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Review

Modeling Non-Cooperative Water Use in River Basins

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Abstract: Conventional water use and management models have mostly emulated purposefully designed water use systems where centralized governance and rule-based cooperation of agents are assumed. However, water use systems, whether actively governed or not, involve multiple, independent decision makers with diverse and often conflicting interests. In the absence of adequate water management institutions to effectively coordinate decision processes on water use, water users' behaviors are rather likely to be non-cooperative, meaning that actions by individual users generate externalities and lead to sub-optimal water use efficiency. The objective of this review is to evaluate the advantages and disadvantages of recently proposed modeling systems dealing with non-cooperative water use regarding their ability to realistically represent the features of complex hydrological and socioeconomic processes and their tractability in terms of modeling tools and computational efficiency. For that purpose, we conducted a systematic review of 47 studies that address non-cooperative water use in decentralized modeling approaches. Even though such a decentralized approach should aim to model decisions by individual water users in non-cooperative water use, we find that most studies assumed the presence of a coordinating agency or market in their model. It also turns out that most of these models employed a solution procedure that sequentially solved independent economic decisions based on pre-defined conditions and heuristics, while only few modeling approaches offered simultaneous solution algorithms. We argue that this approach cannot adequately capture economic trade-offs in resource allocation, in contrast to models with simultaneous solution procedures.

Keywords: water allocation; non-cooperative; river basin; decentralized decisions; sustainability

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1. Introduction

The complexities of biophysical and socio-economic processes in water allocation and use present a considerable challenge to manage water resources efficiently and sustainably. The challenge is more evident in regions where adequate institutions for large-scale water use governance have yet to emerge and non-cooperative water use is dominant [1]. There has been a growing awareness that appropriate policy instruments and institutional arrangements are needed to promote an efficient and sustainable water use. Identifying policy options that fit the complex situation of a water management in coupled human–natural system requires addressing a number of questions: What are the potential efficiency gains from implementing market-based water allocation compared to command and control approaches or completely uncoordinated water use? Can gains from such policies offset any increased administrative or monitoring costs? What is the distributional impact of implementing such policies, and do they give rise to or rather reduce externalities? How do these conclusions depend on spatially and temporally dynamic economic-hydrological conditions as well as the interactions among them in the coupled system?

Answers to these questions demand appropriate decision support tools for the ex-ante impact evaluation of proposed water policies and institutional arrangements. Water policies cannot be meaningfully evaluated if models used do not realistically simulate the interaction of hydrological conditions and water users' behavior [2]. Combined hydrologic and economic simulation models have been used for economic impact assessment of water management institutions at the river basin scale [3]. Wang et al. [4] described these models as hydrologic-economic river basin model (HERBM), a terminology adopted by Kuhn and Britz [5] and Britz et al. [6]. These models aim to account for the complex biophysical and socio-economic processes of water use and management problems. The main advantage of this modeling approach is the integration of spatially distributed hydrologic, engineering, ecologic, social, and economic components of the water resource system in a consistent framework for a comprehensive assessment of the trade-offs between water policy choices [7,8]. The integration is based on a node–link network, where the nodes represent physical entities producing or using water and links represent the water flows between these entities. Water use by agents represented by the nodes causes costs and generates value, both of which can be expressed in monetary terms. In this way, a multiple-objective use and management problem simplifies into a single-objective optimization problem by summarizing the interests of all agents into a single financial metric.

Most HERBMs are constrained numerical optimization problems that are based on mathematical programming where the basin-wide aggregate social welfare criterion is maximized subject to a set of biophysical and institutional constraints. An early example by Young et al. [9] was used for the evaluation of alternative institutional arrangements for managing water resource for the South Platte River Basin in Colorado. Over the last four decades, HERBMs evolved both in theory and methods and were applied to issues of water allocation and management worldwide. A comprehensive review of HERBMs and their application to river basin water management is given by Harou et al. [3] and Bekchanov et al. [10].

Despite the significant advancement in HERBMs' modeling since the early 1980s, several limitations remain [3], one of them being the simplified representation of individual water user's behavior and interaction with one another and the hydrological conditions. Commonly designed as optimization problems based on aggregate welfare maximization, HERBMs assume the presence of (1) a centralized social planner and (2) water users that are willing to cooperatively reallocate water among each other such that their joint aggregate welfare is maximized. This is equivalent to reallocating water until marginal net benefits (shadow prices) of one additional unit of water are equal among all uses, users, and time in point. According to this hypothesis, some agents (e.g., upstream water users) are willing to decrease their local benefit to improve the benefit of other users (e.g., downstream users), a condition that is hardly plausible in most real-world institutional contexts, as argued by Kuhn and Britz [5].

Generally, water use modeling that leads to optimal solutions based on aggregate optimization may not well fit many real-world situations characterized by weak institutions and market failures. Non-cooperative behavior in water use may be much more common when multiple, institutionally independent but physically interconnected decision makers base their water use decision primarily on individual rationality ignoring the spatial externalities [11]. For instance, excessive water use by upstream users may reduce the aggregate basin-wide welfare by reducing water availability for economically more efficient downstream users [12]. Transnational river basins are a good example in that water flow creates hydrological interdependences, whereas each riparian country is institutionally independent to manage and allocate water within its national boundary [13]. In such a scenario non-cooperative water use is likely to dominate, degenerating the common water resource into an open access system marked by free-rider behavior and sub-optimal system performance. Various factors including lack of financial and administrative capacity and political will may cause ineffective institutions for water allocation and management. For example, Acemoglu [14] showed that an ineffective economic institution, in general, may persist due to private interests of national or regional elites.

Even though this limitation of HERBMs was recognized in the literature much earlier [9,12,15], it is only recently that explicit alternative model designs have been suggested to address this problem. The suggested modeling approaches include decentralized hydro-economic models (HEM) based on individual optimization [5,6] and Agent-Based Models (ABM) [13,15–17]. Game-theoretic models (GTM) have also been used to simulate water allocation problems based on both cooperative and non-cooperative game theory [11,18].

The objective of this review is to evaluate the advantages and disadvantages of these alternative modeling approaches with respect to several aspects. The first is the capability of the suggested models to realistically simulate non-cooperative water use under absent or weak water institutions. We will also ascertain whether these novel models retain the classical HERBMs' extensive capacity to simulate the specific features of the hydrological and economic processes. Finally, we will discuss implications of the alternative modeling approaches for the design of sustainable water management systems.

The remainder of the article is organized as follows. In the next section, we present a brief overview of the unique features of water resource and use systems and implication for institutional design. This is followed by a description of the methods we used to select the relevant literature. In Section 4, we present the main results of the review. Section 5 discusses the results before we conclude in Section 6.

2. Spatio-Temporal Dynamics of Hydrological Conditions, User Interaction and Implications for Institutional Design

In this section we lay out hydrological conditions and water use systems to define an analytical framework to guide the assessment of models suggested in studies we reviewed in this paper. The peculiar characteristics of water resources pose special challenges for designing efficient institutions for water allocation and regulation [19,20]. Water resources have a number of unique features such as mobility and supply uncertainty that distinguish them from most other resources and commodities [21] (p. 35). Like any other natural resource, water supply and demand are characterized by spatial and temporal dynamics [22] and pervasive interdependence among heterogenous users [21].

The mobile nature of water combined with often uncertain availability creates unique interrelationships between heterogenous water users. Water flows downstream in river basins, and actions by upstream users generate unidirectional externalities that affect downstream users. In an unregulated setting, an upstream user has a locational advantage to use all or part of the water within his or her boundary and has no incentive to consider externalities such as reduced water availability or quality for downstream users. This would result in a reduced total net benefit and suboptimal outcome, especially if the downstream users are economically more efficient, as described by Hirsch [23] in general and Nepal et al. [24] for the Himalayan region. Actions of downstream users, however, are rarely able to influence the behavior of upstream users. This locational disadvantage of downstream users may be compensated to some degree by the hierarchical structure of most basins in which the main river channel is fed by an increasing number of tributaries that collect runoff from the watershed as it flows along, increasing potential water availability for downstream users as compared to users farther upstream.

These locational (dis)advantages of users in a river basin have significant implications not only for socio-economic and hydrologic interactions, but also for the design of appropriate institutional arrangements [19,25]. Consider a hypothetical river system that consists of a finite number of n users (A1, A2, A3, . . . An) sequentially located along the river, as shown in Figure 1. The subscripts denote the geographical location of the users. It has three channels or river sections—the upper mainstream is represented by Q1 water flow and joined by a smaller tributary represented by Q2 water flow to form a bigger river channel in the lower mainstream with Q3 water flow.

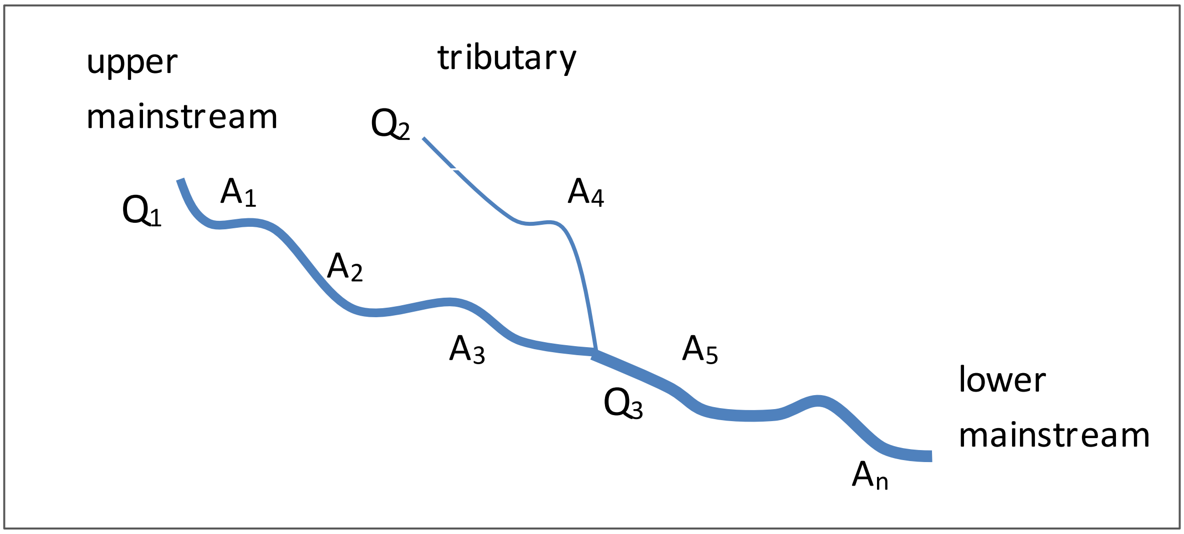

Figure 1. Spatial distribution of water resource and users in a river basin system (Qi and Ai represent water flows and water users along the river, respectively).

In this case, the enforcement of water rights without an adequate regulatory system would be problematic. The two upstream agents, A1 and A2, may divert more water than their allocated quota as long as the marginal benefit from water use is larger than the punishment for the illegal abstraction if detected [1,26]. As pointed out by Livingston [19], the nature of water as a mobile and high exclusion-cost resource could also impede the establishment and functioning of a market for water use rights. For instance, it could be difficult for A1 and A3 to reach a water rights trade agreement if the middle agent, A2, is not willing to take part but decides to free-ride such that water sold by A1 may not be fully transferred to A3. Moreover, consider the trade of water rights between agents, such as A5, located at a river section with relatively abundant water, and the upstream agents, such as A4, located at a river section where flow is small. It would be impossible to transfer water upstream without extra investment on infrastructure, i.e., efficiency gains are only achieved if the benefit of reallocation exceeds against-gravity transfer costs.

In addition to its physical nature, spatial and temporal dynamics due to natural variability of precipitation and temperature determine the distribution of water supply over space and time, especially in arid regions [27,28]. This has important impacts for the economic viability of water management institutions: As long as water is abundant, externalities generated by upstream users may hardly be noticeable. During periods of water shortages, however, users may react, for example, by overexploiting available water and free-riding may become difficult to manage [20]. The often volatile nature of water supply makes the establishment and maintenance of effective institutional arrangements difficult due to high transactions costs [29,30]. As Bardhan [29] points out, when water is extremely scarce, cooperation is challenged by highly profitable cheating, whereas when water is abundant, there is no need to cooperate.

In conclusion, the following key points will guide the assessment of alternative modeling approaches suggested in the studies we reviewed in this paper: For effective evaluation of alternative water policies in a river basin, models should explicitly address externalities due to spatial and temporal heterogeneity and variability in an integrated modeling framework. The models also need to consider the sociopolitical realities, specifically the existence of adequate water institutions and administrative capacities for effective monitoring and enforcement in water governance. Under absent or weak institutions, a model should be able to simulate non-cooperative water use baseline scenarios against which outcomes of alternative policies can be compared.

3. Methods

To understand the current state of the art of water policy evaluation models, we carried out a systematic review of relevant studies between 2000 and 2020. In this section, we describe the process we followed to carry out the systematic review including the selection criteria and search method.

Search Method and Selection Criteria

We performed a systematic search of the academic literature to identify relevant studies for our review using Web of Science and Google Scholar to compile post-2000 relevant studies. We used the topic search in Web of Science's core collection database and Advanced Search in Google Scholar. We used search keywords that covered five aspects of the focus of this study—modeling, water use and management, non-cooperative, river basin, and water policy and institutions.

To keep the search broad and minimize the chance of missing any modeling approach in the literature, we used a combination of eight search terms: "agent-based model*", "game-theor* model*", "non-cooperat*", "individual optimization", "multiple optimizations", "bi-level program*", "decentralized approach", "hydro-economic model*". To identify studies that deal with water use and management, water policies, and institutions in a river basin setting, we used another combination of eight search terms: "water use", "water allocation", "irrigation", "river basin", "spatial external*", "watershed"," policy", "institutional arrangements" and "asymmetric access". Each of these search terms were joined with a Boolean "OR", and the two sets of combinations of search terms for modeling and topic were combined using a Boolean "AND". We carried out the initial literature search on 5 July 2019 and updated 12 March 2021, extending the search period to 2020.

From our search result, we retained studies that met the following eligibility criteria:

(1) Study used a decentralized rather than a centralized approach to model water users' decision-making behavior.
(2) Study was at river basin scale with upstream and downstream setup.
(3) Study dealt with surface water or groundwater use and management or both. Study that dealt with groundwater pumping but not connected streamflow at basin scale was excluded.
(4) Study that discussed a theoretical model with hypothetical example or an empirical application.
(5) Study was relevant to the theme of our study—modeling, water use and management in river basin, non-cooperative behavior, and water policies and institutions.
(6) Only one of substantively similar versions of the same study, e.g., only published papers and not their associated working papers were included in the review.

In total, 370 items returned by Web of Science and Google scholar matched the search criteria. After removal of duplicates, screening at title and abstract, and reading full text, a total of 47 studies were selected for review. Figure 2 shows the screening process and number of studies excluded at each stage. Of the 47 studies, 12 relied on hypothetical data to demonstrate the performance of newly developed or extended modeling frameworks. A majority of the studies with empirical data were applied to river basins located in different parts of Asian countries followed by North America.

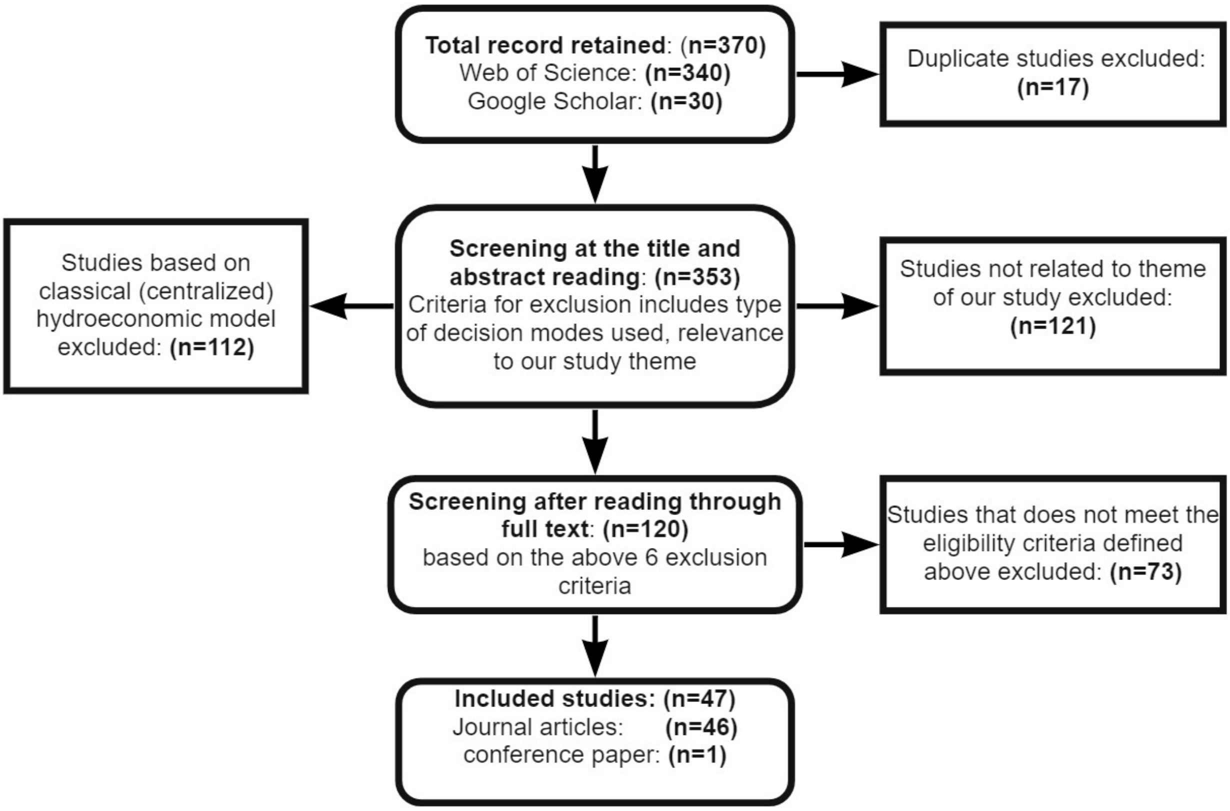

Figure 2. Screening process of the retained studies from the database search.

4. Results

4.1. Description of Selected Studies

In this section, we present a brief scientometric analysis of the selected 47 studies to understand the research and publication patterns on the topic of this study. Annual scientific production on the modeling of non-cooperative water use steadily increased from 2010 to 2018. About 66% of the selected studies were published during this period. However, there was a declining trend over the recent years. This may not necessarily imply a decreasing interest in the field. To better understand this, we looked at scientific production by top authors in the field. Figure 3 shows that, as much as new authors are joining, the leading authors active in the field for a longer period continued producing scientific publications with up to two articles per year and these publications also received big total citation numbers per year. This demonstrates that the field of modeling non-cooperative water use is still an active research agenda.

4.2. An Overview of Decision Models Used in the Studies

The results showed most of the studies used Agent-Based Models (ABMs), 23 studies, to characterize a water user's decision process. This was followed by decentralized Hydro-economic Models (HEMs) and Game-theoretic Models (GTMs), 12 studies each. We will present a detailed description of the model types in this section.

As mentioned above, we classified the decision models used in the studies into ABMs, HEMs, and GTMs based on how they characterize the decision behavior of water users interacting with each other and the physically connected hydrological systems. However, classifying into these three categories was not straightforward. Authors may denominate their model as 'game-theoretic', which can also fit well into the ABMs' category or vice versa. For example, Filho et al. [1] claimed they modeled users' behavior with a game theoretic approach. Nevertheless, their analytical model to simulate the role of price and enforcement in water allocation where water users' interaction, decision behaviour, and possible system level emergences were characterized following an ABM framework. Zhao et al. [26] cited this work as an example of an early application of an ABM model in water economics. We encountered similar issues when trying to classify models as HEMs or GTMs. It may not be surprising to observe similar features among these models since game theory lends an overarching theoretical framework for both HEMs and ABMs. Nevertheless, we classified the reviewed publications into the three categories based on certain distinct features, for example, how an agent's decision rules were defined and system equilibrium emerged, in addition to what was claimed of the model type in the study.

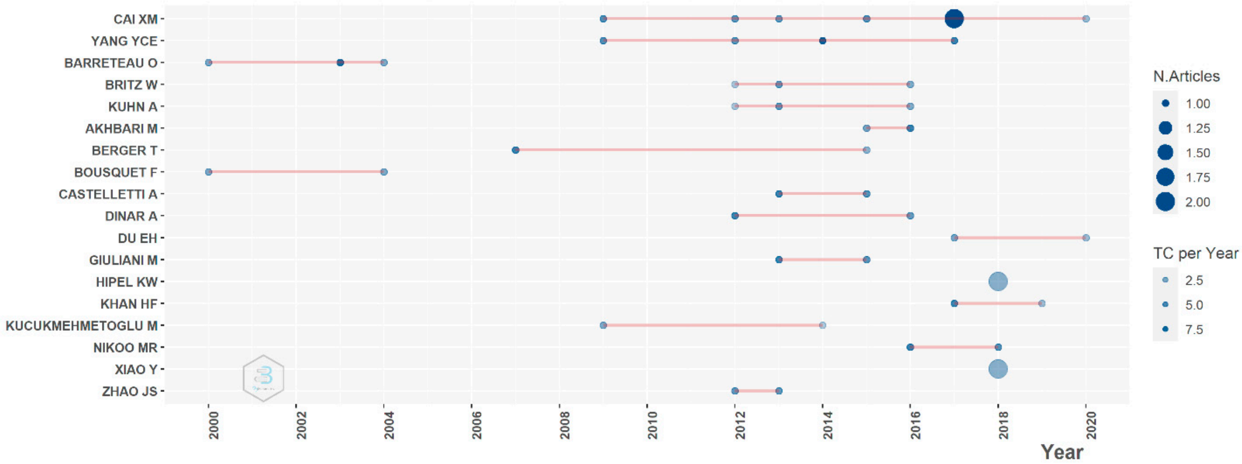

Figure 3. Scientific production by top author per year. The *y*-axis represents the list of authors; the *x*-axis represents number of articles per author per year (N. Articles) and total citation per article per year (TC per Year).

Agents in the reviewed studies were usually not real or stylized individuals, but rather 'representative agents' that signified locally or regionally aggregated groups of water users. They were represented by different economic, social, and ecosystem agents that interacted with one another and the hydrological environment to achieve certain defined goals. In HEM- and GTM-based studies, individual water users were typically aggregated to representative agents at sub-basin or regional [30–39] or national [40–43] levels within a river basin. Jeuland et al. [44] used hydropower facilities in the Nam Ngum Basin as individual agents that decide on the timing and quantity of water releases for hydroelectric generation and agricultural production. Britz et al. [6] used hypothetical firms as individual agents that make water and factor use decisions to maximize individual profit. Hypothetical riparian countries sharing river water were also represented as single agents in game-theoretic models [45–48]. Hydro-economic and Game-theoretic models tend to work with fewer agents on the aggregated level, whereas this is less uniform in ABMs.

4.2.1. Studies Based on Hydro-Economic Models (HEMs)

Table 1 summarizes selected studies that used HEMs' simulation. The HEMs are decentralized partial equilibrium models that integrate economic, hydrologic and biophysical, and policy and institutional aspects of water resources management. They are driven by a decentralized optimization framework based on an individual decision-making process to realistically represent a water user's behavior at the micro-level. Under non-cooperative water use, HEMs characterize individual water users as independent decision makers that use the water available at each location to maximize their own utility. In doing so, upstream users ignore the externalities generated to downstream users. In this approach, the water that flows out, after satisfying an upstream user's demand, is viewed as an exogenous resource endowment by the next downstream agent.

Table 1. Summary of studies based on hydro-economic models (HEMs).

Document	Water Resource and Their Location	Purpose of the Study (Broadly Defined)	Decision-Making Mechanism	Solution Algorithm	Modeling Tools and Computational Efficiency
Bauman et al. [31]	South Platte River Basin in Colorado, USA.	Explore welfare impact of imperfectly competitive conditions for water market with transaction cost	Constrained Optimization	Simultaneous	Coded in GAMS and solved using MOPEC approach
Britz et al. [6]	Hypothetical	Demonstrate alternative decentralized modeling approach of water allocation problems using MOPEC framework	Constrained optimization:	Simultaneous	Used EMP in GAMS to automatically generate MOPEC and solved using path.
Digna et al. [41]	Eastern Nile Basin	Simulate the benefits of cooperative and non-cooperative management of hydraulic infrastructures	Bi-objective constrained optimization	Sequential	Coded in MATLAB and solved using a Genetic algorithm (GA).
Dinar and Nigatu [49]	Eastern Nile Basin	Conduct comparative analysis of water allocation under social planner and different coalitional arrangements with water trade and soil erosion externality.	Constrained optimization	Sequential	Coded in GAMS and solved using NLP solver
Dozier et al. [32]	South Platte River Basin, Colorado, USA	Analyze the impacts of alternative institutional and policy scenarios for water rights administration and urban conservations	Constrained optimization	Simultaneous	GAMS was used to solve the MOPEC problem, Python to run the entire workflow
Jeuland et al. [44]	Nam Ngum sub-catchment in Mekong Basin	Compare benefit from full cooperation with non-coordinated infrastructural development	Constrained optimization	Sequential	The nonlinear model was coded in GAMS
Kuhn and Britz [5]	Hypothetical	Develop a decentralized water allocation approach using mixed complementarity programming (MCP)	Constrained optimization	Simultaneous	NLP was converted into MCP using manually tied FOC equations and decision variables in GAMS.
Kuhn et al. [30]	Lake Naivasha basin, Kenya	Simulate economic viability of water institutions under climate variability	Constrained optimization	Simultaneous	GAMS was used to solve the MOPEC problem
Mahjouri and Ardestan [35]	Irrigation schemes in Khuzestan Province, Southern Iran	Compare benefit of cooperative and non-cooperative water allocation	Constrained optimization	Sequential	No information
Pande et al. [36]	River Basin in Gujarat and Rajasthan, India	Simulate decentralized water allocation dealing with the externalities from upstream-downstream linkages	Constrained Optimization	Sequential	Coded in GAMS and solved with MINOS5 DNLP solver
Teasley and McKinney [43]	Syr Darya Basin, Central Asia (CA)	Apply HEM and game theory concepts to analyze various cooperation and benefit-sharing arrangements	Constrained Optimization:	Sequential	The nonlinear model was coded in GAMS
Tu et al. [39]	Irrigation district of Gan-Fu plain in Jiangxi Province, central China	Administrative and market-based optimization method to solve the regional water allocation problems	Bi-level constrained optimization	Simultaneous	The model was solved using a GA, but no information about modeling tools

In HEMs, the agents' decision mechanisms are represented by constrained optimization, which is solved simultaneously or sequentially using conventional calculus-based optimization algorithms or Genetic Algorithms (Table 1). A Genetic Algorithm is an evolutionary optimization approach used to solve complex non-linear models not well suited for standard optimization algorithms [50]. Eight out of the 12 HEMs were coded in General Algebraic Modeling System (GAMS) while one used MATLAB and no information was provided for the remaining two. The tractability and computational efficiency of the models used was not regularly reported in the reviewed studies.

Six of the 12 HEM-based studies used the model to analyze large-scale water allocation problems at the river basin scale [30–32,35,36,39], focusing on the policy and institutional aspects of water allocation problems. Moreover, three studies used HEM to analyze the benefits of cooperative water use in transboundary rivers shared by two or more riparian countries and compared the outcome to non-cooperative use [42,44,45]. The non-cooperative scenario was also used for the benefit-sharing and stability analysis. Two studies, Britz et al. [6] and Kuhn and Britz [5], used a conceptual model with hypothetical examples to demonstrate how HEM can be used to simulate water allocation problems based on decentralized decision-making under non-cooperative water use. Kuhn and Britz [5] specifically designed a decentralized modeling framework to address the limitation of HERBMs based on the centralized approach. The model was further developed by Britz et al. [6] using the MOPEC (Multiple Optimization Problems with Equilibrium Constraints) framework [51] in mathematical programming. The MOPEC framework allowed a simultaneous solution to the problem by defining equilibrium constraints.

Apart from individual optimization, HEMs based on a bi-level programming approach were also used in some of the studies. Bi-level programming allows the maximization of system-wide social welfare while considering individual-level decision-making in resource allocation. In this case, individual water users reacted to a chosen policy instrument through their decision on water use. Tu et al. [39] used this approach to model joint administrative and market-based regional water allocation problems in which the regional authority is the top decision maker at the administrative level, while sub-regions were the decision makers of the market level. However, this modeling approach made the institutional assumption that full or partial coordination and enforcement of water allocation policies were provided by the central agency.

4.2.2. Studies Based on Agent-Based Models (ABMs)

Agent-Based Models emerged as promising decision support tools in the area of environmental and natural resource management [52]. In the field of water resource management, early ABMs were used to simulate the management of irrigated ecosystems, evaluate scenarios based on policy options, and represent the interaction between stakeholders by formalizing their views as decision makers [15,53–56].

The 23 ABM-based studies used different nomenclature such as "agent-based modeling", "multi-agent simulation", and "multi-agent simulation systems" to identify their model. Here, we refer to all as agent-based models to avoid any confusion. The studies dealt with different issues of water management and allocation problems using ABMs either as a methodological framework to demonstrate its suitability or empirical application to a specific problem. Of the 23 ABM-based publications, seven did not explicitly model externalities and spatial interaction of agents in non-cooperative water use. For example, Barreteau and Bousquet [54] developed an ABM model called SHADOC to study the effect of social networks on the viability of irrigation systems and applied it to the Senegal River Valley irrigation system [53]. Their heuristic-based model was limited to a single irrigation scheme with a focus on the role that collective action plays in the evolution of irrigation systems. Even though the authors recognized asymmetric access of users to water due to geographic location, they did not explicitly model this. Berger et al. [56] introduced a mathematical programming-based ABM called MP-MAS and demonstrated its suitability to simulate policy options in complex water use systems in the Maule River

Basin in Central Chile. An extended version of the same model was used to study the economic importance of irrigation water reuse in the watershed of Loncomilla River in Central Chile [57]. Similarly, spatial interaction between upstream and downstream users and the resulting externalities under non-cooperative water use was not their primary focus. Other ABMs were used as decision support tools for managing conflicts in water use [58] or to understand the role of individual groundwater users in coupled human–natural systems [59,60] with less emphasis on the spatial interaction between water users in a river basin.

Table 2 presents a summary of shortlisted ABM-based studies that explicitly modeled interaction of sequentially located water users with non-cooperative water use. We will specifically focus on these models in the discussion, excluding the seven abovementioned studies.

Table 2. Summary of studies based on Agent-Based models (ABMs).

Document	Water Resource and Their Location	Purpose of the Study (Broadly Defined)	Decision-Making Mechanism	Remarks on Modeling Tools, Computational Efficiency, and Special Assumptions
Becu et al. [55]	Mae Uam small catchment, Northern Thailand	Simulate the impact of upstream water management on the downstream farming viability under different irrigation management options.	Constrained optimization: combined with heuristics solved sequentially	Developed with CORMAS platform under VISUALWORKS environment using object-oriented programming language called SmallTalk.
Du et al. [61]	Heihe River Basin, China	simulate the impact of water policies on farmers conjunctive water use and on hydrological processes under spatial heterogeneity and temporal dynamics	Heuristic optimization	No information is provided about the modeling tools used and computational efficiency. Yet, as their model integrates different models, more than one modeling tools might have been used
Ding et al. [62]	Nile River Basin	Simulation of fair distribution of benefits from efficient water allocation with empirical example from Nile Basin	Constrained optimization solved simultaneously.	Coded in MATLAB and solved using GA.
Giuliani et al. [63]	Theoretical	A modeling framework for regulatory design in water management	Distributed constrained optimization solved sequentially	The authors indicated that the issue of computational efficiency could arise when used for large-scale water allocation problem
Giuliani and Castelletti [13]	Zambezi River Basin	Assess value of cooperation and information exchange using MAS framework	Constrained dynamic optimization solved sequentially	The model predictive control (a variant of stochastic dynamic programming) was coded in C++
Khan et al. [64]	Niger and Mekong River Basins	Simulate the impacts of water management decisions that affect food-water- energy-environment (FWEE) nexus at a river basin	Heuristic optimization: Agents interact through a willingness to cooperate by changing their water management actions.	Coded in R, the socio-economic decision mechanism is highly simplified.
Khan and Brown [65]	Frenchman River Basin, USA	Simulate the impact of water permit and climatic variability on the performance of groundwater market	Constrained optimization	Coded in R and solved using Active set solver
Mulligan et al. [66]	Republican River Basin, USA	Assess groundwater policy with coupled economic-hydrologic model	Constrained optimization: unregulated water use problem is sequentially solved	ABM is coded in MATLAB and solved with Active set
Schlüter and Pahl-Wostl [16]	Amu Drya River Basin Delta, Central Asia	Application of ABM to study system characteristics and mechanism of resilience in complex water management	Heuristic optimization:	No information is provided about the modeling tools and model efficiency. The model assumes agents are homogenous in terms of their predictive capacity of water availability.
Xiao et al. [67]	South Saskatchewan river basin, Alberta, Canada.	Simulate impact of water demand management using	Constrained optimization:	Coded in GAMS and solved using MINOS. Unlike Britz et al. (2013) agents interact indirectly through the central processor, no direct interaction between agents.
Xiao et al. [68]	South Saskatchewan River basin, Alberta, Canada	Compare centralized and decentralized approaches to water demand management	Constrained optimization:	Same as Xiao et al. 2018a
Yang et al. [17]	Theoretical	Developed a decentralized optimization approach for Multi-agent-based watershed management	Distributed constrained optimization solved simultaneously	Coded in MATALB and solved using a solution algorithm for distributed constraint optimization problem.
Yang et al. [69]	Yellow River Basin, China	Decentralized approach for water allocation management (empirical application of Yang et al. 2009)	Distributed constrained optimization: sequentially solved for unregulated water use	Same as Yang et al. [17].
Zhao et al. [26]	Theoretical	Developed ABM and conducted a comparative analysis of administrative and market-based water allocation	Constrained optimization solved simultaneously	It is only an analytical solution without numerical simulation.
Izquierdo et al. [25]	Theoretical	Extended an already existing land use ABM model to FEARLUS-W that deals with water allocation and pollution control problems	Heuristic optimization	Analytical model with no numerical example

4.2.3. Studies Based on Game-Theoretic Models (GTM)

Game Theoretic Model has been applied extensively to common-pool resource management problems, including water following Ostrom's [70] seminal work. The model is based on the game-theoretic principle that multiple economic and social agents frequently interact in a strategic and competitive setting. As discussed above, this strategic interaction between water users in a river basin can be affected by their spatial location. In the game-theoretic approach the assumption of perfect cooperation among the decision makers is relaxed and each decision maker acts to optimize one's own objective, knowing that other players' decisions affect one's payoffs [18]. However, the game-theoretic approach is often used to simulate water allocation problems that involve only a few players (actors), and cooperative game theory applications are more common than non-cooperative ones [18]. Moreover, it is difficult to interpret the restrictive upstream–downstream setup—where actions of the downstream users have little influence on the outcome of upstream users—as a game.

Table 3 summarizes studies that used GTMs to simulate non-cooperative water use problems. Whether they are theoretical or empirical applications, studies based on GTMs focused mainly on efficient allocation through different coalitional agreements among water users and fair distribution of additional benefits from cooperation [34,42,45–47].

Table 3. Summary of studies based on Game-theoretic models (GTMs).

Document	Water Resource and Their Location	Purpose of the Study (Broadly Defined)	Decision-Making Mechanism	Remarks on Modeling Tools, Computational Efficiency, and Special Assumptions
Ambec and Ehlers [45]	Theoretical	Fair river sharing problem	Constrained optimization	A theoretical model with analytical solutions, agents maximize satiable water benefit function
Ambec and Sprumont [46]	Theoretical	Fair river sharing problem	Constrained optimization	A theoretical model with analytical solutions, agents maximize non-satiable water benefit function
Ansink and Ruijs [47]	Hypothetical River	Climate change and stability of water-sharing agreements	Constrained optimization solved sequentially	Analytical solutions and hypothetical numerical simulations with increasing and concave objective functions
Bhaduri and Barbier [40]	Ganges River Basin	Water transfer in international river basin context	Constrained optimization	Analytical solutions
Han et al. [33]	Hanjiang River Basin	Optimal water allocation and benefit-sharing	Bi-level constrained optimization solved sequentially	Highly simplified regarding the biophysical aspect with five water users
Kahil et al. [34]	Jucar River Basin, Spain	Optimal water allocation and benefit-sharing	Constrained optimization solved sequentially	Coded in GAMS. Non-cooperation is equivalent to fixed water right
Kucukmehmetoglu [42]	Euphrates and Tigris	Impact of infrastructural development on water allocation and benefit-sharing	Constrained optimization solved sequentially	Linear programming model coded in GAMS
Kucukmehmetoglu and Geymen [71]	Euphrates and Tigris	Simulate the impact of price variability for energy, water and transport on inter-basin water allocation	Constrained optimization solved sequentially	Mixed integer programming coded in GAMS
Madani and Dinar [11]	Hypothetical groundwater aquifer	Proposed non-cooperative management of Common Pool Resources (CPR)	Constrained optimization solved sequentially	Numerical simulations using three hypothetical aquifers. Cooperative and non-cooperative water use is represented by whether the agent internalize externalities or not
Ng et al. [48]	Hypothetical River Basin	Joint effect of physical and social mechanism on cooperation in water sharing	Constrained optimization solved simultaneously	Analytical and numerical simulation in MATLAB. They argue the action of downstream users could affect the outcome of upstream users
Safari et al. [37]	Zarrinehrud River basin, Iran	Leader-follower game-theoretic for water allocation problem	Bi-level constrained optimization solved simultaneously	Assumed followers have equal bargaining power which violates the asymmetric access to water. Also assumes established a functioning market for water
Sedghamiz et al. [38]	Irrigation scheme in Golestan province in Iran	Leader-follower game-theoretic for water allocation problem	Bi-level constrained optimization solved simultaneously using non-dominant sorting genetic algorithm	Recognizes unequal bargaining power but the source of power heterogeneity is not spatial asymmetry, population size

The simulation often follows two steps. First, a constrained optimization problem is solved using conventional mathematical programming or a Genetic Algorithm to simulate optimal water allocation by maximizing the aggregate utility of different parties in coalitional arrangements. Then, game theory concepts are applied to calculate the fair allocation of the additional benefit to the parties in agreement. Finally, benefits from different coalitional agreements are compared with the non-cooperative outcome where each user sequentially and unilaterally maximizes one's own economic benefit given the water release decisions from upstream users, following a similar approach as HEMs.

Bi-level programming is also used in GTMs. In that case, the strategic interaction is not only between the users but also between the users and enforcing agents at the top level. A leader–follower game often consists of one leader, the government agency, and multiple followers representing different water use agents [33,38,39]. The only difference between the bi-level approach in HEMs and GTMs is that the former allows the representation of relatively large numbers of follower agents.

5. Discussion

In this section we present and discuss how these models simulate non-cooperative water use focusing on the decision rules and solution algorithms employed and implications for water policy assessment and sustainable water management. Then, we analyze the models' ability to retain the ability of classical HERBMs to represent complex hydrological and socioeconomic processes without greatly compromising on computational efficiency. We do so by exploring the representation the biophysical and economic processes in the model, their linkages, the heterogeneity of agents, and their mutual interactions. We will also analyze if the stochastic nature of water supply can be captured in the model realistically. Finally, we discuss the implications for informing water policies and the design of sustainable water resources management. The discussion will follow the model-type sequence from above but will make comparisons between modeling approaches when necessary.

5.1. Decision Rules and Solution Algorithms

Individual-based modeling allows the representation of decision-making behavior of multiple agents [51,69]. In our context, the decision makers include regulatory agencies or markets and agents demanding water for off-stream (agriculture, municipal, and industry) or in-stream use (hydropower and ecosystem services) [58]. These heterogenous users act and interact based on different water-related value systems and objectives [72].

In HEMs, decisions of agents are simulated by individual optimization, formulated as mathematical programs (e.g., NLP, MCP, MOPEC, etc.), and solved using calculus-based conventional optimization or genetic algorithms (Table 1). The problems are formulated as maximization (or minimization) of single or multiple objective functions subject to biophysical and institutional constraints. The problem is solved either simultaneously or sequentially. When the sequential solution approach is used for non-cooperative water use, each user's problem is solved independently and sequentially starting with the uppermost user [42,44,45]. Then, water outflow from the optimal state of the upstream user represents a regulated inflow used by the program to optimize the downstream user's individual objective function. By contrast, a simultaneous solution, as proposed, e.g., by Kuhn and Britz [5] and Britz et al. [6], allows independent optimization problems across all individuals to be solved in a single step and, thereby, the solution for market equilibria of relevant factors and products other than water. This approach is equivalent to solving Nash Equilibria of non-cooperative games and is implemented using the mathematical programming format MOPEC (Multiple Optimization Problem with Equilibrium Constraints). MOPEC offers considerable flexibility compared to other decentralized hydro-economic models by allowing the definition of multiple objective functions per individual agent that can be solved simultaneously. The MOPEC approach was employed empirically to simulate water allocation problems in the Platte River Basin in Colorado focusing on water rights markets and transaction costs [31,32], but a non-cooperative water allocation scenario was not simulated. Kuhn et al. [30] applied MOPEC to simulate the viability of water institutions including unregulated (non-cooperative) water use for the Lake Naivasha Basin in Kenya.

In ABMs, the decisions of agents are guided by optimization or heuristics (prior defined rules) [73]. Our review showed that the use of optimization-based ABMs in water resource management is on the rise. Of the 16 ABM-based studies that simulated non-cooperative water use, 10 are based on optimizing agents [13,17,26,62,63,65–69]. Three ABM studies, Schlueter and Pahl-Wostl [16], Khan et al. [64], and Du et al. [61], used heuristics while Becu et al. [55] combined optimization with heuristics for decisions on rice planting and off-farm labor participation. The optimization approaches are theoretically strong but accused of seeing the human decision makers as rational optimizers with perfect foresight based on classical microeconomic theory. Even though the heuristic approach, in general, is intuitive and based on simple decision rules, identifying the most important decisions, their correct sequence, and appropriate conditions might not be easy.

In ABM-based studies both uncoordinated (non-cooperative) and partially coordinated scenarios are simulated. The coordinated optimization problem assumes the presence of a third party to coordinate the agents' distributed decisions based on administrative rules [63], market mechanisms [33,68], or the combination of both [26,69]. This modeling framework is based on the concept of *rational crime* where agents can violate imposed constraints (normative policy) as long as the potential benefit of the violation exceeds the penalty [1,74]. Although both sequential [13,63,66] and simultaneous [17,26,67,68] solution algorithms were used to solve the coordinated optimization problems, all ABMs represent the non-cooperative scenarios as a sequence of optimization problems where each agent is considering one's local objective function only from upstream to downstream. The total inflow to the agents' subsystem is modeled as *deterministic* [63,67–69] or *stochastic* [13] input. In Ding et al. [62] two problems were solved simultaneously for each agent using a parallel search algorithm. The first problem described a coalitional group of water users in the basin maximizing their aggregate benefit. The second problem represented an agent that left the group and maximized one's own benefit in singleton and competed for water with the coalitional group. The model was applied to solve the water sharing problem of countries in the Nile River Basin and to simulate fair revenue distribution from an efficient central planner (CP) solution after identifying the contribution of each nation to the CP solution.

Varying solution algorithms were employed to solve the ABMs' optimization problems, based on the nature and scale of the problem. These include conventional mathematical programming [17,26,55,66–69], model predictive control (MPC) [13], the ADOPT (Asynchronous Distributed OPTimization) algorithm [63], and genetic algorithms [62].

In the selected GTMs, the scenarios were formulated as optimization problems. Of the 11 GTMs, only three were solved simultaneously [37,38,48]; the rest used a sequential solution approach. Ng et al. [48] used an evolutionary-based game-theoretic approach to show how physical mechanisms (asymmetric payoffs) and social mechanisms (reciprocity) jointly affect water sharing cooperation in a river system. Heterogeneous water users located sequentially along the river system simultaneously played an iterative N-person Prisoner's Dilemma Game (PDG), which enabled the direct reciprocity mechanism under which peer punishment could be enforced in future encounters between any two actors. They assumed that the behavior of downstream users can affect the upstream user to consider the interaction between actors located serially along the river as a game. As discussed in the introduction, this may not hold. Safari et al. [37] and Sedghamiz et al. [38] used a bi-level programming model, assuming that a water resource manager as a leader in a game set the water price, and multiple water users as followers competed among themselves by maximizing a Nash bargaining solution. A simultaneous solution approach was used to solve the model.

In conclusion, the reviewed studies used both sequential and simultaneous solution approaches for solving non-cooperative water use problems in a river basin. The ABM-based studies try to overcome the limitations of the fully centralized decision-making approach by creating agents that made a completely independent economic decision that was solved sequentially, both in time and space. Water user's problems were sequentially and independently evaluated using either heuristic or optimizing agents, at the cost of dropping the simultaneous solution approach. However, as Schreinemakers and Berger [73] pointed out, an isolated evaluation of economic decisions by agents may not completely capture the economic trade-offs of alternative allocations of scarce resources. Water users may exchange commodities or factors of production other than water that could also affect water allocation decisions. Trade in energy and agricultural products between countries in the Syr and Amu Darya Basins of Central Asia [43] could be cited as an example. In general, countries and regions can interact in product and factor markets other than water according to their comparative advantage, which needs to be jointly evaluated in a simultaneous setting. The simultaneous solution approach proposed by Kuhn and Britz [5] and Britz et al. [6] allows the joint evaluation of problems involving numerous water users that are solved across all individuals in one step.

5.2. Agents' Behaviors, Interactions, Uncertainties and Spatio-Temporal Dynamics

In studies based on ABMs, agents represent water users and administrative controllers or market coordinators. The water user agents include farmer agents—representing individual farm units [16,55], spatial grids [25,56,62], or aggregate pumping wells [65,66]; sectoral water users such as agriculture, domestic, industrial, and ecosystem [13,17,63,67–69]; politically or hydrologically similar sub-regions consisting of agricultural sector, hydropower plants, and ecosystem [64]; or riparian countries [62]. Ecosystem agents are represented by fish habitats, preserved areas, wetlands, or river delta [13,64,69]. The ecosystem agents are defined as passive agents who do not make decisions but react to decisions made by active agents. Accordingly, the water demand for ecosystem agents is typically implemented as a minimum flow requirement

The relative spatial location of the water users in the river basin is a primary source of heterogeneity, as already discussed above. Moreover, the intensity of water-related economic activities, which determine water demand, such as cropping patterns or hydropower generation, as well as population and local climatic conditions, are other sources of heterogeneity among decision makers. In addition to this, heterogeneity among water users emerges from their priorities and objectives regarding water use. For example, Dozier et al. [32], in their decentralized HEMs, represented the objective of municipalities as cost minimization and of agricultural producers as profit maximization.

The representation of the economic and biophysical processes at appropriate levels of detail and their integration in a coherent manner is important to understand the spatio-temporal characteristics of human–hydrological interactions. The classical HERBMs made important progress in this direction where hydrologic, agronomic, engineering, and economic processes are tightly coupled using the node–link network framework [3]. Yet, rainfall-runoff processes are mostly not explicitly modeled, and water supply is exogenously derived from historical streamflow data instead. Our results showed that the majority of the reviewed studies focused on the development of a decentralized modeling framework with a simplified representation of the biophysical and economic processes. Of the 26 studies with empirical applications, only 11 (five HEMs, one GTM, and five ABMs) explicitly represented the hydrological and economic processes in relatively rich detail. Overall, the ABM-based studies put more focus on the biophysical processes where physically based distributed hydrological models are linked to simplified economic model. The agents in ABM studies are often defined as rule-based agents, meaning that water-related economic decisions draw on predefined heuristics [61,64]. This is mainly due to model tractability and computation time, especially with large numbers of agents.

Only a few studies accounted for inter-temporal dynamics and uncertainties in water supply. Kuhn et al. [30] conducted stochastic simulation to account for variability in water supply based on randomly drawn rainfall from monthly average time series data. Giuliani and Castelletti [13], in their ABM model for Zambezi Basin, modeled the temporal dynamics by stochastic inflow to the reservoir, which is updated as each time step based on predicted value. In Becu et al. [55] and Schlüter and Pahl-Wostl [16], farmers' expectation of water supply was continuously updated according to past experience, which also varied with farmers' recollections of the past [16]. Farmers' crop choice and yield was updated accordingly. Khan and Brown [65] analyzed the impact of water supply uncertainty based on the range of variability for climatic input. Accordingly, crop irrigation requirements were varied in each growing season.

The reviewed studies modeled interactions between heterogeneous water users and between water users and the hydrological systems differently depending on the type of models they used, seemingly as a result of a trade-off between representing biophysical and behavioral detail. In HEMs and GTMs, in the absence of water institutions (administrative or market), interaction between water users is implemented using inter-spatial water balances. The water balance that represents the hydrological process is often simplified relying on exogenous hydrological and weather inputs. Thus, the economic and hydrological models are typically integrated in a loose manner, exchanging input and output data externally. As indicated above, the interaction between water users in this case was only unidirectional, where water outflow from the optimal state of the upstream user was used as a regulated inflow to optimize the downstream user's problem. In ABMs, especially the ones basing behavior on heuristics, spatially explicit and fully calibrated hydrological simulation models are coupled with the ABM model to endogenously simulate the stock and flow of environmental variables linked to the ABM models. However, this is achieved at the cost of simplifying on the socio-economic decision process due to computational efficiency.

In summary, even if a number of interesting modeling frameworks has been put forward to overcome the deficiencies of existing tools in dealing with non-cooperative water use problems, there are still limitations that need to be addressed. First, the sequential solution approach mostly used in ABM models may not be appropriate as it fails to capture the full economic trade-offs of alternative allocation of scare resources. Second, due to computational efficiency and tractability, the biophysical and economic processes are overly simplified and less realistic to capture many real-world problems. Third, only a few studies accounted for inter-temporal dynamics and uncertainties in dealing with decentralized water allocation problems.

5.3. Insight for Sustainable Water Management

The demand for fresh water is projected to increase as populations and economies expand [75]. As demand increases, developing management institutions that ensure the sustainable use of water resources is essential. In addition to designing water institutions, clear regulation and enforcement mechanisms are equally important to achieve the required outcome.

An evaluation of alternative water policies and institutions needs to consider the expected levels of enforcement of and compliance to water use rules. In the studies we reviewed, explicit modeling of weak enforcement or lack of compliance to any proposed water policies (water use rights, maximum exploitation limits, taxes, and penalties) was emphasized less. There were a few exceptions, though. Based on the theory of rational violation, Filho et al. [1] developed an analytical ABM model to simulate strategic interaction between user agents and enforcing agents considering social and climatic risk. Their model accounted for regulatory effectiveness using the probability of detecting transgressors conditional on the capacity of the institution, proxied by budget allocated to it.

In CPR management settings where all actors hold the same strategic position, such as small-scale irrigation from the same groundwater body, water users may base their water use decision on group rationality and cooperate [18] to minimize externalities and, thus, ultimately contribute to its sustainability. In this situation, reciprocity mechanisms or punishment could be enforced to discourage the deviation of an individual user from the cooperative agreement. Even under non-cooperative water use, individual water users, based on learning from experience, may develop a heuristic CPR management plan considering future outcomes and externalities [11,70].

However, in the context of a river basin or large-scale irrigation system, the mobile nature of water results in a fixed order of priority to act among water users. As indicated above, in this situation, upstream users act before the downstream counterparts and, very often, the action of downstream users has no influence on the outcomes for upstream users, resulting in unidirectional externalities. Consequently, such a water resource resembles a sequential chain of private goods [25] instead of a CPR because a system of mutual restraint cannot emerge. Under such conditions, a lack of institutional structures that enforce sustainable water use and management leads to the growing problem of a variety of the free rider's problem, in which some members exploit the resource with no restriction while investing little or none for the management of the resource [76,77]. Therefore, regulation and enforcement of water rules and policies in such a context becomes increasingly challenging, which needs to be properly considered in the evaluation of alternative water policies to provide reliable evidence for policy makers.

6. Conclusions

In this paper we reviewed water management models that simulate water allocation problems as a decentralized decision process. The primary focus was on how a non-cooperative water use scenario is realistically simulated in complex water use and management systems.

From our review result, the following important conclusions can be made. First, even though there has been some progress in modeling water allocation problems using decentralized approaches, only a few studies demonstrated the ability to retain the ability of classical HERBMs to represent the economic and biophysical processes in detail without compromising on computational effort. Second, most agent-based and game-theoretic models employ a sequential solution approach where economic decisions are separately evaluated using pre-defined conditions and heuristics. However, independent evaluation of the economic decisions by agents cannot adequately capture trade-offs and synergies in allocation of scarce resources. Third, even though the decentralized modeling approach is pursued to model decisions by individual water users in non-cooperative water use, most studies assumed the presence of a coordinating agency or market in their model. This may not be a realistic assumption for most river basins, which future studies should consider. Finally, more emphasis is needed to capture the inter-temporal dynamics and uncertainties in water supply due to climatic variabilities in modeling alternative water policies for reliable impact evaluation.

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