Accounting for Confounding Externalities

A Coupled Systems Study of Groundwater Management and the Unanticipated Effects of Hydrogeological Heterogeneity

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Accounting for Confounding Externalities: A Coupled Systems Study of Groundwater Management and the Unanticipated Effects of Hydrogeological Heterogeneity

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Abstract

Permitted trading has become one of the leading approaches to manage groundwater supplies and mitigate issues such as scarcity, contamination, and aquatic biodiversity loss. Water markets have developed all over the world, reflecting varied priorities and accommodating regional economic, geographical, and political realities. Proponents of these markets extol their efficiency and flexibility, arguing that negotiated transactions provide a transparent process to determine the price of water, and that the voluntary exchange of permits leads to an optimal reallocation of property rights. Further, they allow regulators to place a limit on the amount of total water that can be withdrawn.

However, groundwater remains a critically scarce resource in the case of numerous aquifers regulated with market mechanisms around the world. Indeed, continued overexploitation and multifarious concomitant issues such as sinking water tables, pollution, and land subsidence suggest deficiencies in this approach. While a well-designed market may ostensibly ensure that property rights are explicitly defined and that there are no transaction costs, I argue that as aquifers are complexes of dynamic, interrelated systems, such broad policy instruments miss critical confounding variables; where water trading has failed, hydrogeological particularities and the heterogeneous effects of trading over space generate information asymmetries, challenge pricing accuracy, and preclude efficiency.

Following a brief explanation of some key terminology, I survey the history of water management in the U.S and discuss the economic justifications of market-based water management efforts. I then conduct a coupled human and natural systems based investigation into why Coasian bargaining may not lead to a Pareto efficient outcome for groundwater permit trading schemes, and the computational, economic, and political sources of market inefficiencies. I find that resource permitting and trading in a free market is not an adequately dynamic groundwater management solution, and leads to a set of unanticipated consequences I refer to as confounding externalities. I perform a case analysis of the Edwards Aquifer in San Antonio, Texas through this framework before suggesting ancillary instruments that may enhance the performance of cap-and-trade schemes.

In the West, it is said, water flows uphill toward money. And it literally does, as it leaps three thousand feet across the Tehachapi Mountains in gigantic siphons to slake the thirst of Los Angeles, as it is shoved a thousand feet out of Colorado River canyons to water Phoenix and Palm Springs and the irrigates lands around them. It goes 444 miles (the distance from Boston to Washington) by aqueduct from the Feather River to south of L.A. It goes in man-made rivers, in siphons, in tunnels. In a hundred years, actually less, God's riverine handiwork in the West has been stood on its head. A number of rivers have been nearly dried up. One now flows backward. Some flow through mountains into other rivers' beds. There are huge reservoirs where there was once desert; there is desert, or cropland, where there were once huge shallow swamps and lakes.

It still isn't enough."

- **Marc Reisner**, *Cadillac Desert: The American West and Its Disappearing Water*, 1986

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The definition of groundwater, and some other key terms

As one of the principal elements of this paper is an analysis of the political, economic, and legal context in which groundwater is exploited or conserved, and as the jurisdiction and mandate of any institution licensed to manage a resource are determined by the definition of that resource, it is necessary, at the outset, to define some key terms. Broadly, groundwater is any water that saturates soil or rock, is naturally banked within the crevices or pores of earth's geologic material, and may move through this structure to resurface again at springs and wells. When a geologic structure yields usable quantities of water, it is designated an aquifer. The upper limit of this saturated area, referred to as the water table, exists where the liquid pressure generated by the presence of water, termed the hydraulic head, equals atmospheric pressure (USGS). Intuitively, as the volume of water contained within the structure decreases, the hydraulic head follows suit, and the water table declines. Of course, this conceptualization of a linear relationship between water table and content is a simplification; in some cases, aquifers retain water in deeper wells, preventing it from traveling upwards, and the estimation of how high the water in these sub-reservoirs would ascend if allowed to flow is termed the potentiometric surface (Freeze and Cherry, 1979).

Aquifers are described in terms of various interdependent properties, such as porosity, hydraulic conductivity, and geologic composition, and while a complete survey of these classification metrics exceeds the scope of this paper, additional terminology is explained as it becomes relevant.

A brief survey of the history of water management in the United States

In the U.S., the human right to exploit natural water resources, both surface and subsurface, has been defined legally by way of one of two different doctrines. The common law approach of riparian rights establishes a correlative dynamic, under which any land owner whose property is contiguous with a water-body is entitled to its consumptive and non-consumptive use, but not without accountability to other users entitled to the same. A different pattern of water law, denominated as *prior appropriation*, developed in the arid west, grants priority entitlements to those users who first accessed and made a claim to the resource. In practice, water systems have historically been regulated through some combination of these two frameworks in most states (Ostrom and Ostrom, 1972).

In order to appreciate the political and economic complexities that characterize water use and management throughout the country, it is necessary to consider the broad incentives that each paradigm creates when there is scarcity in the absence of regulation. Under a system of correlative or riparian rights, galvanized by the possibility of losing access in the future, users are likely to engage in myopic behavior, exploiting the reservoir as intensively as possible without considering the entitlements of other present and prospective users sharing the resource. Such a hold-out strategy has been popularized as the theory of the Tragedy of the Commons. On the other hand, without the network arrangement, a user who enjoys primary access of a diminishing water supply is motivated to eliminate the demands of users granted lower orders of appropriation (Ostrom and Ostrom, 1972, p. 7).

According to Ostrom and Ostrom (1972), "The structure of incentives inherent in the law of water rights is clearly not sufficient to constitute a variety of collective enterprises capable of increasing the supply of water services available to a community of water users" (p. 8). Not to mention, this diagnosis predates the increasing environmental awareness for groundwater conservation, a type of use for which both legal approaches prove to be inadequate.

Due to their relative accessibility, surface waters have historically been exploited in greater measures than subterranean stocks, and for this reason, alternative policy frameworks first evolved for the conservation of stream-flows. As groundwater volumes have followed this trend (Megdal et al., 2014; Gleeson et al., 2012), and are increasingly managed through similar market mechanisms, a brief history of the institutional governance of instream flows illuminates the theoretical substrate that underlies modern aquifer supply management efforts.

The system of prior appropriation was first conceived as an extralegal arrangement in the 19th century by gold prospectors seeking to divert flow away from streams. The doctrine was incorporated into state law throughout much of the west to better manage growing scarcity, precipitated by industrial development and burgeoning human populations. Under this system, states, not individual users, retained ownership of stream-flows, but granted appropriators usufruct rights of varying priority to utilize the resource (Scarborough, 2010, p. 3).

Before the end of the century, much of the natural stream-flow in western states was over-appropriated to what states designated 'beneficial' use, which consisted almost entirely of offstream diversions for mining, agriculture, industrial, or municipal applications, with no entitlements for instream users, such as environmentalists and recreationists. Initial policy solutions to supplement water quantity proved either to be unsustainably expensive and environmentally deleterious, such as supply augmenting damming projects (Chong and Sunding, 2006; Scarborough, 2010; Colby, 2000), or politically untenable and ecologically uninformed, such as administratively calculated minimum instream flow requirements achieved through moratoriums on new offstream diversions (Scarborough, 2010). Texas, a state examined later in this paper, has historically addressed issues of scarcity

> "by building reservoirs and dams, diverting more water from rivers and lakes, and pumping more groundwater. These are no longer viable solutions, physically or economically…Surface water is over-allocated in the majority of the state. Aquifer levels are rapidly declining, resulting in negative externalities like decreased springflow, land subsidence, and increased costs of drilling deeper wells" (Ballew, 2014).

Despite research findings that a re-appropriation of water entitlements from agricultural to urban use would be more economically judicious than new reservoir development and water augmentation projects, federal support for such financially exhaustive programs ceased only in the 1980s (Colby, 2000).

From a conservation perspective, a principal deficiency in the doctrinal underpinnings of U.S. water law seems to be that it was developed primarily to superintend and economize human access, that is "In the sense that form follows function, rights in water have evolved to ensure that societies' needs are met" (DuMars and Minier, 2004), without much consideration for the environmental consequences of overexploitation. Both paradigms discussed above seem to have historically favored agricultural and industrial use and have generated incentives to overexploit; indeed, early cases of adjudication in England regarding water (this being relevant as the riparian, or correlative rights doctrine is a Common Law import), "spoke not in terms of what one could do with the resource as a matter of right, but rather what one could not do to others in the use of the right" (DuMars and Minier, 2004). Some analysts have proffered that, without a trading provision, prior appropriation may not be able to offer any compelling reason to users to conserve or, in the case of agrarian applications, re-examine crop choice (Chong and Sunding, 2006).

As environmental concerns for the preservation of both surface and groundwater escalate, the need for a reorientation of the human relationship with natural water resources has become increasingly exigent.

This is as valid of an assertion for groundwater as it is for surface resources. Subterranean reserves yield roughly 50% of global drinking supply and 43% of global irrigation supply (van der Gun, 2012), and while aquifers are often more capacious than surface reservoirs (Wheeler et al., 2016), their finitude is progressively made more evident across the world by overdraft. Gleeson et al. (2012), compute the total sum of the water balance between inflows and outflows for a set of large, hydrologically active aquifers, and estimate that the global groundwater footprint, or "the area required to sustain groundwater use and groundwater-dependent ecosystem services of a region of interest, such as an aquifer, watershed or community" (p. 197) is ~3.5 times the actual area of the aquifers examined. Even if environmental flows are expropriated, the footprint remains ~2 times the area. The researchers further calculate the ratio of global consumption to the global recharge net the global environmental stream-flow as ~0.2, and caution that "1.7 ± 0.4 billion people live in regions…where groundwater consumption could affect groundwater availability and/or groundwater-dependent surface water and ecosystems in the future" (p. 199).

Water markets and their economic justifications

As global water resources are depleted at a disquieting rate, and demand in the U.S. shifts from agricultural to urban and environmental uses, queuing based appropriation measures without any arrangements for rights trading lead to inefficient distributions of a finite resource and limited adoption of capital intensive conservation options. Chong and Sunding (2006) provide a thought experiment to illustrate, assuming no externalities or transaction costs:

> Suppose that a river has an average flow of 1 million AF; 850,000 AF of senior water rights are held by the agricultural (AG) district, and 150,000 AF are held by the urban (URB) district, which may have outside sources. With prior appropriation, allocation and pricing are not determined in a market context…[Suppose that in an average flow year without trade, the marginal values of water are $30 in the AG sector and $180 in the URB sector]…However, actual prices may be lower; prices are often set using the concept of cost recovery for an agricultural or urban district. If the price set in AG is less than $30, the quantity demanded at that price would be higher than 850,000 AF, and there would be an apparent shortage. Furthermore, the last acre-foot used by AG is worth only $30, but the last acre-foot used by URB is worth $180…A voluntary between the two sectors would increase welfare and lead to more economically efficient use.
>
> "A second inefficiency stems from distribution in the event of a drought. In a hypothetical drought year, the rive supply is 850,000 AF. URB would receive no water from the river, even though it values water more, whereas AG would receive its full allocation…A third in efficiency comes from the response to urban

> growth. Suppose that urban growth expands the demand of URB…The marginal value of water increases to $300…but the URB allocation remains fixed at 150,000 AF. A final inefficiency has to do with conservation technology choice…Absent trade, the low price of water may cause AG to underadopt water-saving irrigation technology (p. 244-246).

One of the more robust feature of the prior appropriation system has been the exchangeability of water rights from one user to another, so long as the transfer does not violate state requirements of beneficial use and non-injury to other users; this provision allows for the reallocation of finite volumes of water to other, potentially more welfare-enhancing applications (Scarborough, 2010). This right of transfer is one of the hallmark design features, and perhaps one of the more frequent arguments made in favor of market-based water resource management, such as cap-and-trade systems, which have come to replace the supply-side oriented federal projects (Hadjigeorgalis, 2009).

In fact, Chong and Sunding (2006) aver that theoretically, that is to say, presuming no transaction costs and discounting any inadvertent effects on third-parties, a trading mechanism should preclude the four types of inefficiencies discussed above.

Proponents of markets as an alternative solution extol their efficiency and flexibility, arguing that negotiated transactions provide a transparent process to determine the price of water (Gao et al., 2016) and facilitate cost-effective processes leading to an optimal reallocation of property rights (Thompson et al., 2009). Cap-and-trade schemes specifically, some researchers contend, provide policymakers, who can establish a quantitative ceiling, a more lucid mechanism to reduce actual water use, as opposed to usage fees, which may only deter overexploitation to varying degrees based on the price sensitivity of demand. The market may also, theoretically, adjust water price naturally, ushered by supply and demand dynamics, whereas fees or taxes are complicated by economic realities such as inflation (Baumol and Oates; 1988).

Further, as Chong and Sunding (2006) explain, "Trading helps equalize the marginal prices faced by various water users, thereby providing information about the value of water in alternative uses and creating compatible incentives" (p. 239).

Specifically examining the Nebraska Republic Basin, which researchers maintain is a fair representation of water resource issues in western states, Thompson et al. (2009) realize that in those cases where irrigation is the primary application of groundwater, and where the political intention is to reduce the total amount of water lost as evaporation or transpiration, capping pumping rights is likely to prove satisfactory. Moreover, their analysis finds that trading of water entitlements allocated under all quantitative caps currently deployed at or under consideration for their study area reduced consumptive use.

Market based mechanisms, which provide users economic incentives for better administration of natural resource stocks, have become some of the leading approaches to mitigate a variety of issues such as scarcity, contamination, the generation of externalities, and biodiversity loss. In the U.S., market solutions have been prescribed for the management of fisheries, air quality, freshwater, lead content in gasoline, and the release of ozone-depleting chemicals and nitrogen oxide (Colby, 2000).

Water markets have developed all over the world, reflecting varied priorities and accommodating regional economic, geographical, and political realities (Colby, 2000; Hung et al., 2014; Wheeler et al., 2016). In survey of groundwater governance conducted across all 50 states and the District of Columbia, Gerlak et al. (2013) report that resource rights permitting is the most prevalent of a number of complementary management strategies, relied upon by about 88% of respondents (followed by monitoring at 84%, planning at 70%, designated protected areas at 54%, land use regulations at 36%, and extraction fees at 16%). This is a noteworthy statistic, due to the tradability of permits within cap-and-trade scheme architecture.

In the most elemental respects, water markets function quite like the markets for any other depletable resource; administrators, ideally informed by sufficient apposite scientific research, establish a total limit on water use (or in the case of groundwater, on withdrawals), and either auction or allocate rights, or permits, of varying priority to users, who may then trade these entitlements among themselves. In principle, these exchanges should allow for the redistribution of the initial allocation to their highest valued uses, increasing overall economic welfare (Dinar et al., 1997; Ballew, 2014; Heaney et al., 2006).

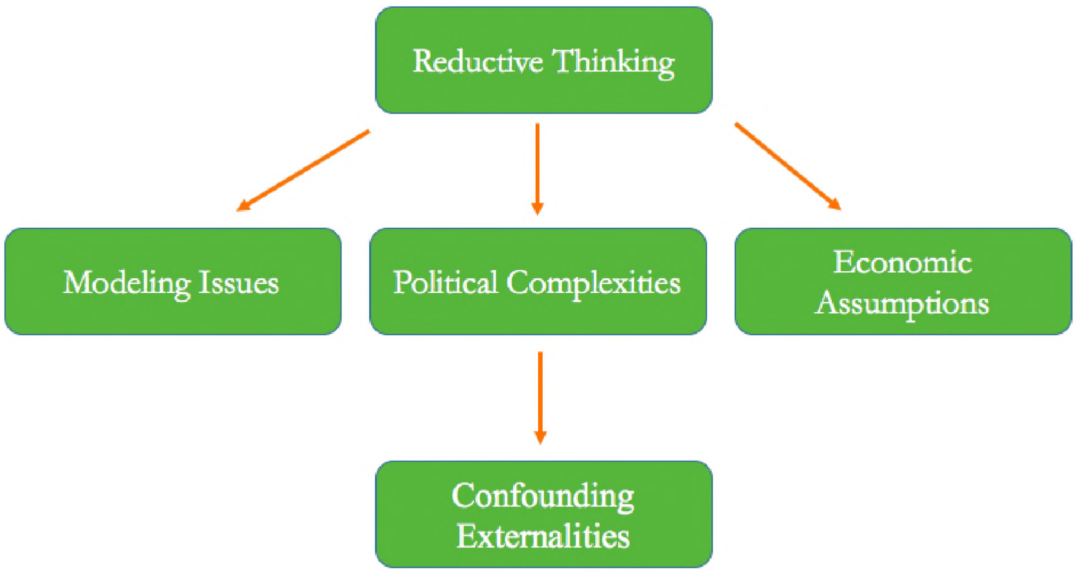
Ballew (2014) provides a simple, demonstrative example of the groundwater trading mechanism:

> …consider a farmer and a nearby city within the same watershed. During a drought year in a market-based allocation system, the farmer would be incentivized to conserve the amount of water used to grow crops because he could sell his surplus water to the city [or to other users], making a profit greater than the profit he would make from growing his crops. During non-drought periods when water supply is greater, the farmer would keep his water, running farm operations as usual, and the city would turn back to its usual supply (p. 2).

The actualization of these benefits depends upon a set of conditions and market features, the most salient of which include the presence of: some critical mass of market participants, or economic agents, motivated by profit maximization; clearly elucidated rights to water, including a specification of term and total allowable withdrawal quantity, as well as any other constraints that may be deployed in special circumstances; low barriers to entry and low transaction costs associated with trading; perfect, complete, accurate, and accessible scientific information so that participants can make informed and rational purchase and sale decisions; metering technology that helps ascertain the volume of water withdrawn so that a register of available quantity can be accurately maintained; institutional stability, and a scientifically informed governance structure that designs regulation in a way such that conservation objectives can be met, guarantees consistent enforcement of rights, and communicates price information to participants (Dinar et al., 1997; Ballew, 2014).

Notwithstanding the theory that supports market based initiatives, a substantial body of research controverts claims about the natural efficacy of water marketing and permit trading, particularly as it is applied to groundwater management. Indeed, while they are growing in popularity, as of 2000, only four markets across the country with the volume of trading activity required to maintain stable pricing, and although the literature on water markets is rather extensive, it focuses primarily on surface-water trading (Chong and Sunding, 2006; Maddock and Haimes, 1975; Heaney et al., 2006; Colby, 2000; Skurray and Pannell, 2012; Wheeler et al., 2016; Hung et al., 2014).

At the most fundamental level, where cap-and-trade founders, the nonspecific diagnosis is poor design, which results in the establishment of an incomplete market, often itself a symptom of reductive thinking. The next section of this paper elaborates on the diagram below, investigating some common pitfalls that lead administrators to miscalculate the consequences of their policy-based solutions.



Sources of incomplete markets

Reductive Thinking

In a 2008 study attempting to enumerate the global issues scientists from a variety of disciplines consider most exigent, a participant pool of 4,169 professors, postdoctoral fellows, and research staff members at Cornell University were asked to produce a list of crises and then rank them (on a scale of 1-5 of ascending magnitude) in terms of *importance* and *solvability*. Of the 116 unique problems identified, "Climate change and its effect on ecosystems" was ranked first in importance, and "shortage of potable and clean water" was the only one that featured in the top ten for both importance and solvability (Cabrera et al., 2008).

The researchers, reflecting on the insights produced, diagnose a meta-crisis of thinking that contributes to our repeated practical failure when attempting to solve these problems, a symptom of both the harrowing combination of the time-sensitivity and complexity of these issues, and our inability to completely conceptualize their nuances when formulating solutions. Cabrera and Cabrera (2015) argue that our thinking is: reductive and preoccupied only with the parts of a compound problem rather than the whole; one-dimensionally hierarchical, and therefore rather obtuse when it comes to understanding more complex, distributive arrangements; dependent on static categories rather than part-whole couplings; rigidly linear and causal; imperceptive of dynamic relationships; and biased towards bivalent rather than multivalent logic. They assert, "Climate change, hunger, wealth distribution, and childhood obesity, while all legitimate crises, are not the *root* crisis. The root crisis is the way we think. That is the problem that underlies all the other problems" (p. 13-14). In other words, analysts of any problem are prone to oversimplification, patterned thinking, and a number of other types of logical fallacies and heuristics that lead them to suboptimal assessments.

A rather conspicuous example, as it relates to groundwater management: many of the earliest efforts to analyze optimal water withdrawals that conceived aquifers as subterranean bathtubs, physically homogenous underground stocks with consistent water tables and inter-structural pressure, compromised accuracy for mathematical simplicity (Athanassoglou et al., 2009). In reality, these reservoirs are complex snarls of countless tunnels and apertures passing through geologic structures of varying porosity, each aquifer made distinct by multifarious hydrogeological idiosyncrasies.

It is a matter of paramount importance that, in order to operate effectively and without any unintended consequences, market mechanisms are designed accounting for these heterogeneities; indeed, put simply, water systems are dynamic, and the repercussions of human action that transforms the manner in which the systemic components interact are not always anticipatable. For these reasons, sustainable management schemes must not sunder the natural hydrogeological features of groundwater resources from economic and political phenomena.

The complex mechanisms of a groundwater system may be understood with more exactitude when studied within the coupled human and natural systems (CHANS) framework, a theoretical and directional tool for conservation research that seeks to bridge the gap between the natural and social sciences by moving beyond traditional conceptualizations of the nature-society dynamic in which the natural world was isolated from human socioeconomic considerations (Lassoie and Sherman, 2010).

Liu et al. (2007) explain CHANS in terms of a number of defining characteristics and principles, which can be condensed as follows:

Reciprocal effects and feedbacks

As humans exploit resources, they risk destabilizing or transforming the states in which their environment exists, thereby precipitating devastating natural processes. These human-environment interactions are patterned as negative or positive feedback loops.

Indirect Effects

The complicated arrangement of most CHANS, and their sometimes confounding components and interrelationships, renders them rather unpredictable, making it difficult to establish causal relationships between two events or processes, or to anticipate fully the consequences of a particular interaction, development, or incident. The extinction of a keystone species, for instance, may propel broader trends that reconfigure an entire ecosystem.

Emergent Properties

Certain characteristics of CHANS exist only as a result of idiosyncratic inter-system processes, and it is important to understand the particular agents or entities that produce them, as well as their functional relationships. For example, "spatial distribution and quality of panda habitat result from human activities (e.g., timber harvesting, fuel wood consumption) and natural processes (e.g., forest succession)" (p. 641). If these relationships are better understood, management efforts can direct their limited resources with greater precision.

Vulnerability

This is a measure of the susceptibility of a CHANS to exogenous, detrimental uncontrollables, and can be conceptualized as either 'outcome vulnerability,' or a function of only the magnitude and nature of external hazards, or as 'contextual vulnerability,' that is, an extension of a pre-existing state, an a priori condition that exists irrespective of any hazard (Shukla et al., 2016) but which determines the state-shift of a system. It is important to note that vulnerability is not determined simply by the natural durability of an environment; rather, as human agents are considered an inextricable part of any ecosystem, their social and infrastructural integrity is an important factor as well.

Thresholds and Resilience

Once a system's current state is compromised, it is important to consider the permanence of a shift, which is measured by resilience, or "…the ability of CHANS to retain similar structures and functioning after disturbances" and is a property that is additive, as "subtle losses of resilience can set the stage for sudden, surprising, and large changes in ecosystems that are difficult or impossible to reverse" (Liu et al., 2007, p. 641). The points at which these critical shifts occur are referred to as thresholds, or tipping points, and may often lead to rapid ecosystem collapse (Lassoie and Sherman, 2010).

The subsequent sections apply CHANS theory to the analysis of the computational, political, and economic sources of groundwater market failure.

Computational, or Modeling Issues

As Chong and Sunding (2006) state, a free-market allocation of rights does not offer an efficacious solution when managing nonstandard commodities such as water, which is a flow that circulates through the Earth's hydrologic cycle. The volume of the resource that is available in any given stock, whether surface-level or subterranean, at any given time, depends upon innumerable variables, such as precipitation and the material structure of its reservoir.

Groundwater management is further complicated by the fact that "it is less visible [relative to surface water] and recharge is more difficult to measure than stream inflows. Also, the hydraulic interconnectedness between different aquifers and between aquifers and surface water is still not fully understood in many regions" (Wheeler et al., 2016, p. 494).

Therefore, in many instances, an aquifer exists as part of a more expansive system in which precipitation and return flows move through underground passages, across varying elevation and potentiometric pressures, supplying surface-level waterways, and this can generate some key feedback loops, indirect effects, and emergent behavior.

Within an interdependent water supply system, surface level extractions, even those diverted from stream-flow, may diminish subterranean volumes, and vice versa, and changes in upstream flow are not without consequence for downstream users (Jordan; Hartman and Seastone as cited in Hadjigeorgalis, 2009).

Not all use of water is consumptive, and in the case of certain types of use- such as for hydropower generation and recreation- some of the exploited resource is restored to the original stock by way of return flows. Trade of entitlements may result in a reorganization of the points of extraction, which can in turn diminish return flows, a key source of water for some users that are not consulted during the transaction (Merett as cited in Hadjigeorgalis, 2009).

Numerous repercussions of overdraft such as land subsidence, saltwater intrusion (Wang et al. as cited in Hadjigeorgalis, 2009) and mineral leaching may interact to initiate feedback loops, decreasing usable resources at a faster rate than projected as based on historic drawdown. The convergence of these phenomena has the potential to breach hydrogeological thresholds, beyond which feedback loops of even more considerable magnitude, occurring across greater spatial and temporal scales, can further accelerate depletion and produce presently unpredictable emergent trends.

For the sake of most applications, whether municipal or environmental, a diminution in water quality has essentially the same effect as a reduction in quantity, as degradation can render the resource unsuitable for consumption. Vulnerability of any stock or flow to pollution is also inconstant, and depends on pedological and edaphological properties, geographical location, the human use of chemicals such as fertilizers and pesticides, and the disposal of waste (Wheeler et al., 2016).

Often times the nuances of this systemic behavior, with all of its constituent interdependencies, are neglected for the sake of easily delimiting administrative boundaries and jurisdictions. Even if the political will exists, and despite great advances in the field of hydrologic modeling (which now makes use of sophisticated software tools such as MODFLOW to solve complex groundwater flow equations), it is difficult to accurately simulate tortuous hydrogeological structures; the governing partial differential equation utilized by the MODFLOW program takes a number of factors into consideration, such as hydraulic conductivity in three dimensions, potentiometric head, volumetric flux, storage of the porous material, and time, but may not be able to anticipate more dynamic emergent patterns and feedback loops.

Economic Assumptions

The economic justifications for cap-and-trade, such as the redistribution of a limited resource to its most efficient users, are predicated on the economic theory of *Coasian bargaining**, which argues broadly that if property rights to a resource are fully and clearly defined, and if the transaction costs concomitant with their trade are negligible or nil, and if economic participants have access to complete information, then the problem of externalities generated by pollution, or the consumption of a limited natural resource (such as clean air, or by extension, some volume of clean water) can be mitigated.

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*In reality, the true internalization of externalities by way of Coasian bargaining is conditional on a set of unrealistic economic conditions. See "The Problem of Social Cost" by Ronald Coase (1960).

In such an ideal scenario, agents inflicted by an externality can bargain with the producers of the externality until all parties are satisfied, and it should not theoretically matter to whom the property rights are initially granted as redistribution will occur until some Pareto optimal equilibrium is achieved (Coase, 1960; Baumol. and Oates, 1988).

However, the unique properties of groundwater described above contribute to making the management of these systems a problem that may not be best addressed by Coasian solutions. Some potential problems of entitlement transfer include:

- Redistribution: Transfers can cause the spatial and temporal redistribution of the impacts of groundwater extraction
- Concentration: Groundwater transfers can cause the spatial concentration of extraction, thus potentially concentrating and compounding its impacts at particular locations
- Transformation: Impacts of groundwater extraction may differ in their nature and extent between the original and newly-transferred locations
- Uncertainty: Negative effects from groundwater transfers may be uncertain (Skurray and Pannell, 2012, p. 880).

Heaney et al. (2006) caution that in the absence of completely defined property rights, trade of entitlements may create negative effects for parties not directly involved in the transfer; these are referred to as third-party effects. Skurray and Pannell (2012) further corroborate this argument, writing that "the wide range of impacts from groundwater extraction, and their potentially wide spatial extent, mean that their costs may be born by an equally wide range of third parties" (p. 881).

Although the literature on these effects is expansive, for the purpose of defining and expounding the theory of confounding externalities, which is one of the objectives of this section of the paper, a subset of all third-party impacts is reviewed.

First, a spatial redistribution of permits may unexpectedly reduce the quantity or reliability of water supply. Heaney et al. (2006), examining the southern Murray-Darling Basin in Australia, write illustratively:

> …entitlements are defined at the point of delivery. The number of potential sources from which these delivery points can be supplied increases moving downstream as the effective catchment area increased with tributary inflows. Unless traded entitlements retain the features of the reliability of supply from the exporting catchment, net trade that spans one or more tributaries can affect the reliability of the entitlement in both the source and the destination regions. If water is traded upstream of a tributary, a given pool of resources may be spread over a greater number of users, thus decreasing supply reliability for those users. At the same time, there is an increase in the share of resources that is potentially available to users below the tributary (p. 281).

Adapting this argument to groundwater, a straight, free-market transfer of the right to pump from one location to another does not account for the hydrogeological inconsistency of the subterranean reservoir system, and it may be that the ease with which water can be exhumed from the earth varies between the two geographical points. Therefore, in order to guarantee volumetric reliability, it is critical to determine whether the permits should be defined at the point of origin or delivery, and to carefully consider spatial heterogeneity.

Second, the monetary value of a permit, which is somewhat one-dimensionally realized at the intersection of supply and demand in an open market, may not reflect the degradation or improvement of water quality, which is partially a function of the quality of return flows. If pumping activity shifts to a type of application that increases salinity and toxicity, such as irrigative use that relies heavily on fertilizers, pesticides and insecticides while creating significant return flows, the transfer has generated an externality by reducing the general regional quality of the resource as well as the volumetric availability of usable water.

For many aquifers, drawdown naturally reduces water quality as it increases mineral leaching, but the anthropogenic introduction of noxious chemicals can create positive feedback loops and indirect effects across larger regions than can be anticipated. Further, as the hydrogeology of an underground basin is location-specific, it is crucial to have users understand the full consequences of rearranging the points of origin and destination (Skurray and Pannell, 2012; Healey et al., 2006; Hung et al., 2014).

The market value of permits also neglects the temporal aspects of present groundwater use, as time-lagged effects (a sort of emergent trend) in larger, less transmissive aquifers can significantly reduce the available supply in the future, increasing pumping costs (Skurray and Pannell, 2012).

Finally, trade can impose a cost on non-sentient entities such as the environment, or non-human species, and it is not possible to integrate the priorities of those parties in a Coasian bargaining program (save for an indirect representation as reflected in the priorities of environmentalists and recreationists) as they obviously cannot be satisfied with monetary remuneration, and the total impact of the externalities on these other agents may be difficult to monetize (Skurray and Pannell, 2012).

For these reasons, it may be argued that it is quite impossible to achieve the conditions requisite to realize the benefits of a Coasian scheme as it is applied to groundwater; as permit prices reflect only the economic valuation of water vis-à-vis human demand, they are ipso facto unable to capture many of the nuances that factor into resource availability or scarcity. The result is an incomplete market that suffers from information asymmetries, transaction costs, and nebulous property rights.

This is not to completely discount the economic rationalization for trading, which does provide a mechanism through which human third-party interests or representatives of non-human third-party interests can work to reallocate use. For example, if the superintending agency identifies an environmentally sensitive area, it may actively engage in trade or create incentives using a menu of policy instruments to relocate pumping. Without the ability to transfer rights, the spatial pattern of usage remains static regardless of its negative impacts (Skurray and Pannell, 2012). It is important to note however, that this correction cannot occur without some measure of regulation.

Political Complexities

The construction of a sustainably and efficiently operating cap-and-trade scheme is quite a multidimensional political problem. Policymakers face the arduous task of establishing an effective, economically infrangible, socially equitable, and environmentally innocuous institutional arrangement. Some major considerations include:

> (1) who may claim [the resource] and for what uses or purposes, (2) exclusiveness or jointness of use, (3) exposure to the claims of others, (4) stability or perishability of the right over time, (5) transferability of the right, (6) burden for bearing the costs or risks of adversity, and (7) the structure of authoritative arrangements for reaching and enforcing determinations in relation to conflicts of interest between individual users and among communities of water users (Ostrom and Ostrom, 1972, p. 6).

Colby (2000) expounds the process of design that precedes the establishment of rights, which commences with a determination of a maximum limit on how much water can be exploited within a temporal frame. This initial estimation, which must be realized at the fountainhead of the entire venture, is already a scientifically perplexing assignment due to the hydrogeological uncertainties and attendant economic complications described in the previous sections. If a cap is set without sufficient scientific research, the probability of unanticipated repercussions rises significantly, and it is unlikely that the superintending agency will be able to furnish accurate information regarding aquifer capacity and optimal groundwater use, a requisite condition of a complete market.

The pattern of the original distribution of entitlements must also be scrutinized, as political incentives may be misaligned with social, environmental, or economic objectives. As an extension of the prior appropriation doctrine, water markets often prioritize the needs of users who have demonstrated beneficial use over some period of time in the past; at the Edwards Aquifer, for example, initial allocations were granted to applicants who made such use in any given calendar year within the historical timeframe 1972-1999; this was followed by a rather tempestuous period during which numerous parties- including environmentalists, galvanized by the concern that water was over-appropriated, as well as other users, who felt that the allotments were inequitable- filed objections (Colby, 2000). Such litigatory episodes are expensive, and are likely to engender a fissiparous political and social environment.

Some researchers maintain that auctioning initial permits may be a more advisable alternative to free allocation. James P. Barrett, regarding the dispensation of carbon permits under a cap-and-trade system, defends this position unequivocally, avouching that "Under grandfather, polluters receive a lump-sum distribution of valuable assets. This represents a pure wealth transfer from energy consumers to energy producers. There is no incentive attached to this transfer, and thus produces little or no change in marginal behavior…" (Barrett, 2009).

Permit auctions generate revenue for the government, which can capitalize a variety of economically productive policies, such as the reduction of taxes to encourage enterprise, or the subsidization of new technology development. Regarding this, Barrett (2009) asserts:

> Energy efficiency falls into a class of goods called 'public goods,' i.e., goods that can be consumed by more than one person simultaneously. Markets tend to yield suboptimal investments in efficiency research and development. Using auction revenues to fund energy efficiency, or any other public good for that matter, would produce economic gains. The increase in energy prices would increase the economic return to energy efficiency, all else equal.

Here, an analogue argument can be constructed for groundwater rights. Erosion of economic and agricultural activity is amongst the most common grievances lodged against the regulation of water use (Colby, 2000), and while the market *should* redistribute access to those rights-holders who make the most efficient use of their entitlements, a review of permit exchanges reveals that trading activity seldom emulates theory.

Perhaps the most intractable of political problems is that of consensus-building amongst numerous stakeholders and claimants. Administrators must attempt to achieve some equilibrium with the inconsonant interests of direct resource users, environmental advocates, policymakers, competing claimants such as new market entrants and aboriginal groups, regulators such as fisheries services and the EPA, and economically linked entities such as agriculture-dependent counties and recreationist-dependent businesses (Colby, 2000).

Often, additional considerations must be made as to how the scheme will be restructured in extraordinary circumstances, such as drought, during which time managing rival interests may become even more difficult.

In some places, such as Texas (a point revisited with the Edwards Aquifer case study), surface and underground flows are legally regarded as different entities, and are managed by different agencies, despite the physical interconnections. This sort of distinction often reflects entrenched political and social cultures, which are difficult to revise, but will regardless limit the accuracy of simulation and optimization modeling, as well as the ability of administrators to predict indirect effects of dissonant policy decisions.

Then there is the matter of defining objectives. Research in favor of permit trading reasons that it is the most cost-effective route towards Pareto optimality, or socially optimal allocation, and so this is often the theoretical underpinning behind cap-and-trade schemes (Chong and Sunding, 2006). This should not always be the policymaker's intention, however, as Pareto efficiency implies that the priorities of *all considered agents* are best satisfied, but not that the priorities of *all impacted agents* are. As stated at numerous points in this paper, these agents have included environmentalists and recreationists in the past, and now may include the environment itself, or other species.

As the political contours within which a market operates are a critical determinant of the economic dynamics of water management, which in turn can significantly transform hydrogeological and ecological structures, it can be argued that the absence of a secure institutional and political context is closely related to a growth of systemic vulnerabilities. That is to say, if legislators fail to bear in mind the priorities of a diversity of stakeholders (including the environment's entitlement to sustain its natural functions and guarantee habitat for other species), or if they do not prioritize the right objectives, or if they do not holistically assess the economic and natural dimensions of their jurisdiction, or if they do not lucidly define property rights, or if they do not preemptively outline plans for extraordinary scenarios, or if they inadvertently create incongruous incentives, they may promote contextual vulnerability.

Confounding Externalities

Reductive thinking- which relies on oversimplifying economic assumptions, does not holistically assess political complexities, and is constrained by computational difficulties- foments poor policies which have a high potential for constructing an incomplete market besieged by third-party effects. A specific group of these effects, referred to in this paper as *confounding externalities*, consists of those externalities that are, ironically, created by policy efforts to internalize existing externalities. These recursive externalities result directly from the limitations of extant economic solutions in managing the indirect, heterogeneous spatial and temporal effects of trading water over geographical space.

As a simple expository thought experiment, consider a cap-and-trade scheme for groundwater located in a region characterized by an inconstant topography of varying elevation. The subterranean reservoir is a carbonate-rock structure characterized by some medium level of porosity and permeability; in certain areas, water travels unimpeded, as if through a sponge, and in other places, it is confined by relatively impermeable rock. Water rights trades occur in a free market, with no arbiter to determine prices, and no directive regulation. The permits, which are allocated by some sort of grandfathering process, are subject to temporal and use restrictions (that is, they can be temporarily leased or permanently transferred, and must specify either agricultural, municipal, or industrial application). It is speculated that, in accordance with the Coase theorem, the initial permit spread will self-restructure to maximize social welfare as trading occurs. The superintending agency provides data on past transactions so that individuals wishing to bargain for an entitlement can predicate their positions on historic pricing. As is the case with most water markets, trading across applications, such as from irrigative to municipal use, is rare as most users value their collective type of use. Agricultural agents in particular are hesitant to allow their grandfathered rights to shift to municipal or industrial use, as that may precipitate a future shortage of supply for irrigative use. One of the administrative objectives of the scheme is to limit total annual drawdown so as to maintain some amount of natural discharge at wells.

Two market participants, agricultural users D and U, decide to engage in a trade. The former, who lives at a relatively lower elevation, wishes to permanently sell x acre-feet of her allocation to the latter. They bargain, referring to the ledger of past trades, and arrive at a mutual agreement that a payment of Px, where P is some dollar value, made by U to D is an appropriate remittance. Sometime after the trade occurs however, agent D realizes that there is significantly less volume of water available within her wells than she anticipated; the total drawdown is in fact a volume of x+y acre-feet. Not only this, a number of other groundwater dependents in D's vicinity, as well as those downstream, also experience a decline in natural discharge.

What has happened is this: A shift in pumping to a higher elevation (from user D's wells to user U's wells) has reduced hydrostatic pressure within the aquifer system; as more water is drawn at greater altitudes, there is a decrease in the total weight of the liquid exerting pressure on intra-system flows from above, and therefore a concomitant diminution in the volume of water that is naturally pushed upwards to wells at lower altitudes. Further, as D has decreased her total groundwater use by x, she has also limited her contribution of return flows by some proportion of x, and some users further downstream who relied on these flows can no longer access them.

As U and D bargained, they relied on some idea of a mean market price for water in their region based on historic trends, but what they failed to anticipate are the idiosyncratic hydrogeological elements of their particular trade. In this market, the price of water is a reflection of aggregate human valuation based on supply and demand, and the trade between D and U is theoretically a welfare improving transaction; as water moves to a higher value use it should reduce associated externalities. In reality, reductive thinking evident in market design has neglected dynamic system properties, and the monetary appraisal of x acre feet of water at the sale price of Px is an inaccurate pricing of the resource, which should in fact have been P(x+y+o), where x+y is the total supply shortage D experiences as a result of a change in hydrostatic pressure, and o is the total supply shortage all other users experience as a result of a change in pressure as well as in return flows.

Although this is a rather uncomplicated exemplification, this general principle of confounding externalities can be applied to further gradations of problems related to the unanticipated, heterogeneous effects of trading water over a heterogeneous landscape.

The final two sections of this paper are a systems-based examination of the Edwards, a high-yielding aquifer in central Texas, featuring an interview with Marc Friberg, an executive at the chief groundwater superintending agency on-site, followed by a survey of alternative groundwater management instruments that may mitigate the problem of confounding externalities.

Edwards Aquifer Case Study

Hydrogeological Details

The Balcones Fault Zone Edwards Aquifer is a highly porous, honeycombed, underground water system that lies within the Edwards Plateau, a region in west-central Texas. Water within the Edwards, referred to as such, or as the EA, in this paper, passes through a complex underground structure at very high speeds, eventually moving up due to hydraulic pressure and discharging at wells and natural springs; for these unique hydrogeological properties, it is considered a *karstian artesian* aquifer (these are topographical terms used to describe a landscape characterized by subterranean sinkholes and caves, formed of limestone, gypsum, and dolomite). This formation, which is considered one of the most productive basins in the U.S., spans a 4,350 square mile area and underlies parts of 11 counties. The aquifer is the primary source of water for approximately two million people who reside within and around its boundaries, in the City of San Antonio, as well as for downstream users in the Nueces, San Antonio, Guadalupe, and San Marcos river basins. It also provides habitat for numerous aquatic and subterranean species (Eckhardt).

The San Antonio segment of the system is confined by groundwater divides at the cities of Brackettville in the south-west and Kyle in the north-east, between which it arches for a distance of roughly 180 miles, and consists of three major contiguous regions: the catchment, or contributing zone, where the densely wooded land surface captures rainfall; the recharge zone, where runoff from the contributing zone falls through fractured limestone into the aquifer; and the artesian zone, a porous limestone formation in which the water is stored and through which it moves by way of faults, tunnels, and other interstices (Eckhardt).

Roughly 75-80% of the EA's water replenishment is allogenic recharge, which occurs when water runoff from the catchment area flows in streams and rivers and sinks into faults along the recharge zone surface. Other sources include precipitation that falls directly on the recharge zone, referred to as autogenic recharge; surface water reservoirs; and neighboring groundwater systems such as the Trinity aquifer. While the volume of annual allogenic and autogenic recharge may vary greatly from one year to the next, the median for the period from 1934 through 2014 was 556,100 acre-feet, with the lowest measurement recorded at 43,700 acre-feet during a severe drought in 1956, and the highest at 2,486,000 acre-feet in 1992. It is not certain how much water enters the Edwards through inter-formational flow, such as from other adjacent aquifers, and estimates range from 5,000 to 60,000 acre-feet per year (2010-2015 Groundwater Management Plan, p. 18). The system is also marked by sinkholes and caves, which can absorb large volumes of recharge.

Once the water flows down gradient into the artesian zone, it is captured within a highly porous, and typically karstian structure of rock matrices, conduits, and caves between the relatively impermeable Del Rio Clay below and Upper Glen Rose limestone formation above. Here, water can sink to depths of 3,400 feet below the surface. As is the case with artesian aquifers, when new recharge enters the structure it applies immense hydraulic pressure on the stored stock, which consequently rises upward through pores and natural tunnels to achieve hydrostatic equilibrium, and is eventually discharged at wells and springs. Due to its permeability, high volumes of water move into and through the Edwards relatively unimpeded, and hence aquifer levels are quite sensitive to recharge (Eckhardt).

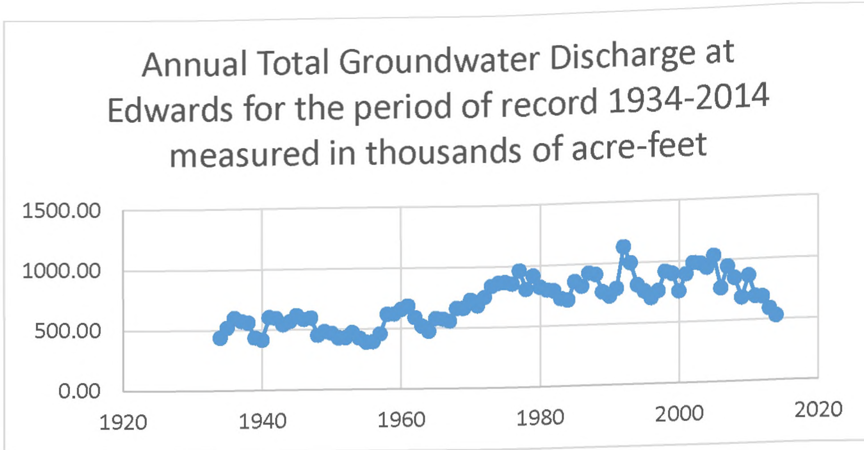
While most of the Edwards carries freshwater, a deeper portion of the reservoir along its southern and eastern edges is less pervious and so water stored here over a high residence period absorbs minerals from the surrounding limestone and becomes saline. In this area, freshwater typically flows closer to the surface while saltwater is contained deeper underground, and the two converge along an interface colloquially referred to as the "Bad Water" line. If the aquifer is overdrawn, the more saline water (considered non-potable when the concentration of its dissolved solids exceeds 1,000 parts-per-million) may move further up, adulterating the freshwater and further reducing the total potable volume available. However, a number of studies have reassured that such contamination, if it does occur, will likely be temporary, as new recharge will force the saltwater back down (Eckhardt). The residence time of the water within the aquifer, which determines its salinity, varies from a few hours to several years, and depends on a number of factors including depth and location (Tremallo et al., 2015).

Groundwater is either naturally discharged from springs, many of which are clustered within the Comal and San Marcos systems, or withdrawn from drilled wells. While the former is used primarily for the recreational economies in the Cities of Braunfels and San Marcos, the latter provides a significant amount of the agricultural, municipal, and industrial supply in south-central Texas (Tremallo et al., 2015).

Although it is difficult to determine the aquifer's total capacity precisely, due to its complex geology, estimates based on effective porosity, or the percentage of total pores that are connected to other pores allowing water to travel through the structure and up to wells and springs, fall somewhere around 19.5 million acre-feet of stored water in the confined freshwater zone (Maclay and Small, 1984), 45 million acre-feet of circulating freshwater (38 million acre-feet in the confined area and 7 million acre-feet in the unconfined region) (Maclay and Small, 1995). More generous estimates speculate that the total volume of water in the confined portion may be as high as 157 acre-feet (Hovorka et al., 1996)

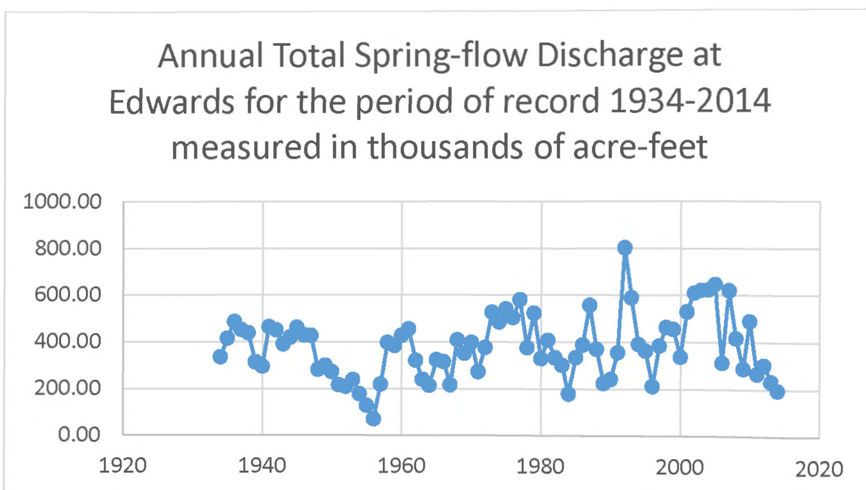
Practically, however, the amount of groundwater available is much lower, as the complicated relationship between depth, recharge, and hydraulic pressure determine how much water is discharged at natural springs, and withdrawing water from deeper within the system is generally cost prohibitive (Eckhardt).

Statistics reporting the volume of aquifer water use by county were initially furnished by the United States Geological Survey from the 1950s till the late 1990s, and then the Authority hence. Estimates of annual total groundwater discharge for the period of record 1934-2014, which consists of both spring-flow and well-water withdrawn, range from ~388,800 acre-feet recorded in 1955, to ~1,130,000 acre-feet in 1992, with the mean and median figures at ~687,000 acre-feet and ~694,100 acre-feet, respectively.



(Graph created with data provided in the Edwards Aquifer Authority Hydrologic Data report for 2014, published in November 2015)

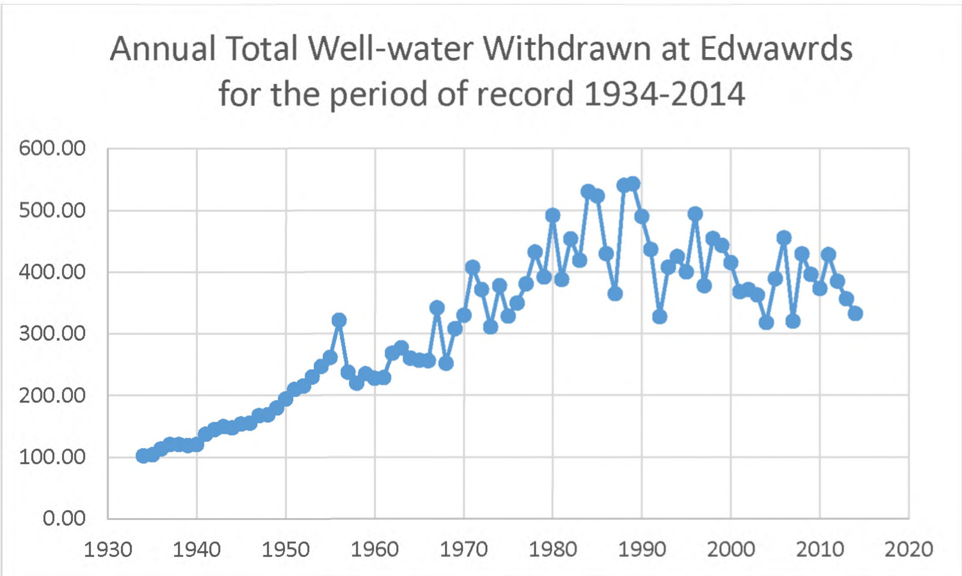
Spring-flow discharge is determined by measuring downstream-flows with electronic data loggers at Leona, Hueco, Comal, and San Marcos springs, and periodically also at San Pedro and San Antonio springs. Data for the period of record 1934-2014 ranges from the low of ~69,800 acre-feet measured in 1956, to the high of ~802,800 acre-feet in 1992, with the mean and median figures at ~375,800 acre-feet and ~379,000 acre-feet, respectively.



(Graph created with data provided in the Edwards Aquifer Authority Hydrologic Data report for 2014, published in November 2015)

The mean natural discharge at the San Marcos springs system during the period of record 1940-2009 was ~164 cfs, and the minimum of 46 cfs occurred in 1956. The mean for the Comal springs system during the period of record 1927-2009 was ~291 cfs, and the minimum occurred when the system ceased to flow for 144 consecutive days in 1956 (EARIP, 2009).

Total well-water withdrawn consists of an estimate of unreported discharge from unpermitted wells (such as for domestic, livestock, or federal facility use) and a measurement of reported discharge from metered wells. Data for the period of record 1934-2014 indicates that the total volume of well-water withdrawn has generally increased steadily over the years, presumably due to increasing population, as well as agricultural and industrial activity, and the median and mean are ~329,400 acre-feet and ~315,300 acre-feet respectively.



(Graph created with data provided in the Edwards Aquifer Authority Hydrologic Data report for 2014, published in November 2015)

Projections of future water demand, based on projections of population growth in the jurisdictional area sourced from the 1998 Groundwater Management Plan and the January 2006

South Central Texas Regional Water Planning Area Regional Water Plan, estimate municipal use to grow from 314,000 acre-feet per year to 488,000 acre-feet per year, and industrial use from 32,798 acre-feet per year in 2010 to 52,377 acre-feet per year in 2060, but for irrigation use to fall from 129,299 acre-feet per year in 2010 to 104,863 acre-feet per year in 2060 (Groundwater Management Plan 2010-2015), which is consistent with the notion that a more productive reallocation will lead from to be divested away from agricultural use and towards municipal and industrial uses (Debaere and Tianshu, 2016).

Administrative Structure and Governance History

Groundwater and surface water are considered separate legal entities in Texas, and while the former is managed through a number of groundwater districts, which submit Groundwater Management Plans to the Texas Water Development Board, the latter is typically regulated by the Texas Commission on Environmental Quality through river authorities. Though its use may be regulated by the government, groundwater is considered property of the permitted user, an extension of the Common Law import of the *rule of capture*, which awards ownership of a natural resource to the first user to capture it. On the other hand, surface water is legally the property of the State of Texas. While conjunctive management procedures have not been formalized, different regulatory authorities do attempt to cooperate when making policy decisions, especially regarding future use. The Edwards Aquifer Authority (EAA, or alternatively, the Authority), the management agency entrusted with groundwater management at Edwards, has jurisdiction over the recharge and artesian regions, and only a small section of the catchment area (Eckhardt; Friberg, 2016).

As per the Edwards Aquifer Act, the prevailing legal directive created by the Texas Legislature to conserve groundwater at the site, the Authority's regulatory domain is limited exclusively to subterranean flows; as water emerges at any orifice, the appropriate legal and governance structure changes hands (Friberg, 2016).

Following a ten-year drought, the Texas Legislature established the Edwards Underground Water District (EUWD) in 1959 to monitor the aquifer and support conservation, but granted it no authority to limit the quantity of water pumped. For decades the EUWD surveyed the Edwards and argued that reducing withdrawals is a requisite for sustainable groundwater use, but state legislators were disinclined to sanction such authority until finally, in 1991, a group of environmental interests, galvanized by the increasing number of endangered species at Edwards, litigated against the United States Fish and Wildlife Service (USFWS), claiming that the defendant failed to execute ecological and wildlife preservation duties assigned to it under the Endangered Species Act. This lawsuit led to the passage of Texas Senate Bill 1477, also known as the EAA Act, a legislative milestone that authorized the state government to regulate withdrawals from the aquifer by mandating that user rights to groundwater be permitted. The Act required that the State of Texas maintain continuous flow at Comal and San Marcos springs at some minimum level adequate to protect endangered species to the federally mandated extent. To this end, it created the Edwards Aquifer Authority as the primary steward of the aquifer's groundwater. The Authority drafts and executes groundwater management and strategic plans, monitors water quality, availability and compliance, and coordinates with a number of regional, state, and federal authorities and agencies to carry out different programs. While it has been required to review and submit its Groundwater Management Plan (GMP), which expounds its strategy to achieve these deliverables, to the Texas Water Development Board every five years heretofore, as of the current Texas congressional session it no longer needs to seek legislative approval, and can continue operations independently (Colby, 2000; Friberg, 2016).

Initial goals for the EAA included limiting total water withdrawn to 450,000 acre-feet per year, to be achieved by 2004, and 400,000 acre-feet by 2008. These targets, suggested by the USFWS, were in accordance with what was determined to be an adequate level of water retained within the Edwards to support endangered species at times of record scarcity, benchmarked against rainfall during the ten-year drought.

The Authority commenced operations in 1996 and allocated the first set of permits based on historical use rates to applicants who paid the necessary application and registration fees (which, as per the Act, are not to exceed $25 and $10 per application, respectively) and demonstrated, through corroborating documentation, that they had beneficially used aquifer supply in any one year within the 1973-1993 period. The number of applications for this year, for 800,000 acre-feet of groundwater, were much higher than expected (Friberg, 2016) and the 1996 allocation of 549,000 acre-feet, although generous, was still restrictive (Colby, 2000). While this could have been inimical to conservation efforts, a large number of the 881 permits issued ultimately went unutilized.

In 2007, the annual cap was revised to 572,000 acre-feet, reflecting the volume of groundwater covered by permits outstanding, as it was determined by the USFWS and the Edwards Aquifer Recovery Implementation Program (EARIP) that as long as additional Habitat Conservation Plans (HCP) are initiated, this figure is sufficient to maintain minimum spring-flow levels and preserve covered wildlife (Friberg, 2016).

Permitted aquifer water, measured in acre-feet per year, is withdrawn from the Uvalde pool in the south-east, and the San Antonio pool in the metropolitan region. As the purpose of regulation at Edwards is to safeguard spring-flow, which is contingent on the hydrostatic pressure of a certain amount of water within the aquifer, this volume-based unit is relevant. Municipal, agricultural, and industrial users operating non-exempt, metered wells, are allocated rights to pump water from one of these two pools, based on their geographical location, and are required to record their water withdrawals monthly, report usage annually, pay management fees, and practice prescribed or voluntary conservation strategies. Total fees due are calculated on a per-acre foot basis for different types of use. For example, as per the Act, the rate for agricultural use is to be under $2 per acre-foot withdrawn. Water districts within the jurisdiction of the EAA may also contract with the Authority to pay fees through taxes instead of individual user payments (EAA Act).

The authority issues three types of water rights: *regular permits*, which provide uninterruptible access and have no term limits, remaining in effect until they are cancelled; *term permits*, which allow interruptible access, that is, access conditional on water level readings at index wells and flow volume at the two major springs, for a period of time not exceeding ten years; and *emergency permits*, which are issued only to prevent critical health and safety threats, and have renewable terms of 30 days. In a sense this system favors existing users, as additional regular and term permits are only issued to allocate rights to the amount of capped water that remains beyond what has already been permitted. Indeed, the entitlements issued in 1996 that granted existing users access to their respective historic volumes of water were regular permits with no term limits, and so these initial permit holders have enjoyed a degree of seniority.

Permit-holders can engage in voluntary trades, either to permanently transfer their water rights or to lease them out over a specified period of time, and have a great deal of latitude as to how to structure the transaction; they may sell or lease all or any portion of their entitlements at any price they deem appropriate. While the Authority reassures that there are unlikely to be any detrimental or heterogeneous hydrogeological effects of pumping over space, analysis conducted by the EARIP did conclude that decreasing pumping near the spring systems has a positive impact on flow volumes, particularly in the case of San Marcos. As such, when the Authority realized that a number of transfers occurring between 2007 and 2009 enabled pumping to be localized around the springs in the eastern region of its jurisdiction, it passed the only major local constraint, colloquially referred to as the Cibolo Creek Rule, which restricts water users to the West of Cibolo Creek in Bexar County from selling their entitlements to those East of it (Friberg, 2016).

The EAA provides access to, but does not maintain, an online trading platform which lists all water permits for sale, along with seller contact information, permit number, minimum and maximum acre-feet for sale, transfer type, and contract lengths. Analysis of transfer records published by the authority indicate that over the period 1998-2012, an average of 75.8% of total trading can be attributed to leasing, that an average trade transacted about 37,500 acre-feet of water, and that prices were rather volatile, fluctuating between $80 per acre-feet to $6,000 per acre-feet.

While, consistent with the notion that water markets lead to a more efficient reallocation of resource rights, trading tended to increase during periods of water scarcity, a majority of the transfers at Edwards have occurred between agricultural users and not from agricultural uses to municipal or industrial uses. Furthermore, on average only about 8% of the total issues permitted were transferred.

Generally speaking, all wells within the regional domain of the authority must be registered, have meters installed, and permits must be granted for any water withdrawn from them. However, a well may be exempt from regulation if: it produces 25,000 gallons of water or less for domestic or livestock use; it was drilled prior to June 1, 2013, and does not produce more than 1,250 gallons of water a day; or if it is metered and does not produce more than 1.4 acre-feet of water per year (EAA Act).

Over the years, particularly following the adoption of the HCP, the management strategy has expanded in some significant ways, not the least of which includes the adoption of the Critical Period Management Plan (CPM), which provides the Authority with license to reduce the cap on total withdrawals during scarcity by a set percentage, interrupting access for even regular permit holders, conditional on the severity of the drought. The EAA may purchase permits that are made superfluous by this restriction, financing for which is dispatched by a number of institutions and funds, including the Texas Water Development Fund. Critical periods are classified into one of five stages, determined by ten-day average readings taken at index wells and the two major springs. The table below presents information about each stage, associated triggering minimums, and authorized reduction amounts. Readings are measured in feet above mean sea level at index wells, and cubic feet per second at springs.

Trigger	Critical Period				
San Antonio Pool	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Index Well J-17 (MSL)	<660	<650	<640	<630	<625
San Marcos Springs Flow (CFS)	<96	<80	N/A	N/A	N/A
Comal Springs Flow (CFS)	<225	<200	<150	<100	<45 (for ten consecutive days)/<40 (for three consecutive days)
Withdrawal Reduction	20%	30%	35%	40%	44%
Uvalde Pool					
Index Well J-27	N/A	<850	<845	<842	<840
San Marcos Springs Flow (CFS)	N/A	N/A	N/A	N/A	N/A
Comal Springs Flow (CFS)	N/A	N/A	N/A	N/A	N/A
Withdrawal Reduction	N/A	5%	20%	35%	44%

(Adapted from figures provided by the Edwards Aquifer Authority)

Further, the CPM plan differentiates between discretionary (voluntary) and non-discretionary (obligated by a governmental program) withdrawals, requiring maximum feasible reductions of the former, and then reductions of the latter if necessary, by use. For example, non-discretionary withdrawals for recreation are reduced before those for industrial and crop irrigation. However, the authority has set a floor, currently at 320,000 acre-feet per year, below which withdrawals are not to drop. During a critical period, all municipal, industrial, and irrigation-use permit holders are required to submit monthly, rather than annual, reports.

A number of incentive-based, regulatory, and voluntary programs also exist to support groundwater management and wildlife preservation. The HCP, which has a term of 15 years, advises a number of conservation measures (organized into two broad categories and detailed below), to ensure the protection of species designated endangered or threatened by the USFWS to the extent mandated at the state-level in the EAA Act, and at the federal-level in the ESA.

These *covered* species include the Comal Springs Dryopid Beetle, the Comal Springs Riffle beetle, the Fountain Darter, Texas Wild Rice, and the Peck's Cave Amphipod.

Habitat and Flow Protection Measures

I. The *Voluntary Irrigation Suspension Program Option (VISPO)* allows eligible permit-holders of irrigation rights to suspend all or a portion of their withdrawals for specified period of time in exchange for monetary compensation. If the water level at the J-17 index well in San Antonio declines to or below 635 feet above mean sea level, measured by the Authority on October 1 every year, then the program is deployed and participants cease withdrawals for the next calendar year beginning January 1.

II. The *Regional Conservation Program (RCP)* provides municipalities with financial remuneration to refrain from pumping half of conserved water for a period of 15 years, with the goal of conserving 20,000 acre-feet of the total permitted or exempt volume. The RCP supports municipal water providers through low-flow toilet programs and leak detection.

III. The *Stage 5 Critical Management Period*, which was amended to the CPM plan through the HCP, is triggered when water levels fall to or below 625 feet above mean sea level for the San Antonio pool, measured at the J-17 index well, or 840 feet above mean sea level for the Uvalde pool, measured at the J-27 index well, and allows the Authority to reduce groundwater withdrawals by 44%.

IV. In addition to these, the Authority also collaborates with the SAWS in deployment of a flow augmentation program; water from the Edwards is stored at the SAWS *Aquifer Storage and Recovery* (ASR) facility, and used a baseload supply during extended droughts.

<u>Supporting Measures</u>

The Authority carries out a number of research and modeling efforts to support its conservation work including:

I. The *EAHCP Applied Research* program to collect data and further understand the ecological dynamics at Comal and San Marcos springs- which is then used in creating computer simulations to conduct project evaluations and generate information about the ecological consequences of plausible or hypothetical environmental scenarios.

II. Extensive *Biological Monitoring* of species, spring-flow, water quality and environmental conditions at Comal and San Marcos springs, which is published in annual reports.

III. The creation of off-site *refugia* facilities where covered species may be preserved during unanticipated or catastrophic events such as chemical spills.

The mandates set by the Act are enforceable by state law, and in the case that a covered facility violates them, whether related to withdrawals or contamination, the Authority may impose an administrative penalty, generally a fine between $100 and $1,000 for each infraction and each day that the infraction is not corrected. In some cases, the Authority may also file a civil suit in a state district court to recover a penalty between $100 and $1,000 for each violation, for every day the violation continues, and for attorney fees. It also reserves the right to seek injunctive relief regarding water use, and has the power to enter land to enforce it, although it seeks permission in most circumstances (Friberg, 2016).

An Interview with Marc Friberg

Marc Friberg is the Executive Director of Public Policy and External Affairs at the Edwards Aquifer Authority. Some of the information presented above was collected during an interview with him in August, 2016. In a second interview (transcribed below), conducted on July 21, 2017, he addressed questions relevant to topics discussed in this paper, such as dynamic systemic effects of trading on third-parties.

Kanishka: Thank you so much for your time Mr. Friberg. Before we start the interview, I'd like to provide a brief overview of what I'm hoping to address with my research if that's alright?

Marc: Of course, sure, go ahead.

K: Thank you. I've read quiet a bit about the Edwards, from legal, political, hydrological, geological, and economic perspectives. I understand that regulation at the aquifer is unique in the sense that it exists to protect stream-flows, which provide aquatic habitat for some endangered species, whereas at many other groundwater market sites across the country, the objective is to maintain some minimum volume for human use, or to reallocate usage to more efficient applications. Also, it seems to me that the cap-and-trade scheme instituted by the Authority is working well, as the flow at Comal and San Marcos springs has been acceptable as has the volume of total withdrawals. My thesis explores the heterogeneous effects of trading water over space, and I am particularly concerned about things that the market might not reflect, such as changes in hydrostatic pressure, and how sometimes an effort to internalize the externalities generated by distributing access to a shared, common resource like groundwater, may inadvertently generated new externalities *(Here, the thought experiment that appears in the previous section of this paper was provided for illustration).* So I realize that this theoretically might occur in some regions, but I was hoping to incorporate some of your insight on whether this happens at Edwards in my paper. I have a set of questions for you, but before I ask them, do you have any questions for me?

M: Sure, I don't think so, I think I understand what you're looking at here.

K: Excellent. So the first question I have is regarding the legal status of different kinds of water. From what I gather, surface flows and subsurface flows are managed by separate agencies in Texas. Considering that water systems are dynamic, and there may be interconnections between subterranean and surface waters, I am wondering what your assessment of this current institutional arrangement is? Do you think things could be better regulated under a conjunctive management structure?

M: I think things would be better if there was conjunctive management. But I think that we are so far down the road with this split process we have that it would be, administratively speaking, very cumbersome to get to that point. While I believe that everybody involved with groundwater management in this state recognizes the interconnections and the consequences one type of flow has on the other, it would still be very difficult to bridge the [institutional] gap. This is actually a very relevant issue as Texas begins to share water across the state, which is what a lot of our current politicians want to happen, a lot of them want to take water from East Texas and start helping out the drier regions in West Texas, especially since the Ogallala Aquifer is not going to yield forever, which is what mostly supplies the water needs of West Texas.

K: I see. And what do you think are the primary restraints to doing that? Is it just that it would be a very difficult legal process to change the way that groundwater and surface waters are governed?

M: It is that, and it's also that the long-standing property rights laws that have developed in Texas, as well as the long-standing property rights culture that has developed with them would be really difficult to reverse. Landowner rights are so connected with groundwater rights issues, and that would be the biggest hurdle. A lot of our policymaking has historically respected landowner rights, and since we have proceeded with the rule-of-capture sort of approach with groundwater, it would just be very difficult to change that.

K: On the subject of administrative dominion, just to confirm, do you lose your jurisdiction over water as soon as it becomes surface level water, as it leaves the springs?

M: Yes, we do, from a usage standpoint, at that point it becomes property of the state. We do have some jurisdiction over water quality, but we cannot permit any water that has left the ground. Once groundwater has moved through the system and its discharged into a river through a wastewater plant or something, we do not have jurisdiction over that water either. So basically we lose jurisdiction after its first beneficial use.

K: Is there any coordination at all between surface water management agencies and the EAA?

M: There is some level of cooperation, but this mostly exchange of information. There is also some collaboration on maintaining water quality, but not really quantity.

K: That makes sense, thank you. So another thing I wanted to discuss is the initial distribution of permits. Some economists, especially when they analyze the rights of economic agents to pollute in a cap-and-trade scheme, prescribe permit auctioning as opposed to permit allocation. They argue that this allows you to generate revenue, which the government could reinvest in productive ways. At Edwards, I understand they were allocated based on beneficial historic use, right?

M: Right.

K: What is your perspective on this issue?

M: I guess moving forward in time, as new people come into the area, the historical rights perspective has come under fire in Texas. These new people do not have any historical rights, so they cannot do with their property what they want to. There probably will not be another Groundwater Management District that uses historical rights the way that Edwards does. There was actually an attack on historical rights this last legislative session that would have done away with the whole system altogether for basically all areas in the state except for Edwards, but from an auctioning standpoint, it is difficult to determine an ownership for the government to auction off, so there has to be some mechanism for a starting point. Do the terms 'Desired Future Conditions' and 'Modeled Available Groundwater' mean anything to you?

K: No, could you tell me a little bit more about that?

M: Sure, so basically the way it works for everybody else in the state, is that the district asks 'What do we want our aquifer to be like in 30, 40, 50 years?' And a prime example of this is the Ogallala. If they are managing the Ogallala, they have to consider how much drawdown can they allow over time. Many of the districts would estimate, say, 50 feet of drawdown over 50 years, and they send that determination, which is called the Desired Future Condition to the State Water Board, where they do a lot of groundwater modeling. They do this modeling to estimate how much water can be withdrawn every year in order to maintain that condition over that time frame, to generate a number, called the Modeled Available Groundwater, which the district then uses as a cap for permitting. So, in a sense, they are sort of auctioning it off, but nobody is paying for it. In a sense, they are capping with scientific information, and limiting how much a district can have, based on the district's application. That is the direction that Texas is moving, and that is how I anticipate that groundwater is going to be managed outside of the Edwards for the foreseeable future.

K: Just a quick digression on modeling- I know that these subsurface structures are so complicated that sometimes simulation efforts can lead to somewhat of an oversimplification. I'm assuming that the modeling accounts for the fact that conjunctive management isn't happening, and that can limit system boundaries in an undesirable way?

M: Yes, they basically just look at the water balance, so what's coming in, and what you're taking out, and what that's going to mean. And to be fair, the Desired Future Conditions that are determined by the districts are often based on spring-flow, and that's the way that Edwards has set theirs up.

K: Oh I see, so the objective function is set with respect to spring-flow, and that is the important variable that determines how much water can be withdrawn?

M: Yes, so there are some that are based on spring-flow, the Edwards is, but not as many of them. Many of them are based on actual aquifer declines.

K: That make sense. Changing gears just a little bit- economists who advocate for cap-and-trade type schemes hypothesize that permit trading will occur in a way that is welfare maximizing. That is to say, usage, which is of course limited, will move to those users who value it the most. My review of the literature around this leads me to believe that much of this would lead to a shift from irrigative use, which might be water intensive and low efficiency, to municipal and industrial use. How much trading is actually happening at Edwards, and are there any trends there that can corroborate this theory?

M: At the Edwards it's a pretty robust trading system. There are hundreds of trades that happen each year, and most of them are leased on temporary terms. When the San Antonio Water System got their permit and started planning for the future, they bought a lot of permits aggressively, and so we saw a lot of water moving from agriculture to municipal use. They have, since then, attempted to find alternative water supplies. So they have a desalination process from another aquifer that is high in salinity, and then they have a large pipeline project that is supposed to become operational by 2020 that will physically transport water from a distant area in Texas. Since they've tried to expand and diversify their supply, the irrigative to municipal trend has slowed. The Authority has been the main player in the market as we've been attempting to gather permits on a long-term lease basis for spring-flow protection measures as a part of the measures carried out under our Habitat Conservation Plan. We never intended this to be the case, but we are the biggest purchaser.

K: And how is the pricing determined? Do the individual actors have all the latitude to determine the price of a permit? Does the Authority arbitrate at all or are there any guidelines it provides?

M: It is an open market, and the Authority has always tried to stay out of any type of influence on the market. It has stabilized over time. It started out at around $1,000 to $2,000 per acre-foot, and it has now plateaued at about $5,500, if you are buying. We do ask people who are trading how much they paid just so that we can keep a record, but there is no legal requirement for them to tell us.

K: In order to prevent some of the heterogeneous effects of spatial trading, I know that there is something called the Cibolo Creek Rule, that is supposed to prevent pumping from concentrating around the spring systems. But are there any other measures? And if not, do you think that there should be?

M: That's really the only rule looking to address that kind of impact to the system. Interestingly, you asked about the market, and because of that rule, there is a subset of the market that is East of Cibolo Creek, and the water values there are double, so the price there is about $10,000 per acre-foot, because there is a restriction in supply and you cannot get water from the West. From our perspective, that is probably good enough, that has actually prevented all this pumping from concentrating around the springs. There are a number of advocates in this region that have wanted us to look at the hydrogeological impacts on a transfer-by-transfer basis, and their argument is that any movement of water that is going from West to East is going to have some sort of impact, because the groundwater moves in that direction. Personally, I cannot advocate for that. Because we permit on a year-to-year basis, and because of our Critical Period Reduction Plan, I believe the administrative difficulties that this would create would far exceed the potential benefits it would give to spring-flows.

K: What about return flows? With irrigative use, these flows could provide some of the water that third-party users rely on, and so non-consumptive use becomes important. How important are these flows at Edwards? And if trading causes a shift from non-consumptive to consumptive use, do you think that will be a problem?

M: There really isn't any impact of return flows in the Edwards region. Where that becomes an issue is basically, what is called the basin estuary system, so downstream surface water inflows are where the return flows are going to be a big deal. For us, it doesn't matter, because our recharge is not dependent on return flows, it's just dependent on precipitation. Also, any region that relies on return flows is south of here, so no return flows move over our recharge zone, or a negligible amount do. But it is a big issue downstream, and it is a big issue as big cities start to reuse their water instead of just discharging it, then downstream water rights from a surface water perspective is something that will need to be dealt with.

K: Got it. As I conducted my research, I found some theoretical evidence in support for trading programs in which some kind of superintending agency such as the EAA, or other agency of the government, would weight the price of the permits by a factor corresponding to its elevation and location. The idea here is that it would create a more dynamic pricing scheme which accounts for heterogeneous effects of trading over space and possible internalize third-party effects. Do you think this would be a practical solution for Edwards, or for most water management institutions?

M: I think that might be cost-prohibitive. One thing to remember: the Edwards is brought up as a model in a lot of research, specifically its use of a market, but due to the karstic nature of the aquifer, when you trade your withdrawal right, there is no associated infrastructural change. In most of the rest of the state, groundwater is stored in sand aquifers, not karst aquifers, so you actually need piping infrastructure to move the water. You cannot just trade the right; you have to figure out the piping system in order to actually move that water from one point to another. In these cases, the point of withdrawal is not really changing, just the point of use. In our case, at the Edwards, the point of withdrawal does change, and it goes right with the point of use. So essentially, when you look at the impact of trade on our system as a whole, for all intents and purposes, the pumping is actually still actually taking place at the same spot. Our system works more fluidly, because you do not need a pipeline, as the aquifer itself is a pipeline.

K: That's actually very helpful. So would it be accurate to say that at the Edwards, there is not as great of a hydrogeological impact of trade due to the high porosity of the aquifer?

M: Yes, that is what I would say. Granted, I'm more of a regulatory person, but there are legal arguments going back 20 or 30 years that argue that the Edwards isn't really even a true aquifer, it is just a giant underground river, and so it should be regulated like a river, but it is not. The final determination was that it is indeed an aquifer, in a definitional sense, and so it's regulated as an aquifer. Regardless, the pressure heads at the Edwards work a little differently. As the water moves from the recharge area into the artesian zone, there is so much head pressure there that, as it moves West in the direction of the springs, it really doesn't have as much of an impact, except for when you get really close to the spring systems. This is why we implemented a simple solution like the Cibolo Creek line, and even that is not a true hydrologic division. There is just some subterranean fault there that makes it the most appropriate place to draw a line based on the information generated by MODFLOW if we want to minimize impacts of trade to the aquifer system.

K: Do you keep a track of the location of the wells as they rearrange as a result of trade?

M: We do have a map of where all the wells are, but we do not keep track of permit transfers between wells. So if there are new wells, we have an image of that, but it would be very difficult to follow each permit that goes from one set of wells to another. And in most cases when there is a transfer, it's only a portion of total water rights, so the original well stays and there are basically just new holes punched into the aquifer.

K: Are there are concerns related to changes in climate, or to natural gas and hydraulic fracturing, that the Authority has had to address?

M: We are not too concerned about fracking. Some of the districts south of here who do supply water for fracking may be. There has been some positive collaboration between the oil and gas industry and groundwater districts in the permitting process. Historically, water used for oil and gas is in Texas is exempt from permitting. That is not true in our case at Edwards, as we do not exempt that industry, but in any case we do not have any drilling or fracking that is happening within our jurisdiction. It is also not possible to use our water at a location outside of our jurisdiction for fracking, as we have a prohibition on export. For the rest of the state, I'm not so sure that water use for the natural gas industry has gotten to the point where they are concerned about consumption. On the other hand, regarding climate change, we are starting to look into how we can best adapt, especially when it comes to aquatic species protection. The consequences of climate change are starting to become apparent. Historic droughts, for example, have always been these long periods of low precipitation and low yield, but what we think, and although we don't have any substantive literature to back this up so this is just anecdotal, but the notion is that weather extremes will become more commonplace. So we are looking at three or four years of drought, followed by two or three years of fairly intense rain, and the weather will oscillate between times of plenty and times of nothing. We do believe that our drought reduction plan is a perfect mechanism to handle that.

K: So what you would do is toggle existing or newly established drought period restrictions on and off in accordance with where you are in the cycle in order to maintain a certain volume of spring-flow?

M: I think we might just keep the drought restrictions in place permanently, and we think that because of the intense period of rain, we would maintain a good volume. This is, again, all anecdotal though, we actually have yet to discuss the programmatic specifics. The drought restrictions we have in place have been working well to protect spring-flow.

K: Moving into the future, with commercial growth, and the associated population growth, do you think the system you have in place is sustainable?

M: I think so. I think the cap is here to stay. I do believe that with climate change and growing demand, there will be more Aquifer Storage and Recovery Projects, that aren't necessary at

Edwards but at other aquifers in the state, which will allow you to take water from the Edwards and store it in times of plenty. This is basically like an off-channel reservoir, but it's underground. I think users in the area will also have to start diversifying their supply, as the San Antonio Water System has done. Alternative sources are going to have to be important, and we will have to be constantly cognizant of whether we are achieving our conservation goals, but if we diversify and start limiting the total urban use, I think our scheme will be effective as far as maintaining the discharge at Comal and San Marcos. The farm irrigators out in the West may also have to change their crops as well, so that they are doing less water intensive agriculture, and the state may have to create incentives for this. It used to be corn only, and now we are seeing a shift in the direction of sesame seeds and maybe a little more cotton. You are going to see a combination of creative things happening if the consequences of climate change are severe, but I think in tandem with all of that, the permitting scheme will continue to operate.

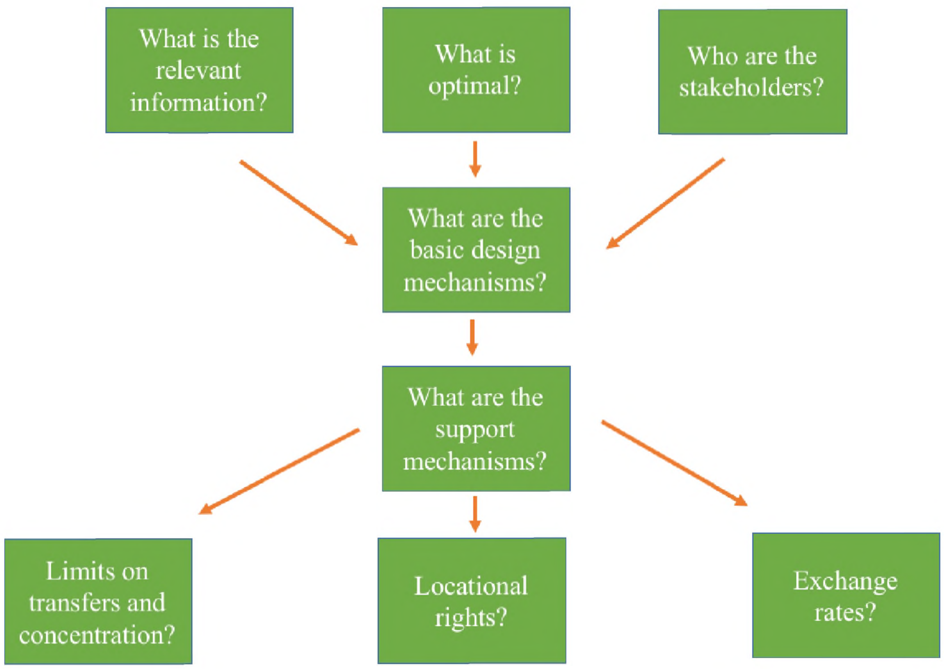
K: Those are all the questions I have for you today. Thank you so much for your time, that was a very illuminating conversation. I'm grateful for your generosity.

M: No problem at all, I'm happy to help. Good luck on your thesis.

Alternative Solutions and Ancillary Instruments

The conversation with Marc Friberg, paired with an assessment of annual total discharge statistics and the Authority's manifold ancillary programs, suggest that the groundwater management system deployed at Edwards is dynamic, and if appropriately manipulated and supported in the future, may prove to be adequate even as the consequences of climate change become more pronounced and frequent. While some of this reflects careful planning on the part of the state, and the fact that governance was engineered specifically to promote wildlife conservation, the physical properties of the aquifer itself certainly facilitate successful management; as Skurray and Pannell (2012) intimate, "Under high-transmissivity conditions, limiting extractions to the sustainable yield addresses most impacts" (p. 885).

Nonetheless, a review of groundwater protection instruments, policies, and frameworks yields some valuable direction for market design in general. This section expands on the illustrative graph below to briefly review some mechanisms that may serve as alternatives to, or ancillaries for, cap-and-trade.



As has been discussed in a number of sections throughout this paper, groundwater transfers, and the associated rearrangement of pumping, can create the potential for significant systemic shifts and unanticipated consequences due to hydrogeological transformation. There are spatial considerations, such as changes in points of origin and points of withdrawal, and as the effects of pumping are localized, there may be disparate impacts at each of these sites. There are also temporal considerations, such as delayed effects that manifest only after certain feedback loops or emergent properties are realized. Further, as trading transfers water from one type of use to another, it may generate significant repercussions; one example is that irrigative use is seasonal and cyclical, and provides some time for off-season aquifer recovery, a feature which may be lost as use shifts to municipal or industrial applications (Skurray and Pannell, 2012).

Given all of this, it is imperative that any agency tasked with developing a groundwater management program commence with a holistic evaluation of the human and natural elements of their region, and the necessary data collection and analysis. The definition of what is the optimal use of a given groundwater system cannot be reduced to social welfare maximization, and it cannot be assumed that a permit trading scheme will reallocate use most efficiently. To address the former, planners and policymakers must bring a multitude of stakeholders into the fold, including not just beneficial users such as farmers and municipal water institutions, but also environmentalists, recreationists, hydrologists and geologists, ecologists, biologists, and hydrogeological modelers. The entitlements of the environment, natural systems, and of other species to continue to exist sustainably must be accounted for as well.

Region-specific modeling should help demystify structural and hydrological idiosyncrasies, and consultations with varying concerns may reveal aspects of the CHANS that had not initially been considered.

A simple monetization of the value generated by aquifer yield is not likely to lead to a sufficiently thorough understanding of the groundwater complex or an accurate valuation of its natural resource yield; it may be necessary to have economists perform non-market valuations of the environmental benefits provided. Indeed, “a sound groundwater transfer scheme should address unvalued (non-market) impacts, as well as financial externalities” (Skurray and Pannell, 2012, p. 884).

Economic ripples generated by human actions in the absence of transparent and full information generates confounding externalities, and considering a comprehensive panel of stakeholders can support a fair conceptualization of optimality and an accurate determination of sustainable yield, this completeness of information must also reflect in permit prices and property rights. Skurray and Pannell (2012) recognize that collecting and disseminating meticulous information regarding biophysical processes and prospective third-party impacts may be a cost-prohibitive and time-intensive process. The researchers suggest instead that the composite groundwater system be separated into parts with distinct hydrological boundaries, and an estimation of sustainable yield for each subsystem be derived through the analysis of net recharge information from the immediately preceding year, or from the rolling average of a number of years. Further, they advise that while…

> …a certain volume of water left in a river may provide 'environmental flows', while the same approach to groundwater systems may leave water-tables too low to meet the needs of surface GDEs [groundwater-dependent ecosystems] and/or to provide sufficient water levels in caves or baseflow to streams. This is the case for phreatophytic vegetation, for wetland flora and fauna, as well as for ecosystems dependent upon baseflow to streams (p. 884).

Essentially, what is being recommended here is what can be understood as somewhat of a *zoning* effect, through which subterranean details of the natural system can be understood and better integrated with their corresponding economic, or human aspects. A number of policy-based instruments that can work in tandem with permit trading exist to achieve this, some of which have been reviewed below. Two important points worth reemphasizing here are that auctioning may serve as a better format of permit dispersal than grandfathering, as it allows the government to generate supplemental revenue, and it may be more equitable to distribute entitlements in accordance with the present and prospective future needs of a variety of stakeholders, as opposed to historic rights, which are somewhat of a vestige of the prevailing paradigms of water development in the U.S., which have proven to be rather shortsighted.

Limits on Transfers

One of the more problematic scenarios groundwater market architects should attempt to preclude is the spatial concentration of withdrawals. From a groundwater hydrology perspective, such activity can create a cone of depression, leading to aforementioned unanticipated system phase shifts through feedback loops and emergent behavior. From a socio-economic point of view, they can lead to market disruptions and negative externalities; Skurray and Pannell (2012) ask readers to "consider a large horticultural operation that buys groundwater allocations from surrounding smaller users. By not selling their allowance, a small neighbor user incurs disproportionate but compensable increases in pumping costs, but may also suffer the loss of a particular local way of life as other affected community members move out of the area" (p. 885).

To avoid this, it is suggested that regional boundaries for trading be demarcated, either with geographical limitations that restrict the movement of water trading within a certain area, or with volumetric limitations that decrease the total amount of water moved from one zone to another. Skurray and Pannell (2012) discuss another scenario:

> ...where adjacent management areas are hydraulically connected...there is a potential for cross-border concentration. High-value uses located closely together, but on either side of a management boundary, could cause accumulation of pumping rights such that, at the extreme, the entire transferable volume of both management areas becomes concentrated at the two closely adjacent locations. To guard against the potential impacts of such a situation using trading limits alone would require them to be set lower than otherwise necessary, thus presenting unnecessary restrictions on other potential transfers. Using trading limits in combination with other tools such as concentration limits or exchange rates, would be preferable in such cases (p. 886).

Exchange Rates

Having the monetary value of permits reflect different gradations of the hydrogeological effects of trading them through differential exchange rates indexed against categorically or regionally specific weight functions is perhaps one of the most intuitive and sophisticated mechanisms through which to internalize the confounding externalities of groundwater entitlement transfer. Broadly speaking, it provides a mechanism through which superintending agencies can signal the potential for third-party effects to economic agents, and therefore deter or promote certain kinds of market activity. Of course, the process of aggregating, analyzing, and supplying the relevant information is likely to be unfeasible on a transfer-by-transfer basis. Instead, if regional or categorical boundaries have already been established, exchange rates can be calibrated between them (Skurray and Pannell, 2012).

To illustrate, consider again the thought experiment from a previous section in this paper involving users U and D who shifted the point of groundwater withdrawal from a region of low elevation to high elevation. If the potential for the reduction of hydrostatic pressure and return flows could be generally understood through hydrological modeling in that specific region, an exchange rate could be determined for all transfers that take place from one range of elevations to another range of elevations. Perhaps in that particular case, the two users may have realized that such a trade was suboptimal and the confounding externalities generated could have stymied.

Beyond elevation, parameters that could be used in the calculation of exchange rates are: the environmental stressors associated with trade; the distance or position of a pumper relative to key hydrogeological locations, such as spring systems, recharge areas, and other high risk zones; upstream and downstream statuses (Skurray and Pannell, 2012); volume of return flows generated; type of groundwater application; and the potential for other neighborhood effects.

Locational Rights

Hung et al. (2014) make the case that certain hydrological certainties can serve as the foundation for location-specific regulation of water trading. Their research suggests that a system of locational rights, through which caps on maximum resource exploitation are mandated based on the relative upstream or downstream status of points of withdrawal, can mitigate third-party effects related to quantity declines due to the exhaustion of upstream sources and return flows. The basic idea here is that since water flows unidirectionally downstream, the management scheme accounts for status quo flows, diversion trading, consumption trading, locational water right access, environmental flows, and return flows, calculating a limit on use at each point along the river system in order to achieve volumetric objectives. The paper, titled "Water Trading: Locational Water Rights, Economic Efficiency, and Third-Party Effect" elucidates Hung et al.'s (2014) optimization modeling methodology, which is outside of the scope of this paper, but is recommended reading for researchers and students interested in the mathematical expression of dynamic flow properties. While their work assumes perfect information, the researchers admit this to be an unrealistic expectation, and suggest that two schemes be deployed, one for the actual locational water right flows, and when the wrinkles in this market are ironed out, another for return flows; the hypothesis here is that as trades yield more information, the economics of the two policy systems will synchronize. Furthermore, organizing a market to follow the physical direction of flow can support a market architecture that also achieves a natural cadence over time, so that if entitlements must be rescinded in extraordinary circumstances such as drought, the downstream ramifications can be more accurately predicted.

Groundwater is of course distinct from surface reservoirs in that many system dynamics are obfuscated by confounding subterranean physical structures, and intra-aquifer flow may not be unidirectional. Nonetheless, if management zones are constructed along the lines of general topographical and hydrogeological features, a causal chain of hydrologic reactions can be realized within each, so that entitlements and their corresponding restrictions during times of scarcity can be determined to reduce the probability of unintended effects, confounding externalities, and third-party impacts. Locational rights may be a policy instrument that buttress a more complicated and extensive management scheme, such as exchange rates and limits.

Concluding Remarks

It is evident that groundwater conservation is as intricate a problem as it is exigent. Given the dynamic properties of subterranean flows, the nebulous geophysics of their encasing structures, and the indefiniteness of their system boundaries, it is evident that replicable market-based solutions that have only economic theoretical foundations are insufficient for aquifer management, as the idiosyncratic hydrogeological features of these systems are incommensurable. For these reasons, there is also a greater potential for unexpected and pernicious consequences of myopic policy efforts applied to aquifer stewardship relative to surface waters. Indeed, policy analysis that neglects to account for these third-party effects may lead to the construction of an incomplete market and at its worst, precipitate irreversible system phase shifts.

This is not to say that underground water resources are ungovernable; it is necessary, however, to understand these systems holistically, considering both their natural and human elements, in order to design truly efficacious governance plans. Each superintending agency must holistically evaluate the manifold aspects of the coupled human and natural groundwater system they are attempting to manage, prognosticate the consequences of climate change and other forms of disruptive natural and anthropogenic phenomena, and anticipate the probability of emergent behavior, feedback loops, and sources of vulnerabilities.

The primary objective of this paper is to appraise the efficacy of property rights-based groundwater conservation, illuminate factors that this approach may miss, apply systems thinking concepts to better appreciate the complexity of subterranean water resources, and propose alternative and supporting management strategies with apropos conceptual corroboration. In reality, different combinations of the ancillary mechanisms reviewed (as well as others not reviewed) will have to be deployed at different aquifer systems, depending on site-specific properties.

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