Review

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Challenges to Water Resource Management—Role of Economic and Modeling Approaches

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Review

Challenges to Water Resource Management—Role of Economic and Modeling Approaches

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Abstract: The field of water management is continually changing. Water has been subject to external shocks in the form of climate change and globalization. Analysis of water management is subject to disciplinary developments and inter-disciplinary interactions. Are these developments well documented in the literature? Initial observations on interdisciplinary literature suggest that results are fragmented, implying that a state-of-the-art review is needed. The objective of this paper is to close this gap by reviewing recent developments in water economics that address the increasing perceptions of water scarcity by looking first at changes in supply and quality of water, and then at impacts of climate change on water extremes. Among responses to such challenges, the paper identifies changes to water use patterns by including and co-managing water from different sources—surface and groundwater, wastewater, and desalinated water. Technological advancements also are among the resources that address water challenges. Water challenges reflect also on management of internationally shared water. A recent surge in scientific work identified international treaties as playing a significant role in water management. The paper reviews recently employed economic tools, such as experimental economics, game theory, institutional economics, and valuation methods. And finally, it explores modeling approaches, including hydro-economic and computable general equilibrium models that are being used to deal with water challenges.

Keywords: Water; economics; globalization; climate change; competition; conflict; environment; valuation; CGE; game theory; experimental economics; institutional economics; international water; hydro-economic modeling

JEL Codes: Q25; Q52; Q54; Q55; Q57

1. Introduction – Water shocks and future projections of water availability, quality, and use

A closer look at the conditions facing the water sector in many countries around the world makes the observer realize that major changes have been taking place in the supply patterns, the demand configurations, and use arrangements. For example, using estimates of global renewable water supplies [1–5], (Table 1.1: [6]) present changes to continental and global available renewable water resources. Using the global figures, mean global available renewable water resources are 42,780 Km^3 and range between 39,780 and 44,750 km^3 in dry and wet years, respectively. Data in [4] provides estimated and forecasted global water withdrawals that show an exponential increase between the years 1900 and 2015 rising from 750 km^3/year in 1900 to 5,200 km^3/year in 2015. While the available renewable water resources are fairly consistent, over time the need for water for different uses will increase due to population growth and changes in consumer taste and might be marginally decreased due to technological advancements and institutions. The net effect is that much of the world's total renewable water resources per capita are declining over time in a hyperbolic manner. Due to intensive development and industrialization, the level of pollution of water resources will increase and water will become less available for various types of consumption.[1] Challenges to these forecasts have been introduced recently in different publications, such as by Boretti and Rosa [7] by developing and

[1] For example, increased salinity in irrigation water makes it less adequate for irrigation of certain crops, and increased nitrate load in groundwater from agricultural pollution and fertilizer use makes groundwater use risky for residential consumption.

applying global models that account also for the effect of climate change and not only on population growth. Another set of considerations include alterations to water demand, which are the results of increase in living standards, and adaptation to water scarcity by technology development and institutions (both of which may not be well functioning in all countries). In a different approach a non-parametric framework was applied to analyze seasonal hydroclimatic regimes by classifying global land regions into nine regimes [8]. These regimes are used to assess implications for water availability due to concomitant changes in mean and seasonal precipitation and evaporation changes. Concluding the future water availability would drastically change by regions of the world. Using continental population and surface water availability, the per capita water availability in the world and its six continents between 1950-2080 is calculated and presented in [9]. They suggest that it is the local (regional) policies that consider societal preferences and priorities for allocation of available water for food production, residential consumption and environmental usage.

Where does all that lead to? In the next subsections we review the highly dynamic nature of the water sector and the interactions it realizes from global and local conditions. Later in the paper we will refer to the dynamic nature of water resource management being challenged by these changing conditions, and their need to adjust to using new economic and institutional approaches.

What does economics have to offer? Why is it important that economic considerations are part of the solutions? Does water play a role in growth and development of nations ([10–12])? As questioned in [11,12] would an increase in water scarcity affect the economic growth of countries? Theoretical and empirical analyses have an inverted-U relationship with economic growth and the rate of water use. Comparative analysis shows little evidence of severe diminishing returns to water allocated to production, thus resulting in falling income per capita. All it suggests is that the claims of some hydrological-based studies of a widespread global "water crisis" should be taken with caution. While there is strong evidence that rainfall variability and water availability have significant impacts on certain sectors such as agriculture, [10] suggests evidence of its effect on economic growth and other measures of aggregate economic activity remain inconclusive.

The water sector faces multiple challenges and objectives, including increased water use efficiency and improved conservation, land and other resource conservation, improved food security, and regulated pollution of water bodies from water use in the irrigation and domestic sectors. To address such challenges and achieve the objectives, the water sector realizes different policy interventions, including institutional reforms (e.g., water rights, water trade), pricing, quotas, taxes, and subsidies [6].

Economic models provide a useful framework for valuing water and its allocation among different uses. They assess the economic costs and benefits of different water uses and employ this information to guide decisions about water allocation and pricing. Approaches such as hydrological and water allocation modelling can provide insights into the dynamics of water resources management and help forecast water availability under different climatic and institutional scenarios. These models can be used to inform decisions about water allocation, infrastructure investments, and policies to address water scarcity and pollution.

Several recent papers provide reviews of the economic role in dealing with water challenges. Work in [13] surveys the literature on the economics of water scarcity and water demand. It provides information on demand for water in urban, agricultural, industrial, and demand for instream water uses. The review provides an overview of what is known about efficient water pricing, water allocation, and water trading. The paper highlights particular water management issues, such as allocation, to which economics has made important contributions, and areas in which additional research is needed.

A different perspective, suggesting to rethink water economics in light of such challenges is included in [14]. The authors observe that privatization, pricing, and property rights—the conventional economic policy interventions—have not performed well due to their failure to address adequately political economy considerations, including distributional conflicts. The paper identifies particular social and physical characteristics of water supply and demand and discusses their implications for three major aspects of water policy: infrastructure finance, water pricing, and property rights reforms. All these aspects show a major concern in sustainable management of water resources under uncertain climate change conditions.

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A very useful review in [15] focuses on the role of economic analysis for helping to guide infrastructure investment choices, and for comparing the effectiveness of non-structural regulation approaches to water management. Among the economic approaches reviewed are optimization hydro-economic models (HEM), economy wide water-economy models (WEMs), socio-hydrological models (SHMs), spreadsheet-based partial equilibrium cost-benefit models, and others. The paper highlights recent cutting-edge works with WEMs and spreadsheet-based Cost-Benefit Analysis (CBA) models. Other advancements include multicriteria decision analysis, and game-theoretic modeling of noncooperative water institutions.

Under such changing conditions, it is important to compare available sets of traditional and new economic tools and approaches that could be put into action in order to address increased levels of scarcity, water quality deterioration, and water conflicts, to name a few challenges. This paper focuses on a review of advancements in economics of water management in recently published literature. The next section describes the methodology of selecting the publications to be included in this review. Section 3 reviews the various physical changes affecting the water sector in the recent two decades, which are reflected in the number and nature of the reviewed papers. Section 4 shows progress in water management approaches for dealing with local and international water uses. Section 5 reviews progress in management of international water. Section 6 presents specific economic tools and their contribution to dealing with water issues. It reviews experimental economics, game theory, institutional economic approaches, valuation approaches, and modeling approaches, such as hydro-economic modeling and computable general equilibrium models. In section 7 all these advances are linked and assessed for their joint ability to address future challenges in water resource management. Finally, section 8 discusses unaddressed issues and agenda for future research.

While previous published reviews have focused on either sub-disciplines, or specific issues, this review provides a wide coverage of disciplines and issues. This paper calls for the adoption of an interdisciplinary approach to solving water issues; however, it has its own limitations that should be shared with the reader. The review addresses the role of economics in assessing different types of interventions, such as institutional reforms, taxes and subsidies, and support of water-saving technology adoption. The objective of the paper is to highlight traditional and new economic tools and modeling approaches that could address increased levels of scarcity, water quality deterioration, and water conflicts.

The review includes more than 200 citations of publications mainly from the past 20 years. However, it is obvious that many important and relevant publications may have been missed and do not appear in the reference list.

2. Materials and Methods

The methodology used to identify papers to be included in the review is based on both keywords search and personal expertise. Given the relatively long lasting experience of the author in the field of water economics, a structured outline of the review paper was first designed, helping with the topics of papers to be reviewed. In addition to this first step, a list of keywords was constructed including the major topics to be addressed in the review paper, which follow the list of advancements in water economics that have been experienced in the past two decades (e.g., water and CGE, water and Experimental economics, water and game theory, water and valuation economics, etc…). The search was conducted in datasets such as Google scholar and JSTOR. In addition, references in each paper that was included in the dataset were also searched and considered.

A total of 756 papers and reports were found and held for further relevancy evaluation (including working papers, and book chapters). All records were read by the author. This first screening yielded a workable dataset of 299 publications. The 451 publications that were removed from the initial dataset were less comprehensive in terms of the economic implications of the issues and methodologies applied. The remaining 299 publications were placed in bins that follow the sub-sections in the paper structure. An additional elimination of papers from the dataset was done by removing works that were found less relevant, based on a complete content review. The final usable dataset consists of 213 publications, most of which have been published during 2000 - 2024, but few also from years prior to 2000.

3. Physical changes faced by and introduced by the water users

As indicated earlier, water users have been facing major changes in terms of quantity, quality, and extremes to the supply of water. As a result, the way water has been managed had to be reconsidered. The following sections identify all observed changes and realize their impact on the tools needed for appropriate water management under the new water reality.

3.1. Changes to water scarcity levels

Water scarcity is lack of a source of freshwater resources to meet the demands of water users for consumption, irrigation, and other uses. It can result from quantity shortage or access problems from water suppliers, or it may be due to water quality problems. Water scarcity affects people on all continents, and water use is increasing globally and has surpassed the rate of population increase by more than two-fold in the last century. Such unprecedented increase in water consumption has many regions facing water scarcity [16].

An interesting evaluation of the economic impact of water scarcity in various river basins around the world, implementing a Global Change Analysis Model (GCAM) is provided in [17]. GCAM is a hydro-economic model that decomposes the world into 32 geopolitical regions, 384 land-use regions, and 235 water basins. The model includes joined representations of the Earth's climate, economic, hydrologic, land-use, and energy systems in each region. Water scarcity is measured in the model as physical water scarcity according to the water withdrawal-to-availability ratio. Using several climatic scenarios, the GCAM suggests various interesting outcomes of the effect of exogenous impacts of water scarcity due to climate change in various river basins. While we are used to a negative effect of water scarcity on economic welfare, results suggest that, depending on the institutional and economic setups, positive basin-level impact from global scarcity can be realized in certain basins that demonstrate a comparative advantage over others. This comparative advantage can be realized if trade allows that basin to become a virtual water exporter through inter-basin trade and export of water-embedded goods to other basins. Such foundations of the hydro-economic models and their important role in addressing policies responding to water scarcity will be further discussed in a special section in the paper.

3.2. Changes to water quality

The quality of water resources in the world (both surface and groundwater) deteriorates over time, which presents a major challenge for policymakers in the water sector [18–21]. The authors in [18] review the types of contaminants, the type of water vulnerable to contamination, and the effects of such contaminants on human health. Contamination of surface water and groundwater from agricultural pollution of aquifers' water and waterways, industrial pollution of water resources, and elevated levels of household chemicals in wastewater have increased over the years. In the case of irrigated agriculture this is due to the needs of farmers to compensate for water scarcity, uncertainty in water supply, and increased effects of climate change on agriculture, such as elevated temperature levels that necessitate compensation with more fertilizers. Increased contamination levels in drinking water from different sources, resulting from loose regulations, has a direct effect on the health of populations consuming such water.[2] Regulation of these negative health and damaging effects vary and have different levels of effectiveness [22].

Mateo-Sagasta et al. [20] describe the extent of various pollution sources (nutrients, pesticides, salts, sediments, and organic matter) in irrigated agriculture and the possible policy interventions (regulatory instruments—standards; economic instruments—pollution taxes); education and awareness campaigns; cooperative agreements—tradeable pollution permits to address them [23]. In addition, Quinn et al. [24] examine a set of decision support models to address water quality management in real time, in different countries and sectors.

Lall et al. [21] focus on the deteriorating quality of groundwater globally. Pollutants from agriculture, industry, mining, energy production, and legacy landfills are an increasing threat to

[2] Similarly, contamination of groundwater and surface water affect the performance of the water-dependent ecosystems. Increased levels of various contaminants in irrigation water (including wastewater for irrigation) may find itself also affecting consumers through the food they consume.

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groundwater. The authors suggest advances in modeling and data collection techniques (e.g., satellites) to support better management of water quality in aquifers around the world.

3.3. Impacts of external shocks (droughts, floods)

With climate change intensifying and altering the temporal and spatial distributional patterns of different water resources, it is anticipated that frequency and intensity of extreme hydrological events, such as heavy rainfall, floods, and droughts will increase. These extreme hydrological events may result in catastrophic effects on individuals (deaths) and communities (destruction of infrastructure). Economic evaluation of such effects and the possible approaches to manage natural resources under catastrophic events have been studied in [25,26] who examined the theoretical foundations for dealing with any catastrophic event, including droughts, and by in [27], who focused only on drought impacts assessment and handling.

3.3.1. Droughts

Drought differs from other disasters, and especially water-related disasters, in that it is a continuous phenomenon rather than having a short effect that strikes in a specific location (e.g., wind, flooding). Drought is a complex natural hazard since it doesn't have a universal yardstick. Drought conditions may vary, depending on the region [28]. Different definitions of drought reasoning include meteorological, hydrological, agricultural, and socioeconomic [28,29]). In addition, the different types of drought impacts are direct, indirect, and intangible. Each type (or combination of impacts) requires certain estimation methods and different policy intervention tools. Droughts not only affect the agricultural sector but also regions beyond the drought-stricken area, and sometimes the entire economy [30]. In many cases the indirect impacts of droughts could be more substantial than the direct impacts, affecting other industries and production sectors and seen along supply chains [31]. For example, drought can affect hydropower generation and, through loss of electricity supply, the production of food and other input to various production sectors of the economy, leading to a significant impact on the country's gross domestic product [32].

Several analytical frameworks have been suggested to address measuring of economic impacts of drought. Freire-González et al. [33] propose a conceptual framework based upon two sources of economic impact: "green water" and "blue water," arguing that since each source impacts the economy in different ways, they must be differentiated in any assessment of economic impact.

Additional studies refer to the impact of climate change on the severity and frequency of droughts, and the resulting economic losses. Naumann et al. [34] estimate that with no climate mitigation or adaptation, drought-related losses in the European Union and United Kingdom combined could reach more than €65 billion per year by the end of the century, compared with €9 billion per year at present. In a different focus, Gil et al. [31] measure direct and indirect effects of drought. They use a direct attribution model to measure direct effects, and a nested indirect attribution model for the indirect effects. The transmission of additional water scarcity effects from agricultural production to macroeconomic variables is measured through chained elasticities. While ample literature on drought effects on rural regions provides a good understanding of the social effects of this disaster, fewer studies have been focused on the urban sector. One example is the work in [35] who use monthly labor force data from 78 cities in Latin America to show the negative effects of droughts on the probability of urban employment and income. The authors find that the negative impact of droughts is greater than the impacts of flood events affecting these cities. Another line of works estimates the role of policy interventions to reduce the negative impact of droughts. For example, Booker et al. [36] applied a basin-level model to the upper part of the Rio Grande Basin to test whether institutional adjustments can reduce damages caused by drought. Findings suggest that future drought damages could be reduced by 20% and 33% per year through intra- and interstate water markets, respectively, that would allow water transfers across water-using regions affected differently by the drought.

3.3.2. Floods

Several studies were published recently that address the economics of flooding. Flooding is the "opposite" side of extreme effects of climate change and differs from droughts by having a more targeted and short impact duration. Allaire [37] provides a review of economics of flooding in recently published work.

Sun et al. [38] argue that in addition to the significant flood damage to an area, such as effects on the local economy, disrupted transportation, and damaged infrastructure longer-term impacts and recovery occur within that area and the interaction between neighboring areas during the recovery process. The authors estimate the short- and long-term impacts of major and minor flood events on employment and business initiations in different sectors of the economy. Their findings indicate negative short-run impact on agricultural services and particularly small establishments, and positive impacts in the service sector. Tonn and Czajkowski [39] evaluate the inland flood risk in fluvial and pluvial plains from water ponding and insufficient drainage in urban areas. While pluvial and fluvial flooding are sometimes lumped together for purposes of modeling, insurance, and risk management, the authors treat them separately due to key differences that exist in the damage associated with these types of inland flooding. Floods originated from tropical cyclones have a higher percentage of pluvial flood insurance claims and higher average pluvial damage than non-tropical cyclone floods. For example, analyses of 2017's Hurricane Harvey claims show that zip codes with higher-than-expected losses tend to have high percentages of pluvial claims. Pluvial flooding and its local nuances exhibit the potential to reduce the accuracy of catastrophe models of expected flood damage. An interesting aspect of flood damage is its indirect impact of daily activity of the affected population. Ahmed et al. [40] identify short- to long-term adverse effects of the 2010 colossal flood on educational outcomes of children and adolescents in the flooded districts of Pakistan. They use a difference-in-differences approach to estimate the impact of the flood on educational outcomes by using household surveys' dataset to compare between flooded and non-flooded households before, during, and after the flood. The educational outcomes of children and adolescents in flooded households in rural areas compared with their peers in non-flooded districts were severely affected by the flood. And finally, Allaire [41] identified effective strategies for mitigating and coping with losses from flood. She compared two intervention policies—subsidized insurance and *ex post* compensation—in a theoretical model applied to the case of flooding in Bangkok. Findings suggest that an intervention to increase uptake of subsidized flood insurance does not deliver net social benefits relative to the status quo compensation program.

3.4. Changes in use of water sources (surface water, groundwater, treated wastewater, desalinated water)

Market conditions, such as changes in relative prices of goods or inputs, and changes in consumer tastes and preferences may lead to changes in use of the type of water for certain economic activities (irrigation or residential consumption). Water resources with potential for trade off, depending on prices and qualities, include surface water, groundwater, treated wastewater, and desalinated water. Several studies dealt with single water sources use while other studies focus on the opportunities with conjunctive use of various types of water, such as surface water and groundwater, surface water and treated wastewater, and even a conjunctive use of all types of water.

Esteban [42] reviews the challenges faced by groundwater (GW), including climate change, role in supporting GW-dependent ecosystems, effectiveness of regulatory interventions, and impact on land subsidence. Indeed GW is a resource threatened by both malmanagement of aquifers and by external shocks due to climate change [43–45]. With a 'future as usual' behavior of GW management, it is most likely that many locations on earth would face extreme water scarcity [46] and damages from land subsidence caused by long-term pumping of groundwater [47].

In addition to studies that estimate status of groundwater aquifers and changes in their water stock over time, other studies focus on behavioral consequences of users, and the effectiveness of policy interventions [48,49] for the case of groundwater-dependent ecosystems.

A large body of the literature addresses groundwater management options and their advantages and disadvantages. Esteban and Dinar [50] evaluated the ability of cooperative management of an aquifer to deal with over pumping and damaging groundwater-dependent ecosystems, while Molle and Closas [51] evaluated co-management options of an aquifer. Some of the works in this group evaluated policy intervention means. Esteban and Dinar [52] modeled effects of packaging and sequencing of pricing and quota interventions on both stock of the GW and the welfare of the users. Several works referred to the role of environmental flows services from groundwater. Pereau et al. [53] compared under various conditions the outcomes of optimal control approach (environmental

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flows are introduced as an externality) with the outcome of an approach, in which environmental flows are modelled as a constraint to be satisfied. An interesting analysis of reduction of GW loss due to water uptake by an invasive tree is provided in Pongkijvorasin et al. [54], who provided decision rules to trigger the removal of the invasive tree. A recently gaining popularity is the technology of managed aquifer recharge (MAR) that allows the intended recharge of aquifers with different types of water. In developing an MAR model for a region in California, Reznik et al. [55] demonstrate that intentional recharge is of high benefit to the region, potentially increasing average groundwater levels in the region by 20% over a 20-year horizon.

As suggested and proven by Dinar and Tsur [6], different types of water and different water-using sectors should be considered jointly for handling water issues and for finding socially acceptable solutions to water issues. Following are several examples for the conjunctive use of surface water, groundwater, and treated wastewater. Economists have long advocated for integrating treated wastewater in irrigated agriculture to achieve both surface water conservation and reduce environmental pollution from disposal of residential sewage to the environment. Reznik et al. [56] develop a regional multi-sectoral model of water quantity–quality interaction among the urban, agricultural, and environmental sectors. Highlighting the feasibility of reuse, they formally construct sufficient conditions that support the superiority of infrastructure development and conveyance of treated wastewater for irrigation, when measured against other common disposal alternatives. In a more empirically related work, Reznik and Dinar [57] apply the framework in [56] to a particular region in California accounting for uncertainties in the availability of natural water resources and regulatory constraints concerning wastewater discharge. While they find reuse for avocado crop irrigation unwarranted, still utilizing that practice to support the agricultural economy in the region is economically inexpensive and could be feasible under a set of circumstances that are most likely noticeable in the region. Wastewater treatment cannot be addressed without introducing considerations of climate change. Climate change does affect cost of wastewater treatment and its inclusion in future investment plans for wastewater treatment. Reznik et al. [58] find evidence of climate change impact on treatment costs, using a unique dataset from China. The analysis also simulates potential impact of future policy and climate scenarios on costs of treatment.

A resource that increases in importance in certain locations around the world is desalinated sea (or brackish) water. Not too many studies exist on the economics of desalination and the use of desalinated water for irrigation. Economic considerations are essential for dealing with desalinated water for any use (either for residential or for irrigated agriculture). Younos [59] provides an overview of factors that determine desalination cost, typical desalination cost estimation models, various cost factors, and approximate costs based on a review of case studies and available literature at that time. More location-relevant work is also reviewed. The desert countries in the Arab region, such as Saudi Arabia, initiated irrigation of crops with desalinated water. This has been seen at the early stages as an infeasible practice, but as water became scarcer, more and more of such practices are seen in the region. Sewilam and Nasr [60] describe the process of expanding desalinated water use for irrigated agriculture and the economics of such a practice in the Arab world. Kaner et al. [61] develop and apply a biological-physical model for crop response to salinity coupled with economic calculations of farm-based costs and benefits to determine the impact on yield from irrigating with desalinated water in Israel. The value of yield is then compared with the economic feasibility of investment in farm- or regional-scale desalination plants to supply high-quality water as an alternative to irrigation with brackish water that is available in the region. The results suggest that the predicted profit from production of high-value, salinity-sensitive crops irrigated with either pure desalinated or blended desalinated and locally available brackish water justifies the desalination cost for agriculture at present market prices.

Technology adoption and use in water-consuming economic activities has long been the center of addressing water scarcity and quality challenges. The next section focuses on economics of technology use to conserve water and sustain economic productivity.

4. Role of technological advancement in addressing water resource management challenges

Technological advancement is one of the strategies to cope with water quantity and quality challenges. Governments and the private sector invest in technology development and in their wide adoption by water users in the various sectors. The next three sections will address technical and

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economic feasibility of water-saving and pollution-reduction technologies, and new studies on adoption of such technologies by water consumers in the agricultural and residential sector.

4.1. Feasibility of water-saving technologies and pricing

Studies on the feasibility of water-saving technologies are an important first step in the economic assessment of the possibility of new technologies and/or management practices to produce economically credible flows of benefits from water savings, while keeping production (in agriculture) or satisfaction from water usage (in residential uses) at a level that will lead to a positive benefit/cost ratio. Inman and Jeffrey [62] conducted a review of residential demand-side management (DSM) tools aimed to save water in various types of household under varying conditions. Tools include financial approaches (metering, pricing), technological tools (indoor, outdoor), educational approaches, operations and maintenance tools, and regulations. The paper also compares implementation costs and effectiveness of the demand-side management tools and approaches.

Several representative studies include review of the literature and several case studies, all providing methodological framework and evidence for the relevance of the approaches used. Perry and Steduto [63] found that very few examples exist of carefully documented water-saving impacts of hi-tech irrigation. Their conclusion is that introducing hi-tech irrigation in the absence of controls on water allocations will usually lead to increases in water consumption per unit area, increase in the irrigated area, and increase in the amount of water extracted and applied. Pérez-Blanco et al. [64] reach a similar conclusion, specifically that water conservation technologies should not be viewed as a tool for achieving water conservation, but rather as a means for stabilizing and increasing agricultural water productivity and farmers' income in regions facing water scarcity. Ward and Pulido-Velazquez [65] demonstrate by using an integrated basin-scale analysis linking biophysical, hydrologic, agronomic, economic, policy, and institutional dimensions of the Upper Rio Grande Basin that adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge, hence increasing water scarcity. Similar finding, namely that higher efficiency rarely reduces water consumption are reached by Grafton et al. [66], who show that to mitigate global water scarcity, increases in irrigation efficiency must be accompanied by comprehensive water accounting and measurements, a cap on extractions, an assessment of uncertainties, valuation of trade-offs, and a better understanding of the incentives and behavior of irrigators. These findings are similar to those reached by Dinar and Zilberman [67] when evaluating economic consequences of resource-conserving, pollution-reducing technologies. By coining the concept "expansion effect" they introduced consideration beyond the field level and the interaction between water scarcity and water quality. Depending on the relative limiting factor (quantity-quality), they argue that modern (resource-conserving) technologies may provide incentives to conserve resources if combined with appropriate policies of input and output prices and regulations on pollution [67:pp346].

Several studies introduce benefit/cost analysis as to the financial/economic feasibility of water conservation irrigation systems under local conditions. Siderius et al. [68] develop a modified traditional cost curve approach with an improved estimation of demand and increasing marginal cost per water conservation while also correcting for impacts on downstream water availability. The framework is applied to three major water-stressed river basins—Indus, Ganges, and Brahmaputra. Results suggest that at basin the equilibrium price for water is too low to make the majority of water conservation measures cost effective. Vatta et al. [69] look at a monitoring device to assess the impact of tensiometer technology on the consumption of groundwater and electric power in paddy cultivation in Indian Punjab, and its subsequent economic benefits. Findings suggest that compared to the continuous flooding and furrow irrigation methods at present, the tensiometer-based application of irrigation water reduces water and power consumption without any yield reduction.

Table 1. Studies on water conservation and their findings.

Published article	Finding
[67]	Resource-conserving technologies may provide incentives to conserve resources if combined with appropriate policies of input and output prices and regulations on pollution.

[62]	Relative effectiveness of different DSM water saving tools in the residential sector.
[65]	Adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge, hence increasing water scarcity.
[63]	Introducing hi-tech irrigation in the absence of regulation on water allocations will usually lead to increases in water consumption per unit area, increase in the irrigated area, and increase in the amount of water extracted and applied.
[66]	Increases in irrigation efficiency must be accompanied by a whole arsenal of regulations such as water measurements, a cap on extractions, an assessment of uncertainties, valuation of trade-offs.
[69]	Compared to the continuous flooding and furrow irrigation methods at present, the tensiometer-based application of irrigation water reduces water and power consumption without any yield reduction for rice irrigation.
[64]	Water conservation technologies should not be viewed as a tool for achieving water conservation, but rather as a means for stabilizing and increasing agricultural water productivity.
[68]	At basin the equilibrium price for water is too low to make the majority of water conservation measures cost effective.

Another strand of the literature, mentioned here very briefly, has focused on the effectiveness of different tariff design to achieve water conservation and the tradeoffs between equity, economic efficiency, and cost recovery [70]. Using a hypothetical community served by a water utility, the authors analyze how moving from a uniform volumetric tariff to increasing block tariff (IBT) affects households' water use and water bills, and how such changes affect measures of equity and economic efficiency. Investigation of behavioral aspects of responses to water tariffs in a survey of the implementation [71] provides international evidence on using IBTs to conserve water, which is mixed. This highlights the operational challenges of implementing effective IBTs.

4.2. Feasibility of water pollution reduction technologies

Pollution reduction technologies could include residential wastewater treatment or irrigation-related chemical return flows pollution reduction technologies. Goffi et al. [72] compare the economic feasibility of 37 wastewater treatment technologies, considering cost-related indicators for selecting the "ideal" technology by fitting it to specific features in cities. Using the criteria of net present value and annualized net present value, they prioritize the evaluated systems. In the agricultural sector, leaching from fields of irrigated agricultural sector is often the largest source for aquifer recharge in semi-arid groundwater basins, but contamination from fertilizers and other agro-chemicals may degrade the quality of groundwater. Mayzelle et al. [73] compared the viability of two low-impact crops—alfalfa and vineyards—and new recharge basins as an alternative land use in recharge buffer zones around communities facing contaminated groundwater in the southern Central Valley of California. Buffer zones would maintain the economic integrity of the region and concur with prevailing regulations.

4.3. Adoption of new technologies (residential, agricultural)

Technological and economic feasibility of new technologies do not guarantee their implementation by water users. The following studies report the determinants of adoption of technologies that save water both in irrigated agriculture and by households, and adoption of technologies that reduce pollution.

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A study by Schaible and Aillery [74] in the United States finds that despite technological innovations, at least half of U.S. irrigated cropland acreage is still irrigated with less-efficient, traditional irrigation application systems. Studies on adoption of irrigation technologies, such as the ones cited below may explain why. de Witt et al. [75] investigated personal barriers of farmers to a water-scheduling technology that was developed and provided free of charge by the government. The non-use of the free service is explained mainly by the time and cost associated with the technology's initial set-up, use, and interpretation of information by the individual farmers. Gui and Gou [76] explain regional differences in adoption of technologies to capture alternative water sources for different domestic uses. One of the important findings is that adoption of water technologies in rural and metropolitan areas differ and, thus, both technologies and distributional policies should be different. Given the high share of domestic water consumption for irrigated landscape (in Florida and California), [77] studied urban landscape water conservation innovation adoption in Florida to find major differences in speed of adoption among households in different societies. Results suggest opposite processes of diffusion of water-saving technologies by societies, which leads to a need for different dissemination strategies.

A different approach to measuring adoption of water-saving technologies has considered a process of adopting not one technology, but rather a bundle of technologies that benefit each other. For example, using drip irrigation could be made much more effective if a fertilization technology takes advantage of the precise water allocation via the drip system. In a study focused on avocado growers in California, [78] showed how a variety of irrigation technologies bundled with water management practices help growers through times of limited water supplies and elevated salinity levels. And yet another example of budling irrigation water sources was demonstrated in [79] that evaluates the benefits to irrigated agriculture in California from having access to multiple sources of water, each characterized by quantity, security (water right), and quality (salinity content). As in other bundled technology adoption, while lower-quality waters, less-reliable water, and less water all negatively impact agricultural land values, holding a water (bundle) portfolio positively impacts land values through its role in mitigating the negative aspects of these factors and reducing the sensitivity of agriculture to climate-related factors.

So far, the review referred to domestic water challenges and economics approaches to address them. The next section introduces an issue—international water—with rising importance in regional management of water resources.

5. Management of Internationally shared water

International river basins are water bodies that are shared among more than two riparian states. As of the 2018 update, 310 international river basins cover nearly 47% of the global land area [80]. With such a major mass of land, dealing with management of international water may have a wide impact globally, and is of interest to various disciplines dealing with international water, such as economics, engineering, political science, international relations, international law, and combinations of these disciplines. The literature on management of international water has seen much collaboration among scholars from these disciplines as was summarized in [81]and [82].

One of the most effective arrangements for dealing with international water is the treaty tool, which is used among riparian states to address different aspects of water management in the basin (e.g., allocation of the water, allocation of benefits and costs, regulations of pollution). The analysis of international treaties has gained momentum in the literature, allowing economists and political scientists to join forces in addressing research on the efficiency of such treaties. Recent developments in the roles of treaties for cooperative management of international water are discussed in [83]. Author says that treaties provide states with a platform for dealing with conflict at the basin level in addition to having the means to produce benefits for sustained cooperation in the basin.

Given the economic-political nature of cooperation in international river basins, joint work by economists, engineers, and political scientists is most adequate to address issues of water management on a basin scale. A sample of recent works that highlight different angles of the issues faced by riparian states follow. One of the obvious observations highlighted by many researchers is why there are so few agreements on international water. To answer such question, [84] developed an economic-political framework to explain the likelihood of treaty formation in international river basins with a different number of riparian states. They used the interaction between the transaction cost theory, and the economies and diseconomies of scale theory to explain the likelihood of expanding a coalition of collaborator states in a large basin. Some important findings suggest that transaction costs increase the likelihood of treaties with environmental regulation, and greater economies of scale lead to fewer treaties with environmental regulation. Transaction costs raise the likelihood of treaties with water allocation, but economies of scale have the opposite effect. Transaction costs tend to reduce the number of issues included in the treaty, while economies of scale tend to increase it. Higher transaction costs tend to increase the number of institutional mechanisms incorporated in a treaty, and greater economies of scale increase the number of treaty institutions for managing the basin to be shared among the riparian states.

The findings confirm the results in [85], who focused on the impact of the negotiation context on the treaty content, as was already suggested by [86], and [87], who stressed the importance of the transaction costs of negotiating and sustaining treaties, along with the need to invest in institutional design to address transaction costs.

Global analyses of treaty performance was conducted in [88] for all bilateral river basins, and in [89–91], focusing on the effectiveness of water management during climate change on cooperation. The conclusions from all these studies show that well-designed and crafted treaties can create stable arrangements under extreme climatic conditions.

Another important aspect motivating cooperation among states has been identified in [92] in the case of differences in power, attitude, and capacity of riparian states with regard to the environment and environmental pollution. Asymmetries in concern for the environment, or the ability of the parties to abate pollution, are most likely the result of economic differences, and influence the willingness to pay for pollution abatement. While such differences could result in tensions, they can incentivize the states (most likely richer and more developed states) to encourage cooperation in the basin.

A strand of research uses the concept of issue linkage to allow pulling the parties in a deadlock conflict to move to a cooperative solution. Several works [93,94] identified the theoretical advantages of issue linkage, and others demonstrated its application in the case of the conflict over the Mekong River Basin between China and the lower Mekong States—Laos, Cambodia, Viet Nam, and Thailand—[95–97].

Other works focus on the role technology plays in addressing conflict in river basins facing high water scarcity, via exchanges (linkages) between water and energy [98], and via production of new desalinated water in exchange for traditional surface water [99].

Cooperation also can be challenged by the allocation arrangements of incremental costs or benefits from cooperation to the participating parties. More on that can be found in section 4.2 (Game theory), which is part of a broader section that introduces economic tools such as experimental economics, game theory, institutional economics, valuation methods, and modeling approaches (such as hydro-economic modeling and computable general equilibrium modeling.

6. What do new economic tools and approaches have to offer?

Recent developments in software and computer capacity gave rise to use of several economic tools and approaches in analysis of integrated water resources management (IWRM), which was less apparent in previous decades. The increased use of experimental economics, game theory, institutional economics, valuation methods, and different modeling approaches, such as hydro-economic (HEM) models, and computable general equilibrium (CGE) frameworks will be reviewed next.

6.1. Experimental economics

Experimental economics is a relatively new field that has been applied in recent years to issues related to policy evaluation for water management under conditions of scarcity, deteriorated quality, and external shocks such as climate change. A recent review of the role of studies applying experimental economics to evaluate policy reforms in the water sector [100] suggests that experimental economics, either by itself or in conjunction with other approaches, can save society the grievance of high social costs of failing policy implementation. Evaluation of policy reforms using experimental means can be performed in the lab or in the field prior to the actual implementation of the policy. The challenge faced by experimental economics as identified in [100] is the need to consider how scaling up the proposed policy interventions can remain relevant and not create or exacerbate societal disparities and ethical challenges from the externality addressed. It included works on establishing water markets and conservation, water use and conservation regulation in different sectors, payment for water-related ecosystem services, and emissions trading to regulate water pollution reduction.

An earlier review of advantages and challenges in experimental economics applications to water sector issues [101] addresses the role of experiments in advancing economic understanding of water resource issues. The review included works focusing on self-regulating behaviors in common-pool resources (groundwater), the efficiency of alternative water quantity and quality markets, the comparative efficacy of alterative types of ambient pollution control instruments, and water conservation measures.

A hand-picked set of works presented in [100,101], and elsewhere are summarized in Table 2. While experimental economics is growing in coverage of water issues, the table below identifies five major issues for which experimental economics approaches are reported in this review, including water conservation, water markets, subsidy regulations, watershed management, and international water [102–113].

Table 2. Recently published works on water and experimental economics by issue.

Published article	Policy focus	Issue addressed
[102]	GW regulation	Water conservation
[103]	Residential water	
[104]	Water Conservation regulation	
[105]	Smart water Markets	Water markets
[106]	Water markets and instream values	
[107]	Water quality trading	
[108]	Agricultural subsidies to regulate water quality	
[109]	Electricity subsidies and GW level	Subsidy regulations
[110]	Electricity subsidies and GW level	
[111]	Electricity subsidies and GW level	
[112]	Collective action for watershed management	Watershed mgt.
[113]	Issue linkage	International water

Experimental economics has a significant role in the design and evaluation of policies in the water and environmental sectors, aimed at internalizing or mitigating effects of negative externalities. However, Banerjee [100] argues that experiments have to take into account that policies don't operate in a vacuum. Therefore, for an experimental design to be relevant, the context of the analysis is important. Context may include the institutional setting, the social and political settings, and the physical setting. All these considerations may have far reaching unintended consequences, even if the negative externality is internalized.

6.2. Game theory

Game theory approaches have been applied to deal with water resource management, given that water is a common pool resource subject to strategic behavior. As climate change is expected to result in water scarcity and deterioration of water quality around the world, water quantity and quality are becoming a major challenge for water managers and for nations that share limited water resources. The literature has seen an increase in published works on the use of various game theory frameworks at local regional and international setups. Publications such as [114–116] provide collections of studies that apply game theory models to various types of water issues at local, national, and international levels. A review of works that apply game theory models spanning the years 1940 through 2014 can be found in [82].

Game theory studies apply cooperative and non-cooperative frameworks and their relevance to various water management issues. Several of the studies refer to domestic conflict situations among sectors or regions [117,118], and others refer to water issues in international river basins ([119–127]). All of these works refer mainly to allocation of scarce water. Some works [124] develop basin-level hydro-economic models to calculate the benefits and costs of the various basin riparian states. Others [121] calculate the coalitional benefits and costs outside of the game theory framework and then incorporate the calculated values into the game theory allocation equations.

To be more specific about the contributions of several of the studies cited in the previous section, [117] compare the outcomes of two analytical frameworks set to optimize scarce water allocation between agricultural production and environmental consumption. The two analytical frameworks—a cooperative game theory framework and a negotiated role-playing framework—were applied to a river basin in South Africa. The authors concluded that the role-playing negotiated framework has more flexibility to incorporate real world situations, and thus, to provide more options for the stakeholders to consider in their allocation challenge.

The works by [119,120] develop a basin-level game focusing on geographies that can affect the stability of the allocations. The former work suggests measures of equity among the participants in the simplified game while the latter work is more realistic in the sense that it reflects conditions in the Amu-Darya river basin and actual agreed allocations among the several riparian states under scenarios of high water scarcity that this basin faces.

Pham Do [128] identifies challenges facing game theory, as well as opportunities that game theory can address, to help water managers achieve sustainability, equity, and optimal conditions. An interesting part of the paper deals with distinguishing between cooperative and noncooperative game models and static, versus dynamic game models. I will refer only to the latter classification.

Both cooperative and noncooperative games can be classified as *static* or *dynamic*. They differ in the timing decisions that are made by the players. Participants in static games consider the immediate action of the opponent player, while players in dynamic games consider the responses by the opponent players following their own decision. In static games, all players choose their strategy at the same time. The static approach has been developed and applied to decision-making in WRM, particularly groundwater resource management [129–131]. Players in dynamic games can move with their strategy sequentially or repeatedly. Dynamic game models have been developed as both discrete and continuous. The dynamic approach (both theoretical and empirical analysis) has been recently applied to multipurpose water projects [132,133], and analysis of spatial groundwater management and policies [134].

In recent years we observe a surge in works applying game theory to situations with the impact of climate change on water resources [135]. The authors of this publication demonstrate the use of a bargaining game and the Nash bargaining solution with two methods: a symmetric, and an analytic hierarchy process (AHP) method in allocating water of higher level of scarcity to users. The AHP method provided better outcomes for players than the symmetric method. The results suggest that in the use of a cooperative bargaining game, water allocation can be achieved in a more efficient way.

In a different study focused on the Colorado river basin [136] the authors apply a bankruptcy game framework to allocating climate-induced, over-committed water rights agreements to competing stakeholders of different sectors in the Salton Sea region. They used two models for allocation: one involving a social planner approach that maximizes regional welfare, and the second focusing on the bankruptcy rules of proportional deficit (cutback) and constrained equal award. The findings suggest the proportional cutback framework to be less conducive to regional welfare, although it presents a more politically feasible and robust option.

Game theory modeling has demonstrated an ability to address cooperative and noncooperative aspects of water resource management situations. However, the ability of game theory to provide "operational" suggestions to water managers has been limited by the intensive computational needs of the algorithms developed. An example of such computational intensity needed for making the game theory results useful for managers can be found in [137]. The authors refer to a heterogeneous project both in terms of the landscape of the area under development and the participants (users), both of which lead to a more complicated set of cost allocation mechanisms than in homogeneous projects. The analysis presented in their paper uses cooperative game theory to develop schemes for sharing costs and revenues from a project involving various beneficiaries in an equitable and fair way. The proposed approach is applied to the West Delta Irrigation Project in Egypt. It utilizes a differential two-part tariff that reproduces the allocation of total project costs using the Shapley Value. The proposed differential tariff, applied to each land section in the project reflecting their landscape-

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related costs, would be preferred by the users in the different land blocks of the project. It contrasts the unified tariff that was proposed, using the traditional methods in the project planning documents.

6.3. Institutional economics

The analysis of water institutions has been on the rise in recent years. Failing or malfunctioning water sectors have been challenged with a need to improve their institutional performance. Most of the published work is descriptive, attempting to explain why some institutional arrangements have worked in some places but failed in others. For example, [138] examines searching for panaceas in irrigated agriculture, such as coordinating institutions, and looking at policies promoting government agencies, user organizations, and water markets. Questions such as how to measure institutional success have been rarely answered. Most water institutional analyses have been conducted using the case study approach, so extrapolation from one location with certain conditions to another location with different conditions was impossible.

Decentralization is one of the institutional reform interventions attempted in recent years in many water systems, such as river basins. The literature has mainly described the process rather than explained its determinants. A quantification of a global institutional reform focusing on the process and performance of decentralization in river basins in 83 and 27 river basins around the world was performed in [139] and [140], respectively. The studies estimated the contribution of local conditions and supporting policies to the effectiveness and speed of the reform and identified the level of success as a function of conditions in each of the basins.

In two separate studies, [141] and [142], the authots apply quantitative models to decompose water institutions in 43 and 17 countries around the world, respectively, for a comparative analysis of performance of their water institutions. And [143] developed diagnostic models applied to 87 poor countries to find that water-related public services contribute to per capita GDP and to improved public health outcomes across these developing countries. The relationship between the wellness of the water institutions and the performance of the economy were also shown in [144]. Maria-Saleth and Dinar A. [145] applied the analytical framework they developed in [141] to quantitatively show the structural and functional linkages within institutional structure, and to indicate their performance implications and strategic importance for promoting institutional reforms. Bandaragoda [146] builds on the suggested framework in [141], (which was published in a couple of World Bank working papers and technical papers [147,148], and develops a qualitative framework for institutional analysis of water resources management in the context of a river basin.

To promote the important analysis of water institutions, Berbel et al.[149] dedicate a special issue in which they demonstrate the role of institutions during scarcity and drought situations. In a similar vein, authors in [150] quantify the significant factors of water institutions and their effect on the different aspects of water sector performance under scarcity and water quality challenges in India.

6.4. Valuation methods

Recent years have brought a significant increase in publications that focus on environmental valuation [151]. Some argue that this is the result of global change, affecting vulnerable water resources, but also increasing their attributes that can benefit different segments of society. Globalization has made it easier to move along the attribute spectrum due to advances in availability of technologies that can help alter water quality and make it usable for different purposes. Another reason for the increased importance of valuation methods is the objective of increased water efficiency by maximizing the value of the resource as water becomes scarcer. Environmental valuation has an important role in informing the development of standards for water used for different purposes, such as drinking, irrigation, and water-dependent ecosystems. In addition, environmental valuation can inform optimal investment in water treatment, such as the net benefits of desalination, treatment of recycled water, and managed aquifer recharge, to name a few.

For obtaining values associated with global changes to water demand, water supply and water quality, valuation methods need to rely also on non-market values. As such, valuation requires the use of either indirect valuation approaches (e.g., travel cost, hedonic pricing, defensive expenditures), or direct survey techniques (contingent valuation, choice experiments) [152,153].

The use of valuation methods has seen a strong boost with the unfortunate well-known Exxon Valdez oil spill on the shores of Alaska on March 24, 1989, causing some 11 million gallons of crude

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oil to spill into the water [154]. Since then, valuation methods have been used to assess damages of other oil spills [155,156], as well as assessment of values of the environment resulting from development projects, such as [157], who conducted an ex ante benefit–cost assessment and forecast market-clearing prices and quantities for ecological infrastructure investment contracts in the Panama Canal Watershed. And [158] ,who assessed the extent of altruism vs. self interest in the valuation of community drinking water quality improvements investments in Canada. Another example is [159], who compared the contingent valuation and choice experiment methods in developing solid waste management programs in Macao.

Johnston et al. [160] propose contemporary best-practice approaches for stated preference (SP) studies. These recommendations consider the use of SP methods to estimate both use and non-use (passive-use) values, and cover the broad SP domain, including contingent valuation and discrete choice experiments. The paper focuses on applications to public goods in the context of the environment and human health.

Valuation methods are not innocent of problems and caveats. Some of the issues raised regarding their reliability and validity can be found in [161], who consider contingent valuation and travel cost approaches in their analysis. In a different study, authors [162] review previous literature and empirically show that presentation of the topic may matter in the case of contingent valuation and choice experiments, as broad descriptive terms may mask the many design and methodological differences seen in implementations of the approaches.

Valuation methods, such as the travel cost method and the choice experiment method, were also used in the case of cultural heritage [163], natural attractions [164], climate change hazards to coastal regions [165], and evaluation of services from the Rasmar-protected Cheimaditida wetland in Greece [166].

And finally, a review of water valuation metrics for the manufacturing sector is presented in [167]. The authors define the full value of water as price+true cost+other internal costs+indirect/opportunity costs, and compare results across 20 industries and 8 countries between 2005 and 2020. The authors show, using many international cases, that by extending the concept of water value to include various relevant cost and value components, such fuller water valuations the development and deployment of cost-effective water-conservation technologies more economical, thus, improving the sustainability of the manufacturing sector with respect to water.

6.5. Modeling approaches

6.5.1. Hydro-economic modeling

Hydroeconomic models (HEMs) help in analyzing water management problems by integrating models that explicitly represent interactions between the hydrology aspects of the water body analyzed and the economic, infrastructure, legal, and institutional aspects of the region under consideration. The combination of these aspects of management provides better-informed results for decision-making in the complex environment in which water management operates. HEMs allow both water supply and demands to be economically and hydrologically defined and described in [168]. Over the years, HEMs have been developed to address several important issues, such as adaptation to climate change, environmental flows, conflicts among domestic sectors, and international water, to name a few.

Several publications provide reviews of the body of literature on HEMs. Such publications include [169], which reviews 80 HEMs applied to water analysis in 23 countries. The paper identifies the key stages in model design, formulations, levels of integration, spatial and temporal scales, and solution techniques. Bekchanov et al. [170] classify reviewed HEMs into network-based (simulation or optimization) models and economywide (input-output or computable general equilibrium) models. The paper highlights the primary differences in the applications and interpretations obtained using these approaches. The paper suggests that additional efforts are needed to account for the range and complexity of linking water systems and society more realistically, particularly regarding ecology and water quality, and the food and energy sectors. A review integrated hydro-economic models that aim to capture the complexity of interactions between water and the economy can be found in [171]. The paper identifies issues and future research directions in integrated hydro-economic modelling, which are demonstrated using a variety of case study applications worldwide.

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A different angle is presented at a review in [172], comparing the relevance of HEM approaches for large-scale decision-making in multi-sectoral and multi-regional river basins.

Daclin and Fernandes [173] propose modeling approach that identifies how to apply water management instruments integrated with each other to deliver a water allocation strategy reconciled with economic development projections and changing water use preferences.

A couple of publications demonstrate the use of HEMs to address transboundary river water sharing disputes [174,175] by introducing benefit-sharing arrangements to the analysis and developing a continental-level HEM [176].

Another aspect of water management addressed by HEMs is the handling of water pollution either by urban centers [177], or by the agricultural sector [178,179].

Environmental flows and impacts of water scarcity on ecosystems are a recent focus of HEMs. Several papers demonstrate this relatively new trend. Crespo et al. [180,181] develop an HEM to assess the value of environmental flow in the Ebro Basin in Spain. Levers et al. [182] develop an HEM to assess the effects of buying water for the environment in the Salton Sea in California. And Momblanch et al. [183] develop and apply an HEM that allows the use of ecosystem services to represent the environment.

Groundwater management is well addressed by HEMs, showing an ability to account for the open access of groundwater and their significant negative externalities [184,185]. The interactive relation between groundwater and a river are modeled by [186] in an HEM aimed at guiding sustainable basin management.

Sectoral integration is also one of the special features found in HEMs. Authors [187] evaluate integration policies to allocate water between agriculture and the urban sector.

Several papers demonstrate the use of HEMs for assessment of possible adaptation strategies to climate change. Esteve et al. [188] assess climate change impacts and adaptation in irrigated agriculture. Expósito et al. [189] review applications of HEMs to assess effectiveness of water policies under climate change at basin scale, and Kahil et al. [190] model with HEM the impact of water scarcity and droughts for policy adaptation to climate change.

6.5.2. Computable general equilibrium (CGE)

Because of their central role in both developing and developed economies, water resources are the focus of many intervention policies. Since agriculture consumes the lion's share (70–90%) of annual renewable fresh water on earth, it is a sufficient reason for policymakers to focus their efforts on improved performance of scarce water use in irrigated agriculture. Policies targeted at multiple objectives, including income transfer, food production security, environmental sustainability, and resource conservation may lead at times to pervasive outcomes at various interacting sectors. This system of cause and effect holds also for the urban water sector, as well as for the industrial and environmental sectors. Therefore, water as a policy target has to be regulated at the economy-wide level when being allocated among competing uses.

In recent years, we have witnessed increased globalization and climate change considerations, both of which strongly suggest that water policy is no longer a sectoral, or regional, but an economy-wide matter. Recognizing this trend gave rise to studies of an economy-wide nature. While many economy-wide analyses (mainly computable general equilibrium—CGE—models) have been published in the economic literature on water, little can be generalized, mainly because these studies use different assumptions and structures of the economy. For example, many CGE studies on water that have been reported in the literature treat irrigated agriculture as one sector or activity. Such structures are only appropriate in economies in which physical (soil quality, water availability, etc.), economic and social conditions (crop mixes, proximity to markets, farm size, water delivery costs, etc.) are identical or similar across regions. However, existing spatial variation within economies makes that assumption of little use for simulation of real-world policy interventions [191].

Two extensive review papers on CGE and water have been published recently. They provide insight into methodological issues associated with the modeling approaches. The first paper [192] focuses on the implications of using different assumptions regarding water as an implicit or explicit factor of production. They further distinguish within models in which water is assumed an explicit factor of production between assumptions of a high degree of substitution between water and other primary factors, as opposed to low degree of substitution. The paper also differentiates between

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regional and global models, including international trade. The review identifies several gaps that need to be considered in the future, such as inclusion of non-consumptive uses, and heterogeneity among the water-using agents or regions. The second review [193] focuses on how the water-energy-food nexus (WEFN) is dealt with in CGE models, discussing their design, importance, and possible ways of improvement. A growing literature is seen lately with focus on WEFN and understanding the modeling structure would be critical for evaluating their results. The paper argues that most CGEs in the literature face difficulties representing the competing water uses across sectors, especially in the energy sector. Thus, addressing the issue of precise distinction across competing water use sectors as a necessary objective in future research.

While policy interventions at the regional (micro) levels could lead to desirable results, local considerations also may lead to a sub-optimal outcome, from a social point of view. This point is demonstrated in recent findings from works on economy-wide considerations and linkages in Morocco, South Africa, Turkey, and Mexico [194–198], respectively, which were summarized and synthesized in [191]. It was found that reforms in sectors other than agriculture have major impacts on rural households' income, and that water reforms that are designed without taking into account reforms outside the major consumer of available water—irrigated agriculture—may lower overall productivity of irrigation water and impede a negative impact on the other sectors competing for the limited resource.

Additional interesting and useful CGE works include studies examining investments in the water sector to address possible investments in reservoirs or water transfers, aimed to relieve regional water scarcity [199], and national investment in extending the water portfolio by considering wastewater treatment facilities and desalination plants [200]. Several studies introduced consideration of new irrigation technologies and irrigation management practices, and their likely effect on the water-using sectors [201,202]). A large body of work focusing on international trade impacts on water-sector performance is the reflection of globalization impacts on national economies [203,204].It should be mentioned that the analysis by [202,204] is at the global level, rather than at regional or a country levels.

Another brand of studies introduces the use of CGE models for national or sectoral planning by government agencies (Australia [205]; New Zealand: [206]). And finally, one study of many that demonstrated the usefulness of the CGE framework in analyzing economy-wide and sectoral impacts of climate change is [207], which was able to break down economic consequences of climate change by sector and region.

And finally, [208] provides an extensive review of challenges when incorporating water into a CGE model operating at global scale. Challenges are due to absence of standardized data, the sheer overlap caused by intersecting river basins with countries (in the case of international water), and difficulties to model demand for and supply of water of different jurisdictions. Simplifications to the modeling has been introduced to face such challenges. The paper refers to the three most used simplifications in the literature: (a) tackling global questions in a national level model; (b) collapsing irrigated and rainfed crop production into a single sector; and (c) removing river basin boundaries within a country. The paper compares the impact of such simplifications on the ability to predict impacts of future irrigation water scarcity on land use, crop output, international trade, and regional welfare, relative to the full-scale model. Findings suggest that it may be sufficient to ignore the sub-national hydrological boundaries in global economic CGE analysis.

7. Linking all the above into one framework

Water suppliers and the water-using sectors face major challenges due to external (climate change, globalization) and internal (population growth, failing institutions) interruptions in water availability and quality. This review has identified several ways in which scholars in the field handled such challenges at local, regional and, sometimes, global levels.

One of the lessons from reading the literature calls for work that integrates the entire set of water types—surface water, groundwater, wastewater, and desalinated water. Some of the works cited demonstrate the conjunctive use of some of these water types, but not all of them. Having models with use, investment, and tradeoff among those types of water demonstrates the usefulness of such integration, especially when the water supply sources are sensitive to climate change [6]. An important consideration is the role of technological innovations in securing/conserving water

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resources and regulating its quality. Many studies investigated the feasibility (physical and economic) of water quality-enhancing and quantity-conserving technologies. But such studies are incomplete in that they cannot guarantee the adoption and use of such technologies so that the water sector can benefit from their performance.

A recent surge in scientific work identified international water as a critical issue in sustainability of water in internationally shared river basins. Given that more than two thirds of the world land area contains international river basins [80], sharing water in a sustainable way becomes critical in many parts of the world. As a common pool and strategic resource at the local and international levels the use of allocation methods that account for behavioral and experimental economics and game theory to deal with strategic issues, are quite important and needed.

It is quite intriguing to think about the possibility of having interactions between the results obtained by tools, such as experimental economics, game theory, valuation, and institutional innovation and modeling frameworks that can demonstrate their use in a basin, a region, and globally. Water resources are of different natures, being valued differently by different users, and being considered by different users a strategic resource to different extents. Therefore, a framework that includes various analytical approaches would contribute more than a single approach to addressing challenges faced by water users.

8. Unaddressed issues and agenda for future research

It is only natural that this review cannot address the entire spectrum of new water issues and how economic and modeling approaches may help. An attempt to cover all water issues and all possible approaches may not be achieved. The listed issues and the discussion below are a good assessment of what is still left to be addressed.

In terms of the types of water and water uses, this review does not cover the area of treated wastewater and desalinated water, although they were included in reviews of works that deal with multi-sectoral and intertemporal considerations. These two sources of water were almost taboo in the early 2000s, but as natural water (precipitation) becomes more unreliable and scarcer, the value of conjunctive usage of surface water, groundwater, treated wastewater, and desalinated water increases dramatically. A recent example is the diversion of the Israeli National Carrier Project from using only snowmelt water, originally stored in the Sea of Galilee and conveyed to Southern Israel, to become the destination of desalinated sea water from seawater treatment facilities along the Mediterranean. This revolutionary concept will allow the water system in Israel not only to sustain the economic activity of the state of Israel, but also to support thirsty Jordan with additional drinking and irrigation water in a long-term agreement (https://www.timesofisrael.com/israel-to-be-1st-in-world-to-pipe-desalinated-water-into-a-natural-lake-the-galilee/).

This brings us to another aspect—use of technology to increase regional cooperation in water-scarce regions. The situation described in the previous paragraph—involving a technology in sustainability of water resources, and increasing economics and political stability of a water-scarce region—is only one example of the possible use of a technology to enhance cooperation in managing joint water resources. Another technique is cloud seeding, which can be relevant to many international river basins. By setting rules for allocation of the cost of cloud seeding among the riparian states, including compensation for cost of cloud seeding if rain falls in the parts of the basin belonging to a riparian state that did not invest in the seeding.

Moving along the untouched issues brings us to a very acute policy question of dam removal. Recent work on the economics of dam removal has brought to light many controversial opinions that are seen in publications such as [209], in which cited works identified severe flaws in the consideration of the benefits of dam removals and fish passage.

A different perspective on dams is seen in [210], where the state of knowledge about dam values and impacts is reviewed. The paper argues that evidence suggests that investment in additional surface water storage may not always be the best solution for addressing water scarcity. The author suggests that perhaps due to existing heterogeneity in the sector that affects the performance of dams, policymakers do not appear to make much use of economic tools for decision-making of dam operations. This calls for advancing economic analysis of dam evaluation to avoid costly mistakes related to construction and removal of such infrastructures in the future.

And finally, many works deal with groundwater, and even a conjunctive management of groundwater and surface water. Relatively few studies exist that evaluate groundwater policies to prevent negative externalities from groundwater extraction over time. Several directions have been proposed in previous sections of this review. However, given the relatively few works involving economic considerations of GW-led land subsidence [47,211], more needs to be done on the economics of GW-led land subsidence. GW-led water quality crises are occurring in several parts of the world [212,213] and need to be reflected in more economic analyses. Another groundwater-related important direction of work is the regional analysis of managed aquifer recharge (MAR) and how MAR can ease long-term regional water scarcity. Research on MAR combines all components that have been recommended in this review—inclusion of different types of water and allowing regional cooperation and multisector considerations.

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