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# Water Management in the Western U.S.

## An Economic Research Agenda

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Shanchao Wang

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# Water Management in the Western U.S.: An Economic Research Agenda

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## Abstract

This report discusses water management in the western U.S. and investigates related problems. The first part reviews theoretical and empirical economics literature on the motivations for water management. Following that, it discusses barriers to effective water management and potential knowledge gaps. The final part of the report presents three broad research topics, as well as related researchable questions that may contribute to ongoing policy debates. Research topics come from literature reviews and interviews with Environmental Defense Fund internal experts, academic communities and stakeholders. Topics include fragmented water management, groundwater market design and agricultural adaptation to reduced water supplies.

## Keywords

Water management, groundwater, Sustainable Groundwater Management Act (SGMA), water market

## JEL classification numbers

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# 1. Introduction

Water is essential for many human activities and a critical precondition for economic development. Nevertheless, due to overexploitation, poor management and climate change, water-related problems such as polluted supplies, seawater intrusion and groundwater overdraft have become serious concerns. Governments and other organizations have gradually recognized these problems and are exploring different ways to solve them. For example, historically, supply management (the construction of water reclamation infrastructure such as dams) was the main tool to tackle water scarcity in the western United States. Under the pressure of growing demand, supply augmentation attempts have dwindled since the 1970s due to the rapidly increasing costs of developing new water supplies (Vaux and Howitt 1984). Subsequently, efforts for surface water management have focused on effectively managing water demand and mitigating impacts of human activities on ecosystems. For example, on the basis of water rights defined by the prior appropriation doctrine, water markets have been implemented to facilitate the transfer of surface water rights and manage water scarcity in the western United States (Goemans and Pritchett 2014). [1]

Compared to surface water management, groundwater management is more complicated due to the limited information we have about aquifers (Schlager 2006) and poorly defined groundwater rights. Some western states are experimenting with market-like regimes that can manage groundwater efficiently. For example, water banking was set up in Kansas in 2005 to restore flows and support water trading for both surface water and groundwater in the central part of the state. However, the bank has not often been accessed by water users due to its inefficient market design (Guilfoos et al. 2016). In 2014, California legislated the Sustainable Groundwater Management Act (SGMA), its first statewide groundwater management program (Aladjem and Sunding 2015). Although it grants local groundwater sustainable agencies (GSAs) rights to develop their groundwater sustainability plans, the Act provides little guidance on how to basins should be managed to achieve sustainability.

One of the main causes of water-related problems is the conflict created by increasing water demand and water scarcity. Economics studies resource scarcity and how to allocate resources most effectively. A considerable economics literature has focused on the management of natural

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[1] Prior appropriation doctrine states that the first person to use water for "beneficial uses" has the priority in water use in the future. More details in section 3.

resources such as minerals, forests and fisheries, as well as water. Hence, economics may shed light on, and offer new solutions to, water management.

The first part of this report reviews the theoretical and empirical literature on the motivations for water management. Following that, it discusses barriers to effective water management and potential knowledge gaps. The final part of this report presents three broad research topics, as well as related researchable questions that may contribute to the current policy debate.

## 2. Economics for water management: theoretical and empirical analyses

Surface water and groundwater are typical common-pool resources (CPRs): it is difficult for a user to prevent others from accessing the resource (i.e., it is nonexclusive), and another's use of the resource will reduce the quantity (and/or quality) of the resource that may be accessed by the user. The latter property is called "subtractability" by Nobel laureate Elinor Ostrom (1990). For example, in the case of surface water, upstream river diversion will result in reductions in availability for downstream water users, and in the case of groundwater, a user's pumping activities can lower the static level and the stock of groundwater for other users. Since resources are scarce and have limited carrying capacities, reduction in quantities can generate negative impacts on all users and even cause the collapse of some resources. There is a consensus in the economics literature that if CPRs are left unregulated, they are subject to economic rent dissipation, where the inherent value of the resource is exhausted, and the society may no longer benefit from it (Gordon 1954; Hardin 1968). For example, groundwater overdraft leads to a lower groundwater level and higher pumping costs, and farmers may eventually find it unprofitable to dig new or deeper wells. Although no mathematical analyses were presented in Hardin's 1968 work, his arguments have the structure of a prisoner's dilemma, where all users end up worse off by myopically maximizing their own profits. Half a century before Hardin, Coman (1911) identified the problem in which groups need to cooperate to reach a desirable, welfare-maximizing outcome but individuals have strong incentives to avoid contribution. As a result, the collective benefit is not achieved.

These ideas were further developed by Ostrom in her book *Governing the commons* (1990), in which she analyzes the CPR problems in southern California groundwater basins. She argues that the core of these problems is the free-rider issue, whereby whenever one person cannot be excluded from the benefits that others provide, each person is incentivized not to contribute to the joint effort. If everyone in a group is taking this strategy, the collective benefit will not be realized. A concrete example mentioned in Ostrom's 1990 book was the continuing overdraft conditions in southern California groundwater basins caused by individual irrigators competitively withdrawing water to maximize their own profits. In contrast, water users in other Californian basins, including Raymond Basin and Central Basin, negotiated and reached private settlements that ended competitive pumping activities. These collective actions saved tremendous time and money in preserving groundwater sustainability. In addition to failing to achieve collective benefits, surface water and groundwater depletion degrade species habitats and threaten the sustainability of economic development (Kuwayama and Brozovic 2013). In order to prevent resource depletion and reach collective benefits, Hardin calls for management by either state involvement or privatization, while Ostrom proposes self-governance as a third option (Sarker and Blomquist 2019).

Economists have found evidence of economic gains from surface water management, and studies often focus on improvements in water allocation. In economics, the social optimum of water allocation is the one that exhausts all the welfare-enhancing trades and technology options (Chong and Sunding 2006). A direct result of optimal water allocation is that the marginal values of water are equal across all uses. One way to achieve this is through voluntary water transfers. Early literature that advocated for water markets includes Vaux and Howitt (1984), Hamilton et al. (1989), Dinar and Letey (1991), and Howitt (1994).

Vaux and Howitt (1984) simulate an interregional trade model to analyze surface water and groundwater trading in California. They find that water trading from agriculture to municipal and industrial sectors generates substantial gains by increasing the value of agriculture water, reducing total water use, and increasing net welfare for both agriculture and nonagricultural users. Hamilton et al. (1989), on the other hand, study the economic implications of transferring water from agricultural to hydropower use in periods of low river flow (i.e., dry years) in the Snake River Basin of Idaho. Their model estimates that the hydropower benefits from shifting water are 10 times greater than farm income losses. Dinar and Letey (1991) apply a micro-level production model to the San Joaquin Valley in California and the water market between agriculture and the urban sector. Their results indicate that agriculture–urban water marketing is beneficial to agriculture, urban areas and the environment. In particular, a water market encourages agricultural farmers who use irrigation to save water by allowing their unused quota to be traded. This then increases the water availability for urban water users. Since excess irrigation is reduced, agricultural drainage problems will be alleviated, and the environment will also be improved. Howitt (1994) pinpoints the impacts of water trading and the water bank established by California in 1991 on mitigating the effects of droughts.

These papers simulate water trading from the agricultural sector to other sectors, including municipal, hydropower and environmental users, and compare estimated farm income losses due to water transfers with profits gained from using the water elsewhere. While the models in these papers incorporate rich institutional and hydrological settings, the key economic parameters are often calibrated, and the results rely heavily on functional forms (Mérel and Howitt 2014). More recent works use actual water transaction data to estimate water demand curves and simulate welfare gains from either expanding water markets or allocating water in a socially optimal way (Libecap 2011; Hagerty 2019).

For groundwater management, evidence supporting economic gains has materialized as more and more microdata on groundwater extraction become available. Groundwater systems are dynamic in the sense that snowmelt and precipitation slowly recharge aquifers while human activities constantly discharge them. If outflows persistently exceed inflows, groundwater depletion will occur. One way to manage groundwater is by restricting extraction. However, early literature (Gisser and Sanchez 1980) implies that the difference in welfare between open access and temporal optimal control is negligible.

Koundouri (2004) reviews the Gisser–Sanchez effect (GSE).[2] She highlights that GSE is mainly caused by steep marginal groundwater use benefit curves. The increase in marginal costs of groundwater caused by a lowering in groundwater level is smaller than the increase in marginal benefit, hence groundwater usage is not price sensitive. Koundouri then finds that the welfare gains from optimal groundwater extraction management could vary dramatically given different slopes of demand function and interest rates. Some examples are documented in Worthington et al. (1985), Knapp and Olson (1996), Koundouri (2000), and Burness and Brill (2001), who state that the welfare gains of managing groundwater extraction are 29.0%, 2.6%, 409.4% and 2.2%, respectively. Burlig et al. (2020) find that farmers are very responsive to electricity and groundwater prices, which challenges the validity of GSE assumptions.

Work by MacEwan et al. (2017) integrates savings in energy pumping, drought reserve values and avoided capital costs into a cost–benefit analysis and compares three different groundwater

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[2] GSE means that the optimal control of groundwater pumping activities results in few improvements within a competitive extraction regime.

management regimes: open access, perfect foresight and managed pumping. Through their model simulations on the Kings and Tulare subbasins of California, the authors find that the long-run benefits from restricting pumping activities can surpass the short-run crop losses, which provides another empirical counterexample to GSE. Guilfoos et al. (2016) apply a spatially detailed model to the northern Kansas section of the Ogallala Aquifer, and investigate the performance of simple groundwater polices (i.e., spatially uniform permit price and extraction quantity restriction). They find that simple market management polices perform poorly but can be improved dramatically by localized policies that consider the spatial heterogeneities. Their result indicates that even the second-best policy can result in welfare gains compared with no management.

As with studies in surface water management, economists have analyzed possible gains from groundwater markets and promoted water marketing (Hanak et al. 2019). Kuwayama and Brozovic (2013) and Palazzo and Brozovic (2014) estimate the costs of groundwater restrictions at a well level in the Republican River Basin of Nebraska, finding that basin-wide groundwater permit trading can generate sizable cost savings. Bruno (2018) constructs a structural model, coupled with well-level groundwater extraction and price data, and simulates the economic impacts of a 20% basin-wide groundwater reduction in the Coachella Valley under the SGMA. She concludes that the economic surplus under a cap-and-trade system is 47% greater than under a cap-only system, assuming that markets are perfectly competitive. Bruno and Sexton (2019) conclude that the cap-and-trade system will still outperform the cap-only regime even under a groundwater market with market power. Ayres et al. (2019) utilize a regression discontinuity design to estimate the benefits from assigning groundwater rights and allowing for groundwater trades. Their results show that land values under a market-based regime are significantly higher than that under open access. This is mainly due to the fact that landowners under a market-based regime have outside options to sell groundwater property rights to urban users.

# 3. Barriers to effective water management

On the one hand, economists have identified potential gains from managing water, both theoretically and empirically. On the other, we observe surprisingly little movement toward more robust management in areas where water-related problems persist. This apparent puzzle suggests that barriers to conducting water management might be high. This section lays out some barriers to effective water management, including water rights definitions in the western United States, fragmented management entities, climate change, transaction costs and political objections.

## 3.1 Water rights definitions

One potential solution to CPR management is the creation of property rights. The Coase theorem (Coase 1960) states that, under certain conditions, private property rights ensure efficiency. Nevertheless, the theorem rests upon several unrealistic assumptions (zero transaction costs, no strategic behavior, perfect information and no income effects), and assigning private property rights alone is not a panacea for all CPR problems. In the western United States, prior appropriation is a dominant doctrine for surface water management. In this, those users who have the earliest water claims are “senior” appropriators and take priority in using water over “junior” appropriators, who establish their water rights later. Some researchers contend that this definition of water rights is problematic (Burness and Quirk 1979). If rights holders fail to keep using their water for a certain period of time, they may lose their water rights and these pass to the users next in priority. This provision is called forfeiture or cancellation for nonuse. Forfeiture generates perverse incentives for water conservation, since farmers who conserve water receive no benefits and face the risk of losing their water rights (Brewer et al. 2008). Groundwater rights, on the other hand, are often associated with land ownership. Although land ownership is exclusive, groundwater rights are usually realized upon extraction. Due to the mobility of groundwater, users cannot prevent others from accessing the resource beneath their lands, and the classic CPR problems persist. In the presence of CPR problems and the current definition of water rights, better management regimes are needed to solve water-related problems effectively.

## 3.2 Fragmented management

Water systems are interconnected hydrologically but often managed in a fragmented manner. For example, managing surface water and groundwater separately and ignoring their interconnections may not generate desirable results. Related third-party effects from water transfers arise from hydrological factors under separate water management schemes. If farmers sell surface water and substitute it with open-access groundwater, this will result in a lower level of groundwater, higher pumping costs and lower water quality (Glennon 2002). In addition, when upstream surface water is shipped out of the watershed, it affects both upstream groundwater recharge and downstream surface water level (Brewer et al. 2008). The interconnected nature of water systems adds to the complexities of water management, and it can be difficult and costly to understand how the different systems interact with one another.

## 3.3 Climate change

Climate change creates uncertainties and adds complexities to water management. The uncertainties are twofold: responses of the hydrologic cycle to climate change (e.g., increasing precipitation variability, higher air temperatures) have not been sufficiently explored by scientists (Green 2016), and agricultural adaptation to climate change has not been fully assessed. The development of a water management regime can be regarded as an investment, with up-front costs linked to future benefits. Uncertainty, as a result, is likely to reduce the current value of an investment (Savolainen et al. 2019) and hence reduce the willingness of users to adopt water management practices. Agricultural adaptation to climate change can take place through various methods, including choosing different crops, investing in irrigation infrastructure and water-saving technologies, and changing cultivation practices (Peck and Adams 2011). Failure to account for adaptation may lead to an overestimation of the impacts of climate change and the adoption of less stringent management schemes, thereby reducing incentives for water conservation.

## 3.4 Transaction costs and political objections

Leonard et al. (2019) assign the roots of barriers to market-based management to two broad categories. One is the transaction costs associated with executing and monitoring trades of environmental goods and services, while the other is the political economy of defining and transferring property rights.

Measurement issues can impede the development of water markets. There is sometimes a gap between legal definitions of rights and actual water use, which results from a lack of verification of diversions and consumptive use measurement technologies. The process for defining volumetric rights is known as adjudication. Without adjudication, each water trade requires measurement and verification of the rights that will be transferred. This increases the transaction costs and reduces the net benefits from water markets (Hanemann et al. 2015).

Besides measurement issues, transaction costs increase as the size and the complexity of trades grow. Some researchers have suggested that rapidly increasing search costs are one of the reasons that water trades are relatively rare and localized (Olmstead 2010). Exchanges and clearinghouses for water rights could reduce search costs, but developing these institutions is costly (Leonard et al. 2019). Moreover, executing surface water trading requires investment in conveyance infrastructures, which is also expensive. While conveyance costs are not salient in groundwater trading, there is an exception. In Texas, groundwater permit trading is allowed, but a water rights buyer can pump water only from the seller's land (Brozovic and Young 2014). Transaction costs also stem from the uncertainty of appropriative rights (Leonard et al. 2019). Since water rights are usufruct rights in the western United States and typically include a beneficial use provision, water must be used for predetermined beneficial purpose or the rights might be expropriated. For example, if a farmer conserves some water and sells it to other parties, the conserved water might be interpreted as an unused portion of water rights and hence expropriated. If owners worry about the future security of their water rights, they may not be willing to sell their rights in water markets or participate in them.

In addition to associated transaction costs, assigning water rights usually involves negotiations among various interest groups, who may not reach an agreement on the distribution of rights. Even if property rights are assigned and markets implemented, Brewer et al. (2008) and Olmstead (2010) point out that political objections are likely to increase when water trading involves multiple jurisdictions and sectors. Water transfers across basins or irrigation districts will induce larger hydrological changes than transfers within the same basin, because within-basin transfers maintain water in the same hydrological system (Barzel 1997). Likewise, within-agriculture water transfers are less likely to impose externalities on third parties than transfers to urban or municipal districts, as the latter have higher consumptive use and hence fewer return flows to basins (Chong and Sunding 2006). Water transfer across different sectors can also bring major economic changes (Leonard et al. 2019). For example, agricultural communities have historically been opposed to transactions that move water out of their districts to urban and environmental sectors. Agricultural communities include not only farmers with water rights, but also agricultural products processors, who rely on the existing water distribution (Howe et al. 1990). These groups can form strong political objections to the implementation of water markets.

# 4. Research agenda: background and literature

So far, this survey has reviewed theoretical and empirical studies in the economics literature of water management. Empirical studies have documented gains from surface water management, in particular due to reallocation via surface water markets, although until recently evidence on the gains from groundwater management has been less clear. While barriers persist and complicate effective water management, economics has offered various proposals to reduce them.

This section explores three broad research topics derived from reviewing barriers to effective water management, namely interconnected natural resources with fragmented management, water market design and agricultural adaptation to shifts in water supplies.

## 4.1 Management of interconnected natural resources

One broad problem faced by policy makers is how to regulate interconnected natural resources that are subject to fragmented management jurisdictions. Mobile natural resources, such as water, fisheries, and oil and gas traverse interconnected systems or open spaces. However, management regimes often cover only part of a system holding the natural resources and/or different parts of the system are managed separately. The interconnections between systems create externalities, such that the extraction of natural resources in one system will affect the resource users in other systems. In the context of water resources, hydrological interconnections include surface water and groundwater connections, as well as connections within groundwater basins. Water systems are intentionally divided into separate jurisdictions according to different property rights systems (surface water and groundwater) or hydrogeological boundaries (basins). This may create conflicts between regions and increase transaction costs. One concrete example is when a basin managed by one set of groundwater sustainable agencies (GSAs) is hydrologically connected with other basins. In many cases, there are hydrological gradients that cause water to flow from one basin to other basins. Property rights to these transboundary flows are undefined and may be difficult to define, and this can cause conflicts among resource users.

Ideally, if one could pool private property rights and act like a sole owner, then one could extract natural resources according to the socially optimal path. This would achieve first-best outcomes without worrying about externalities created under separate management regimes. For example, Libecap's 1998 study  points out that unitization is the most complete solution to CPR problems in oil and gas reservoirs. With unitization, one firm operates on the entire reservoir, while other firms also exert their efforts to jointly maximize total profits and earn rents from the total net revenue through predetermined agreements. Libecap shows that, under unitization, there is no difference in oil and gas supplies between private firms and a social planner. However, unitization or sole ownerships are not commonly observed in practice due to the complex process and high transaction costs of reaching an agreement among firms (Libecap and Wiggins 1985). Other factors preventing unitization include imperfect and asymmetric information (Wiggins and Libecap 1985), and low concentration of land ownership with low industry concentration (Libecap and Wiggins 1984). In the real world, therefore, incomplete or partial management schemes are frequently applied to regulate mobile natural resources. Like oil and gas, groundwater can become depleted if outflows consistently surpass inflows. Experience in managing oil and gas can therefore be drawn on when it comes to understanding the complexities of managing groundwater.

The economics literature has proposed various schemes for managing interconnected natural resources under fragmentation and has evaluated these schemes by comparing their outcomes with those resulting from socially optimal management and/or open access. The partial management scheme proposed by Costello et al. (2015), and defined by the authors as "partial enclosure," assigns exclusive property rights to a fraction of a resource and allows the fringe to remain unregulated (i.e., open access). In their model, one area is assigned property rights such that individuals within it must abide by the property rights regime. The remaining areas are open access. They build a theoretical framework and find that, compared with a scenario with no property rights, partially assigning property rights improves welfare for all users — including those in the open-access areas. Moreover, the resource under partial enclosure maintains higher stocks than if there were no property rights. This is mainly because the managed area creates positive externalities that spill over to adjacent areas. Ayres et al. (2019) empirically confirm that even partially assigned groundwater property rights substantially increase land values for compliant users.

Kaffine and Costello (2011) offer another management scheme by extending unitization from the oil and gas industry to other mobile natural resources such as fisheries. In their setting, individuals are encouraged to contribute a proportion of their profits to a pool and receive individual-specific dividends from the aggregated profits through redistribution. Their analysis applies a Nash reversion framework, whereby if one individual deviates from unitization, other players will also stop unitization and the game reverts to uncoordinated open access. Under these specifications, the authors find that first-best outcomes can be achieved by individuals contributing all their profits to the pool and through certain pre-specified redistribution rules. Note that the participation in unitization is voluntary, which indicates that contractual obligation for all users is not necessary for efficiency. The sharing institutions in Kaffine and Costello's model are reminiscent of agricultural co-ops. Indeed, co-ops might play a positive role in groundwater management by gathering water rights and redistributing them in a socially optimal way, as Kaffine and Costello suggest.

In contrast, Quérou et al. (2017) propose that renewable concessions can be used to mitigate spatial externalities, as long as the owners of property rights can maintain resource stocks above prespecified levels. If owners fail to do so, they lose their rights, and these are allocated to other owners. In each period, policy makers set the stock level for each patch and the concession tenure length, while a concessionaire can choose to adhere to the minimum stock requirement or to defect and maximize their profits on the concession patch. The authors model and derive an individual's profits under compliance and defection, and their results suggest that, under certain conditions, all concessionaires will comply with stock requirements and near socially optimal outcomes can be achieved. The limited concession regime requires regulators to monitor stock levels only at the end of each contractual period, and unlike a unitization scheme, it does not rely on profit redistribution. Therefore, this regime may reduce costs from a regulator's perspective. Further, the results highlight the importance of monitoring in managing interconnected resources like groundwater. Although GSAs will not void a farmers' rights to extract groundwater when they fail to comply with extraction quota, it is critical that penalties are set when violations occur — as Quérou et al. note.

While economists have proven that welfare gains can be achieved from the regimes mentioned in this section, whether these regimes will actually work in practice and improve economic efficiency requires further empirical tests.

## 4.2 Water market design

A water market refers to the mechanism by which, after water rights are defined, rights owners can lease or sell their rights to other parties in exchange for compensation (Brewer et al. 2008). In the western United States, local agencies (irrigation districts or municipal water departments) hold water for surface water rights owners and are responsible for distributing it according to appropriation priority and beneficial use, as well as maintaining water distribution facilities. For example, the Imperial Irrigation District (IID) in southern California owns rights to divert water from the Colorado River. The IID sells and leases water to the individual farmers who make up the district (Emerick and Lueck 2015). As for groundwater, water rights are usually associated with land ownership in the western United States. Here, landowners have the right to drill wells and pump water from their lands, although some states/counties require wells to be registered and metered (Heard et al. 2019).

Active participants in water markets can be categorized into three main groups: agricultural producers, municipal residents and environmental entities. Farmers are both sellers and buyers of water rights. High-value agricultural producers actively participate in water markets during dry years to protect their capital investment in less flexible crops such as fruit and nut trees. In contrast, low-value agricultural producers have the option to leave land fallow or reduce production in some years, and to sell or lease their water rights.

Municipal residents are also major water users. The water demands from municipals are often inelastic, and the users often have a greater willingness to pay for water than agricultural users. As cities grow, municipal water departments are typically responsible for acquiring new water rights. For instance, in 2003, to secure water from IID, San Diego offered $255 per acre-foot for water, whereas IID farmers paid $15.50 (Murphy 2003).

Finally, environmental entities are becoming increasingly involved in water markets. These users focus on *in situ* values of water and are most interested in maintaining water in stream or subsurface for recreation or fish/wildlife habitats. In California, the U.S. Fish and Wildlife Service, California Department of Water Resources and California Department of Fish and Game are the major public entities that secure water for environmental purposes (Emerick and Lueck 2015). Water transactions can be made between public entities or between individual users. The price of each transaction varies, reflecting the changes in water supply and demand. The benefit of managing water within market-based regimes have been discussed in previous sections, and there is a rich literature on the evidence of gains (e.g., Vaux and Howitt [1984]; Hamilton et al. [1989]; Dinar and Letey [1991]; Howitt [1994]; Libecap [2011]; Bruno [2018]).

Many researchers have proposed the cap-and-trade system as a regime for managing groundwater. In the western United States, examples include Bruno and Jessoe (2019) for California; Thompson et al. (2009), Brozovic and Young (2014), and Palazzo and Brozovic (2014) for Nebraska; and Guilfoos et al. (2016) for Kansas. These papers emphasize the gains from trading by simulating and comparing welfare under cap-and-trade and cap-only regimes. Empirical studies evaluating gains from groundwater markets under quasi-experimental settings are relatively sparse (Ayers et al. 2019).

Despite gains from water markets, problems in groundwater market design persist. The cap part of a cap-and-trade system requires basins to set an overall cap, as well as assign individual allocations. Determining initial allocations in a way that limits political objections can accelerate the implementation of the cap-and-trade scheme. More importantly, allocation determination rules should not encourage perverse incentives of overextraction that undermine the cap-and-trade regime. For example, if grandfathering is used to determine initial allocations, it may lead water users to pump more than they need in order to raise their baseline. It may also reward large water users rather than those who have already invested and adopted water-saving technologies (Zetterberg et al. 2012).

Temporal and spatial differences in water values are another important feature that policy makers have to consider. Incorporating these heterogeneities in market design can assist sustainable groundwater management (Aladjem and Sunding 2015). Previous economics literature has demonstrated that localized policies that consider spatial heterogeneity within an aquifer can improve the performance of water markets in groundwater management (Guilfoos et al. 2016). In practice, groundwater trading schemes in Nebraska use trading ratios that adjust for the difference in stream depletion between locations of buyers and sellers of groundwater rights. Likewise, temporal variation in water values due to variable precipitation in the western United States is another important consideration. One way to incorporate temporal heterogeneities is by coupling existing water management regimes with banking and borrowing (see Section 5 for further discussion on this).

## 4.3 Agricultural adaptation

In addition to market design and fragmented management, agricultural adaptation to reduced supplies or supply reliability is an area that warrants further research. Reductions in supplies can result from both climate change and conservation policies. For example, coastal agricultural communities may change their farming practices in response to seawater intrusion caused by climate change and sea-level rise. As groundwater salinity increases, practical responses include planting salt-tolerant crops, or converting farmland to other uses such as residential or habitat land, or leaving it permanently fallow. Taking these responses into account is important for water policy makers if they are to foresee and avoid unexpected consequences. Furthermore, agriculture sectors respond differently under different policy schemes. For example, farmers' responses to simple supply reductions and cap-and-trade markets will be different (Bruno and Jessoe 2019). When farmers do not exhaust their water allocations, a cap-and-trade policy encourages conservation by providing pecuniary incentives. Understanding which policy scheme will better assist agricultural adaptation is one of the critical steps toward reaching a sustainable management goal.

The hedonic approach is one methodology applied by economics researchers for estimating the impacts of climate change on United States agriculture. In a canonical work by Mendelsohn et al. (1994), the researchers utilize the variation in temperature and precipitation across United States counties and regress farmland value according to these climate variables. They then represent the impacts of climate change on agriculture by the changes in farmland value in response to the precipitation and temperature variations.

Schlenker et al. (2005, 2007) argue that Mendelsohn et al.'s (1994) approach is problematic, in that it doesn't account for irrigated agriculture in the western United States. In addition, they argue that, for it to work, the hedonic approach relies heavily on two assumptions: that precipitation measures water supplies, and that production costs are capitalized into farmland values in the same way, regardless of whether this happens in the past or in the future. However, these assumptions will not hold, for two reasons. First, irrigated agriculture areas in the western United States complement insufficient surface water by turning to groundwater. Irrigation water supply is not captured entirely by precipitation. And second, production costs include the costs of obtaining water, but water supply costs may vary over time and/or with the supply source, and hence violate the second assumption. The two papers by Schlenker et al. conclude that, when using hedonic approaches to estimate climate change impacts on agriculture, dryland and irrigated agriculture areas should be treated separately and local climate variables cannot accurately measure the water supply in areas with irrigation. Their results underline the importance of obtaining accurate micro-level groundwater extraction data in order to study adaptation in irrigated agriculture.

Agriculture can adapt to water reduction through various margins. For example, Olen et al. (2016) use a fractional logit model to assess the impact of water scarcity on the irrigation decisions of agricultural producers in Washington, Oregon and California. They find statistically significant results indicating that producers in these states apply water-saving technologies in response to water supply reductions caused by climate change and to mitigate damages due to extreme weather. Manning et al. (2016) focus on the planting decisions of agricultural producers in response to shocks in surface water supply. Their theoretical model shows that, when facing supply reductions, producers will concentrate water on a smaller area in order to maintain high yields and reduce harvest costs. They apply their model to the South Platte River Basin in Nebraska, and find that the negative impact of climate change on agriculture production will be overstated by 17% if adaptation is ignored. Drysdale and Hendricks (2018) use difference-in-differences methodology to study agricultural adaptation to water reduction due to policy shocks (as opposed to long-term adaptation to climate change). They find that, in the short run, farmers reduce water use intensity on the same crops instead of decreasing irrigated acreage or switching to drought-tolerant crops.

These studies inevitably address one of the margins along which agriculture can adapt given data limitations and challenges in identification. Further studies can combine different margins and investigate the joint effects of these margins on water use.

## 5. Research questions

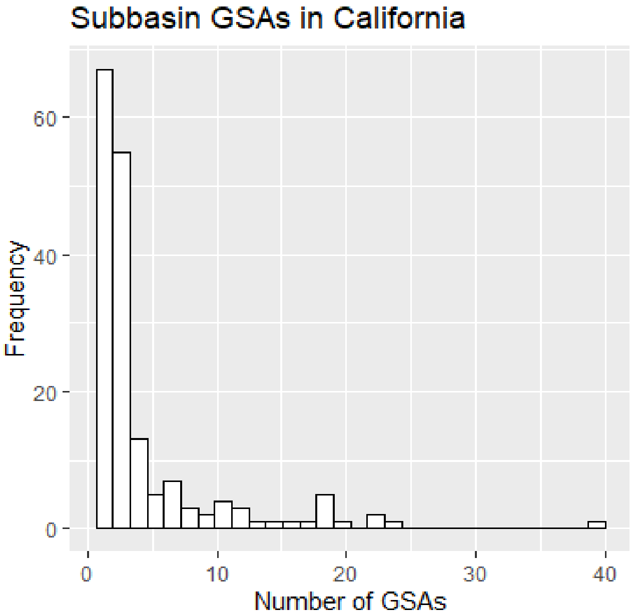
Under three broad topics, this section discusses concrete research questions and examines the related literature. The purpose of the section is to highlight the importance of these questions as well as identify potential economics toolkits that can be leveraged to shed light on them.

### 5.1 What are the causes of fragmented groundwater management?

As discussed in Section 3, fragmentation is a widespread phenomenon in natural resources management, and economists have proposed different management regimes that, in theory, can improve economic efficiency (e.g., Kaffine and Costello [2011]; Costello et al. [2015]; Quérou et al. [2017]). However, the causes for fragmented groundwater management are not well understood. Figure 1 shows the number of GSAs in each of the 173 subbasins that have formed groundwater management agencies in California. There are discrepancies in the number of GSAs across different subbasins, and 106 subbasins have more than one GSA. The maximum number of GSAs in a single subbasin is 39, in the San Joaquin Valley Delta-Mendota subbasin.

FIGURE 1

**Subbasin GSAs in California**



Gaining a clearer understanding of the reasons for fragmentation can help us better understand how we can increase welfare by integrating management where appropriate. For example, if the formation of subbasin GSAs is caused by a concentration of water rights, such that large local farm owners and water users who have access to both groundwater and surface water form and govern GSAs, then individual farmers in white areas whose water supplies rely solely on groundwater pumping might need to be compensated.[3] This is because they will find it more challenging to adapt following the implementation of restrictions in groundwater pumping as they have no access to surface water. Owners of surface water rights can store water, which they acquire from water districts at low prices, in private water banks and then sell them to white

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[3] White areas refer to irrigated areas that are outside the service areas of irrigation districts.

area farmers at high prices in dry years. White area farmers may stop producing crops or purchase water from owners of surface water right if they cannot leave land fallow (e.g., perennial crops are less flexible than annual crops, and water supplies for these plants cannot be suspended), or invest in water-saving technologies or other methods in response to the increasing water costs.

Fragmentation factors can be categorized as exogenous, which focus on the process of forming management regimes, and endogenous, which explain why fragmentation persists. Exogeneous factors investigate hydrological and political causes for fragmented water management regimes, while endogenous factors scrutinize transaction costs, imperfect information and market power.

Exogeneous factors explain the formation of fragmented water management. The first step in managing groundwater basins is by reaching agreement on their boundaries. Under the SGMA, the boundaries are determined by hydrogeological factors, which — given that groundwater basins in California sometimes extend for tens or even hundreds of miles — may result in basins crossing different counties. Political boundaries exist prior to the management of mobile natural resources, and these may incur fragmentation in groundwater management since different jurisdictions may have different management regimes. In addition, basin users can identify an existing local water agency or combination of agencies as a GSA under the SGMA. Within a single basin, multiple local agencies may coexist, leading to the formation of multiple GSAs. One example of existing local agencies is water districts that distribute water to the holders of surface water rights. These water districts tend to be localized due to the high conveyance costs of delivering water and the fact that local water demands are more homogeneous than demands from different sectors, which facilitates the formation of local water agencies. For instance, agricultural and urban users have different water demands and are supported by surface water districts and municipal water departments, respectively. Hence, localized water districts, which are subsequently chosen as GSAs, may contribute to the fragmentation in groundwater management.

Beyond exogenous reasons, economics literature may shed light on endogenous causes for fragmentation. Libecap and Wiggins (1984) discuss reasons for failures in gathering land ownership or unitization in the oil and gas industry. Libecap and Wiggins (1985) point out that the typical negotiation of unitization takes about four to nine years. The negotiation process is costly and time-consuming. In many ways, this is analogous to groundwater management fragmentation, since it is costly and time-consuming for GSAs to reach an agreement to merge. Ayres et al. (2019) document how transaction costs impeded collective action in California's groundwater management historically. Furthermore, Libecap and Wiggins (1985) argue that imperfect information can severely limit the effectiveness of private contracting. General uncertainty of oil migration patterns and asymmetric information about estimated oil and gas values between leasers and contractors block consensus on profit distribution rules.

For groundwater, it may also be the case that GSAs cannot reach agreement on water distribution rules that could spur integrated management. Wiggins and Libecap (1985) point out that a high degree of concentration of landownership is typically necessary to complete unitization since it reduces the number of bargaining parties. The more heterogeneous a market is, the harder it is for all parties to negotiate and unitize their rights — and hence the harder it is to reach agreement. The same logic can be applied to groundwater basin management, where demands from the same sector tend to be more homogenous and it is easier to form water management agencies. Further studies can focus on empirically testing these endogenous causes and determining the extent to which these reasons contribute to fragmentation in a groundwater management context.

## 5.2 How would banking and borrowing affect groundwater management?

Spatial heterogeneities in groundwater pumping externalities have been studied by many economists (e.g., Kuwayama and Brozovic [2013]; Brozovic and Young [2014]; Palazzo and Brozovic [2014]), but the literature on management of water's temporal heterogeneities using markets is limited. One question related to temporal heterogeneities is how banking and borrowing pumping permits would affect groundwater management and its objectives of facilitating reliable supply and reallocating water to higher-value uses. Hanak and Stryjewski (2012) argue that well-functioning groundwater banking and water markets are complementary. Water markets allow users to purchase and bank extra water for future uses, while groundwater banking may expand water trading volume by allowing water to move from wet years to dry years.

Groundwater banking and borrowing may reduce water user abatement costs and smooth water prices over years. Compared to reservoir storage, groundwater banking can take advantage of basins as storage with extensive capacity, low maintenance costs and slow evaporation. However, the benefits from banking and borrowing do not come without costs. Concerns around groundwater depletion arise when water users carry water over in wet years and use these carryovers (or borrow water from the future) at the same time during a dry year. To prevent possible groundwater depletion and intensification of local cones of depression during dry years, some agencies restrict the amount of water that can be carried over and/or borrowed.

Previous literature has documented benefits and drawbacks of surface carryovers on water management in Australia (Hughes 2009; Grafton et al. 2011). Traditionally in Australia, state governments centrally manage major water storage infrastructure, making decisions on water allocations to irrigators given storage levels. Nonetheless, centralized management may not be optimal since decision makers have limited information about individuals' marginal water valuations. The authors argue that carryover can overcome this asymmetric information since irrigators know their own water demands and make individual carryover decisions accordingly. Meanwhile, they point out that carryover can consume storage space and contribute to storage losses, either through evaporation or storage spills. This may also happen in groundwater aquifers when the static groundwater level is high and carryover causes water spillover to other basins. Those who do not carry over water are adversely affected by those who do (Hughes 2009). However, these papers evaluate only carryover or banking in a qualitative way, and no empirical tests or models are presented. Arellano-Gonzalez and Moore (2020) use a 22-year dataset of individual cropping decisions in California, finding that access to groundwater banking increases the probability that farmers will plant perennial crops. However, the ways in which groundwater banking would interact with water market regimes remain unclear.

While the literature on water banking and borrowing is sparse, banking and borrowing in emission permits markets has been studied extensively. In his seminal 1996 paper, Rubin argues that, in the absence of cost uncertainty and assuming competitive behavior, an emission permit system that allows trading, banking and borrowing can achieve the emissions target over a finite time horizon at the least costs to firms. Later studies by Rubin and coauthors extend his paper. Rubin and Kling (1997) point out that the unrestricted banking and borrowing of flow pollutants is not necessarily socially optimal due to the increasing marginal social damage caused by banking. Rubin and Leiby (2001) further investigate emissions that can cause instantaneous damage (flow pollutants), finding that the extent of damages depends on the accumulated stock (stock pollutants). They conclude that the social optimum will not be reached unless regulators set the correct intertemporal trading ratio for banking and borrowing. In summary, borrowing and banking in emission markets can create negative externalities that may undermine the performance of a cap-and-trade system.

Emission markets and water markets share some common features, and hence the dynamic models discussed above can be borrowed and extended to groundwater markets. Furthermore, how different carryover percentages would induce different abatement cost savings remains an interesting question to be examined empirically.

## 5.3 How would climate change affect agriculture fertilizer application and water quality?

Fertilizer is an important input for modern agriculture. For example, United States corn farmers spend about 25% of their total production expenditure on nitrogen fertilizer (Beckman et al. 2013). Fertilizer application is closely related to crop type and soil condition, and especially weather (Paudel and Crago 2019). For instance, rainfall can dissolve and transport fertilizer to the root zone, but excessive rain can also lead to leaching of nutrients. Hence, the timing of fertilizer application needs to account for rainfall patterns. Likewise, temperature affects crop nutrient uptake from fertilizer and therefore has an impact on the frequency of fertilizer application. The literature on fertilizer application responses to climate change is limited.

Varying fertilizer application in response to climate change also has implications for water quality. Fertilizer contains nutrients such as nitrogen and phosphorus, which may negatively affect water quality through nutrient runoff, damaging ecosystems and threatening human health. Wigginton (2015) found a strong positive correlation between nitrate levels and the presence of soluble uranium in groundwater. Nolan and Weber (2015) found that nitrate levels are positively correlated with the presence of uranium in two major aquifers in the United States that provide drinking water to 1.9 million people. More research can be conducted in this direction.

Mendelsohn et al. (1994) mention fertilizer application as one of the margins for agriculture in response to climate change but do not provide empirical evidence on this point. Paudel and Crago (2019) investigate farmer adjustments in fertilizer application in response to warming temperature. They claim that their paper provides the first estimates in the United States of fertilizer application responses to climate change. However, they do not make a distinction between dry and irrigated farmland in their specification, which might be problematic. Schlenker et al. (2005) point out that dryland and irrigated agriculture should be treated differently when studying the economic impacts of climate change on agriculture, especially when precipitation is used as a measure of water supply. Meanwhile, water and fertilizer have a complementary relationship in crop production (Cai et al. 2008), hence an exercise separating dry and irrigated might yield different results.

Economists have developed various tools to study the impacts of climate change on agriculture. Early literature focuses on responses of economic outcomes (such as land value or crop yields) rather than agricultural production decisions. Mendelsohn et al. (1994) applied Ricardian cross-sectional approaches to estimate damages to agriculture caused by climate change. This method is straightforward but is also vulnerable to omitted variable bias (OVB). Any component of land value that is correlated with climate variables but omitted from regressions will bias estimates of climate impacts (Auffhammer 2018). Hence Auffhammer et al. (2006) propose use of the panel data method to mitigate OVB. Their approach, however, is unable to capture long-term agriculture adaptation since climate variables such as temperature and precipitation record only short-run weather fluctuations and not long-run climate change. Burke and Emerick (2016) use a “long difference” approach, which estimates climate change impacts on agriculture while accounting for long-term adaptation. However, such an approach demands broad spatial data with long temporal coverage. These approaches can, with appropriate data, be used to estimate both short- and long-run fertilizer application responses to climate change.

Several public datasets could help researchers make progress on this question. Fertilizer application data are available from the U.S. Geological Survey, while Roberts and Schlenker (2009) present climate data on precipitation and degree days. Other controls such as various agricultural inputs can be obtained from the National Agricultural Statistics Service and U.S. Department of Agriculture.

# 6. Conclusion

This survey reviews the theoretical and empirical economics literature on water management, with a focus on the American West. CPR problems cause pecuniary losses and environmental damages, providing a major justification for increased effort to manage water more effectively. Although water rights are defined in the western United States, surface water rights do not encourage water conservation and groundwater rights are nonexclusive, so CPR problems persist. Barriers to water management include the fragmented management of interconnected nature of water systems, climate change uncertainties, transaction costs and difficulties in addressing political objections. Three broad research topics derived from the literature review and interviews with experts were presented, along with related concrete research questions. Future studies can dig deeper into these research topics and questions, thereby informing policy recommendations.

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