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Review

Hydro-Economic Modelling for Water-Policy Assessment Under Climate Change at a River Basin Scale: A Review

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Abstract: Hydro-economic models (HEMs) constitute useful instruments to assess water-resource management and inform water policy. In the last decade, HEMs have achieved significant advances regarding the assessment of the impacts of water-policy instruments at a river basin or catchment level in the context of climate change (CC). This paper offers an overview of the alternative approaches used in river-basin hydro-economic modelling to address water-resource management issues and CC during the past decade. Additionally, it analyses how uncertainty and risk factors of global CC have been treated in recent HEMs, offering a discussion on these last advances. As the main conclusion, current challenges in the realm of hydro-economic modelling include the representation of the food-energy-water nexus, the successful representation of micro-macro linkages and feedback loops between the socio-economic model components and the physical side, and the treatment of CC uncertainties and risks in the analysis.

Keywords: hydro-economic modelling; water policy; climate change; river basin management

1. Introduction

Population growth and economic development constitute the main forces behind processes such as irrigation expansion, urbanization, and industrialization, all of which trigger increasing water demands and therefore water scarcity as well as water stress, both in terms of water quantity and water quality [1–4]. Climate change (CC) may act as an amplifier of these impacts on water resources [5]. Water scarcity also constitutes an economic problem and has become a serious limitation for socio-economic development worldwide [6]. The gap between water demand and supply capacity that exists in many parts of the world leads to higher competition between alternative uses (and economic sectors). Water scarcity and extreme events exacerbate this competition for water resources and generate negative social and economic impacts, which need to be assessed to guarantee the sustainable management of water-resource systems. Understanding the allocation of water in catchments (or river basins) and its impacts in economic and hydrological dimensions is crucial in this context [7].

Hydrological and economic tools have been commonly used to model hydrological and socio-economic interactions in order to assess the impacts of certain policy measures in specific hydrological and climatic contexts. At the policy level, the use of integrated multi-disciplinary methods (e.g., hydrology, engineering, and economics) to support water decision-making has been promoted for the assessment and development of sustainable water-management strategies in integrated

water-resource management (IWRM) [8,9]. One example is the paradigm shift represented by the EU Water Framework Directive (WFD) that imposes the use of economic science, including the use of scenarios in the characterization of water uses (Art 5) and the consideration of economic instruments in order to reach sustainability goals (Art 4 and Art 9) [10]. In line with this reasoning, hydro-economic models (HEMs) have been widely used by academics and policy-makers in recent decades.

This study aims to offer an updated review of the advances in hydro-economic modelling in the last decade, focusing on the assessment of water management in the context of a changing climate. Ever since the general reviews were published at the end of the first decade of the current century [11–15], significant advances have been achieved regarding both the assessment of the impacts of water-policy instruments (e.g., water markets, water banks, insurance instruments) at a river basin or catchment level, and regarding the consideration of CC implications in HEMs. In contrast to recent general reviews [16], this work focuses on recent developments of river-basin HEMs for the analysis of water policy instruments in the context of CC.

With this aim in mind, Section 2 offers a brief overview of HEMs and definitions, followed by a classification of alternative approaches used during the last decade in hydro-economic modelling to address water-resource management issues and CC at the river basin (or catchment) scale (Section 3). Subsequently, Section 4 discusses recent advances achieved regarding the assessment of water-policy instruments in the context of CC through hydro-economic modelling, while Section 5 centres the analysis on how uncertainty and risk factors of global climate change have been addressed in recent HEMs. Finally, Section 6 offers a brief discussion and some concluding remarks.

2. Overview and Definitions

HEMs arose from the combination of water-resource planning models with considerations of welfare economics in the 1950s [9]. In those years, Krutilla and Eckstein [17] considered the basin as "the natural scale for hydro-economic modelling", thereby challenging previous methods based on a sectoral division. Furthermore, this conceptual development clearly established that both quality and quantity of freshwater are affected by all water users, accepting that all uses are hydrologically connected at catchment scale. The work of Vaux and Howitt [18] constituted one of the first applications of HEMs at a regional scale for the assessment of water transfers in California. Subsequently, Booker and Young [19] extended the approach in order to account for all hydro-economic and socio-economic characteristics of the Colorado River basin.

In the last two decades, HEMs have incorporated an integrated analysis of impacts related to CC on water-resource systems, both spatially and temporally [16,20]. River basins in arid and semi-arid regions worldwide face major challenges in water scarcity, which will probably be aggravated by CC in the coming decades. In this context, HEMs play a major role for informing water policy and advancing sustainable use of water resources. One advantage of HEMs is the capability to capture the interrelationships between economic, hydrological, institutional, and environmental dimensions for a comprehensive assessment of the trade-offs among water-policy options [14]. Potential impacts of CC have largely been assessed using the approach developed by Hurd et al. [21], Hurd et al. [22], and Hurd and Harrod [23], based on the use of different climatic scenarios. At a river-basin scale, a first attempt was carried out in the upper Rio Grande basin, where Ward et al. [24] developed an HEM to assess the effects (i.e., socio-economic, hydrological and environmental) of sustained drought at the catchment level, which was further extended by Ward et al. [25] to include the protection of endangered species in the same basin. Finally, HEMs also address questions regarding the adequacy and sustainability of water-supply sources and infrastructures under changes in climatic conditions [9,26]. These models have recently shown significant capacity to identify strategies for the improvement of various sets of policy decisions, such as investments to improve irrigation efficiency, infrastructure design, and institutional reforms in a global change context [27]. Examples of recent work that addresses the potential impact of CC on water supplies include the works of Jeuland [28], Tilmant and Arjoon [29], and Amin et al. [30].

Throughout the advancement of research in the context of water resource management and linkages between socio-economic and physical aspects of hydrological systems, various terms have been used to describe the models applied. The bandwidth of terminology ranges from "hydrologic-economic" [31], "economic-hydrologic-agronomic" [32], "integrated economic-hydrologic" [33,34], and "holistic water resources-economics" [13,35], each highlighting the predominant factors and the weight of the hydrological vs. the economic model components, as well as the methods and the spatial and temporal scope of the analysis. Hereinafter, this review uses the term 'hydro-economic', as used in the latest reviews for models that combine hydrological and economic components to analyse water-resource systems [16,36].

While Bekchanov et al. [16] differentiate economy-wide models (referring to computable general equilibrium (CGEs) and input-output models) and network-based HEMs, our definition of HEMs focuses on the latter, as they are especially relevant for the analysis of water policy issues at a river-basin scale. They combine microeconomic theory and stochastic hydrological operation models and can be differentiated into simulation models and optimization models [16]. HEMs differ from economy-wide models, since the latter aim to widen the analysis to include the general and/or global economy (e.g., by considering inter-sectoral linkages and trade exchanges). An interesting review of these economy-wide models is presented by Dinar [37]. In contrast, HEMs focus on river basins or catchments and analyse specific water-management solutions at this scale. Similar to network-based models, river-basin HEMs use simulation and/or optimization methods within the wider concept of water-economy models and aim to integrate hydrologic and economic systems to provide appropriate policy (e.g., allocation, infrastructure) solutions at different spatial and temporal scales [16]. These models can be used to assess future scenarios in water-resource systems when external shocks (climate change, macroeconomic conditions, infrastructure, policy decisions, etc.) occur.

3. Classification of HEMs

Following Cai et al. [38], HEMs can be classified as either holistic or compartmental models. While compartmental models are constructed on separate modules (e.g., economic, hydrological) that use each other's input/output data, holistic models are designed to integrate all modelled aspects in a single consistent framework. In compartmental HEMs, feedback loops are generally needed, which require appropriate model interfaces between alternative compartments.

Furthermore, network-based HEMs can be differentiated into simulation models and optimization models [16]. Hydro-economic simulation models are employed to assess specific "*what if*" scenarios (such as climatic conditions) for certain management decisions. Simulation models are suitable for the exploration of precise and specific management policies and for the exploration of the ability of a quantitative approach to simulate the behaviour of certain variables. Moreover, simulation models can be applied both at smaller and larger water-resource scales to examine the effects of specific water-management strategies and behaviours at different management levels [39]. The main disadvantage of simulation HEMs arises from the problem to identify the best policy option under the various model scenarios that may potentially be considered.

In contrast to simulation models, hydro-economic optimization HEMs can help to identify "*what's best*" and assess alternative decisions and action sets within natural and human-made constraints, such as the availability of water resources and institutional and legal issues. Optimization techniques, such as linear and dynamic programming, largely focus on water-allocation optimization and profit maximization and are generally applied to assess water-allocation decisions subject to the maximization of water-use economic gains under certain environmental constraints, such as water availability. This approach has recently been extended to include the impacts of alternative water uses on water quality, catchment ecology, and non-market economic values [16].

There is no dominant modelling approach (simulation vs. optimization), since the management of extreme events (droughts and floods) must handle uncertainty and the likelihood of event occurrence while water policy analysis relies on the identification of optimality assessments. To address and

counteract the limitations of each modelling strategy, simulation and optimization methods can be combined. Such "hybrid" models enable the results from optimization models to be tested and refined with simulated outcomes [40]. This approach has been extensively used in recent years. Both simulation and optimization models constitute constructive approaches for the implementation of IWRM alternatives to address socio-economic and legal-political objectives, thereby also facilitating the integration of stakeholder concerns and the implementation of adapting water-resource management to changes in climatic conditions. Meanwhile, integrated and sometimes dynamic hybrid HEMs are increasingly being applied in order to consider shifting conditions of greater complexity, especially those concerning potential CC impacts and scenarios [16]. Along similar lines, Herman et al. [41] argue that hybrid HEMs can be extremely helpful in exploring potential CC concerns by identifying vulnerabilities of water-resource systems and adaptation strategies.

An alternative approach is the inclusion of stochastic elements in optimization HEMs. This opens another line of differentiation between deterministic and stochastic modelling approaches. Most HEMs assume perfect foresight, but river basin managers cannot perfectly foresee water availability and have to deal with high risks [42]. Such risks can be accounted for by the use of a variety of possible future scenarios (hybrid models, see above) and/or by including stochastic risk components in the optimization problem [43].

As Hanemann [44] remarks, water resources are subject to challenges derived from institutional settings and property-right schemes and to the conflicting interests among multiple agents. While the hydrological component helps to reveal where the water is distributed to in physical terms, the economic component contributes by considering the net economic values of any such distribution. Therefore, the combination of economic modelling with hydrological processes provides a more realistic framework for the analysis of potential impacts of climate-related issues on the management of water resources at a catchment scale [12,45]. Assessments by HEMs can lead to useful findings to report water allocation and policy decisions, as well as other economic and performance results, such as water-use values, management and the construction of supply infrastructures, as well as the design of sectoral policies (e.g., agricultural policies) [14,46]. Along these lines, HEMs are often classified into hydrological management models (e.g., assessment of water-infrastructure design or management), and policy and allocation models that are mainly focused on the efficient management of water resources under certain spatial, hydrological, and climatic conditions. This work focuses on this latter type of HEM.

4. Recent Developments

Changes in water and environmental policies are generally catalysed by external factors, such as political, economic, and sectoral interests (e.g., agriculture, industrial), and extreme events that modify the prevailing water conditions [47]. Any model designed or implemented to support policy analysis should be realistic and sensitive to changes in critical variables (e.g., water availability, prices of agricultural products) and should allow for changes in the operational rules of the water infrastructure, climatic variables (e.g., water supply, temperature), characteristics of decision-makers (e.g., farm size, household size), and decisions on policy instruments, such as subsidies, taxation, input pricing (e.g., water, pesticides), quantitative limits (e.g., water abstraction, discharge limit, fertilizer use), and technology adoption (e.g., water efficiency use, energy mix). Since the work involved in covering all these topics is beyond the possible scope of analysis, most models are driven by sectors and focus on specific policy options (e.g., prioritize infrastructure investment decisions, water pricing). Among the different applications of HEMs, there are many examples with a main focus on water-quality issues (e.g., [48–52]), water-allocation strategies (e.g., [34,53–56]), water-policy instruments (e.g., [57–59]), and land-use planning policies (e.g., [60]), among other concerns. Furthermore, interest in the assessment of the impacts of and adaptation to CC of water-resource systems, and the consideration of the associated uncertainties and risks to various climatic scenarios in the application of HEMs have attracted increasing attention [14,43,61–68].

The recent bibliometric review by Bekchanov et al. [16] shows that the largest number of studies using HEMs in recent years have focused on the impact of climate on water-resource systems and the assessment of adaptation policies to decreasing water availability. Obviously, human activity and extreme events affect hydrological balance and both need to be considered in hydro-economic modelling assessments, otherwise modelled outcomes could lead to sub-optimal decisions and to an increase in risks for the viability of economic activities and the sustainability of water-dependent environments. The most recent HEMs take into account rising global warming, the increasing risks of extreme events (i.e., drought and floods), and their negative consequences in terms of economic losses, food security, and human health, among other factors, in order to identify promising adaptive measures and to provide accurate information for decision-makers [43,69]. Nevertheless, despite these efforts, there are still very few HEMs that address the potential impacts of CC on water-resource systems at a river basin scale, and even fewer studies consider the interlinkages of physical and economic extreme events effects in terms of the costs and also the benefits of potential adaptation actions [68].

To analyse water policies at basin scale, both qualitative and quantitative models have been applied. The process of prioritizing public policies for economic development implies the need for quantitative and qualitative models that support ex-ante policy evaluations as close as possible to the complexities of the real world. Hydrological models are used by engineers, water agencies, and for land-use planning and constitute a necessary tool for water and environment resource management. When the system under analysis integrates both a hydrological model and the socio-economic factors, it can be used for policy assessment and evaluation of water management decisions. Qualitative models have frequently been used to support policy making. One example is the Driver-Pressures-State-Impact-Response (DPSIR) framework [70], employed by EU institutions and other institutions such as OECD [71]. One evolution from this DPSIR framework is the systems thinking approach, for more advanced qualitative modelling at a basin level to support policy decisions. Mai et al. [72] used a systems-thinking approach to develop a conceptual model of a water-trading scheme in Australia. This is essentially a holistic approach that accounts for interrelations of a system's constituent parts, and it has been used in the construction of economic-environment scenarios.

Still in the field of microeconomics, with the support of mathematical programming techniques and database management, several relevant models take into consideration the fact that water policy is closely related to land-use policy, since agriculture is the main user in many regions of the world [73]. This is especially true for arid and temperate regions that are on course towards basin closure or have already reached a mature economy state where demand surpasses the available supply. Therefore, land-use agricultural models that include water-management decisions are frequently seen [43,69,73].

The EU normative that promotes ecosystem-based thinking as a way to influence policy- and decision-making should account for the behaviour of natural resources. In this line, the Blueprint to Safeguard Europe's Water [74] aims to inform the EU water policy through the assessment of both quantitative and qualitative aspects of water resources, thus taking into account climatic and environmental issues and offering water balance assessments at catchment (or basin) scales [74]. A major part of this water balance involves accounting for water removed from rivers or aquifers by different sectoral needs, which are significantly impacted by CC. Mubareka et al. [75] used the CAPRI (Common Agricultural Policy Regionalised Impact) model for EU agriculture and integrated a water module that had previously been used for scenario building to analyse the impact of Common Agricultural Policy (CAP) measures under different scenarios. Blanco et al. [73] assessed the role of climate change as a driver of the agri-food systems and include agricultural water demand. This model uses microeconomic/macroeconomic integration since farmers' decisions affect local and global market outcomes, and therefore also affect local and world prices. CAPRI is mainly a land-use and farm economic model for agricultural policy support. Other models integrating micro- and macro-components are more detailed regarding hydrological impacts. Parrado et al. [76] included two-way feedbacks, decentralized irrigators, and a regionally-calibrated CGE model to assess interlinkages.

Engineering-based hydrological models, which were originally developed for water management and infrastructure operation, usually include an economic module of cost minimization, profit maximization, or management of supply failure. These models are usually labelled as operational models. As part of the evolution of the operational models, several economic modules are integrated that are part of engineering processes and respect the allocation of water rights and operational rules to simulate marginal changes in water supply or demand and to evaluate changes in the value of the production functions. The AQUATOOL model for Spain [77] and CALVIN model for California [41] constitute good examples of hydrological models that integrate such economic considerations. These models seldomly integrate macroeconomic feedbacks, and the level of representation of sectors becomes increasingly complex in order to be as close as possible to real decisions including some behavioural models that are more accurate than neoclassical profit-maximizing assumptions. These models operate at the basin or sub-basin scale as management units. The time scale is usually monthly in order to include water storage and seasonality of demand. Uncertainty in water resources, including the occurrence of extreme events, such as floods and droughts, is usually included by integrating available information regarding past climate observations or future projections [68]. An example of an HEM focusing on infrastructure valuation for energy and irrigation is the model WHAT-IF [78], where the objective is to maximize economic welfare expressed in terms of the sum of consumer and producer surplus subject to environmental, physical, and institutional constraints.

Since water and energy systems are interlinked [7], the number of models addressing the food-energy-water (FEW) nexus is growing. Brouwer et al. [79] reviewed six key models employed to support policy-making institutions (European Commission, OECD, and the World Bank). Many of these models give priority to the evaluation of energy (hydropower) and irrigation, as does WHAT-IF model [78,80]. Recently, certain models, such as CLEWs (Climate, Land-use, Energy and Water strategies) [81,82], have included the FEW nexus. At this point, we believe that CC mitigation and the integration of food production, irrigation, and energy use are critical and should be considered as a set when designing agricultural or water policies. An example of this is given by the promotion of solar-based pumping for irrigation, which may have advantages for energy policies but may also exert potentially negative impacts on the environment caused by excessive resource abstraction [83].

Another major development in recent years has been the integration of potential CC impacts in hydro-economic analyses. Jeuland [28] emphasized the importance of integrating both the potential CC effects on physical water availability as well as the economic implications that arise due to CC. Many analyses addressing scenarios of CC in HEMs have mostly merely focused on the physical aspects and have ignored not only the economic uncertainty and risk components but also crucial feedbacks between the economic side of water demand and physical water supply. The successful inclusion of feedback effects and model linking to account for the full range of physical and socio-economic global change effects is a major challenge in hydro-economic modelling.

A primary element of the study of the potential effects of CC involves the identification of system vulnerabilities and the measurement of system performance under possible projected climate scenarios. The IPCC defines vulnerability as "a function of the character, magnitude, and rate of climate variation (climate hazard) to which a system is exposed, and of non-climatic characteristics of the system, including its sensitivity, and its coping and adaptive capacity" [84]. Vulnerabilities associated with CC and extreme hydrologic events (drought and floods) determine constraints for an adequate performance of water-resource systems and affect both demand and supply. The identification of such vulnerabilities is key to the development of successful climate-adaptation strategies. On the demand side, recent HEMs have focused on the assessment of water allocation among alternative uses based on the economic value of scarce water resources and the interactions between alternative stakeholders that share surface and groundwater resources in an increasingly complex climatic and hydrologic context (e.g., [20,27,42,82,85]). Under this approach, most studies aim to inform management decisions under conditions of water scarcity and increasing vulnerabilities of water-resource systems likely due to CC.

Table 1 summarizes recent studies that have applied HEMs to the management of water-resource systems that take into account the vulnerabilities and uncertainties associated with CC (and extreme events, such as drought and floods). This summary also offers general information regarding the model type, methods, case study, consideration of surface water (SW) and/or groundwater (GW), and sectors implied (e.g., irrigation, urban, hydro-power, environment).

Table 1. Review of recent applications of HEMs that incorporate potential CC effects.

Study	Models & Method	Model Type	Main Focus	Case Study (Country)	Water Type	Sectors
Amin et al. [30]	Water evaluation and planning (WEAP) model	Simulation, compartment	Water supply & climate change	Upper Indus river basin (RB) (Pakistan)	SW & GW	All sectors
Souza da Silva and Alcoforado de Moraes [42]	Soil and water integrated model (SWIM) + Model of agricultural production and its impact on the environment (MAgPIE) /General algebraic modeling system (GAMS) + Positive mathematical programming (PMP) models	Optimisation, holistic.	Trade-offs between uses & climate change	Sao Francisco RB (Brasil)	SW	Hydropower, urban, irrigation, & environment
Essenfelder et al. [86]	Positive multi-attribute programming (PMAUP) + Soil and water assessment tool (SWAT) models	Hybrid, holistic	Climate change & adaptation strategies	Mundo RB (Spain)	SW & GW	Irrigation
Herman et al. [41]	CALVIN model	Optimisation, holistic	Water-supply & climate change	California (USA)	SW & GW	All sectors
Escriva-Bou et al. [68]	AQUATOOL + (Simulation model for watershed management) SIMGES	Hybrid, holistic	Climate change & adaptation strategies	Jucar RB (Spain)	SW & GW	All sectors
Ruperez-Moreno et al. [85]	HEM for Segura RB	Optimisation, compartment	GW management & climate change	Segura RB (Spain)	GW	Irrigation & environment
Kahil et al. [20]	Modular finite-difference flow model (MODFLOW) + GAMS + PMP	Hybrid, holistic	Trade-offs among water policies & climate change	Jucar RB (Spain)	SW & GW	Irrigation, urban (large cities), & environment
Esteve et al. [67]	WEAP-MABIA modelling framework + PMP	Optimisation	Climate change & adaptation strategies	Middle Guadiana basin (Spain)	SW & GW	Irrigation
Kahil et al. [77]	AQUATOOL + Jucar RB optimization model	Hybrid, compartment	Water scarcity, droughts & climate change adaptation	Jucar RB (Spain)	SW & GW	Irrigation, urban, & environment
Kreins et al. [87]	Water balance model mGROWA + climate model WETTREG	Integrated model framework	Climate-change impacts on irrigation & GW management	North Rhine-Westphalia (Germany)	GW	Irrigation
D'Agostino et al. [43]	Non-linear optimization model + hydrological GIS-based model + CLIMAWARE	Optimisation	Climate-change effects on water balance	Apulia (Italy)	SW & GW	Irrigation
Tilmant et al. [29]	Stochastic Dual Dynamic Programming (SDDP) model	Optimisation, compartment	Water-supply & climate change	Euphrates RB (Turkey, Siria)	SW	Hydropower & irrigation

Table 1. *Cont.*

Study	Models & Method	Model Type	Main Focus	Case Study (Country)	Water Type	Sectors
Yang et al. [65,69]	Indus Basin Model Revised-Multiyear (IBMR-MY)	Optimisation, compartment	Allocation strategies & climate-change adaptation	Indus RB (Pakistan)	SW & GW	Irrigation
Hurd & Coonrod [27]	Water balance (WATBAL) model + circulation models (temperature and precipitation), GAMS	Hybrid, holistic	Trade-offs between uses & climate-change adaptation	Upper Rio Grande (USA)	SW & GW	All sectors
Harou et al. [88]	CALVIN model	Optimisation, holistic	Trade-offs between uses, drought & climate change	California water system (USA)	SW & GW	All sectors
Jeuland [28]	Standard water resources planning model + Montecarlo methods	Simulation, compartment	Water-supply & climate change	Nile RB (Egypt)	SW	Hydropower & irrigation
Varela-Ortega et al. [59]	WEAP model	Optimisation	Water and agricultural policies & climate change	Upper Guadiana basin (Spain)	SW & GW	Irrigation
Reynaud and Leenhardt [89]	Model for water resources management (MoGIRE)	Optimisation holistic	Integrated water management & climate change	Neste basin (France)	SW	Irrigation, urban & environment
Tilmant and Kelman [90]	Stochastic Dual Dynamic Programming (SDDP) model	Optimisation compartment	Water-supply & climate change	Eurphrates and Tigirs rivers (Turkey)	SW	Hydropower & irrigation
Tanaka et al. [61]	CALVIN model	Optimisation holistic	Climate change & adaptation strategies	California water system (USA)	SW & GW	Irrigation & urban

Source: Authors' Own.

It is worth noting that many studies only include one selected CC scenario, without considering the range of CC risks and uncertainties [42,67,87]. For example, Kreins et al. [87] only considered one CC scenario (SRES A1B1 scenario), even though they aimed to assess CC impacts on GW resources in North Rhine Westphalia (Germany). Therefore, they failed to explicitly address CC uncertainty and only include one possible future temperature and precipitation trajectory. In order to address the uncertainty related to CC and risks in the management of water resources, several global and regional CC and GHG-emission scenarios should be included [87]. Souza da Silva and Alcoforado de Moraes [42] used a basin-wide hydro-economic optimization model to analyse trade-offs regarding water-management decisions in the São Francisco River Basin in Brazil. They constructed various operating-rule scenarios under certain institutional constraints and compared the outcomes of shadow prices of reservoir outflow and associated costs and benefits. They did so under a baseline scenario without CC and compared their results to a scenario under CC following the IPCC SRES A2 climate-change scenario [84]. They used this HEM to evaluate the economic effects of different management options ("operating rules"), environmental, technical, and institutional constraints, as well as land-use change and CC, and identified optimal water allocation between various water users.

5. The Challenge of Uncertainty

In order to provide informed policy advice and to assess the real costs, benefits, and associated risks of water infrastructure investment projects under future CC, it is of prime importance to take the uncertainties associated with CC into account. This is the case in recent HEMs, as summarized in Table 2. For example, D'Agostino et al. [43] used a sensitivity analysis of the major water balance components for their hydro-economic analysis of water use in the agricultural sector of Apulia (Italy). Their results revealed that climatic conditions, soil type, and cropping patterns exerted a major impact on the outcome of the model. The variance of the upper and lower bounds of irrigation water

requirements (with a lower bound of 39% and an upper bound of 103%), groundwater recharge (40–53%), and surface runoff (46–59%) show that irrigation water requirements are especially prone to uncertainties of climatic conditions [43]. Ignoring this variance and solely providing point estimates would bias the water-planning decisions.

The consideration of potential CC effects on HEMs introduces many forms of uncertainties into these models. On the one hand, there is data and input-parameter uncertainty: (a) regarding physical input parameters (e.g., precipitation, runoff, among others); and (b) with respect to economic inputs (e.g., water demand, water prices) [28,42,43,68,91,92]. On the other hand, there is major model uncertainty: first, inherent model uncertainty of climate models [84,93,94]; second, model chain uncertainty from deriving information from global to regional data and from regional to spatially more explicit climate data [91]; and third, there are biases involved when using upscaling and downscaling methods [42,68].

Due to the conjunction of hydrological and economic components, HEMs are prone to data and input-parameter uncertainty from both the physical side of water availability as well as the socio-economic side of data demand and its complex interlinkages [95]. Even in the absence of relevant CC effects, the physical availability of water itself is highly uncertain in nature due to short-term weather variations and upstream water extractions by other water users. There is temporal (seasonal, annual, long-term) variation as well as spatial variability in water supply. Similarly, crop water requirements are highly uncertain [92,96]. These uncertainties are amplified in the presence of CC. Changes in climatic conditions and precipitation induce biophysical and hydrological uncertainties as well as socio-economic risks [28,42,43]. Through changes in rainfall patterns, glacier melt, recharge rates, runoff flows, extreme events (floods, droughts, storms, heat waves), and sea-level rise, CC affects the availability of usable freshwater [28,68]. On the demand side, household, wastewater treatment, industrial, and agricultural freshwater demand are affected by changes in ocean and surface temperatures and precipitation patterns. Changes in plant growth, crop water requirements, and evapotranspiration all influence irrigation water demand [28]. Industrial water demand might increase due to greater cooling requirements and due to the complex links of energy prices that might increase demand for hydropower. Moreover, environmental water needs might increase due to potential CC impacts (e.g., due to saltwater intrusion in costal ecosystems associated with sea-level rise [84]). There are feedbacks between water-management decisions, socio-economic effects, and water availability that further increase uncertainties and risks in HEMs [43,91].

Input parameter and data uncertainty can be addressed by: (a) various scenarios combined with a sensitivity analysis in the case of simulation-HEMs, or (b) stochastic programming, that is, through the introduction of a stochastic component in the optimization of the model [43]. Most optimization-HEMs are deterministic in nature. Deterministic models fail to account for uncertainties in the variables and parameters used [97]. In order to account for such uncertainties, a stochastic component can be included in the optimization model. Input-parameter uncertainties can be included in the objective function by including risks in crop prices, yields, incomes, and resource-availability constraints [92]. In this setup, expected profits or expected utility rather than deterministic profit/utility/gross margin functions are maximized. Statistical modelling of input-parameter uncertainty can, for instance, be achieved by "stochastic programming" or "discrete stochastic programming". The latter includes more than one decision stage and a revision of the decision taken by the farmer. Graveline et al. [97] compared the results from a deterministic approach by analysing three different global-change scenarios with respect to climatic conditions, the economic environment, and the regulatory environment with a Monte Carlo approach using 200 random selections under these three scenarios. They showed that the discrete solution of the deterministic model is prone to false conclusions, since it fails to account for uncertainty. In order to provide informed policy advice, it is important to account for uncertainties of input parameters in mathematical programming models.

In order to account for CC impact uncertainties, different emission and CC scenarios can be applied to HEMs. To this end, local HEMs need to be combined with global or regional climate models.

However, feeding HEMs with output data generated by climate models amplifies model uncertainties in HEMs [91,98,99]. Both global hydrological models (GHMs) and global climate models (GCMs) have inherent uncertainties that are translated into HEMs and may be even. Irrigation water demand varies substantially across different global hydrological models (GHMs) and global climate models (GCMs). According to Wada et al. [99], uncertainties from GHMs exceeds GCM uncertainty along the projection period until 2100. While GHMs show constantly significant uncertainty throughout the whole century, uncertainty in GCMs increases along the projection period). According to Döll [100], there is more variation in the outcomes of the models arising from differences between the various climate models applied compared to the differences between the various emission scenarios. Introducing potential CC effects in catchment-based hydrological or hydro-economic models requires the downscaling of results from regional climate models that in turn derive their outcomes from global climate models. This introduces additional uncertainty in HEMs [93]. Sophisticated methods are available to conduct downscaling with bias-correction methods of global to regional information regarding land use and climate change [65,101]. In order to meet the demands for local HEMs, these regional data need to be downscaled even further to obtain climate information at a basin or catchment scale. This process involves uncertainties and biases that are often ignored in HEMs.

In order to address model uncertainty, model chain uncertainty, and upscaling/downscaling biases, various global models can be applied as robustness checks of the analysis [99]. Previous research shows that model selection is crucial when analysing CC impacts in the context of water resources. It is recommended to employ several hydrological models and various emission or climate scenarios [98,99,102]. Wada et al. [99] suggested a multi-model approach to address uncertainties arising from model uncertainty and CC uncertainty in their analysis of irrigation water demand in order to provide robust modelling results.

The majority of HEMs addressing CC risks and uncertainties apply simulation models. Escriva-Bou et al. [68] selected six regional climate models that showed the best-fitting results when compared to historical precipitation and temperature data in the basin analysed (Jucar River basin, Spain). Graveline et al. [66] constructed one CC scenario by downscaling precipitation, temperature, and climate data from regional climate models (ECHAM4/OPYC3 [103], ENSEMBLES EU-project [104], Rossby Centre regional Atmosphere-Ocean Project RCAO [105], and PRUDENCE simulations [106]) and combined them with two catchment-specific agricultural management scenarios (water-storage capacity and irrigated land increase; modernization of irrigation technology) to address the effects of climate and socio-economic changes on water resources in the Gallego catchment area (Spain). D'Agostino et al. [43] used an integrated HEM for the case study area of Apulia in Italy to assess impacts of CC on the water balance and agricultural water use. They explicitly accounted for uncertainty by considering different CC scenarios and by conducting a nominal-range sensitivity analysis. Further to the commonly used A1B SRES emission scenario, four additional CC scenarios were selected. Sensitivity analyses were employed to determine the contribution of single-input parameters to variations in the simulation model output [43]. This enabled the response of input parameters to be assessed that are likely to suffer from uncertainty. Sensitivity analyses are commonly used in HEMs to gain information on outcomes of groundwater recharge, runoff, or crop evaporation under changing rainfall and temperatures [107].

Table 2. Consideration of CC-related uncertainties and risks in HEMs.

Type of Uncertainty	Treatment of Uncertainty	Examples
Input-parameter uncertainty (physical)	Stochastic programming	[28,29,90]
	Sensitivity analysis	[41,43]
Input-parameter uncertainty (economic)	Stochastic programming	[28,43,59,67,89,97]
	Sensitivity analysis	[41,43,77]
Climate uncertainty	Several climate-change scenarios	[20,30,41,43,61,65,68,69,77,86,88,97,106]
Model (chain) uncertainty (Upscaling/downscaling)	Use of different (global/regional) climate models	[27,41,43,65,66,68]

Source: Authors' Own.

Other HEMs apply stochastic methods to their optimization model. D'Agostino et al. [43] included stochastic components in their optimization model. The non-linear stochastic economic component of the HEM that maximizes farmers' utilities takes uncertainties with respect to prices and yields into account. Jeuland [28] used the concept of hydro-economics as an investment planning framework and took the interrelationships between CC and water-resource systems into account. These last two references included both physical aspects of CC (changes in runoff, net evaporation, water demand, and flood and drought risks) as well as economic uncertainties (e.g., real value and productivity of water-system-related goods and services). The innovation of this approach involves extending a hydrological water-resource planning model to include economic uncertainty. Additionally, Jeuland [28] accounted for uncertainties by using a stochastic streamflow generator, a hydrological simulation model, and an economic appraisal model. Regarding CC, the author applied a historical scenario and a scenario based on the SRES A2 emissions scenario presented in the IPCC report [108]. The economic appraisal model calculates the net present value (NPV) of hydrologic projects under a Monte Carlo simulation and considers various possible physical and economic states. Reynaud and Leenhardt [89] took economic risk into account by introducing a probabilistic component in the microeconomic production model and represented each farmer's behaviour in their integrated water-management framework, thereby representing agricultural, urban, and environmental water demand in the case of the river Neste (France). This model includes climate and crop price variation and farmers' risk preferences and influences farmers' choices regarding land use, sowing dates, and water use. Alternatively, Graveline et al. [97] conducted Monte Carlo simulations in order to account for input-parameter uncertainty in their farm-scale model applied to two regions in France, and Varela-Ortega et al. [59] considered uncertainties via stochastic programming methods in the economic model, which is combined with a hydrological model to form an HEM.

6. Discussion and Concluding Remarks

Despite the recent developments in the use of river-basin network-based HEMs to assess water policy in a CC context, several remaining challenges can be identified. One important decision in the context of hydro-economic modelling is the spatial scale of analysis to be used. It is of crucial importance since it may introduce further uncertainties into the model due to aggregation bias or upscaling/downscaling procedures [92]. Clearly, spatial scale depends on the research question or policy evaluation to be addressed. Although the farm scale may be useful to analyse farm decisions and impacts on different farms, regional or catchment models are optimal to determine the social optimal allocation of water resources. However, this scale can only be applied in a relatively homogenous region [109]. Additionally, the models may suffer from aggregation bias. This is especially relevant for water resources, since water availability and use are often heterogeneous within a region [92]. The river basin (or catchment) scale has been acknowledged as the appropriate scale of analysis to address CC challenges in water-resource management [110], since modelling at this scale can provide

essential information for policy makers in their decisions regarding the allocation of resources [33]. Furthermore, non-provision ecosystem services, such as environmental and other in-stream water uses, become increasingly important when economies develop, whereby the basin scale presents the most suitable unit of analysis. In contrast, the use of economy-wide models that include water use are inadequate for water-policy decisions since the lack of hydrological details (e.g., water resources, water abstraction, return flows, temporal evolution) and the level of analysis (e.g., country/region) makes them unfit for specific water-policy evaluation. These economy-wide models fail to recognize a critical variable regarding water use: return flows. These flows are crucial for water analyses since most of the water in many sectors (energy, urban, industry) returns to the system (with lower quality but almost in the same quantity, and usually from a different location as that of abstraction). The global average agricultural return flows are close to 40% (i.e., only 60% is evaporated or "lost from the basin") [47]. Modelling water policy requires this information to be taken into account in order to make a realistic and useful model.

At the same time, micro-macro linking becomes increasingly important in certain modelling contexts. Most applications of HEMs consist of microeconomic analytical tools that include water as the resource under analysis within a neoclassical optimization framework to evaluate specific policy measures. Among these applications, Berbel et al. [111] focused on the hydrologic and economic impacts of water-use efficiency upgrading, and Xie and Zilberman [112] evaluated water-supply increases vs. water-use efficiency policies. These models tend to focus on specific temporal and spatial contexts while ignoring larger scales such as the river basin (or catchment) and climatic variability. Regarding the use of models for policy evaluation, generally, HEMs are built from detailed hydrology models and integrate relevant sectors, mainly irrigation and energy (cooling and hydropower). However, the regional macroeconomic effects of a range of water allocation and investment decisions are generally not considered in most models. They should be integrated as micro-macro feedback loops (e.g., less irrigation, reduced output, multiplier effect, higher prices, consumer impact, and welfare effects). Hitherto, such analyses have seldom been carried out in the literature. Regarding the models of the microeconomic sector, the use of mainstream neoclassical economics, which relies on the optimizing behaviour of agents to determine microeconomic decisions and to link these to macroeconomic decisions, should integrate the insights of behavioural economics in order to improve the usefulness of the model and to improve the predictive capacity of models and the effectiveness of policies. Along these lines, and in contrast to most applications of HEMs reviewed in previous studies ([12,14,16], among others), the use of HEMs at river basin scale should take into account three basic dimensions (or components): hydrological, microeconomic (bottom-up), and macroeconomic (top-down). CC would enter the HEM as an element that influences water and socio-economic systems and incorporates variability and uncertainty into the modelling assessment.

In the context of potential CC impacts, this study highlighted the range of uncertainties (input-parameter uncertainty; scenario uncertainty; model chain uncertainty) that have to be addressed by the models [28,42,43,68,91,92]. Climate-change and global-change (i.e., bio-physical, regulatory, economic conditions) uncertainties can be included by employing alternative possible future scenarios regarding emissions, agricultural policies, prices, and resource constraints [43,92]. More specifically, in order to account for CC uncertainties, optimization models or descriptive models of agent behaviour can be complemented with simulation methods by including diverse scenarios representing different states of certain aspects (water availability, temperature, associated costs and benefits, environmental and economic circumstances, etc.) [28]. Alternatively, a variety of climate, environmental, socio-economic, and market conditions can be included by randomized statistical methods to directly include risk in the optimization model. In our opinion, the embedded uncertainty that is essential to any climate model should be managed inside the model by simulating various climate scenarios. For instance, such models should include several GHG-emission scenarios in order to account for the uncertainty related to future CC; they should take several global climate models into account for robustness checks and/or include stochastic components for both physical and economic input parameters. Furthermore, future

economic growth should be considered in HEMs since the demand for food and energy substantially modifies the demand and supply of water. To summarize, CC uncertainties can be addressed by (a) including different CC scenarios in simulation HEMs or (b) incorporating stochastic components in optimization HEMs. Arguably, the recently more commonly applied hybrid approaches combining simulation and optimization network-based HEMs may be especially well suited to analyse water policies under CC at a river-basin scale.

This paper has reviewed the literature to categorize HEMs used for water-policy evaluation including the integration of CC impacts. This review updates previous efforts to describe the available approaches towards issues of supporting water allocation, infrastructure investment, and policy options. Although in recent years, several HEMs have started to take both bio-physical as well as economic factors and uncertainties and their feedback links into account, significant drawbacks and limitations still persist when they account for uncertainties and risks associated with CC. Thus, further research is needed to overcome these limitations.

To sum up, our main conclusion regarding CC uncertainties is that modellers are striving to introduce certain climatic scenarios. In the past, most of the HEMs that address CC focused on the physical impacts of changing climatic conditions while ignoring economic feedback or assuming fixed parameters for economic factors that are crucial for water management and investment decisions. This generally leads to errors in the valuation of costs and benefits of hydrological projects, especially in terms of socio-economic effects, such as the roles of agricultural adaptation, degradation, and migration, which cannot be addressed under such a setup. Current challenges in the realm of hydro-economic modelling include the representation of the food-energy-water nexus, the successful representation of micro-macro linkages and feedback loops between the socio-economic model components and the physical side, and the treatment of CC uncertainties and risks in the analysis.

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