter-basin Water Transfers (IWT) (Essenfelder and Giupponi 2020) became a subject of growing relevance for scientific and economic reasons due to the expanding infrastructure base that allows for IWTs trading (Delacámara *et al.*

2014; Marston and Cai 2016) and water (re)allocation potential (Pérez-Blanco *et al.* 2020; Rey *et al.* 2019).

The HEMs have taken up new integrated features with the need to understand better cross-sectoral linkages, feedbacks, water supply-demand relations, market and nonmarket values, trading, investment prioritization, and technological innovations. The HEM methods and approaches have evolved to advanced systems analysis and modeling of different types of water supply and demand in interconnected engineering, economic and natural systems. The choice of water management options is often associated with tradeoffs among multiple stakeholders, such as food production, energy supply, and ecosystem services, as well as across space and time (Banzhaf 2009; Hurford *et al.* 2014). These features are usually represented using a set of physical and technology choice equations. Numerical optimization algorithms are then applied to calculate a set of primary decisions that collectively result in the best feasible outcome from the perspective of specific objectives critical to decision-making (Booker *et al.* 2012). For example, an economic objective that focuses on minimizing costs or maximizing benefits is typical in HEM because it facilitates valuing resources and policy constraints (Ward 2009). Similarly, simulation methods can be used in HEM to represent complex water systems more realistically with nonlinear physical or institutional processes. Traditionally, HEMs evaluate the efficiency of alternative water allocation mechanisms under existing infrastructure (Booker *et al.* 2005; Booker and Young 1994; Cai *et al.* 2003; Kahil *et al.* 2015; Noel and Howitt 1982) and identify bottlenecks in the water system, where investments in new infrastructure would be most beneficial (Acquah and Ward 2017; Gohar *et al.* 2015; Qureshi *et al.* 2010). Recently, HEMs have also assessed how effectively the water system can adapt to future climatic and socioeconomic changes and explored the value of various options for doing this (Connor *et al.* 2009; Escriva-Bou *et al.* 2017; Kahil, Ward *et al.* 2016; Medellín-Azuara *et al.* 2008; Tanaka *et al.* 2006).

The complexity of water systems analyses is increasing to explore the connections with other sectors (e.g., ecosystems, industry, energy and agriculture), and HEMs can be coupled with other models to integrate the dynamics of multiple systems in their formulation. This integration can be internal (by incorporating the other systems' mathematical definitions into the simulations or optimizations performed by the HEM) or external (by using a modular coupling framework where the HEM and the models for other systems dynamics are solved separately but using input-output feedback). These approaches to integrate multiple systems can be used to assess the impact of water operations and water management policies in other sectors at different spatio-temporal resolutions, including the food–water–energy–ecosystem nexus. Additionally, these frameworks allow to assess potential impacts and tradeoffs besides economic performance by including performance metrics from other sectors in the water allocation or water policy assessment, such as water security, water affordability, and ecosystem services. This allows HEMs to be more relevant to practical applications, including adaptation to climate change and hydroclimate hazards management.

Advanced hydro-economic decision support systems combine advanced hydrological simulation models, optimization algorithms, uncertainty and risks, artificial intelligence, machine learning, real-time decision-making, or statistical analysis approaches with broad socioeconomic, institutional, political, legal, ecological perspectives, and cultural characteristics. These systems inform water infrastructure developments and public-private policy designs aiming at allocation and quality conservation of water at various scales within a variety of research studies related to water quality, hydropower production, agricultural activities, mitigation of damages from extreme hydroclimate events (e.g., floods, droughts), industrial and households water provision, water security and resilience of water infrastructure, outdoor recreation, environmental and other water-related market and nonmarket benefit values. An example of decision support systems includes the Drought Water Rights Allocation Tool (DWRAT) which is used in California's Russian River Watershed for optimizing water allocation to riparian and appropriative water rights holders (Whittington 2016). Another example is the use of AQUATOOL Decision Support System (Andreu *et al.* 1996) in Spain used for water resources planning and management of their main river basins, including water quality (Paredes *et al.* 2010) and environmental-economics (Pedro-Monzonís *et al.* 2016). HEM represents the economic benefit of water systems with multiple interdependent water users (each having individual goals, constraints, preferences, and risk attitudes) by optimizing or simulating those systems in a structured manner. Simulation models analyze system responses to different scenarios. Optimization models (or mathematical programming) seek to find optimal values for an objective function representing a system using an appropriate optimization algorithm/method. For example, problems can evaluate optimal water reservoir capacity and operation (water releases and water allocation), multiple-reservoir systems management, conjunctive use of water resources, water quality, hydropower generation, crop production, water security, water infrastructure resilience, and flood protection (Bekchanov *et al.* 2017; Ermolieva *et al.* 2014; Kahil, Connor *et al.* 2015; Kahil *et al.* 2015; Kahil, Ward *et al.* 2016; Ortiz-Partida *et al.* 2019; Pulido-Velazquez *et al.* 2004; Strokal *et al.* 2020). Models can target single- and multi-objective optimization, depending on the intended application (e.g., research and policy goals) and practical restrictions (e.g., data availability or computational facilities).

Common objective functions include minimizing costs, maximizing profits, increasing the efficiency of water allocation by sector (agricultural, domestic, energy, manufacturing), or improving ecological preservation (Kahil *et al.* 2015; Strokal *et al.* 2020). Objective functions can include the prices and costs associated with water releases, withdrawal and storage, water infrastructure operation and maintenance, demand and supply, constraints on water quality, disposal into the environment of all residuals of the production, or service activity (Krause *et al.* 2005). Resilience and reliability criteria are particular risk-related system performance criteria. Inclusion of these criteria in addition to the (expected) costs and benefits (Ermoliev and Winterfeldt 2012) allows various stakeholders and groups to better understand how to design robust and secure integrated hydro-economic systems and water–food–energy–environmental nexus in the presence of potential uncertainty and risks (Ermolieva *et al.* 2003).

Depending on the parameter's environment, optimization problems are classified as deterministic and stochastic. Deterministic optimization approaches are applied when all HEM inputs and current and future parameters (such as weather variability, climate change, market risks, varying risk perception, and stakeholder attitudes) are assumed to be known with certainty or when the uncertainty (and the related risks) can be ignored. Stochastic optimization problems and methods have parameters or constraints that depend on random variables and yield probabilistic outcomes that address system uncertainty. This approach is beneficial for climate change and weather variability, and it benefits from increasing computation capacity. Stochastic methods are essential for integrating short- and long-term sustainable development and planning resilient and reliable water management systems in connection to other systems (water–food–energy–ecosystem nexus).

Dynamic optimization is an approach that incorporates the change in time of dynamic variables such as precipitation or streamflow. This approach breaks the overall decision into a series of more manageable smaller decision over time, making it one of the most relevant approaches in HEM giving the natural variability of hydro-economic variables. Most hydro-economic problems concern dynamic water balance equations and optimal water management over different time horizons while pursuing short-, mid, long-term strategic, socioeconomic, and environmental goals and constraints. For example, dynamic problems arise in scheduling optimization, hydropower plants operation, multipurpose reservoirs operation management, water provision for water–food–energy–ecosystem nexus, water infrastructure investments problem, catastrophic risks management, and in many other practical studies.

Integrated HEMs can be holistic or modular (distributed) models (Cai *et al.* 2003). Holistic models combine natural and anthropogenic submodels in one code, e.g., process-based and sectoral models (agricultural, energy, hydrological). However, holistic models often involve aggregation and simplification of rather complex hydro-economic processes. Individual distributed models can be rather detailed and computationally intensive, designed for simulation and optimization purposes (Bredehoeft and Young 1970). They represent natural and anthropogenic systems (e.g., water, food, energy, hydrological, and social). Incorporating distributed models into a one-integrated framework requires appropriate model linkage procedures.

2. Methodology

This review provides a synthesis of progress in recent development and applications of HEMs. To cover a wide range of research, we utilized two article databases: Scopus and Science Direct. As the last comprehensive review on HEM was completed in 2009 (Harou *et al.* 2009), the search was constrained to peer-reviewed articles from 2009 to July 2020 (including *in-press* articles). The first list of articles was obtained using the search term “Hydro-economic model”, outputting 560 research papers. The articles list was supplemented with 33 relevant documents based on the authors’ experience, yielding 593 in total. The total number of articles was later reduced to 530 after removing duplicates.

Table 1. HEM Categories, Primary Words, and Secondary Words used to Select and Categorize 169 Peer-Reviewed Papers

		Primary Words	**Secondary Words**
		cost, hydro-economic, benefits, economics, economy, hydro-economic	↓
Categories	1	Use of hydro-economic models for the assessment of the impacts of water scarcity, climate change and variability (including extreme events of floods and droughts), and the evaluation of mitigation and adaptation policies	adaptation, climate change, drought, extreme climate, extreme event, flood, mitigation, water security, climate variability, water scarcity
	2	Representation of the water–food–energy–ecosystem nexus management challenges in HEMs, including water quality	nexus, food security, energy security, water security
	3	Integration of HEMs with other sectoral models such as climate, hydrological, energy, agricultural, environmental, agent-based, or economy-wide models and use of newly available datasets (e.g., satellite observations, big data, machine learning) challenges and opportunities	link, coupled, agent-based, economy-wide, remote sensing, machine learning, new technology, big data, coupling

Table 1. (*Continued*)

	Primary Words	Secondary Words
	cost, hydro-economic, benefits, economics, economy, hydro-economic	↓
4	Emerging innovative water management options such as market-based mechanisms pricing policies, payment for ecosystem services, and virtual water trade, needed for the adaptation to water supplies variability	water markets, opportunity cost, virtual water, policy instrument, environmental water
5	The possibility for new generation HEMs ranging from micro- to large-scale applications capable of addressing uncertainty, challenges, and opportunities	large scale, robust, stochastic, uncertainty

We created five categories based on emerging HEM applications: (1) climate change impacts and adaptation, (2) water–food–energy–ecosystems nexus management, (3) capability to link to other models, (4) innovative water management options, and (5) new generation of HEMs to address and integrate uncertainty.

Articles were filtered and categorized based on 6 *primary* and 34 *secondary words*. The primary words were economics-related, and secondary words were relevant keywords within categories. If one primary word and any secondary words were contained within an article's title, abstract, or keywords, it was included and assigned to one category. Totally, 169 articles survived filtering and were categorized (Figure 1).

Each article was read, and information was extracted to create a database with information about each application. This database includes identifier information such as author, year of publication, and title. It also considers modeling techniques (results in Sec. 3.1) which include model types (e.g., simulation, optimization), taxonomy (fully coupled vs. modular) to determine if economic variables are directly integrated into the model or not, and other modeling techniques. When possible, we identified model characteristics such as spatial and temporal resolution, software platform, limitations, and their integration with other models.

We extracted the main objective of each hydro-economic model and the type of input variables and decision variables that feed into it. We categorized variable types into hydrology (e.g., streamflow, groundwater depth), climate (e.g., precipitation, temperature, solar radiation, evapotranspiration), energy (e.g., hydropower generation, energy used), agriculture (e.g., crop yield, irrigation water, crop type), environmental (e.g., water quality parameters, environmental flows,

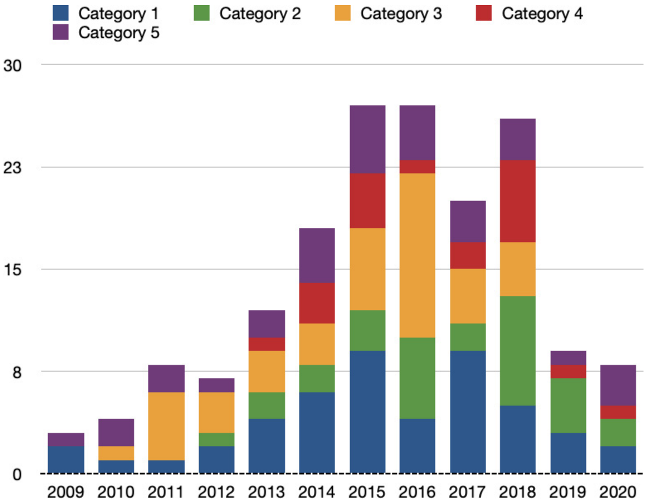

Figure 1. Number of Papers Published per Year in Each Category, Only Considering Articles that Suit the Scope of the Review. We Reviewed 169 Articles in Total

Note: 2020 shows articles up to July.

species numbers), and social (e.g., population, urban and rural water uses, industrial water use). Variables in these categories were used as a proxy to assess the main focus of HEMs (hydrology, climate, energy agriculture, environment, and social), and they may overlap (results in Sec. 3.1.3). For example, a model using crop yield and acreage from the agriculture category and streamflow and groundwater storage from the hydrology category would be categorized as agriculture and hydrology. Finally, we addressed the potential impact of HEMs by identifying their implications for policy changes and development within each category (Sec. 3.2).

3. Review Findings: Modeling Techniques and Applications

3.1. *Modeling techniques in HEM*

HEMs are diverse in terms of their modeling approach (e.g., optimization vs. simulation), objective functions (e.g., single, multiple, maximization, minimization), assumptions (e.g., deterministic, stochastic), integration with other models (e.g., modular vs. fully coupled), water use sector of interest (e.g., agriculture, energy, environment), spatial and temporal scales, as well as their considerations of variables (e.g., hydrology, climate change, water demands). Here we describe the different modeling characteristics used in HEMs since 2009.

3.1.1. *Optimization vs. simulation*

About half (53%) of HEMs utilized optimization procedures, another third (28%) used simulation, and the rest applied a mix of simulation and optimization (19%). Optimization models search for an optimal response ("what is best") given a series of constraints and variables. These models mainly focus on maximizing benefits (e.g., Arjoon *et al.* 2014; Etkin *et al.* 2015; Zhu *et al.* 2015) or minimizing water deficits (e.g., Davidsen *et al.* 2015; Ghosh *et al.* 2014; Hurd and Coonrod 2012; Souza da Silva and De Moraes 2018), whether individually for agriculture (e.g., Fernández *et al.* 2016; Medellín-Azuara *et al.* 2014), hydropower (e.g., Bekchanov *et al.* 2015; Gonzalez *et al.* 2020), or for a combination of diverse water users (Do *et al.* 2020; Jalilov *et al.* 2015; Kahil, Albiac *et al.* 2016). Simulation models apply "what-if" analyses. They have been used to test alternative water policies and management actions (Assaf 2009; Essenfelder *et al.* 2018; Kahil *et al.* 2016) and estimate hydroclimatic events of different magnitudes (e.g., Foudi 2015; Kourgialas and Karatzas 2013). Coupled simulation and optimization models are a hybrid of the former, where simulations test various alternatives that are later individually optimized for most likely scenarios (e.g., Emami and Koch 2018; Foster *et al.* 2017; Settre *et al.* 2019).

3.1.2. *Spatial and temporal resolution*

HEMs can analyze multiple spatial and temporal resolutions, depending on the problem at hand. In general, as scale and temporal resolution increase, the details increase with a clear tradeoff between accuracy and computational cost. Large-scale HEMs have the potential to inform critical areas needing future investments in water infrastructure, and policymakers and stakeholders must navigate management options, future scenarios, and the potential tradeoffs among economic and environmental objectives (Kahil *et al.* 2018). Small-scale models can help the economic development of smaller regions, such as Small Island States, when it relies on water availability, quality, and price. Integrating groundwater hydrology, climate change scenarios, economics, and land use is essential to cope with climate stress in small economies (Gohar *et al.* 2019).

Overall, the most common spatial and temporal resolutions are the basin scale and yearly time-step, but there is variation across categories. HEMs focusing on climate change impacts and adaptation mainly cover basin and regional (whole or parts of multiple basins) scales at yearly and monthly temporal resolutions (Macian-Sorribes *et al.* 2017; Tilmant *et al.* 2020; Yang *et al.* 2016). Models on the water–food–energy–ecosystems nexus are applied to regional or country levels and commonly use yearly resolutions, likely due to these models' complexity and intended reach (e.g., Gonzalez-Salazar 2016; Jalilov *et al.* 2015. Those HEMs with the capability to link with other models usually cover basin-scale followed by regional and include a monthly time-step (e.g., Reddy *et al.* 2015; White *et al.* 2015; Zekri 2017). Some models in this category had multiple scale and temporal resolutions as they linked different models. Given the nature of water management options (e.g., water markets), scales are administrative such as state or country level, and manage planning time-steps like yearly and monthly. Lastly, HEMs that address and integrate uncertainty present diverse spatial applications, ranging from local to entire countries (e.g., Arjoon *et al.* 2014; Weibel and Madlener 2014).

HEMs often cover vast spatial and temporal scales that allow planning but hardly any are operational. The field would benefit by increasing focus on sub-monthly time-steps that can capture nuances from hydroclimatic events (e.g., extreme events). Some examples of current operational HEMs are in the energy sector for hydropower operations. For example, Brazil's energy sector relays on hydropower, and hydropower plants are allowed to sell part of the energy generation potential (water in reservoirs) as energy generation rights to energy traders and large consumers. Energy market price (known as "Preço de Liquidação das Diferenças" or "PLD") depends primarily on natural flows at the catchment point of each dam, and energy traders and large consumers forecast it to know if the sale prices will go up or down to decide when to trade. That can be done at monthly, daily, or even hourly time steps.

3.1.3. *Water use sectors and data requirements*

Most of the HEMs in this review considered hydrology (72%) and climate (47%) variables and primarily focused on agriculture (53%), followed by energy (36%), environment (30%), and social aspects (28%) with common overlap among two or more sectors (Figure 2). Hydrology and climate variables often included in HEMs are streamflow, groundwater depth, runoff, aquifer recharge, hydraulic

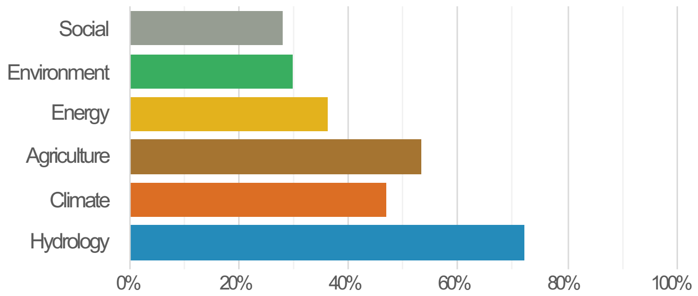

Figure 2. Type of variables used by HEM

conductivity, soil moisture, precipitation, temperature, and potential evapotranspiration (Blanco-Gutiérrez *et al.* 2013; Kahil *et al.* 2016; Varela-Ortega 2011). Data requirements regarding agriculture often consider crop type, area, yield, irrigation method, production costs, applied water, and actual evapotranspiration (Essenfelder *et al.* 2018; Kahil *et al.* 2016; Ponce *et al.* 2017). HEMs focused on energy-considered variables like hydropower generation, energy use, costs and prices, water requirements, reservoir storage, and production capacity (e.g., Arjoon *et al.* 2014; Gonzalez-Salazar 2016; Weibel and Madlener 2014). Applications to the environment commonly integrate environmental flow requirements, cost of conservation, and occasionally integrated water quality parameters (e.g., Nainggolan *et al.* 2018; Varela-Ortega 2011). Environmental flow requirements were generally integrated as constraints and often depicted as 'minimum' in-stream flows to be met, often having the same minimum for the entire period of analysis (e.g., Dogan *et al.* 2018; Girard *et al.* 2015). Social variables were the less portrayed in HEMs and included demographics and water infrastructure, operation costs, water demands, damages from floods, and cost of adaptation strategies (e.g., Escriva-Bou *et al.* 2017; Foudi 2015).

HEMs can help manage water resources, considering water demands from urban, industrial, energy, and agricultural sectors, and environmental requirements. Areas of opportunity to improve HEMs are (i) better consideration and depiction of environmental flows that represent the needs of aquatic and riparian ecosystems, (ii) water quality parameters to inform human health concerns and water treatment methods, and (iii) more sophisticated integration of hydroclimatic projections, including the consideration extreme scenarios to account for low probability but costly consequences that would allow us to plan for an uncertain future.

3.2. *Focus of hydro-economic models and policy implications*

Contemporary HEMs focus on a variety of topics (Table 2). Among the most studied are the assessment of climate change impact and adaptation, sustainable management of groundwater resources, optimization of agricultural production, hydropower operations, governance and cooperation, and tradeoffs associated with water allocations (e.g., integrating environmental flows). Other less recurrent topics were water markets (Kahil *et al.* 2016; Medellín-Azuara *et al.* 2009), water prices (Lopez-Nicolas *et al.* 2018; Pulido-Velazquez *et al.* 2013), the importance of collaboration across multiple disciplines (Girard *et al.* 2015), water quality (Nainggolan *et al.* 2018), desalination (Huang and Lee 2019), reservoir operations (Etkin *et al.* 2015; Ortiz-Partida *et al.* 2019), the relevance of weather forecast (Etkin *et al.* 2015; Siderius *et al.* 2016), and the water–energy–food–ecosystems nexus (Bekchanov and Lamers 2016; Jalilov *et al.* 2016; Souza da Silva and De Moraes 2018).

As climate change advances, analyzing the effects of sustained droughts is becoming an interesting area of study. Models evaluate response to extreme drought using water trading and other adaptation strategies (Jiang and Grafton 2012). For example, droughts in the Mediterranean basin represent a burden for agricultural and environmental users as water availability reduces and irrigated water demands increase, but adaptation activities, while costly, could reduce the economic impacts (Escriva-Bou *et al.* 2017; Etkin *et al.* 2015; Harou *et al.* 2010).

The most common adaptation to drought impacts was finding ways to manage groundwater resources sustainably. Several HEMs demonstrate that groundwater functions as a buffer during dry periods and emphasize the relevance of conjunctive water use (e.g., joint management of surface water and groundwater) (Foster, Brozović and Butler 2017; Foster *et al.* 2017; Hurd and Coonrod 2012; MacEwan *et al.* 2017; Ward *et al.* 2019; Zhu *et al.* 2015. Others highlight the importance of groundwater banking to offset irrigators' lack of surface water and reduce profit losses (Ghosh *et al.* 2014) and offer increasing irrigation water prices along with energy prices to prevent aquifer depletion (Balali and Viaggi 2015). When allocating resources for adaptation strategies, it is essential to recognize that expected impacts may not be significant for specific economic sectors. Accordingly, actions should focus on other sectors or on more relevant impacts to that sector. Also, places with limited access to groundwater and uncertain surface water deliveries during drought are the most economically vulnerable regarding crop revenues, employment, and household income (Medellín-Azuara *et al.* 2015). When there is a tradeoff between socioenvironmental justice and water (or any natural resource) access for major water users, it is necessary to create multi-benefit strategies that preserve justice for the most vulnerable stakeholders while providing economic prosperity for everyone and considering the effects of climate change (Fernandez-Bou *et al.* 2021, 2023).

A recommendation is to encourage governments to protect farmworkers and provide incentives for farmers to adopt more efficient irrigation technologies and shift towards climate-smart agricultural practices. Such improvements would benefit the basin by improving food and energy security, increasing income, and protecting the environment (Bekchanov *et al.* 2016; Grové 2011; Siderius *et al.* 2016). Cost-free adaptation strategies to increasing water scarcity and higher temperatures include changes in cropping patterns and deficit irrigation (Aghapour *et al.* 2020). Climate change will have uneven consequences across farming communities. For instance, a study in Chile estimated that climate change impacts crop yields showing increased yields for wheat but decreases for other crops like alfalfa, sugar beet, and beans (Ponce *et al.* 2017).

The water demand of multiple sectors needs to be considered for an equitable future. Several HEM studies evaluate the value of cooperation and the importance of considering multiple objectives, showing that small losses for one sector may represent significant benefits for another and overall higher benefits for the entire system (Bekchanov *et al.* 2015; Jalilov *et al.* 2015; Kirby 2015). Furthermore, the costs and outcomes of the adaptation strategies vary between stakeholders. Nainggolan *et al.* (2018) illustrate the need to develop joint regional policies for water and climate adaptation that accounts for uneven effects and cost across stakeholders, once again showing the value of transnational cooperation.

Policies are an avenue for protecting the environment and future human water needs. Kahil *et al.* (2016) indicate that without adequate policies protecting water resources and natural ecosystems, water users will strategically deplete reservoirs, aquifers, and river flows for short-term adaptation to climate change, disregarding the environmental impacts and future human activities. The following subsections describe and analyze the range of policy issues addressed by HEM across the five categories.

3.2.1. *Category* 1: *Hydroclimate, extremes, and climate change*

Articles within this category used HEM to assess the impacts of climate change and variability (including extremes such as floods and droughts) and evaluate mitigation and adaptation policies.

Some studies generate water scarcity scenarios by lowering water availability by a percentage as a proxy for climate change effects or only considering changes in yearly average precipitation (Esteve *et al.* 2015; Jeuland *et al.* 2014). Depending on the region, water scarcity results from increasing demand from a growing population, a decrease in water supply due to climate change (Hurd and Coonrod 2012), or the integration of environmental flow requirements (Blanco-Gutiérrez *et al.* 2013). These HEM studies are valuable and could guide the design of policies that support more efficient and sustainable water management.

Policy implications regarding climate change include recognizing that groundwater resources play a significant role in ameliorating price spikes and in the hydroclimate as groundwater serves as a buffer during dry periods (Hurd and Coonrod 2012; Medellín-Azuara *et al.* 2015). In addition, it is important to consider that the economic value of groundwater depends on the initial conditions of aquifers and that sustainable yields increase productivity and maintain drought resilience (Foster, Brozović, and Butler 2017; Foster *et al.* 2017). Another study in

Table 2. Selected Articles and their Main Objective and Policy Implications

Citation	Objective	Policy Implications
(Hurd and Coonrod 2012)	Optimize allocation, use, storage, and management of available water such that the greatest long-run economic benefits are achieved within the legal boundaries of river compacts and treaties, and with available resources, technologies, and infrastructure. It also evaluates cost in three different climate change scenarios.	The article states that groundwater supplies provide an effective buffer for many municipal systems and help ameliorate price spikes. The authors encourage policies that consider the role of water and water services in stakeholders activities, and how these activities would be affected by more frequent and severe droughts (and possibly floods).
(Jiang and Grafton 2012)	Examines the role of water trading, and the economic impacts of climate change and reduced surface water availability.	Water markets are a partial management tool to mitigate agriculture impacts on climate change but should be developed with an equity perspective. It also talks about the importance of considering extreme scenarios to develop adaptation strategies.
(Ghosh *et al.* 2014)	Examines the economic impacts of water banking on the water use decisions of agricultural irrigators, the sector that has accounted for the majority of banking activity to date in Idaho under a range of administration and water availability conditions.	They find that water banking can offset irrigators' economic losses during dry periods, but that its ability to do so depends on whether it facilitates trade across groundwater and surface water users.
(Medellín-Azuara *et al.* 2014)	Estimate local crop yield and revenue losses due to water salinity from water management, large-scale flooding, and future sea level rise scenarios.	Expected climate change impacts may not be significant for certain economic sectors and actions and policies should be either focused on other sectors or on more relevant impacts to that sector.
(Balali and Viaggi 2015)	Analyze and forecast groundwater volume fluctuations under different scenarios of economic policies and climate change.	They conclude that increasing irrigation water price along with energy price can reduce groundwater exploitation.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Bekchanov *et al.* 2015)	Evaluate implications on hydropower generation and irrigated agriculture from the construction and operation of a dam.	They highlight the importance of considering multiple objectives to balance different stakeholders' benefits on the system. For example, they calculate the benefits from only optimizing for hydropower (and the impacts on irrigation agriculture) or optimizing for both. The analysis shows that cooperative basin-wide maximization of benefits would lead to large increases in upstream hydropower production and only minor changes in downstream irrigation benefits.
(Esteve *et al.* 2015)	Assess potential effects of climate change on irrigated agriculture and options for adaptation.	Similarly to other studies, results indicate that climate change may severely impact irrigation systems, reduce considerably the availability of water resources, crop yields, and increase irrigation water requirements. These results support the need to design and facilitate adaptation processes considering the socio-economic characteristics of irrigation agriculture.
(Girard *et al.* 2015)	Integrate climate, economic, agronomic, and hydrological scenarios to design and select adaptation measure ensuring that environmental and supply management goals are achieved.	They illustrate how analyzing long-term changes and adaptation to global change in river basin management requires bringing multiple scientific disciplines together and binding them into a single framework, facilitated by integrated modelling.
(Kirby 2015)	Examine a range of strategies and their impact on flows and the gross income of irrigation.	Adaptation strategies provide a range of flow and economic outcomes and can enhance flows without large adverse impacts on the gross income of irrigation. Some environmental water management strategies enhance flows in the Murray part of the basin even under the drying influence of projected median climate change.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Bekchanov, Ringler *et al.* 2016)	Identify the economically optimal allocation of technological investments in water application and conveyance efficiency across irrigation sites, from a basin-wide perspective.	Governments should provide incentives for farmers to adopt new irrigation technology. Such improvements would deliver benefits across the basin, by improving food and energy security, boosting income, and contributing to protection of the environment.
(Kahil, Ward, *et al.* 2016)	Close the gap in hydro-economic models related to the weak integration of physically-based representations of water sources and uses such as the interaction between ground and surface water sources to inform policy choices.	Results indicate that in the absence of adequate policies protecting water resources and natural ecosystems, water users will deplete reservoirs, aquifers, and river flows for short-term adaptation to climate change, disregarding the impacts on the environment and future human activities. These impacts can be addressed by implementing sustainable management policies. However, these policies could have disproportionate costs for some stakeholders' groups, and their opposition may undermine attempts at sustainable policy.
(Null 2016)	Analyze water reliability without a reservoir (dam removal) but with improved water conveyance.	Improving water conveyance can sometimes substitute water storage. This research highlights the importance of reoperation of existing infrastructure and implies that some systems could restore river flows without compromising human water uses.
(Escriva-Bou *et al.* 2017)	Assess the economic value of implementing adaptation strategies for climate change.	Adaptation action can save money over the long-term. Results show that the system is vulnerable to global change, especially over the long term, and that adaptation actions can save €3–65 million=year. Some of the actions are changes in management like modifying priorities or enhancing water markets that do not require infrastructure investments or reductions in demand.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Foster *et al.* 2017)	Quantify the effects of changes in well yields on the buffer value of groundwater.	Unreliable groundwater levels reduce productivity of groundwater, suggesting failing to consider this feedback may lead to errors in estimates of the value of groundwater management in conjunctive use systems.
(Ponce *et al.* 2017)	Assess the distributional impacts of climate change, considering the geographical location of each farmers' community and the spatial allocation of water resources at basin scale.	Climate change will have uneven consequences across farmers' communities. For instance, wheat production in a region in Chile could increase by 9% (154 tons), while alfalfa, sugar beets, and beans in other regions could decrease by over 40 to almost 60%.
(Essenfelder *et al.* 2018)	Provide means for exploring the dynamics between the behavior of socio-economic agents and their connection with the water system through water and land management.	The results suggest that agents' adaptation strategies in response to the irrigation restrictions have broad economic impacts and subsequent consequences on surface and groundwater hydrology. When representing coupled human-water systems, not only should the complexity of eco-hydrologic processes and their spatial variability be considered but also the complexity and spatial variability of socio-economic agents' behavior so that the relevant feedbacks between the systems can be accounted for.
(Nainggolan *et al.* 2018)	Explores the scope for simultaneously managing nutrient abatement and climate change mitigation in the Baltic Sea (BS) region through the implementation of a selection of measures.	Their findings show that the cost and the outcome of the implementing climate change mitigation projects vary between countries. Joint strategies to improve water quality and to reduce climate change are economically beneficial, especially when there is transnational cooperation. This illustrates the benefits of developing collaborative regional policies for water and climate regulation that considers the distribution of costs and benefits for the countries in the region.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Crespo *et al.* 2019)	Evaluate the tradeoff and political economy aspects of allocating water among economic water uses and environmental flows in water-scarce river basins.	The results of this study highlight the importance of assessing the opportunity costs and political implications of reallocating water from human activities to the environment under impending climate change impacts. Moreover, the results indicate that well-functioning water allocation policies should be not only economically efficient but also socially acceptable to reduce the likelihood of failure of water reallocation to the environment.
(Aghapour Sabbaghi *et al.* 2020)	Explore the economic impacts of climate change on water and agriculture sectors, including cost-free adaptation strategies.	Optimal cropping pattern and a deficient-irrigation strategy provide opportunities for farmers to adapt to climate change. These are examples of cost-free adaptation strategies that can reduce the stress on water systems from climate change and socio-economic changes.
(Ejaz Qureshi *et al.* 2013)	Analyze impacts of increased water scarcity on Australian agricultural production and the magnitude of subsequent impacts on global food security.	Changes in precipitation and water allocations resulting from climate change threaten agricultural production in Australia, that can lead to global food market impacts and food security.
(Jalilov *et al.* 2015)	Investigate water-energy-agriculture linkages in a transboundary context and the economic benefits of various scenarios emphasizing agricultural and/or energy production.	Models help stakeholders see the potential for benefits—and their limits—associated with cooperating in a regional, basin-wide agreement across water-energy-agriculture nexus.
(Siderius *et al.* 2016)	Explore the possibility of national to regional food self-sufficiency as alternatives to an increasing reliance on global markets.	Investments for supporting a transition towards a climate-smart sustainable agriculture are needed to reduce the environmental impacts of increased production in the basin and increase food security.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Hrozencik *et al.* 2017)	Evaluate a basin-wide hydro-economic model to incorporate economic behavior driven by changes in well capacity and changes in depth to groundwater.	Stakeholders and policymakers depend on the accurate integration of economic decisions and policy types to implement effective policy instruments. Omitting the role of well capacity may mislead the magnitude and distribution of groundwater use and policy impacts over time.
(Souza da Silva and De Moraes 2018)	Analyze tradeoffs between environmental demands, hydropower, water supply by public utilities, and irrigated agriculture.	Policymaking for water resources should consider the food-water-energy-ecosystems nexus at a regional scale to minimize environmental and economic costs under water scarcity and land use change.
(van der Zwaan *et al.* 2018)	Analyze the hydrology for the Ethiopian part of the Blue Nile river system and inspect the multiple effects of population growth and the future possible vulnerability and variability of hydro-electricity generation due to likely impacts of climate change.	Government must evaluate possible negative social and environmental effects of a massive deployment of any single alternative (hydropower in this article). The large-scale use of hydropower could produce negative impacts on water users within the country and downstream, in South Sudan, Sudan and Egypt.
(Raso *et al.* 2019)	Identify methods that address change and adaptation at operational and structural levels, and economic evaluation of large dams, specific to the African context.	Water availability may change in the future and affect the economic performance of dams. Adaptation policies at the systems scale can help mitigate negative consequences.
(Do *et al.* 2020)	Quantify the effects of reservoir operation on hydropower generation, irrigated crop production and fisheries yield in the Tonle Sap lake through a novel hydro-economic model at the whole basin scale.	Dam operation can increase water availability for irrigation without severely harming hydropower production. Cross-sectoral and transboundary partnerships should strengthen stakeholder participation in decision-making. Local solutions such as enhanced reservoir operation can respond to the broader global issue of natural resource tradeoffs and sharing.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Bekchanov and Lamers 2016)	Quantify energy requirements on irrigation water supply, as well as energy supply constraints which in previous hydro-economic models might have led to an overestimation of the optimal level of ground and surface water use.	This article illustrates the necessity of considering food-water-energy nexus elements for informed policy decisions. In this case there is an intrinsic link between the water and energy sectors through economic constraints.
(Czajkowski *et al.* 2018)	Model the relationships between urban flood, surface water storage and groundwater levels over time to prevent saltwater intrusion.	In certain coastal areas, there are tradeoffs between lower groundwater levels to reduce flood risk, and high groundwater levels to reduce seawater intrusion.
(Etkin *et al.* 2015)	Provide reservoir operators with a set of strategies that balance the objectives of meeting current and future needs.	Seasonal precipitation forecasts provide more efficient and equitable water release decisions that benefit the variety of stakeholders in the basin.
(Fernández *et al.* 2016)	Estimate economic impacts of changes in water availability on small-scale agriculture.	Water resources planning help to reduce the impact from changes in water availability on small-scale agriculture.
(Grové 2011)	Model key performance indicators for decision-making while taking cognizance of the stochastic dynamic nature of irrigation agriculture. The study takes the opportunity cost of water into account while optimizing water use between multiple crops.	Results indicated that it is profitable to irrigate larger areas in South Africa with water saved from deficit irrigation and increasing irrigation efficiency.
(Jaeger *et al.* 2017)	Examine how climate change, population growth, and economic growth will alter the availability and use of water in coming decades, using the example of the Willamette River Basin, Oregon.	The study shows how water scarcity varies greatly across small distances and brief time periods, even in basins where water may be relatively abundant overall.
(Kahil, Dinar, *et al.* 2015)	Analyze the effects of droughts and assess alternative adaptation policies.	The study shows that the current water management approach in Spain, based on stakeholders' cooperation, achieves almost the same economic outcomes and better environmental outcomes compared to a pure water market. These findings call for a reconsideration of the current management in arid and semiarid basins around the world.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Medellín-Azuara *et al.* 2015)	Examines the economic costs of pumping groundwater during drought and the potential loss of pumping capacity as groundwater levels drop.	In the Central Valley of California places without access to groundwater and with uncertain surface-water deliveries during drought are the most economically vulnerable in terms of crop revenues, employment, and household income.
(Pulido-Velazquez *et al.* 2013)	Simulate water pricing policies linked to water availability, and the design of efficient pricing policies that incorporate the basin-wide marginal value of water.	Pricing policies can increase economic benefits, leading to more efficient resource allocations over time and across competing water uses.
(Torres *et al.* 2012)	Examine the regional effects of water use regulations and product price changes on agriculture.	New minimum instream flow regulations can constrain downstream farmer cropping options especially during drought years.
(Yang *et al.* 2016)	Diagnose conditions that may derail water resources development goals due to climate change or water use among competing users.	Without a new management option, conflict will arise with reduced precipitation falling in the basin in the future as it strongly influences water, energy, and food production in the basin.
(Yang *et al.* 2014)	Assess the economic effect of current and alternative surface water allocation schemes at different hierarchical levels under climate change impacts.	The paper illustrates how current water governance mechanisms make it difficult to adapt to changing climate conditions, having economic repercussions in the basin under both, high and low flow conditions.
(Zhu *et al.* 2015)	Analyze the roles and benefits of conjunctive use of surface water and groundwater and market-based water transfers in an integrated regional water system where agricultural and urban water users coordinate supply and demand management based on supply reliability and economic values of water.	Conjunctive use of surface and groundwater coupled with water transfer mechanisms and artificial groundwater recharge can maximize net economic benefit that includes agricultural production benefits, water conservation, operating costs of groundwater pumping.

Table 2. (*Continued*)

Citation	Objective	Policy Implications
(Bekchanov *et al.* 2018)	Explore market-based water allocation to increase inflows to the Aral Sea while maintaining stable agricultural incomes.	There are multiple alternatives to minimize impacts to irrigated agriculture while increasing environmental flows. Water trading systems are more efficient when allowing trade among irrigation sites and between sites and instream uses.
(Lopez-Nicolas *et al.* 2018)	Design a baseline water tariff at the consumer level considering revenue and equity criteria and test a dynamic urban water tariff using as a basis the scarcity-based pricing policy at river basin scale and the baseline water tariff at the consumer level.	The proposed framework enables the design of a dynamic water tariff considering the role of water pricing as a tool for efficient management of water demand during scarcity periods.
(Pereau and Pryet 2018)	Analyze the importance of aquifer drainage for designing optimum groundwater management in the presence of ecosystem damages.	Water budgets should consider natural drainage from aquifers; otherwise, environmental flow damages to groundwater-dependent ecosystems may be underrepresented.
(Huang *et al.* 2020)	Explore economic interactions of ecosystem services and the use of groundwater to support socio-economic development in dry areas.	Intensive groundwater extraction to support socio-economic development in dry area will be at the cost of environment services function degradation. The cost of environment scarcity will exceed the income from industries groundwater use.
(Jeuland 2010)	Testing the sensitivity of assumptions related to discounting future costs in infrastructure investments.	Consider very well what the discount rates should be given climate change uncertainties.
(Davidsen *et al.* 2015)	Minimize the cost of reservoir releases, groundwater pumping, water allocation, wastewater treatments and water curtailments.	Dilution plays an important role and increases the share of surface water allocations to users situated furthest downstream in the system. This is often an economically efficient strategy for complying with both water quantity and water quality constraints.
(Macian-Sorribes *et al.* 2017)	Improve the economic efficiency by improving conjunctive surface and groundwater management.	Conjunctive management of groundwater and surface water resources increases economic efficiency of the system.
(Gonzalez *et al.* 2020)	Assess benefits of basin-wide co-optimization of hydropower and agriculture water use.	Management tools that optimize benefits for multiple water use sectors help to reduce conflicts among stakeholders.

the Ganges River found groundwater management to be cheaper and more effective than increasing surface water storage (Sadoff *et al.* 2013). Further studies show higher economic returns under non-overdraft policies (Assaf 2009). This research highlights the importance of policies that protect resources and incentivize managed aquifer recharge to promote groundwater sustainability as a strategy to increase resilience and prevent future water deficits (Martinsen *et al.* 2019).

International cooperation is one method to increase water security. Several HEM studies show how international collaboration and coordination would increase water and economic security, even under water scarcity (Jeuland *et al.* 2014; Nainggolan *et al.* 2018). Simulated water scarcity scenarios forecasted impacts of water availability or assessed the efficiency of international policies of countries facing scarcity (Jeuland *et al.* 2014). For example, Jeuland *et al.* (2017) developed a basin-wide model for the Nile River to evaluate large infrastructure projects and their benefits under international cooperation and low-flow scenarios.

A barrier to cooperation is the inequitable distribution of benefits among countries, sectors, and water users (Tilmant *et al.* 2012). Studies show how failing to integrate the interests of upstream and downstream water users from water infrastructure projects (e.g., dams) or only a particular sector (e.g., hydropower) reduces overall basin benefits (Bekchanov *et al.* 2015). Such findings highlight the importance of considering the tradeoffs and synergies at the water–food–energy–ecosystem nexus.

HEMs in this category also can have more specific applications like the economic implications of riparian vegetation and flood damages (Kourgialas and Karatzas 2013), the economic potential of rainwater harvesting systems in rainfed agricultural areas (Pandey *et al.* 2013), sustainable development of hydropower operations (Hirsch *et al.* 2014), or the evaluation of local water markets to aid policymakers in designing regulations (Erfani *et al.* 2014; Ghosh *et al.* 2014).

Integration of climate change is not standard across HEMs. Some of the models' integration of climate change is considering paleorecord climate (Harou *et al.* 2010) or only incorporate simple precipitation metrics based on changes on annual averages (Balali and Viaggi 2015) instead of downscaled data from Global Circulation Models (GCMs). Of the HEM studies that integrate data from GCM, many include only data from a single model, likely missing other relevant scenarios. In many cases, considerations of climate change may be insufficient, with little to no incorporation of extreme scenarios or metrics relevant to water management such as changes in the ratio of precipitation falling as rain vs snow, evapotranspiration, precipitation in extreme events, and frequency of dry and wet years (Persad *et al.* 2020).

Few HEMs focus on damages derived from sea-level rise. Medellín-Azuara *et al.* (2014) built a hydro-economic model to estimate local crop yield and revenue losses due to salinity increases in the Sacramento-San Joaquin Delta in California. While their results show less than a 1% decrease in revenue, they only consider damages to the agricultural sector and no other economic damages from sea-level rise.

Future HEMs that integrate climate change would benefit from a more detailed integration of relevant hydro-economic metrics from climate change models.

3.2.2. *Category* 2: *Representation of the water–food–energy–ecosystem nexus management challenges in HEMs*

The nexus between water, food, energy, and ecosystems is one of the most relevant topics that HEMs have addressed. This section focuses on integrating climate, hydrological, agricultural, energy, and environmental models to improve decision-making related to the food-water-energy-ecosystem nexus and the systems' economic performance.

HEMs are essential decision-making tools for governments to plan infrastructure and manage socioeconomic and environmental risks (Rising 2020; Siska and Takara 2015), including water storage. For example, water availability changes can have adverse impacts on dams' economic performance in the Senegal River basin. However, adaptive policies at the structural scale can palliate the consequences by enabling new water storage in dams (Raso *et al.* 2019). For example, the Upper Indus basin might benefit from new dams to reduce 60% of the unmet water demand, although the recovery of water demand requires sustainable water governance (Amin *et al.* 2018). Also, HEMs considering interactions between water, energy, and food systems can help optimize dam operation to find solutions that jointly benefit irrigation and hydropower production, for example, in the Lancang-Mekong River (Do *et al.* 2020) or in the Amu Darya basin (Jalilov *et al.* 2016).

In regions with high water demand where placing big new dams is infeasible (for example, California), replenishing groundwater and developing sustainable policies to preserve aquifers is one of the best alternatives to maximize positive externalities in the different elements of the nexus. Creating an adequate cost and benefit analysis of the water–food–energy–ecosystem nexus to study the economic behavior driven by groundwater pumping can identify the best operational practices at the structural level and the opportunities to maximize water value (Hrozencik *et al.* 2017; Raso *et al.* 2019; Rising 2020). Significant tradeoffs exist between water, energy, and greenhouse gas emissions in different policy scenarios, including urban water use (Escriva-Bou *et al.* 2018). Groundwater can be a significant source of uncertainty but having groundwater data and understanding it is essential for stakeholders and policymakers, as they depend on accurate information to effectively integrate economic decisions and policies (Hrozencik *et al.* 2017). Otherwise, insufficient groundwater information may misrepresent the water availability and distribution, affecting management and policy development over time and creating adverse effects like lowering groundwater levels, reduction of groundwater storage, depletion of interconnected surface water or land subsidence, among other.

Farming has a significant associated risk because agricultural productivity depends on water and climate conditions, as well as crop price and production cost volatility. Finding the best strategies to alleviate that risk can improve the overall performance of the local economies. For example, in a semi-arid climate like Northern Ghana, credit access for irrigation becomes a significant incentive for farmers to reduce the adversity of climate variability (Wossen *et al.* 2014). Seasonal adjustments in cropped areas, like the Ganges Basin, are flexible strategies to cope with rainfall variability, especially during transplant time and crop management (Siderius *et al.* 2016). Water planning and management in northern Afghanistan influence total economic welfare in irrigated agriculture as storage capacity and water appropriation significantly impact on their agriculture (Gohar *et al.* 2015).

The effects of climate change (significantly increasing temperatures in a dry scenario) may change rainfall patterns and water allocation, resulting in a severe prolonged threat to agricultural production, for example, in Australia (Ejaz Qureshi *et al.* 2013). The relationship between rainfall, growth, and long-term income in Indian states is highly complex and sensitive to rainfall variability (Gilmont *et al.* 2018). The Zarrine River Basin can benefit from shifting from low-value crops, such as alfalfa, to high-value crops that maximize water use, such as canola, saffron, and pistachio (Emami and Koch 2018). By modeling the nexus among water, food, energy, and nature, every region can better understand its local challenges and inform decision-makers about adaptation and successful strategies.

Energy constraints play a crucial role in water allocation decisions. A clear example is the integrated assessment and management of the Aral Sea Basin's water, food, and energy systems (Bekchanov *et al.* 2016). However, governmental entities should consider the social and environmental impacts of massive energy deployments (van der Zwaan *et al.* 2018).

Integrated water-power models point to energy efficiency increases, even in well-developed hydropower generation systems like the Iberian Peninsula. Shifting production toward efficient power plants (such as combined cycle gas power plants) and constraining CO_2 pricing policies create systems less vulnerable to cooling constraints. In turn, more efficient power plants can potentially increase the use of carbon capture systems with cooling needs exceeding those of the steam cycle (Payet-Burin *et al.* 2018). Countries with different challenges, such as Colombia, may require additional measures to mitigate climate change impact as bioenergy alone cannot significantly reduce emissions by 2030 (Gonzalez-Salazar 2016).

HEMs can provide the necessary understanding of the relationships between the climate, water, and sectors to inform the best water infrastructure investments. For example, HEMs can inform decisions about investing in surface or groundwater storage or other agriculture-based adaptation strategies (Yang *et al.* 2013), like transitioning from rainfed towards climate-smart sustainable agriculture or high-income agriculture with less environmental impacts and increased production (Siderius *et al.* 2016), or about facilities to recharge local aquifers optimizing environmental flows, agricultural and urban water delivery, and hydropower generation (Maskey *et al.* 2022).

Advancing innovation in the nexus of food, energy, water, and ecosystems can help bring new opportunities to develop those sectors. For example, gridded global crop models can inform sustainable irrigation water withdrawals given international drivers of change and local environmental constraints, decreasing the adverse effects of irrigation vulnerability, land-use change, and the associated carbon emissions (Liu *et al.* 2017). HEMs can provide helpful information for donor countries to fund initiatives in low-income countries to achieve water and food security (Ejaz Qureshi *et al.* 2013). In addition, HEMs can, for any region, minimize environmental and economic costs under decreased water availability and increasing land-use change (Souza da Silva and De Moraes 2018).

3.2.3. *Category* 3: *Integration of HEMs with other sectoral models*

There is a trend of linking socioeconomic information with biophysical data. Among the reviewed studies, 50 connected to other sectoral models such as climate, hydrological, energy, agricultural, environmental, agent-based, or economy-wide models and use of newly available datasets (e.g., satellite observations, big data, machine learning).

Most HEM tools have focused on connecting agriculture with water and economics. Links include agronomic variables with surface water (Kim and Kaluarachchi 2016; Magombeyi and Taigbenu 2011) and groundwater (Peña-Haro *et al.* 2010) models to incorporate their feedback and assess optimal resources application; quantification of impacts of climate change on agriculture (D'Agostino *et al.* 2014; Ejaz Qureshi *et al.* 2013; Fernández *et al.* 2016; Forni *et al.* 2016; Liu *et al.* 2017; Siderius *et al.* 2016) and energy production (Foster *et al.* 2015);

analysis of the effects of droughts and adaptation policies (Kahil *et al.* 2015) on stakeholder cooperation, water markets, and water pricing (Kahil *et al.* 2016); quantification of costs for increasing groundwater pumping to replace surface water availability (Medellín-Azuara *et al.* 2015); or assessment of cost of compliance with ecological requirements at a river basin scale (Kuhn *et al.* 2016; Nelson *et al.* 2016; Riegels *et al.* 2011).

Achieving multiple hydro-economic objectives is possible by linking economic information with biophysical data. For example, by connecting an agricultural model that relates land and water use with a hydro-economic stochastic model of the Murray-Darling Basin in Australia, Ejaz Qureshi *et al.* (2013) concluded that crop types will be affected differently under climate change. This outcome supports adaptation strategies related to land-use changes or less vulnerable crop types depending on the region (Kahil *et al.* 2015; Medellín-Azuara *et al.* 2015). Pulido-Velazquez *et al.* (2013) and Lopez-Nicolas *et al.* (2018) developed methods to simulate water availability and optimize water pricing policies that resulted in higher economic benefits and efficient resource allocation over time, with competing water uses. Torres *et al.* (2012) evaluated the impacts of minimum instream flow regulations on agriculture of the São Francisco River basin in Brazil. Results from this work suggest that minimum instream flow regulations impact downstream farmer cropping options, especially during drought years, while considering economic and environmental benefits from such regulation.

Agent-based models have also accomplished links between sectors. For example, Yang *et al.* (2009) developed a multi-agent optimization model that integrates human and environmental elements and incorporates the possible behavior of water users, resulting in a more realistic system representation. In addition, Pande *et al.* (2011) elucidated the interaction between hydrologic components, water valuation, and their effects on different agents at sub-basin scales. Other research has embarked on quantifying the value of storing water by calibrating a hydro-economic model to fit reservoir operators behavior through historical reservoir storage data (Khadem *et al.* 2020).

Common challenges in linking models include selecting common attributes and data availability in similar temporal and spatial scales and tandem model processing (results from one are input to another) rather than fully coupled. An approach to overcome these problems is parallel data collection and model development to ensure tailored information exchange between HEMs (Kragt *et al.* 2011). Another approach is when parts of a hydro-economic system (e.g., groundwater, agriculture, and water markets) connect to a central structure, for example through software libraries like Pynsim. Knox *et al.* (2018) describe two uses of Pynsim's in which simulation hydrologic models are connected with optimization models to minimize water deficits or identify the best location of hydropower plants.

Coupled models have also been applied to assess the water–food–energy–ecosystem nexus (Bekchanov and Lamers 2016; Jalilov *et al.* 2015 2016; Yang *et al.* 2016) and find a further discussion on their relationship with HEM in Category 2.

The European Nation Water Blueprint is an example of model coupling. Water management in the regions can be modeled together or separately. European policies related to water use are relatively well defined, and state targets, such as mitigating climate change, improving water quality, and maximizing social benefits of water in ecosystem services. Multi-objective approaches and model coupling create complex platforms to manage water-based on agricultural models (CAPRI), land use models (LUMP), solute (fertilizer, salts, and nutrient) movement (EPIC), rainfall-runoff transformation (LISFLOOD), and biophysical models for water quality, quantity, and hydro-economic assessments (LISQUAL) (Joint Research Centre *et al.* 2012; Udias 2016).

3.2.4. *Category* 4: *Economic valuation, marked-based policies, and pricing policies*

The goal of implementing water management policies is to achieve efficient water allocation while maximizing benefits and considering the stochasticity of water supplies and the institutional and infrastructural boundaries. However, water is rarely traded in market mechanisms, making it challenging to know its price and value in every use and across multiple stakeholders, including the environment.

Different economic and financial policies were analyzed using optimization and simulation HEMs. Applications include estimating the value of water by obtaining shadow prices (willingness to pay) and evaluating the impact of pricing and market policies in multiple temporal and spatial scales while considering changes in water availability, water demand, and environmental flows.

Water pricing as an incentive for efficient allocation or service cost recovery of water has been studied in different basins and management contexts. In the urban sector, Lopez-Nicolas *et al.* (2018) assessed a water tariff for cost recovery, an economically efficient and equitable allocation policy in Valencia, Spain. Water value was obtained in a scarcity-based process and used for developing an urban block tariff. Pulido-Velazquez *et al.* (2013) developed a synthetic model to design a pricing policy linked to water availability and incorporate the marginal economic value of water that works as a scarcity signal (marginal opportunity cost) region-wide and across multiple water users.

Recent water valuation and pricing studies considered the uncertainty and variability of water supplies. Khadem *et al.* (2018) developed an optimization model to estimate carryover storage's economic value in the Central Valley of California, finding that optimal allocation of carryover water reduces costs in interannual reservoir operations. Macian-Sorribes *et al.* (2015) evaluated the design of an efficient scarcity-based pricing policy using marginal recovery cost in the Mijares basin in Spain. The authors used a stochastic programming approach to model uncertainties in water availability. Different water policies were studied, considering scarcity scenarios, including water pricing and water market policies (Kahil *et al.* 2016).

Water markets have shown a growing interest and applications in basins with stochastic water supplies, scarcity, and aquifer depletion problems worldwide. HEMs have been used to evaluate their feasibility, comparing water markets among different stakeholders. Surface water transfers and groundwater conservation between agricultural and urban sectors were studied for farm profit maximization farm profits, urban water reliability, and cost minimization in Brazil (Zhu *et al.* 2015). Water variability, climate, and demand changes presented the water system's most significant uncertainties and were considered to estimate the effectiveness of water markets, as shown by Reddy *et al.* (2015), using a risk-based HEM. The transaction cost component of water markets institutional framework may affect the feasibility of water markets accounting for their effect on the benefit of water use. Erfani *et al.* (2014) studied these, considering a weekly transaction among multiple sectors and different water availability scenarios.

Market-based mechanisms were studied to achieve sustainable groundwater use for agriculture, considering the stochastic nature of the aquifer dynamics and water quotas (Pereau *et al.* 2018) and interacting with water banking during drought periods and different management scenarios (Ghosh *et al.* 2014). Market-based approaches consider multiple benefits and water efficiencies, such as environmental flows, water quality, ecosystem services, and carbon markets. Water rights trading can bring opportunities to increase environmental flows and their value (Bekchanov *et al.* 2018) and water rights or licenses should be designed in a way that accommodates trading and protects environmental flows (Erfani *et al.* 2015). Huang *et al.* (2020) developed a risk-based HEM to evaluate the tradeoff between groundwater utilization for urban, industry, and environmental protection to value groundwater ecosystem services. A study in the Kelani river, Sri Lanka, combined a HEM with a water quality model in an optimization approach to evaluate policies that account for water pollution and water distribution (Gunawardena *et al.* 2018). Settre *et al.* (2019) analyzed joint water market and carbon market policies of carbon sequestration and environmental flows allocation, using a dynamic HEM, which included carbon dynamics, a carbon credit value. Other HEM applications include water footprint and virtual water trading (White *et al.* 2015) and pricing hydroelectric energy considering the opportunity cost of water (Ilak *et al.* 2014).

In some regions, water markets can increase water supply systems' flexibility and mitigate climate change impacts. For example, a study in the Murray-Darling Basin, Australia, quantified that under a prolonged drought scenario, water trading could reduce agricultural losses by 7%, a considerable amount for a $15 billion industry in the region (Jiang and Grafton 2012).

Adapting to new water sources is among the most important water scarcity adaptations, such as desalination. HEMs have been used to quantify the economic benefits of additional water supply for agriculture from water desalination as a strategy to mitigate drought and environmental impacts in the Central Valley of California, demonstrating that such technology can offset economic losses. However desalination costs must be decreased and energy sources need to be clean and renewable to be economically and environmentally feasible (Welle *et al.* 2017).

3.2.5. *Category* 5: *Addressing uncertainty, risk, and robustness*

HEM uncertainty takes different forms, including hydroclimatic variables like precipitation and streamflow, and intangible and seemingly random variables, like prices or human behavior. Neglecting uncertainty can have unintended consequences and ultimately decrease water systems reliability and increase catastrophic event risk (Arefinia *et al.* 2021). Over the last decade, HEMs have integrated uncertainty into a range of applications such as non-point pollution of groundwater (Llopis-Albert *et al.* 2014; Molina *et al.* 2013; Peña-Haro *et al.* 2011), water storage for hydropower operations (Weibel and Madlener 2014) and energy markets (Pinheiro Neto *et al.* 2017), risk assessment (Arjoon *et al.* 2014; Kahsay *et al.* 2019), future water availability (Hassanzadeh *et al.* 2016), and development of robust operations policies for water planning and decision making (Ermolieva *et al.* 2021; Groves *et al.* 2019; Ortiz-Partida *et al.* 2019). In many of these studies, climate change is a leading motivator for uncertainty integration.

Uncertainty can be seen as the range of variability of multiple variables that conform to a hydro-economic system. To incorporate such variability into models, approaches will include stochasticity in model input variables to represent their seemingly random behavior. Randomness in HEM stochastic optimization enters problems in several ways: through stochastic (exogenous or endogenous) costs and prices, stochastic resource (e.g., water, land, biomass) availability constraints, random occurrence of exogenous natural disasters depleting resources and assets, and stochastic endogenous events (systemic risks) induced by decisions of various agents. Stochastic variables can be characterized by probability distribution (parametric or nonparametric) functions or represented by probabilistic scenarios. In the presence of stochastic parameters and risks, the stochastic parts in dynamic hydro-economic systems' optimization rely on stochastic dynamic programming (SDP) (Fosso *et al.* 1999; Gjelsvik *et al.* 2010) or stochastic dual dynamic programming (SDDP). The SDDP approach was successfully applied to develop reservoir operation policies for multi-reservoir systems (Pereira and Pinto 1991; Tilmant and Kelman 2007) and later extended and applied to the Jucar basin in Spain to explicitly include stream-aquifer interactions (Macian-Sorribes *et al.* 2017).

Modeling approaches visualize how international cooperation increases resilience and develop more robust water and energy systems (Jalilov *et al.* 2015; van der Zwaan *et al.* 2018). These transboundary benefits include increased electricity production, agricultural production, and flood damage control (Amjath-Babu *et al.* 2019). While transboundary cooperation may benefit all the countries involved, politics may hinder the process. For example, current water governance mechanisms in the Indus River Basin make it difficult to adapt to changing climate conditions, resulting in economic repercussions for the basin under high and low flow conditions (Yang *et al.* 2014). Another example is the State of California in the United States, where out-of-state or even out-of-county water transfers or groundwater sales are not allowed (Howitt 2012).

Quantifying uncertainty ultimately helps assess risk and support stakeholders in the decision-making process (Yang *et al.* 2016), develop large-scale (Kahil *et al.* 2018) and small-scale (Gohar *et al.* 2019) strategies, and assist in climate change adaptation and mitigation.

4. Limitations

Recent HEMs show innovations in forecast system changes under multiple water availability and demand scenarios. These models assess the impacts of water scarcity by lowering water availability as a proxy for climate change effects, changing yearly average precipitation, and downscaling hydrologic simulations. Such approaches may be insufficient as they do not consider other metrics relevant for water management, such as changes in precipitation as rain vs. snow, evapotranspiration, precipitation in extreme events, duration of dry and wet seasons, and frequency of dry and wet years (Persad *et al.* 2020).

The use of HEMs for operational purposes is limited by their resolution and by the integration with climate models. There is a tradeoff between high and low resolution for computational costs and accuracy, which means that large-scale models can be useful for planning but not for operation and that single extremes that can be identified at a daily scale (such as uncommonly hot days or days with extreme precipitation or streamflow) may be lost when using monthly or yearly averages. Climate and weather forecasting models can be coupled with hydrologic models to produce more accurate economic results by using such techniques as reforecasting (Fernandez-Bou *et al.* 2015) for example, for the cost of energy in hydropower generation in Brazil.

HEMs often lack integration of important values such as ecosystem functions and services, indirect costs of intangible damages (e.g., casualties in flood events), and implications of new technologies. Many of these limitations are caused by detail loss due to increasing spatial resolution and broad assumptions about infrastructure and institutional frameworks.

Stakeholders' behavior and the role of human responses to policy intervention are often oversimplified in HEMs (Essenfelder *et al.* 2018). For example, the optimization of regional planning models assumes the best action for everyone in the basin often without consulting the stakeholders' priorities for decision-making. Advanced decision-making analysis is necessary to model the behavior of important actors and stakeholders, rather than assuming preference.

Another limitation of many HEMs is the simplistic relationship between surface water and groundwater. Groundwater has traditionally been considered a buffer to compensate for the lack of surface water. However, it is necessary to incorporate groundwater as a resource to be optimized and maintained for future use to avoid overdrafting basins. More curated datasets and hydrogeological parameters can help develop more reliable models that include groundwater levels and flows to overcome these and other limitations of HEMs.

There is often a disconnect between modelers and stakeholders. HEMs can improve through co-development with stakeholders (Girard *et al.* 2015). Including the most vulnerable stakeholders in decision-making and incorporating their priorities into policy can create more robust solutions that adapt to and mitigate climate change (Fernandez-Bou *et al.* 2023 2021; Fernandez-Bou *et al.* 2021). Unequal distribution of gains and losses among riparian countries disincentivizes the efficient sharing of existing water resources (Girard *et al.* 2015).

5. Moving Forward in HEM

This review underlines the diversity of water system needs around the globe and the variety of HEM approaches. A primary outcome from this review is the need to develop a portfolio of adaptation strategies together with investment mechanisms to enhance global water–food–energy–ecosystems security. It is also necessary to better represent ecosystems, moving away from the minimum instream flow requirements approach and towards a functional flows approach. Water quality is another essential element often ignored in HEM.

Sustainable groundwater use is becoming a common topic. Studies highlight the importance of policies that protect aquifers, as they provide a buffer in the water supply during dry periods when surface water is insufficient to fulfill demands. Given the increasing complexity of HEMs, machine learning techniques can be a computationally inexpensive alternative to model biophysical systems that cannot be easily incorporated into optimization and management models.

The field of HEM would benefit from a higher temporal resolution (e.g., sub-monthly time-steps) to better capture nuances from hydroclimatic variables relevant to water resources management and that are shifting due to climate change (e.g., maximum three-day precipitation, minimum daily flow, floodplain inundation time). Low spatio-temporal resolution leads to HEMs that are useful for planning. Developing models with higher spatio-temporal resolution that are coupled with atmospheric models can produce more HEMs that can be used for operational purposes. Coupling climate and meteorological models with HEMs can also produce much more accurate hydro-economic forecasts.

Hydro-economic studies largely focus on biophysical and economic indicators and often overlook stakeholders' preferences and perspectives. This is partly explained by the large-scale and technical nature of HEMs. However, more robust integration of social components may increase trust in and adoption of HEMs by local stakeholders. Social aspects intrinsic to water systems, such as health and equity, are still a relevant gap in knowledge.

Future HEMs should incorporate additional ecosystem-related metrics (e.g., floodplain inundation time, peak streamflow, or consecutive days without precipitation during rainy seasons) that have implications for ecosystem restoration, managed aquifer recharge, and precision agriculture, among others.

Finally, our analysis shows that multiple studies encourage international cooperation and coordination to increase water and economic security, even under future water scarcity scenarios. Cooperation in water resources is the most equitable and most economically feasible option to thrive as a united human society. Transboundary partnerships and stakeholder participation in decision-making and local solutions can help to better respond to the broader global issues of natural resource tradeoffs and sharing.

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