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ABSTRACT

This chapter will provide an overview of the contemporary groundwater literature and will show what is currently being done to achieve sustainable groundwater management. First, models for groundwater management will be presented focusing on resource modelling under uncertainty, in particular uncertainty surrounding the effect of climate change on groundwater resources and trans-boundary frameworks. Then, the ecosystem services approach and the concept of the TEV of water will be presented in more detail. Furthermore, we will show where and how these new concepts are integrated in policy frameworks and will present applied examples of sustainable water governance. Last but not least, we will venture out to the future of sustainable groundwater management and have a look at upcoming challenges, opportunities, and cutting-edge research.

8.1 AN INTRODUCTION

Groundwater quantity and quality are exposed to a multitude stressors (Navarro-Ortega *et al.*, 2015). Due to heavy usage as potable water and input in economic sectors – households, industry, tourism, and agriculture – groundwater has been over-exploited, polluted, and degraded. Since groundwater is a pivotal input for all the above mentioned, there have been calls to manage it more efficiently. Gisser and Sánchez (1980) question, however, whether managing groundwater resources will increase social welfare. They show that there is no quantitative difference between temporal optimal control of groundwater and competitive, myopic usage. This apparent paradox, the so-called *Gisser-Sánchez-Effect*, vanishes, however, if one considers water quality issues and their externalities (Kundzewicz & Döll, 2009), allows non-linearity in water demand and supply in the model (Koundouri, 2004b), and considers uncertainties surrounding future availability (Maqsood, Huang, & Yeomans, 2005), due to climate change (Taylor *et al.*, 2013), shortcomings in data on interaction between surface and groundwater, the hydrological cycle (Li, Huang, & Nie, 2006), and unknown recharge rates of aquifers (Brouyere, Carabin, & Dassargues, 2004). Once one adds trans-boundary aquifers to the model, groundwater management issue are exacerbated due to institutional and legal concerns (Koundouri & Groom, 2002). All these issues should be considered when trying to determine the value of groundwater.

The ecosystem services approach (ESA) tries to provide a holistic methodology that identifies benefits and costs ecosystems create, illustrates problems concerning services and trade-offs between them, and finally assigns a monetary value to them which adds up to the total economic value (TEV) of water (Benayas, Newton, Diaz, & Bullock, 2009; Koundouri *et al.*, 2015). An ESA has already been included in policy frameworks such as the European Water Framework Directive (European Commission, 2000; P. 12) or the Marine Strategy Framework Directive (Koundouri & Dávila, 2015). The goal being to design and assess measures, *i.e.* economic instruments providing incentives (*i.e.* taxes, permits, subsidies, pollution fees etc.), to recover the full cost of groundwater services and to choose the most economically efficient one of them by applying a cost-benefit analysis (Birol, Koundouri, & Kountouris, 2010). Since groundwater may exhibit non-market characteristics, it is crucial to consider all different aspects that contribute to water value – its use value, such as irrigation, and its non-use value, such as a subjective value a person may attribute to improvements in, *e.g.* a wildlife habitat (Bateman, Brouwer, *et al.*, 2006). However, due to unobservable or unavailable prices for water, in general other means have to be found to assign a monetary value to groundwater services. Energy, water, or fuel subsidies to the agricultural sector to spur rural development promote groundwater usage further and complicate this estimation (Shah, 2007). Apart from leading to groundwater overexploitation, those subsidies, taxes, and other policy instruments exacerbate the non-market characteristics of groundwater by distorting its price (Groom, Koundouri, & Swanson, 2005; Koundouri *et al.*, 2015). Consequently, in the past years a range of non-market valuation methods have been used to estimate the TEV of groundwater resources (Birol, Koundouri, & Kountouris, 2006; Brouwer, 2008). The results are supposed to help policy makers in deciding on how to allocate water in the future and to design economic incentives to induce more efficient use (Koundouri & Dávila, 2015), in order to ensure sustainable resource management (Kløve *et al.*, 2011).

8.2 GROUNDWATER MANAGEMENT MODELING

Integrated hydro-economic models are formal mathematical models which aim to quantify the complex structure of groundwater management along the lines of the fundamental economic principles of demand and supply. In these models, optimal groundwater management is treated as an optimization problem of an objective function which considers TEV, subject to specific constraints rising from predetermined control criteria on the groundwater resource evolution. A critical literature overview of the available economic models of groundwater use and their potential benefits from optimal groundwater management was provided by Koundouri (2004a). This study analyzed the Gisser-Sanchez model which is the basic representation of economic, hydrologic and agronomic facts that occur due to the irrigator's choice of water pumping. The environmental constraint of the problem derives from the change in the height of the water table which is given by the following differential equation

$$\dot{H} = \frac{1}{AS}[R + (a - 1)w], \quad H(0) = H_0, \tag{8.1}$$

where R is the constant recharge measured in acre feet per year, α is the constant return flow coefficient which is a pure number, H_0 is the initial level of the water table measured in feet above sea level, A is the surface area of the aquifer (uniform at all depths) measured in acres per year, S is the specific yield of the aquifer which is a pure number and w is the water extraction measured in acre-feet per unit of time. In order to model the case of a non-constant river recharge due to stochastic rainfall or a possible exogenous and reversible shock to the groundwater resource, one could consider that R is a random variable (cf. Laukkanen & Koundouri, 2006 and De Frutos Cachorro *et al.*, 2014) or a stochastic process (cf. Zeitouni, 2004). Hence, in this section, we shall present recent advances in such hydro-economic according to different aspects of groundwater management, such as coastal aquifer water management, conjunctive use of surface and subsurface water resources, and game theoretical approaches, including stochastic frameworks imposed by climate change conditions, both in a boundary and a transboundary scale.

In the literature (Tsur & Zemel, 2014) the first type of *uncertainty* that enters into the resource management problems corresponds to the limited knowledge of certain parameters of the resource (for instance abrupt system behavior when the stock process crosses some unknown threshold) and the second one is the exogenous uncertainty that takes into account random environmental elements (for example weather variability). According to these types of uncertainty, many studies dealt with the relationship between precautionary behavior and an increase in uncertainty (see Brozovic & Schlenker, 2011 and Zemel, 2012). Assuming a stochastic recharge rate, Zeitouni (2004) argued that it is optimal to keep the water stock at a certain positive threshold in the case of a limited aquifer capacity. Considering a known decrease in the recharge rate as an exogenous shock, De Frutos Cachorro *et al.* (2014) showed that the optimal adapted extraction of a groundwater aquifer decreases in the short–run for a deterministic occurrence date of the shock and vice versa for a stochastic one.

Groundwater management in coastal regions has been widely studied due to the rapid demand for fresh water and the groundwater quality deterioration from *seawater intrusion*. Karterakis *et al.* (2007) compared the classical linear programming (LP) optimization algorithm of the SM and the Differential Evolution (DE) algorithm, used to compute the optimal hydraulic control of the saltwater intrusion in an unconfined coastal karstic aquifer, concerning the computation time and the values of the water volume flow rates. Katsifarakis & Petala (2006) and Kentel & Aral (2007) studied simulation-optimization coastal aquifer problems subject to a penalty term regulated by the seawater intrusion due to the applied pumping scheme and by the limited groundwater resources in the region, respectively. In order to reduce computation burden and capture the uncertainty in the physical system, Sreekanth & Datta (2014) substituted the numerical simulation model with a genetic programming (GP) stochastic surrogate model to characterize coastal aquifer water quality regarding to pumping, under parameter uncertainty, and obtain a stochastic and robust optimization of groundwater management. Additionally, Koundouri and Christou (2006) analyzed the optimal management of groundwater resources with stock-dependent extraction cost and a backstop substitute. The developed model considers heterogeneous sectors and use multistage dynamic optimal control.

Proper conjunctive use of water, namely *the integrated use of surface and groundwater resources,* is an essential issue due to the increasing water demands of the agricultural sector. An integrated dynamic approach was employed by Chang *et al.* (2011) to simulate the interaction between surface and subsurface water as a system, where the natural groundwater recharge is considered as a water source to the system and its volume is estimated using geographic information system (GIS) tools, a groundwater modular-dimensional groundwater flow (MODFLOW) model, and a parameter identification model. On another strand, Yang *et al.* (2009), Peralta *et al.* (2011) and Rezapour & Soltani (2013) applied genetic algorithms (GAs) and constrained differential dynamic programming (CDDP) techniques to study multi-objective problems associated with the performance of a conjunctive use surface and subsurface water system, considering issues of maximizing the minimum reliability of the system as well as minimizing both the fixed and the time varying operating costs due to water supply. In a different study Peralta *et al.* (2011) quantified limits and acceptable impacts on selected water resources indicators, and developed a new simulation–optimization algorithm with limits to compute optimal safe yield groundwater extraction policies.

Several studies developed an analytical game-theoretic formulation to calculate sustainable groundwater extraction rates in both cooperative and non-cooperative conflict-resolution approaches (Loaiciga, 2004), to find an optimal balance between positive economic benefits and negative environmental impacts among alternative groundwater extraction scenarios (Salazar *et al.*, 2007), to compute cooperative optimal allocation policies in a multi-objective finite difference aquifer subject to water provision costs (Siegfried & Kinzelbach, 2006), and to address the problem of optimal groundwater extraction by multiple spatially distributed users from an aquifer (Brozovic *et al.*, 2006). Bazargan-Lari *et al.* (2009) proposed a new GA methodology for the conflict-resolution conjunctive water use with different users, Saleh *et al.* (2011) investigated both cooperative and myopic groundwater inventory management schemes with multiple users via a dynamic game-theoretic formulation, and Wang & Segarra (2011) studied the game-theoretic common-pool resource dilemma in extracting nonrenewable groundwater resources when water demand is perfectly inelastic and water productivity is heterogeneous. The game-theoretical framework was also employed to conflict-resolution groundwater management in irrigated agriculture (Latinopoulos & Sartzetakis, 2011), in assessing the value of cooperation under the presence of environmental externalities (Esteban & Dinar, 2012), in common pool resources by cooperative (Madani & Dinar, 2012a) and non-cooperative (Madani & Dinar, 2012b) institutions.

In a river basin scale, several hydro-economic models were used to integrate riparian zones and wetlands (Hattermann *et al.*, 2006) and optimize the conjunctive management of surface and groundwater systems (Pulido-Velazquez *et al.*, 2007, 2008, Safavi *et al.*, 2010, Wu *et al.*, 2015, and Nasim & Helfand, 2015), as well as under uncertainty analysis (Wu *et al.*, 2014). The conflict-resolution issues on water scarcity and infrastructure operations concerning river basin management in transboundary water resources allocation, *i.e.* the river is a common water resource to multiple countries, is addressed by the game theoretic approach. Wu and Whittington (2006) investigated the incentive structure of both cooperative and no cooperative policies for different riparian countries that share an international river basin. Eleftheriadou & Mylopoulos (2008) quantified the consequences caused by water flow decrease for different scenarios to estimate compromising solutions acceptable by two countries. Under the effects of climate change, Bhaduri *et al.* (2011) presented a stochastic non-cooperative differential game to obtain sustainable transboundary water allocation by linking transboundary flows to hydropower exports, whereas Girard *et al*. (2016) compared cooperative game theory and social justice approaches with respect to cost allocation of adaptation measures at the river basin scale.

8.3 CALCULATING THE TOTAL ECONOMIC VALUE OF GROUNDWATER

The total economic value (TEV) comprises different types of use and non-use values. The first relates to actual or potential use values (option value) which derive from the direct or indirect use of an environmental resource (*e.g.* water irrigated from a groundwater aquifer that is used in agriculture refers to direct benefits, whereas the increase in jobs this yields in the agricultural sector refers to indirect use). Option value relates to the value that might accrue in the future from the existence of the resource *i.e.* willingness to pay for maintaining a resource although it is possible that it will not be used in the future. For example, the discovery of new species of plants might lead to the development of drugs that fight diseases. Non-use values are grouped into three main categories; bequest value relates to the value individuals place on the fact the future generations will have access to the same benefits. Existence value, refers to individuals' willingness to pay to preserve the characteristics of the resource as it stands. Finally, altruistic value corresponds to the utility that individuals obtain, by knowing that others users in the community obtain benefits from a specific resource.

Koundouri, Palma, and Englezos (2017) examine various valuation methods in detail, extensively reviewing existing for determining the TEV of groundwater. Revealed preference techniques base their results on data drawn from existing markets or actions (*e.g.* driving to visit a natural site) that encapsulate the value of environmental benefits These techniques however, can only estimate the use values of environmental resources. Such techniques are the *hedonic pricing method*, the *travel cost method* and *cost of replacement.* The first aims at tracing the footprint of the value of an environmental good, by observing the prices in markets. In many applications this has been done by observing the real estate markets in two areas with similar characteristics and varied levels of environmental amenities (*e.g.* The second, considers several parameters that relate to traveling to a destination (*e.g.* a park). Such parameters are travel expenses (fuel, overnight stay etc.), time spent traveling, frequency of traveling, distance from the destination, substitutes in the vicinity and characteristics of the destination. Considering these factors, the method can estimate the value that individuals place on the recreational benefits provided. The second family of methods is the stated preferences techniques, which include *contingent valuation method* and *choice modelling.* These techniques can elicit both use and non-use values through structured surveys that ask respondents to state their WTP. A difference between the two approaches is that contingent valuation can elicit the value of whole goods, whereas choice modelling can estimate the value of both whole goods and their specific characteristics. Similar to the above method, Choice Modelling also uses surveys to obtain information from respondents. This method is heavily based on the theory of Lancaster (1996), which ascribes that goods are a bundle of different characteristics.

Besides the above, benefit transfer methods use results from earlier primary studies in areas similar to that under investigation. By first adjusting the value for the differences in the socioeconomic characteristics (income, prices, currency, etc.) between areas, the value is transferred to express the preferences of the users of the study area. Koundouri *et al.* (2016) used this method to assess the value of four ecosystem services of the Anglian river basin in the UK. In order to estimate these values, several other studies had been considered, such as choice experiments and hedonic pricing. Another study by Koundouri *et al.* (2014) used this approach to estimate the benefits of mitigating industrial pollution. They valued the change in water quality from "bad" to "very good" as set by the Directive 2000/60/EC. This was found to vary between 88.28 and 116.94 euros. In relation to this approach, several studies have combined its methodology with GIS (Geographical Information System) data to assess the economic value of conservation and restoration projects (*e.g.* Jenkins *et al.,* 2010), to estimate value of ecosystem services (Plummer, 2009) and to aggregate benefits from non-market environmental goods (Bateman *et al.,* 2006) among others. Finally, other experimental and market techniques exist, such as laboratory experiments. These are techniques that are implemented in a controlled environment (laboratory) and ask respondents to make choices following a well-structured scenario. For example, Drichoutis *et al.* (2014) implemented this technique by engaging respondents in a 6 auction rounds (three of them were hypothetical and three real). Respondents had to choose if they would exchange their endowment with an amount of a good from a river basin with good ecological status and a river basin with bad ecological status that could potential raise health concerns. The results indicated that people would bid higher for the goods that were produced in the region that had water of good ecological status, showing aversion to potential health issues stemming from heavily polluted water. Another study by Carson *et al.* (2011) assessed the economic consequences of the effects of arsenic contamination. The study was concerned about the effect on labor supply in Bangladesh. For this reason, a labor supply model was estimated that used labor data from local households, which was matched with data on arsenic contamination. The results indicated that labor hours are lost, due to the fact that individuals try to hedge against contamination dangers. Also, meta-analysis is a method that is widely used. Such studies include statistical analysis of combined results of previous studies. For example, Van Houtven *et al.* (2006) identified 300 studies that relate to water quality improvements, most of which were stated preference studies. Table 8.1 depicts studies which focus on estimating the value of several services provided by groundwater.

Through the years several ecosystem services classifications have been suggested, such as the Millennium Ecosystem Assessment (MEA 2005) that recognizes four broad types of ecosystem services: *provisioning*, *regulating*, *supporting*, and *cultural* services. While the MEA provides a straightforward connection between the natural environment and the processes that take place within it and welfare, a major disadvantage is

Table 8.1 Summary table of economic valuation studies.

Paper	*Resource*	*Method*	*Values*
Hedonic price analysis and selectivity bias: water salinity and demand for land. (Koundouri & Pashardes, 2002)	Groundwater	Hedonic pricing	£11.5 per hectare
Arsenic mitigation in Bangladesh: A household labour market approach. (Carson, Koundouri, & Nauges, 2011)	Groundwater	Labor Market Approach	$18–38 household/year
Environmental cost of groundwater: A contingent valuation approach. (Martínez-Paz, & Perni, 2011)	Groundwater	Contingent Valuation	a23.52 person/year
The value of scientific information on climate change: a choice experiment on Rokua esker, Finland. (Koundouri, 2012)	Groundwater	Choice Experiment	a9.71–36.92 per household/year
A Value Transfer Approach for the Economic Estimation of Industrial Pollution: Policy Recommendations. *Water Resources Management Sustaining Socio-Economic Welfare*, 7, 113–128. (Koundouri, 2013)	River, Groundwater	Benefit Transfer	a88.28–116.94 household/year

that the framework does not distinguish between intermediate and final services which might lead to double-counting of ecosystem services (Kontogianni *et al.,* 2010; Boyd & Krupnick, 2009).

8.4 INSTITUTIONAL FRAMEWORKS AND POLICY

The governance and management of water as a resource has been at the fore of global environmental and political efforts for decades. The idea of Global Water Governance emerged as a result of a growing consensus that water management was reaching a crisis point and needed to be made a priority (Rogers and Hall, 2003; Cooley *et al.*, 2013). In 2003 the United Nation issued its first Water Development Report, within which water management is identified as a "social, economic and political" challenge (United Nations, 2003). In the wake of the acute impact of climate change felt across the globe today, water management remains a global priority and features prominently in the United Nations Agenda 2030. In addition the issue of water management is embedded within the Sustainable Development Goals (SDGs), addressed both as Goal (#6: Clean Water and Sanitation) in its own right, as well as a cross cutting theme (Sustainable Development Solutions Network, 2015; United Nations, 2016). 2016 saw the convention of the United Nations High Level Panel on Water (HLPW) which has a remit to "ensure availability and sustainable management of water and sanitation for all, as well as to contribute to the achievement of the other SDGs that rely on the development and management of water resources". The panel is expected to provide global leadership in the collaborative effort for inclusive and sustainable water resource management at all scales (HLPW, 2016).

At European level, a number of policies have been introduced in order to regulate the quality of groundwater across the continent. In 1979, the Commission issued

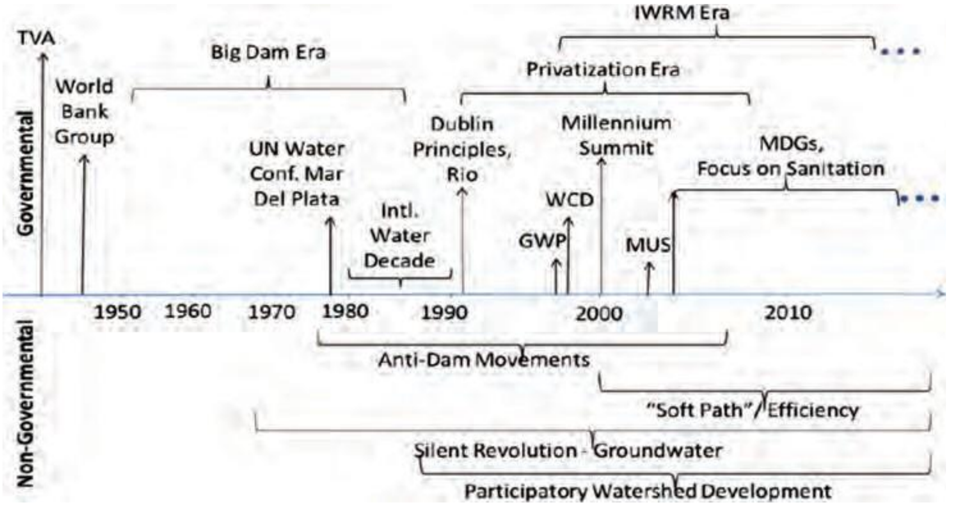

Figure 8.1 Global Water Governance Timeline (Source: Cooley *et al.*)

'Directive 80/68EEC' which aimed at preventing the pollution of groundwater by toxic, persistent and bioaccumulable substances including metalloids and their compounds (European Commission, 1979). Since then several other Directives which consider the preservation of groundwater quality in one way or another have been developed and come into force; these include the Drinking Water Directive (1980), the Urban Wastewater Treatment Directive (1991), the New Drinking Water Quality Directive (1991), the Nitrates Directive (1991), the Plant Protection Products Directive (1991), the Directive for Integrated Pollution and Prevention Control (1996), the Biocides Directive (1998) the Groundwater Directive (2006) and the Directive on Industrial Emissions (2010) (European Commission, 2017).

In 2000, the Water Framework Directive (European Commission, 2000) introduced an integrated legal framework for the protection of European freshwater ecosystems, as well as the means to achieve that which are crystallized within its objectives. The ultimate objective of the Directive is to achieve Good Ecological Status (GES) in all freshwater ecosystems (rivers, lakes, transitional waters, groundwater, etc.) across Europe. In order to achieve that member states must adopt the Directive, define River Basin District and set out a plan of action that will lead to the achievement of GES. The WFD not only assesses the chemical, biological and morphological status of surface water, but it stresses the importance of the social and economic status of each river basin district. It considers economic aspects of the basins in articles 5, 9, 11 and Annex III (Koundouri & Davila 2013). According to these, member states must define the water uses in each river basin district, estimate the total economic cost of water services and design measures that assist in achieving full recovery of this cost.

Within Saleth and Dinar's (2004) framework (see Figure 8.2), endogenous and exogenous factors of change are identified and assessed. These factors are important for the design and implementation of coordinating mechanisms among ministries and

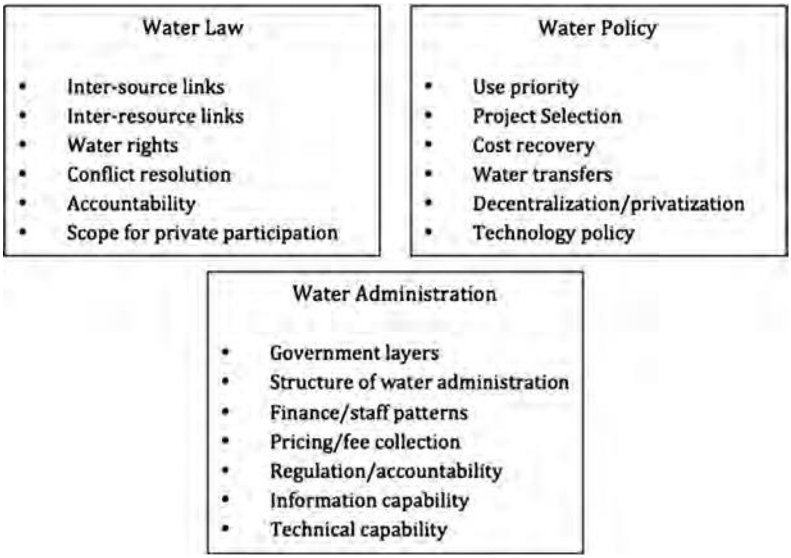

Figure 8.2 Saleth and Dinar's Analytical Framework (Source: Saleth and Dinar, 2004).

may allow or hinder cross-sectoral collaboration between diverse bureaus in the water and green growth fields. Saleth and Dinar's institutional framework is re-categorized into state, market, and community to take into account the arguments about the drivers and instruments of economic and social development and environmental conservation based on the state, the market, and community.

Water Abstraction taxes are taxes that can be used to restrain water users from lowering the water level below a certain standard. Area pricing is the most common form of water pricing whereby users are charged for water used per irrigated area. Output pricing methods involve charging a fee for each unit of output produced per user whereas, input pricing involves charging users for water consumption through a tax on inputs. The efficiency of water abstraction taxes is relative and depends on technical and institutional factors. Volumetric pricing is the optimal water tariff[1] where price is equal to marginal cost of supplying the last unit. The effectiveness of a tax depends on the correct estimation of the marginal tax level and on how risk-averse farmers are with respect to damage from reduced water availability (both in quality and quantity terms). A differentiated tax level has to be created, because of local differences in both the monetary value of reserves and the vulnerability of the environment to changes in the groundwater level. An advantage of a tax is that it improves both economic and technical efficiency. Administrative costs are high, since

[1]A water tariff is a price assigned to water supplied by a public utility through a piped network to its customers. Prices paid for water itself are different from water tariffs. They exist in a few countries and are called water abstraction charges or fees. Water tariffs vary widely in their structure and level between countries, cities and sometimes between user categories (residential, commercial, industrial or public buildings). The mechanisms to adjust tariffs also vary widely.

a differentiated tax is not easy to control and monitor. A volumetric tax on extraction is complicated, because it involves high monitoring costs. A tax on a change in the groundwater level is also complicated, because external and stochastic factors affect the level of groundwater, which is not uniform across any given aquifer.

Pollution taxes represent an efficient method of addressing water quality problems if these are adopted at the optimum level. Pollution taxes to address groundwater pollution are usually targeted at non-point source pollution from agriculture, and are imposed on nitrogen fertilizers. Subsidies can be directly implemented for water-saving measures to induce users to behave in a more environmentally friendly way. Alternatively, indirect subsidy schemes also exist which include tax concessions and allowances, and guaranteed minimum prices. Subsidies however are not economically efficient, they create distortions and do not provide incentives for the adoption of modern technologies. Acceptability however is not an issue, since participation in subsidy schemes is voluntary and has positive financial implications.

Some countries have already taken steps in assessing their subsidies programmes in terms of their environmental, social and economic impacts and in reforming their harmful policies, towards reducing those subsidies that enhance fossil-fuel use and thus act as a hurdle to combating climate change and achieving more sustainable development paths. As discussed in Zilberman *et al.* (2008), rising energy prices however, will alter water allocation and distribution. Water extraction will become more costly and demand for hydroelectric power will grow. The higher cost of energy will substantially increase the cost of groundwater, whereas increasing demand for hydroelectric power may reduce the price and increase supply of surface water. Thus, rising energy prices will alter the allocation of water, increase the price of food and may have negative distributional effects.

Groundwater tradable permits assume the introduction of water markets (Howitt, 1997) in which water rights, or permits, can be traded to address different aspects of the water resource problem (Kraemer and Banholzer, 1999); *e.g.* water abstraction rights, discharge permits and tradable permits for use of water-borne resources such as fish or potential energy. Generally, the government will determine the optimal level of water resource use over a specified time period and will allocate an appropriate number of permits. The financial impact on affected parties and related acceptability of tradable permits depends on the initial allocation of rights. These can either be distributed for free (for example depending on historical use or other criteria), or auctioned off to the highest bidders. While there are some examples of its implementation, the use of tradable rights for groundwater seems to be complicated in practice, since the impact of changes in the groundwater level on agricultural production and nature depends on location-specific circumstances. To avoid transferring rights among areas with heterogeneous characteristics, trading has to be restricted. Tradable water permit systems have been implemented in a number of countries including Chile, Mexico, Peru, Brazil, Spain, several states in Australia and the Northern Colorado Water Conservancy District in the USA (Marino and Kemper, 1999).

Voluntary agreements try to convince farmers (through education) of the advantages of fine-tuned groundwater control. Voluntary agreements on controlling groundwater use are in principle efficient, since they rely on specialized knowledge of participants about local conditions. The principle of allowing the individual members of agricultural organizations and water boards to make decisions on issues that affect them rather than leaving those decisions to be made by the whole group, the so called ‘principle of subsidiary’, is widely accepted. Environmental liability systems intend to internalize and recover the costs of environmental damage through legal action and to make polluters pay for the damage their pollution causes. If the penalties are sufficiently high, and enforcement is effective, liability for damage can provide incentives for taking preventative measures. For liability to be effective there need to be one or more identifiable actors (polluters); the damage needs to be concrete and quantifiable and a causal link needs to be established between the damage and the identified polluter.

8.5 APPLICATIONS TO GROUNDWATER MANAGEMENT

All around the world a variety of projects have focused on applying hydro-economic, game theoretical, and optimization models to groundwater management issues. On top of that a number of strategies to achieve sustainable groundwater management have focused on an ecosystem services approach to calculate the TEV of surface and groundwater. So too, has some of our research been applying these new models and concepts to projects and case studies. In the following, we will present some of the work on groundwater management done at the International Center for Research on the Environment and the Economy (ICRE8: www.icre8.eu) and the Research Team on Socio-Economic and Environmental Sustainability (ReSEES: http://www.icre8.eu/resees) of the Athens University of Economics and Business, which is part of ICRE8’s research cluster structure. Since September 2016, the International Center for Research on the Environment and the Economy (ICRE8: www.icre8.eu) is part of a Horizon 2020 (European Commission) project that will establish a Decision Analytic Framework to explore the water-energy-food Nexus (DAFNE) in complex trans-boundary water resources of fast developing countries. ICRE8 is responsible for developing socio-economic models in a complex trans-boundary framework – the two case studies are river basins that link eight African countries, two respectively – considering uncertainties due to climate change (DAFNE Project, 2017). Game theoretical models will be applied to construct interactions and competing interests in the river basin. Further, the concept of TEV of water will be applied to estimate the value of the resources.

GLOBAQUA is an ongoing project which ATHENA Research and Innovation Center (https://www.athena-innovation.gr/en.html) currently participates in. The project is funded by the European Commission 7th Framework Program. In six case study regions the project aims at identifying multiple stressors, including water scarcity, which affect biodiversity and the services which the ecosystem provides. In a latter step, the project wants to establish socio-economically and environmentally sustainable management strategies in each of the case study regions, consistent with the goals of the Water Framework Directive. A range of models, including the River Water Quality Model and InVest, is consulted to estimate the value of ecosystem services (Navarro-Ortega *et al.*, 2015).

Apart from these two ongoing projects that take into consideration the interlinkage between surface and groundwater, there are a number of ReSEES (Laboratory on Research on Socioeconomic and Environmental Sustainability at the Athens University of Economics and Business: http://www.icre8.eu/resees) projects on groundwater management that have been completed already. These include, among others, GENESIS funded by the 7th Framework Program of the European Commission, which developed concepts, methods, and tools to improve groundwater management (Bioforsk (a)). In the project ReSEES preformed game theoretical and economic-mathematical modeling of surface and groundwater interaction under uncertainty and risk, used non-market valuation methods to assess the TEV of groundwater, and performed cost-benefit analyses on the proposed management strategies (Bioforsk (b)). THESEUS (Innovative technologies for safer European coasts in a changing climate) project that is funded by the European Commission, 7th Framework Program, which examines the application of innovative coastal mitigation and adaptation technologies aiming at delivering safe coasts for human use and development. The primary objective is to provide an integrated methodology for planning sustainable defense strategies for the management of coastal erosion and flooding which addresses technical, social, economic and environmental aspects. Other projects include project funded by the European Commission, 6th Framework Program, such as EUROLIMPACS (Evaluate Impacts of Global Change on Freshwater Ecosystems), AQUASTRESS (Solving Water Stress Problems by Integrating New Management Economic and Institutional Instruments). Also projects funded by the 5th Framework Program of the European Commission, such as ARID CLUSTER (Strengthening complementarity and exploitation of results of related RTD projects dealing with water resources use and management in arid and semi-arid regions) and Sustainable Use of Water on Mediterranean Islands: Conditions, Obstacles and Perspectives; and the CYPRUS (Integrated Water Management in Cyprus: Economic and Institutional Foundations) project, funded by the 4th Framework Program.

In addition to the aforementioned projects, ICRE8 and ReSEES participated in a number of projects funded by non-European sources, such as the World Bank: The significance of subsidized electric energy tariffs on the behavior of groundwater users for agriculture in India in general and in Rajasthan in particular (2003), Bangladesh Arsenic Mitigation Water Supply Project: Water Tariffication Re-structuring in Rural Bangladesh (2003), Water Pricing and Management in Urban China: Welfare Implications (2003–2004), World Bank Desk Work: A Report on the Economics of Arsenic Mitigation: Valuing Cost and Benefits Under Uncertainty and Health Risk (2003-2004); Governments: The Implementation of the Economic Aspects of Article 11 of the Water Framework Directive in Cyprus (Government of Cyprus, 2009–2010), The Implementation of the Economic Aspects of Article 5 of the Water Framework Directive in Greece (the Greek Government, 2007–2008); Sustainable Management of the South East Kalahari Aquifer System (Government of the Republic of Namibia, 2002); The Economic Value of Groundwater (the United Kingdom Environment Agency, 2012); Integrated Management for the ASOPOS River Basin (Greece): Economic Efficiency, Social Equity and Environmental Sustainability (Andreas Papandreou Foundation and National Bank of Greece, 2010); A Methodology for Integrated Watershed Management (International Institute for Environment and Development, 2008); Economic Valuation of Groundwater Review (Environment Agency–Aby Dhabi, 2014); Economic Instruments to Protect Freshwater Resources in the Republic of Buryatia, Lake Baikal Basin (Organization for Economic Co-Operation and Development, 2013–2014); Water and Green Growth Program – Phase 2 (World Water Council, 2014).

All of the above projects combine the aspects of groundwater resources management that we have considered in this paper. Specifically, they integrate stochastic hydro-economic models of groundwater use under different institutional and policy frameworks, and estimate the parameter values of these model using market and non-market estimation methods. Dynamic comparison of status quo values with respective optimal values, defines the level of needed interventions in terms of economic, legal and policy instruments, over time and space. The challenge of achieving environmental-economic-social sustainability in groundwater allocation over time, space and people is huge, multi-dimensional and should be treated in an interdisciplinary dynamics systems approach that can accommodate efficiently the involved complications.

8.6 CONCLUDING REMARKS

The application of economic instruments in the context of groundwater management requires that at least two strong limitations be considered. The first one refers to the set of non-market benefits and dimensions related to groundwater resources. Theoretical models, from which prescriptions to define instruments' design are drawn, should consider the Total Economic Value of the resources. Secondly, economic instruments – tariffs, tradeable permits or some other incentives – are deployed over a space of institutional aspects: customs, laws, decision making procedures, distribution and quality of information, distribution of rights and permits, some of which are far more important than the economic impact of the instruments themselves. These two dimensions jointly configure the set of possible elements for defining and implementing economic instruments. Numerous examples of feasible cooperation mechanisms, which provide tangible benefits for sustainable groundwater management, have been reported in the literature. This chapter concludes by highlighting the role of inter-disciplinary research projects and initiatives in offering useful information about the interrelated – social, economic, environmental – aspects surrounding groundwater management. Modeling these interrelations can help identify the likely impacts of alternative economic instruments, and avoid omitting unexpected effects or consequences. We thus conclude raising the importance of considering any economic instrument, or any combination of some instruments, within the larger sphere of dimensions and interrelations in which they operate.

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