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MARKET DESIGN FOR SURFACE WATER

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ABSTRACT

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Market Design for Surface Water

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December 2023[3]

Abstract: Many proposed surface water transfers undergo a series of regulatory reviews designed to mitigate hydrological and economic externalities. While these reviews help limit externalities, they impose substantial transaction costs that also limit trade. To promote a well-functioning market for surface water in California, we describe how a new kind of water right and related regulatory practices can balance the trade-off between externalities and transaction costs, and how a Water Incentive Auction can incentivize a sufficient number of current rights holders to swap their old rights for the new ones. The Water Incentive Auction adapts lessons learned from the US government's successful Broadcast Incentive Auction.

Introduction

The new field of market design is changing the way economists think about markets. Traditionally, most economists conceived markets in terms of bilateral exchange, often illustrating their ideas with examples in which one supplier of a good sells to one buyer, or two parties enter into some contract involving future deliveries or actions. Inspired by Coase's (1959, 1960) work, any persistently inefficient allocations were attributed to transaction costs that disrupt or impair bilateral trade, which would otherwise correct the inefficiency. These costs were conceived broadly to include frictions due to limited or asymmetric information, imperfect enforcement of agreements, or insecure property rights. While externalities can lead to inefficient allocations, Coase emphasized that with no transaction costs, parties would not need the help of the government to resolve those externalities: they could agree for themselves on mutually profitable, efficiency-enhancing deals. Often, the lesson taken from Coasian analyses is that government policy can best promote efficiency by establishing clear, tradeable property rights, avoiding regulations and mitigating frictions that impair bilateral trade, while leaving the remaining details to free market participants to work out for themselves.

Early contributions to market design went beyond the conception of markets as bilateral exchange between parties that had already been identified. Market design researchers and practitioners often focused on multiple, heterogeneous buyers or sellers and the possible need for multilateral coordination or long periods of time for bilateral trades to match the right buyers and sellers.

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Examples were highlighted in which combinatorial issues led to the possibility of inefficiency even when no profitable bilateral trades remained or in which processing issues led to markets taking too long to find efficient allocations. Because older economic analyses assumed away these problems, the scholars studying matching markets and radio spectrum auctions needed to rethink how markets could be designed to overcome these challenges (Milgrom 2007, Roth & Xing 1994).

This paper returns to the analysis of property rights, externalities and transaction costs, but takes a different view compared to both Coase and past market designers, emphasizing that the design of rights can alter the balance between externalities and transaction costs.[4] In a modern example, rights to residential land may include the right for landowning coalitions – or in some cases individual owners – to veto the construction of nearby wind farms. Such rights provide strong protections against negative externalities on residents, like the noise and ugliness of wind farms, but they also increase transaction costs, so that even if a wind farm is very valuable, it can be hard to negotiate an efficiency-enhancing deal that builds one – an effect known as the "tragedy of the anticommons" (Kashner 2023, Heller 1998).

Some examples used to discuss externalities in the earlier property rights literature have a structure similar to the windfarm example. In one, Coase writes about how the right of a factory to spew smoke may harm a nearby laundry business, but the same smoke may reach and harm many local households. In another, the right of a railroad to operate its trains without spark-arresters may threaten not just a single farmer along the track, but all the other farms and businesses along its route. The specification of a property right determines whose agreement is needed to cancel or transfer it, and that specification affects both the potential externalities and the difficulty of negotiating a rights transfer.

In many historical cases, early rights were created and assigned to be suitable for their original uses. For example, in the United States, radio and television broadcasters received licenses granting them rights to broadcast in a specified geographic area using particular sets of frequencies with protection from interference. Although that solved an interference problem in the early radio industry, those areas, rights, and protections are all different from what is needed today to use the same frequencies for efficient broadband communications networks. Similarly, water rights to divert surface flows specify a location, a season, a point of diversion, and a particular use. Specifying details like those limits externalities from changing uses, but also makes beneficial changes harder and interferes with the trading of rights (Colby 1990). In both of these examples, the externalities – radio interference or return flows – associated with different can be technically challenging to measure. The specification of property rights that best balances externalities and transaction costs thus depends on factors like optimal uses and measurement technologies that are changing over time, posing the twin challenges of how to redefine rights and how to design and promote a transition from the old rights to the new ones.

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[4] In a very recent related paper, Dworczak and Muir (2023) adopt a related view. They take a mechanism design approach to optimal property rights, emphasizing that the structure of rights affects the balance between an owner's investment incentives and related trading frictions.

We examine these market design challenges in the context of *surface water*, which is the water that comes to a region annually from precipitation and flows in streams and rivers. This water can feed farms, ranches, cities, and the environment, or restore aquifers and reservoirs. Long ago, soon after our early human ancestors turned to farming, they began to use and compete for surface water for irrigation, and developed a system of rights to coordinate and limit those uses. Often, *riparian* rights were attached to lands adjacent to a stream, allowing landowners to use the stream for irrigation, but not to sell the water. In other places, first users gained *appropriative* rights giving them priority to continue their historical uses before latecomers got any water allocation.[5]

Fast forward to California today. The crops that are farmed in the state are quite heterogeneous, with very different requirements. Tree crops need a reliable annual supply, or the trees might die. Annual crops can sometimes be left unplanted to save water in a low-water year. Cities, which grew most in population after early farms were established, now have millions of people with relatively modest individual water needs. There is huge heterogeneity not only in uses but also in the prices that water users pay. In San Diego, the urban water supply costs $2,855 per acre-foot, while alfalfa growers in the nearby Imperial Irrigation District pay just $20 (Hagerty, 2023). With these differences, water trading would seem to be an obvious way to make allocations more efficient, especially in drought years when supplies are tight, but the volume of trading remains limited (Hagerty, 2023).

Why is there so little water trading in California despite the heterogeneous uses and huge price differences? The consensus among many economists studying water is that much of the problem lies in an archaic system of property rights, which was perhaps simple and clear enough to function well when California was first settled, but which is dysfunctional today. We will argue below that trading in traditional water rights creates externalities, so efficiency-enhancing changes in water allocations cannot be achieved by exhausting profitable bilateral trades. Rather, it requires a coordinated, multilateral effort. The next section on the Institutional Background provides a description of water rights and the externalities that can result from trade or from certain other decisions about uses. What is most novel in this paper comes after that: we analyze a mechanism that enacts a change in water rights that could lead to much more efficient trade.

Our analysis draws on lessons learned from the US Broadcast Incentive Auction in 2016-17, in which some rights to use radio spectrum for television broadcast were combined, converted, and subdivided into more flexible rights that were better suited for wireless broadband communications. This was accomplished using an auction procedure designed to provide an "incentive" for broadcasters to participate. As in that auction, participation in an analogous Water Rights Incentive Auction could be entirely voluntary, with current water users incentivized to participate because they could trade their existing rights for new, more flexible rights and possibly additional payments as determined by an auction. Just as the Broadcast Incentive Auction achieved its goals described in the National Broadband Plan even though many broadcasters chose not to sell their rights, a Water Incentive Auction could provide the substantial benefits of more flexible water

[5] In other countries, the terms may be different, but adjacency rights and priority-based rights are still common forms.

rights even if many water users decline to participate. We describe some details of a possible Water Incentive Auctions in a later section of this paper.

Institutional Background on Water Property Rights

Traditional Coasian analysis suggests that efficient water allocations are best promoted by clear, tradeable property rights and few regulations, but that analysis holds the rights themselves fixed. It omits analysis of how the content of water rights and the costs of exchanging them are intricately interdependent and cannot be neatly separated, because the allocation of water diversion rights between two uses can affect the availability of water to third parties. The location, timing, purpose, and method of water use can affect both the quantity and quality of water available elsewhere in the system and local economic opportunity (Young, 1986). Clear surface water property rights designed to handle these complexities are necessary for efficient, trustworthy, and responsible water management. But pervasive interdependencies among water uses can make surface water reallocation either impossible to achieve or riddled with externalities (Colby, 1990, Womble & Hanemann, 2020). In this section, we first explain some of the ways in which surface water resources are physically interdependent. We show how cities, farmers, and the environment are affected by these interdependencies and can be harmed by irresponsible/naive transfers. Lastly, we discuss the economic dependence on water resources and how existing regulatory regimes try to protect local agricultural economies.

The physical processes by which surface water flows through and is used along hydrological systems distinguish it from other scarce resources like land. While land can be easily partitioned into discrete units of property to allocate, surface water is always in flux. A key structural property of surface water supply and use is that a single molecule of water may be used many times in a system before being lost to evaporation or transpiration (Young 1986, Hanemann 2005).[6] When a farmer diverts water from a stream to irrigate his crop, any water not consumed by the crop becomes *return flow* that enters a watercourse downstream either through runoff or groundwater percolation (Chong & Sunding, 2006, 241). A farmer downstream may then again divert and reuse the same water that was already diverted by a farmer upstream. The surface water system is a complex and interdependent network of diversions, uses, and return flows that is subject to highly variable climatic conditions (Livingston, 1995).

> "Most diversionary uses of water return up to 50% of the original offtake to aquifer or stream. Users who are downstream and/or interconnected through an aquifer are greatly affected (for good or ill) by the quantity, quality, and timing of releases, return flows, or leaks by upstream users." (Young, 1986)

Unfortunately, accurately measuring these interdependencies is not at all easy. Uncertain hydrology, interactions among sources, and time lags between application of water and the availability of return flow combine to complicate the measurement process (Leonard et al., 2019, 46). Only

[6] At a larger scale, even water lost to evaporation/transpiration is not truly lost; it just re-enters the global water cycle at another point (Rockström et al., 2023).

recently have advances in hardware and modeling made useful approximations possible. When California was beginning to allocate formal property rights to surface water, measurement was nearly non-existent.[7] Because regulators could not estimate flows under counterfactual water uses, they were mostly limited to eliciting information about current uses and then fixing and protecting those. California allocated *appropriative water rights*[8] by asking all water users to report their season of diversion, total quantity and rate of diversion, point of diversion, location of use, type of use, and when they began diverting water (Hanemann et al., 2015, 53). If all water users continued the same patterns in how they were diverting and using water, then the viability of the system could be assured even with their limited understanding of the hydrological details. In drought years, the appropriative system adopted a simple allocation rule: the "first in time, first in right" principle that allocated water property rights in full, in order of seniority—the year in which diversions began (Hanemann et al., 2015, 53). While such a system makes it easier to monitor and enforce rights, it limits shifting water in drought years to more valuable uses and limits users' abilities to share risk.

To illustrate interdependencies from return flows, consider the following example motivated by the competing uses of surface water between agricultural, urban, and environmental uses. Consider a single stream that provides surface water to three appropriative right holders and the environment. In a wet year, the stream is fed annually by 80 thousand acre-feet[9] (taf) of surface water. Alice Irrigation District diverts 48 taf annually at the top of the stream and began doing so in 1895. In 1910 near the bottom of the steam, Farmer Bob began diverting 18 taf each year to irrigate his land. Charlie City started diverting 24 taf in 1924 in the middle of the stream. Lastly, every year 8 taf of water flows out into the ocean providing vital ecosystem services that mediate saltwater intrusion and sustain endangered fish species.

Adding up the varying water uses, the 98 taf that is allocated every year appears to exceed the supply of 80 taf. However, recall that water systems reuse water, with return flows from upstream uses augmenting downstream supply. When Alice diverts and applies 48 taf on her crops, only 36 taf is lost through evapotranspiration and 12 taf returns to the stream. We will say that Alice has a *consumptive share* of 0.75 and that Bob, who unlike Alice uses flood irrigation instead of drip irrigation, has a consumptive share of 0.67, returning 6 taf to the system. Charlie City returns nothing to the system, instead disposing of treated wastewater directly into the ocean. With the reuse of 18 taf of return flow, all property rights and environmental uses are supported by the yearly flow of 80 taf.

[7] This was true for much of the American West, but we focus on California here.

[8] The State Water Commission began regulating appropriative water rights in 1914. Users who claimed water before the state assumed legal control in 1914 are said to have *pre-1914* rights. These rights are senior to those rights allocated after 1914. During periods of drought, pre-1914 senior rights holders are entitled to divert their full quantity, while the remaining junior users face curtailments (Hanemann et al., 2015). Pre-1914 appropriative rights are also not subject to the same regulatory scrutiny.

[9] An acre-foot is the standard measurement of stocks of water and is the amount of water it takes to cover an acre with a foot of water. Surface water is also measured as a flow in cubic-feet per second (cfs). For simplicity in this example we assume that water flows, is diverted, and returns at some constant rate throughout the year.

Suppose that in a drought year, the stream will only see 56 taf. Figure 1 depicts how water is allocated in order of seniority.[10] Alice diverts her full claim of 48 taf, returning 12 taf. To ensure that Bob gets his allocation, Charlie is permitted to divert only 2 taf. Bob then diverts his full 18 taf right and returns 6 taf which undersupplies the environmental services relative to the wet year supply.[11]

This simple example demonstrates the general principles of allocating water resources with appropriative property rights. Importantly, sustaining all the uses of water along the stream required the reuse of return flows in the system. This becomes especially important when users try to improve the drought year allocation by trading surface water between themselves. For example (Figure 2), suppose that in this drought year, Charlie City buys 12 taf from Alice and now diverts 14 taf. Alice, left with 36 taf, diverts her full claim and returns only 9 taf downstream. Unable to receive his full allocation, Bob can only divert 15 taf and returns 5 taf to the system—further draining environmental supplies. Interdependent surface water rights mean that, though beneficial to Charlie and Alice, this transaction infringes on other users and stream dependents.

If return flow dependence is not properly accounted for, trade changes uses in a way that creates externalities. Water reallocation that is beneficial during drought to the two traders can harm third-parties that did not agree to the reallocation. Environmental water needs may be protected or may be the residual claimant of return flows. If they are not protected, these rights must compete with those of water right owners with strong economic incentives to protect their surface water claims (Chong & Sunding, 2006, 253).

Despite its seeming complexity, our example is simplified compared to reality, because it depicts the structure of return flows as fixed and exogenous, omitting various influences and water use decisions. In reality, consumptive shares and the externalities they imply can vary with temperature, crop choice, and irrigation technologies (Ward & Pulido-Velazquez, 2008). If Alice or Bob choose to grow different crops, their return flows could decrease leaving someone downstream with less water. If Bob invested in drip irrigation, he may now have a consumptive share like Alice and return far less to the system. If Alice changed where she irrigated, the return flow could occur in a different season or to a different watercourse altogether. If there was a very hot season, evapotranspiration (evaporation plus plants' loss of water through their leaves) would increase and both Alice and Bob would consume more than the typical year.

Farmers frequently switch their portfolio of crops and invest in more efficient irrigation technologies (Huffaker & Whittlesey, 2000), and as the climate crisis intensifies, weather patterns vary more and more across years (Rafey, 2023). It would be hard to monitor all the relevant decisions made by water users, incorporate uncertain climatic variables, and guarantee that no user will be affected by the choices of upstream diverters, but property rights do not need to perfectly eliminate all externalities. Society can choose which physical interdependencies are recognized in

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[10] Seniority need not accord with stream order, though this is often the case in California (Hanemann et al., 2015).

[11] It is possible for environmental water to be guaranteed in the appropriative water right system as an *in-stream use* (Chong & Sunding, 2006). If the seniority of the appropriative water right superseded other rights in the stream, the in-stream environmental services would be guaranteed during the drought. In this example, we treat environmental water as not held in a specific property right.

property rights, understanding that this decision affects transaction costs. The optimal choice depends on the cost of measurement and surveillance and also on the complexity of water interdependence (Leonard et al., 2019).

The externalities from surface water allocation apply not only to the physical flow of water, but also to local economic entities that depend on irrigation. In many agricultural communities throughout California, the local economy is driven by agricultural production which is in turn dependent on irrigation. If farmers decided to sell water and fallow their crops, the local labor market would lose jobs, companies supplying seeds, fertilizer, and farming equipment would lose sales, and in turn, other economic activity in the local economy like restaurants, movie theaters, etc. would lose business that was supported by the lost laborers/income.

These *pecuniary externalities* are not new to economists (Young, 1986, 1147, Greenwald & Stiglitz, 1986), however, the degree of dependence of agricultural communities on water resources raises its interest for policymakers. In fact, California's approval of water transfers includes an evaluation of the local economic impacts of a transfer. If a voluntary transfer between a buyer and seller is deemed too destructive to the seller's local economy, the transfer can be blocked by the regulators (Hanemann et al., 2015, 57). This concern for the local economic impact of water reallocation is motivated by the history of large transfers from agricultural communities to urban areas, none more notorious than the *water wars* between Los Angeles and the Owens Valley:

> *In the early 20th century, Los Angeles purchased land and water rights in the Owens Valley to export the water to L.A. While L.A. handsomely rewarded most of the selling farmers, the resulting water transfer killed what was a thriving farming community and generated heated local protests. Since then, communities with marginal agricultural economies that use significant water have feared that water markets could siphon off their water for urban use, leaving the selling farmers economically better off but the local community to slowly die (Thompson, 2023).*

Agricultural communities look to the Owens Valley experience as a warning against participation in water marketing and this mentality contributes to additional regulatory and cultural barriers to trade. If transitional assistance had been made to compensate for local economic externalities, valuable water reallocation might be accomplished while maintaining trust in market mechanisms (Howe et al. 1990). Much work has been done to evaluate the magnitude of these pecuniary externalities. Zhang & Hatchett (1998) found an impact of $170,000 of net income loss and eight job losses per thousand AF traded out of the Central Valley. Other work suggests that "transfers involving less than a quarter of a region's water supply are unlikely to have a meaningful economic impact on the region" (Howitt, 1994). While these estimates help inform State regulation of water transfers, most of the protection of communal dependence on surface water is adjudicated by irrigation districts.

Further complicating hopes for efficient water reallocation is that most farmers do not have their own appropriative water rights, which instead are allocated water by their irrigation district. Irrigation districts often have a portfolio of appropriative water rights, along with other entitlements, that they then distribute to their member irrigators[12]. Irrigation districts are managed by a board of directors elected by the members of or citizens within the district (Hanemann et al., 2015, 57). While individual farmers may find it profitable to sell their surface water to higher-value buyers, only the irrigation district typically is granted the power to sell water. Irrigation district board members, caring about re-election, may be wary of selling surface water for a variety of reasons, including the effect on the price of water, the potential loss of political power as the size of the water allocation is diminished, and pecuniary externalities on other voters in the water district (Thompson 1993). While irrigation districts may, in principle, contribute to efficiency by internalizing the pecuniary externality associated with transfers, many believe that the districts are too aggressive in their disruption of water reallocation (Tomori, et. al, 2021, Womble & Hanemann, 2020, Regnacq et al., 2016).

Evaluating a potential water transfer's local economic impact can be expensive and hard to measure, making it difficult to incorporate pecuniary externalities in a benefit-cost analysis. The practical result is that it falls to a complex combination of politically motivated stakeholders at various levels of governance to make binary decisions about the viability of any proposed water transfer (Womble & Hanemann, 2020, Rosen & Sexton, 1993).

Trade frictions in water management are reminiscent of the core market design problems discussed in the introduction. Surface water property rights exhibit a high degree of heterogeneity and extensive physical and economic interdependencies that require multilateral cooperation to achieve efficient allocations. Since the current system does not homogenize rights, internalize externalities, or limit transaction costs, reallocations of surface water do not resemble simple bilateral trades but instead appear more like major acts of diplomacy between several stakeholders.

Market Design Solutions for Water Property Rights

In this section, we step away from the current legal and regulatory regime and consider a possible endpoint of a change: what surface water property rights and market designs could overcome the structural frictions in water management? In order to promote efficiency through simple bilateral trades, any new arrangements would need to establish clear, tradeable property rights, limit both potential externalities and layers of regulatory approval, and leave the remaining details to market participants. As depicted in the previous section, there are currently important frictions that arise from the need for multilateral coordination to manage hydrological and economic dependencies. To minimize transaction costs, surface water property rights could be defined more homogeneously, allowing price competition among buyers and sellers to establish a public market price and reduce the space for costly haggling in bilateral transactions. To reduce externalities, property rights could be defined in terms of water consumed, rather than in terms of water diverted. Consumption rights reduce both trading externalities – because a user can sell only by reducing its net use, and externalities associated with users' decisions – because a user who plants a crop or adopts a technology that reduces its net consumption would be able to sell the water it saved. The advantages of homogeneity are particularly well illustrated by the crown jewel of water marketing

[12] Most commonly irrigation districts allocate water proportional to acreage (Rosen & Sexton, 1993).

in the world: the Murray Darling Basin in Australia (Rafey 2023, Hanemann & Young, 2020, and Turral et al., 2005). Below, we review these ideas more closely.

First, to reduce transaction costs, the heterogeneity of appropriative rights to surface water could be replaced with a homogenous consumptive right. Currently, it is very difficult to compare two different appropriative rights along the many dimensions in which they differ — location of use, purpose of use, seniority (year of first use), season of use, etc. (Thompson, 2023, 5). A homogeneous entitlement to water that simply indicates source and quantity (Howe et al., 1986, 442) allows buyers and sellers to base their trades simply on quantity and price.

Second, to spread risk and promote agreement about the use of dams and other water infrastructure, surface rights could be designed to respond flexibly and uniformly to varying hydrological conditions. A system of proportionality, in which consumptive water rights are defined as a percentage of the water available in a given year, is a promising alternative to seniority-based allocation under an appropriative system partly because it creates the homogeneity needed to promote efficient trade (Livingston, 1995, 206). Such systems seem to be popular among users who determine their own systems. For example, the State Water Project, Central Valley Project, and most irrigation districts allocate water to their users proportionally. A homogeneous system of rights was also implemented in several states in Australia, where water licenses were replaced with shares that entitle users to a proportion of any allocations made to a defined pool of water (Hanemann & Young, 2020, Young, 2014). This structure builds flexibility into the system, reduces the uncertainty faced by junior rights holders who are otherwise not guaranteed water in periods of low availability, and tends to homogenize the interests of users in decisions about investments in water storage facilities and about how much water to store or release in or from reservoirs each year.

This is still imperfect, because the consumption model does not exactly correspond to the facts of hydrology. Consumption-based property rights still leave room for hydrological externalities, so the market design could utilize *ex ante* adjudication about what trades are available between any pair of buyers and sellers or *ex post* compensation for economic damages, or both.[13] An *ex ante* adjudication system could include an easy-to-use public, online platform, on which buyers and sellers input their locations of use and immediately learn the amount of water that can be traded (Raffensperger & Milke, 2017, Regnacq et al., 2016, Colby et al., 2021).

There are two ways that something like this could be accomplished. First, the consumptive use could be clearly indicated in the water entitlement so that buyers know exactly how much net use is available from each seller (Johnson, Gisser, and Werner, 1981). Historically, granular information about the consumptive use of water has been costly to obtain. However, technological innovation in satellite imagery, like the OpenET platform, and increasingly sophisticated hydrological models have made it possible to continuously evaluate consumptive use at little cost (Melton et al., 2022,

[13] Environmental damages may be more difficult to correct with ex post compensation, so ex ante solutions may be chosen for these.

Thompson, 2023)[14]. Water entitlements could be legally attached to an account in the measurement system that automatically determines the consumptive use available for trade.

An alternative solution, adopted by the Murray-Darling Basin in Australia, provides more exchangeability among water entitlements by enforcing *exchange rates* across regions in the basin (Hanemann & Young, 2020). When water is sold between hydrological regions, there is a fixed rate at which the water available for purchase is reduced. All hydrological externalities from inter-region transfers would be approximated for the whole region by a single factor. In this case, transaction costs and heterogeneity are significantly reduced as buyers and sellers need to know only their respective regions to determine how much water is available for transfer.

In both cases, regulatory management of hydrological externalities is approved *ex ante* to make clear and accessible to buyers and sellers what trading opportunities are available (Regnacq et al., 2016). The difference between these choices depends critically on the accuracy and reliability of hydrological measurement. If technology is too constrained for granular consumptive use determination, the exchange rate solution of the Murray-Darling Basin may be more desirable. However, entitlement-specific consumptive use measurement would better represent the space of trades that are nearly externality-free.

If regionally homogenous consumptive shares are not a sufficiently good statistic for hydrological externalities and detailed information is too inaccurate or costly, the market could instead consider *ex post* compensation for economic externalities. Each water transfer could be subject to a tax that contributes to a general fund for injured third-parties (Thompson, 2023, 12). While a transaction tax would introduce a wedge, this tax would be designed to efficiently internalize potential externalities and determined at the beginning of the water year, so that additional transaction costs would not be introduced for regulatory approval. The most important preconditions for such a system to succeed would be comprehensive hydrological monitoring and modeling so that lost water downstream can be attributed to water transfers rather than the normal happenings of a watershed (Colby, 1990, 1190). If it was easy for users to claim harm when it was not the fault of an upstream trade, this system could unravel quickly.

The mix of mitigations between *ex post* compensation and *ex ante* adjudication, as with the choice of how to adjudicate consumptive use, will depend critically on the type of externality and the accuracy and cost of measurement. It is likely that different regions will be better served by different methods, so in this paper, we do not try to identify any best system to manage hydrological externalities. However, technological innovation has come a long way since the water management of the early 20th century and solutions to these physical externalities are now available to support a new water market design.

Communal dependence on water and the political economy of water transfers highlight fundamental economic questions about governing the commons (Ostrom, 2015). In other markets,

[14] While satellite remote sensing has been proposed as a viable solution to fill widespread gaps in monitoring of irrigation water use, the relative accuracy of different satellite-based technologies remains poorly understood, with evidence of large uncertainties when water use estimates are validated against in situ irrigation data (Foster et al., 2020).

gains from trade clearly dominate relatively small pecuniary externalities, but water is so crucial to both human consumption and irrigation that broadly efficient reallocation of water may cause serious harm to local communities (Thompson, 2023, Chong & Sunding, 2006, Livingston, 1995). The current system to protect communities against harmful trading by requiring multilateral coordination between individual farmers and irrigation district board members on a case-by-case basis greatly increases transaction costs and does not effectively balance the gains from trade and potential economic externalities (Womble & Hanemann, 2020, Regnacq et al., 2016).

To handle such concerns in the Murray-Darling Basin in Australia, farmers are subject to *exit fees* to sell water outside of their home irrigation districts. Exit fees, which are determined by the irrigation districts prior to the season, are uniform across trades and capped to not be unduly high (Hanemann & Young, 2020, 120-21). This allows buyers to compensate agricultural communities through the irrigation district for perceived harm without requiring renegotiation or high transaction costs. Trading pairs have ex ante approval of the terms and conditions of a water transfer, greatly reducing transaction costs and the heterogeneity across particular trades.

One concern with such a solution is that there is not perfect pass-through of exit fees collected from the irrigation district to affected individuals. The exit fee mechanism could alternatively be implemented as a local tax on water exports that is redistributed to the residents. For example, some water trades in Arizona are subject to such a tax so that “the state government can adjust local government funding to account for water trade effects” (Chong and Sunding, 2006). Additionally, since empirical work has suggested that the economic impact of a water transfer is small up to a quarter of a region’s water supply, the rules of trade could bound the total amount of water that can be exported[15] (Howitt, 1994).

A more aggressive policy would prevent irrigation districts from inappropriately blocking transfers by applying the *beneficial use doctrine.* Appropriative water rights in California and the American West are held in the public trust and rights holders only have the usufructuary right to divert water for some “beneficial” use – a term that is flexibly defined (Thompson, 2023). California could decide that an irrigation district cannot block the sale of water out of a district if the price is sufficiently higher than the district’s price, as water being inefficiently withheld is not a beneficial use. Such a principle was invoked in a major transfer between the Imperial Irrigation District and San Diego related to the inefficient flood irrigation used in the district (Thompson et al., 2013). While such a policy tool might break through irrigation district barriers, it would certainly be subjected to a political battle.

Regardless of the exact mechanism, the design principle is clear. In order for a trading mechanism to avoid future situations like Owens Valley, irrigation districts and local communities would need to determine clear and uniform rules for how individual water right holders can transfer water out of the region. Buyers and sellers will struggle to reallocate water productively if they must renegotiate every potential trade with every potential affected group. If the magnitude of perceived economic harm is understood *ex ante* and managed consistently, bilateral agreements can be promoted by

[15] Australia has a nationwide cap on transfers out of regions to address this concern (Chong and Sunding 2006).

largely eliminating any uncertainty over how costly trade will be or whether trade will even be approved.

The potential solutions to both hydrological and economic externalities embed a few central themes. First, trading frictions are greatly reduced when water rights specify, without trade-by-trade negotiation or adjudication, how claims among the rights holder, potential buyer, and local communities are to be resolved. Establishing the explicit rules of trade will reduce transaction costs and create security in the water management system, as is necessary for low-conflict and voluntary market participation. With the market environment known, many willing bilateral trading pairs can transfer water according to the rules and guide water allocation toward efficiency.

Property Rights in Transition

The preceding discussion about how trade frictions create barriers to water markets and how rights systems can mitigate these frictions have been widely discussed (Young, 1986, Leonard et al., 2019, Thompson, 2023). While most water economists agree not only that surface water rights reform is needed but also on many details of the desired structure, change has still been stymied both because there is no realistic transition plan and because of the daunting administrative costs of such a change.

In the US, water rights are constitutionally protected property: they cannot be seized or unfairly changed by a government entity without fair compensation (Sax, 1990, 4). Two fundamental barriers to a full water property right transition are the enormous number of stakeholders with protected rights that would need to agree to a new system and the critical interdependencies among the existing rights. These barriers do not just make decentralized trade difficult, but also create challenges to coordinated change.

Similar issues have been faced before in the use of radio spectrum, when the regulator's goal was to reduce the use of airwaves for television broadcast in order to make more capacity available for broadband communications and to impose fewer restrictions on use of those rights. One barrier to change was that each TV broadcaster had the right to be free of interference from other uses. TV broadcast and broadband cannot operate on adjacent frequencies without causing mutual interference, which makes any simple bilateral transaction between companies in the two industries useless. And, to avoid radio interference, there must always be a guard band between the two different uses, in which neither TV broadcast nor mobile broadband operates, so avoiding waste required ensuring that the total size of any guardbands is small. Although the challenges of change were great, the benefits were also clear: explosive growth in the demand for broadband services combined with the decline in over-the-air viewing as some 90% of television viewers had switched to using cable, satellite or internet, making it obvious that changing the frequency allocations could unlock enormous value. The challenge was to find a way to use that value to convince and compensate those who would need to relinquish some rights.

A US presidential commission initiated the solution to this problem, proposing in the 2010 National Broadband Plan to run a "Broadcast Incentive Auction" in which broadcasters would be incentivized to surrender their rights voluntarily in exchange for cash. Broadcasters who chose not to sell their rights in the auction would retain a right to broadcast over the air, but might be required to shift to a different broadcast channel. That allowed the channels reassigned for broadband could be made contiguous and uniform across the United States and Canada, minimizing spectrum wasted on guard bands. Congressional legislation passed in 2012 authorized the Federal Communications Commission to run the auction. Milgrom's firm, Auctionomics, designed the process and provided critical software to execute it.

Planning for a successful Broadcast Incentive Auction entailed a series of steps. Once legal authorization was established, the next step was the *interference study*, which determined potential interference among broadcasters. This study used a mixture of measurement and modeling to create a map of the United States divided into one-kilometer square pixels and, for each pixel, an assessment of the signal strength of each broadcast location on each channel at the center of that pixel. The FCC determined the maximum allowable externality: channel assignments for eligible stations would be made so that no station interferes with more than 0.5% of the population served by another station.

Next, the FCC needed to determine which station rights had to be protected. For example, certain low-power broadcasters operating in otherwise unused frequencies had secondary licenses that were not entitled to protection or compensation in case their operations were interrupted.

There were technical challenges, too. Since the final allocation entailed finding acceptable channel assignments for all continuing stations, the FCC also needed fast algorithms that would run during the auction to check whether and how a given set of stations could be feasibly assigned to the given set of channels. During the auction that followed, the FCC sought to buy enough broadcast rights to allow the remaining stations to broadcast without interference in a specific, reduced set of channels. And, the FCC needed to to decide, based on bids by both broadcasters and broadband users, how many channels to devote to broadcast TV and which frequencies to make available for broadband communications.

Although the preceding steps were technically complicated, the auction rules would need to be simple to avoid discouraging bidders from participating. New auction procedures were invented to make bidding simple and understandable, especially for broadcasters, while still guaranteeing that the resulting channel assignments would be technically feasible and nearly efficient, and could be purchased at prices that would be covered by broadband users' bids.[16]

The Broadcast Incentive Auction, which ran in 2016-17, was widely hailed as a success. When the dust had settled, the process had paid $10 billion to broadcasters who voluntarily sold their rights, raised $20 billion from companies that bought broadband licenses, and caused 70 MHz of new spectrum capacity to become available for wireless broadband communications.

[16] The new class of auctions designed for this purpose and their theoretical properties are both described in Milgrom and Segal (2020).

There may be predictions that water users would resist a similar process[17] echoing the skepticism expressed about the Broadcast Incentive Auction. Some broadcasters were public television stations or religious broadcasters whose missions, it was said, would not allow them to sell broadcast rights for cash. Yet the high prices offered for spectrum rights in big cities convinced even these mission-based broadcasters to participate. In Chicago, a religious broadcaster swapped its UHF station for a VHF station – a modest downgrade – plus hundreds of millions of dollars that it could use for its other outreach operations. In San Francisco, the public television network KQED that owned rights to use three broadcast channels discovered that by upgrading its technology, it could serve 99% of its viewers using just two channels, allowing it to sell the third channel for $95 million. It added those proceeds to its endowment to secure its future operations. In the end, the auction attracted ample participation from broadcasters and the sale of broadband rights generated more than enough revenue to pay them, with funds left over for the US Treasury.

A Water Incentive Auction is no less complicated than the Broadcast Incentive Auction, but can incorporate lessons that were learned. Both kinds of incentive auctions needed to be voluntary processes that would incentivize right holders to participate and convert one kind of right into a different kind. In the Broadcast Incentive Auction, TV broadcast rights were converted into a contiguous set of broadband rights covering the US and Canada. Even if broadband companies could mitigate interference problems, the old individual broadcast rights would still be nearly useless to them. The engineering of broadcast networks requires using a wide band of contiguous frequencies over a large geographic area. So, for example, acquiring channels 47, 49, and 51 is very different from acquiring channels 46-48. Similarly, acquiring rights to use different frequencies in nearby cities is different from acquiring rights to use the same frequencies nationwide. Adjusting interference protections and "repacking" the remaining broadcasters – moving them onto new, equally usable channels – was a crucial part of the process.

We analyze a potential Water Incentive Auction that allows, but does not require, current appropriative property right holders to convert their limited diversion rights to the optimal endpoint discussed in the previous section – secure, transferable, homogenous, proportional, consumptive property rights that manage both hydrological and economic externalities with ex ante mitigation rules and ex post recourse for compensation.

The mechanism we consider constructs new water rights out of the pool of participating appropriative property rights. To encourage participation and preserve an entitlement that enjoys the security of very senior appropriative rights, the pool of water acquired by the mechanism might divide new water rights into three classes - high, medium, and low priority.[18] Depending on the total water flow each season, the total quantity of water within each class will adjust with higher priority classes receiving relatively more in drought years. Individual entitlements within a class will endow the right holder with a proportion of the class' total volume.

[17] Leonard et al. (2019) and Colby et al. (2021) discuss water users' reluctance to participate in these mechanisms due to distrust of regulators.
[18] Water management in the Murray-Darling basin is an example of such a system which offers both high and low priority entitlements.

Since priority classes are coarser than the current right-specific level of seniority, each trade in a class provides a simple benchmark for valuing subsequent trades. In a given year, users can lease the quantity of water determined by their class of rights to any other user. Right holders may also be able to make permanent transfers of their entitlement. While a water right's class will determine the total quantity that year, users would be able to trade across priority classes. Those that do not wish to participate will still be entitled to the water determined by current appropriative rights. However, non-participants will not enjoy the benefits of the new system and instead face the same restricted regime that does not allow changes in season, location of use, point of diversion or type of use. Non-participants will face the same awkward administrative process for transfers and continue to suffer limited adaptation to drought and illiquidity of their water rights, which prevent them from being used as security for loans. In contrast, holders of the new entitlements would be allowed to use those in new ways, such as selling the rights, storing the water in a reservoir, or offering the rights as security for a bank loan. Many users would likely find the new entitlement to be more valuable than their traditional rights even without additional compensation.

The major steps needed for a successful Surface Water Incentive Auction are similar to those that were required for the broadcast auction.

Once appropriate legal authorities are established, the crucial first step would be a hydrological study, playing a role similar to the interference study for the Broadcast Incentive Auction. Using a mix of measurement and modeling, the study would estimate how much water use in one area affects water supply in other areas. This hydrological study would determine both how the consumptive use of different users is to be determined to reduce local return flow externalities and the exchange rates between regions to recognize losses when water is transported. This hydrological model will also determine how priority classes will adjust to drought and will help to manage trade so that non-participating rights are largely unaffected. Property rights would entitle a user to a fixed consumptive quantity, but given the accuracy and cost of hydrological modeling, there are many different methods of consumptive monitoring that could be implemented (Colby et al., 2021).

For consumption rights to be effective, consumption needs to be measured, and satellite technology is one promising way to do that. At the end of the season, if property right holders consume more or less than their right, they could be compensated or charged for their deviation. Alternatively, farmers may be asked to report their crop choices before the irrigation season and their consumptive entitlement must match the expected evapotranspirative water needs for those crops in their region (Colby et al., 2021). In the first case, less oversight is required and farmers have more intertemporal flexibility for crop choice but farmers are subject to potential costs related to overconsumption. In the latter, farmers are assured that their crop choices at the beginning of the season will not face punishment, but they must report and decide crop choices which the state must monitor and if estimates are wrong there is no recourse to reward/punish consumptive efficiency of the farmer.

Ultimately, the choice of method for determining consumptive use will depend on the accuracy of hydrological modeling, the political will for different kinds of surveillance, and the magnitude of externalities that can be ignored. In the TV interference study, a small level of interference was deemed admissible; in the water setting, a small level of return flow externalities could similarly be allowed.

One challenge for a Water Incentive Auction that is different from the broadcast model is that the pecuniary externalities are much larger. The economies of farming communities depend on water, making it important to decide about limits or taxes on out-of-region transfers. It may be unrealistic to ensure that all economic externalities will be addressed. Just as some low-powered broadcasters lost historical access without compensation, some water transfers might be allowed without compensation.

It is possible that new water consumption rights will be so attractive that many users would choose voluntarily to convert to those. One way to start the conversion process quickly and at low cost would be for the government to run a procurement auction (a "reverse" auction) offering to pay the first consumers who agree to convert their rights. The designer can create new rights out of the set of old rights successfully purchased in the auction. The creation of consumptive rights out of the pool of purchased legacy rights will involve estimates, so there may need to be an appeal procedure in which some non-participants claim that their rights have been harmed by the conversion of others. Since any losses suffered by a plaintiff would consist of reduced consumption, which could be remedied by purchases of consumption rights to water at market prices, the value of damages will be easy to estimate. If an appeals system is needed, it might be funded by a fee charged on water transactions.

Encouraging participation will be important for creating a robust new system of rights. Attracting participation from more appropriative rights increases the amount of water used to construct new rights which will make it easier to construct priority classes and protect non-participating rights. Because widespread participation has so many benefits, another possibility, similar to the Broadcast Incentive Auction, would include both forward and reverse auctions. In a forward auction, new water rights will be sold to willing buyers. Bidders in the forward auction might include growing cities that – seeking to secure future water supplies – will offer high prices that would imply significant compensation for sellers participating in the reverse auction. The availability of revenue from the forward auction would motivate participation by sellers who can find the least painful ways to reduce their water use. Current users who seek to convert their rights without significant changes to their operations would be permitted and encouraged to make "swap" bids, in which they act simultaneously as buyers and sellers in the auction (Milgrom, 2007). Additional options could also be included to make participation safe and easy for swappers who seek the advantages of converting to the new rights without actually selling their rights.

The improved design of water rights makes trading simpler and would allow buyers and sellers to make more beneficial trades than in the current regime. With an active water market, the price of water would also help to inform regulation of users who decline to convert their rights. Traditional appropriative water rights require that any diverted water must be put to a "beneficial use," which is a standard that can be reset over time, using the market price as an objective standard. Holders of traditional rights whose uses are far less valuable than market prices could be subject to challenges that their uses are not beneficial.

Conclusion

The theory and practice of market design has evolved over its twenty five year history. It is no longer just about algorithms, but should now include rethinking property rights. Details of the rights specifications can affect both the ease of trade and the likelihood of externalities, as when a water transfer from a farm to a city reduces return flows to local aquifers and streams, harming other users. Trading can cause externalities that can involve many users, but giving veto power to too many users based on uncertain assessments about externalities, as in the current California regulatory regime, results in very high transaction costs and too little trade.

In this paper, we analyze some possible structures of property rights and a framework for promoting a transition. Replacing diversion rights with consumption rights would reduce externalities from changing uses of water and could be paired with reduced regulations, promoting beneficial trades and limiting negative externalities. There is a promising path to a voluntary transition, in which no protected user has to surrender its existing rights. And just as in the Broadcast Incentive Auction, a Water Incentive Auction could unlock enormous value, encourage ample participation, and promote much more efficient allocations.

Figures

Figure 1: Drought water allocations under an appropriative system

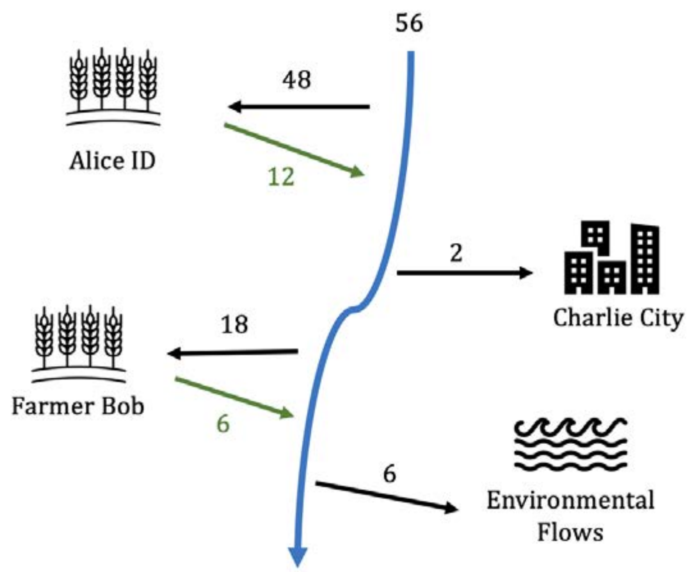
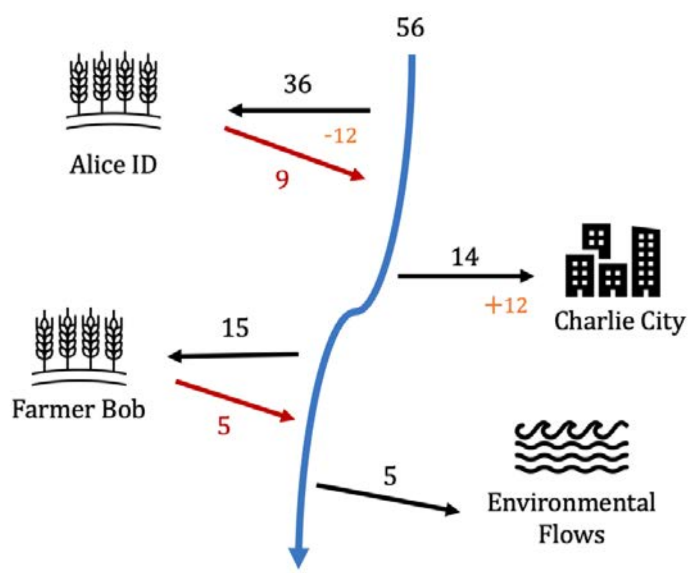


Figure 2: Drought water reallocations with transfers under an appropriative system



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