Groundwater Trading as a Tool for Implementing California's Sustainable Groundwater Management Act

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Mammoth Trading specializes in the design and implementation of trading programs, smart market platforms, and incentive-based policies for water resources. At Mammoth Trading, we believe that successful water management is the product of informed, engaged stakeholders and thoughtful, science-based policy.

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Background

Until recently, the State of California lacked comprehensive groundwater management policy. While many basins havebeen adjudicated in court or have adopted voluntary groundwater management programs following Assembly Bill 3030 and Senate Bill 1938, the vast majority of groundwater use remained unregulated. In 2014, the State Legislature passed the landmark Sustainable Groundwater Management Act (SGMA) in response to wide-ranging consequences of prolonged and unchecked groundwater pumping. While groundwater serves as an important primary and supplemental water supply for many water users, over-pumping can result in negative consequences, six of which are listed as "undesirable results" under SGMA: chronic aquifer overdraft, reduction of groundwater storage, seawater intrusion, degradation of water quality, land subsidence, and depletion of hydrologically connected surface water. SGMA requires local Groundwater Sustainability Agencies (GSAs) to develop and implement Groundwater Sustainability Plans (GSPs) to manage groundwater to avoid such consequences.

To meet the requirements of SGMA, GSAs will need to employ a wide range of management tools. This paper focuses on one set of these tools: groundwater trading programs. Trading goes by many different names, including markets, cap and trade, transfers, credit programs, banking, pooling, and exchanges. For the purposes of this paper, we have elected to use the terms "trading" and "trading programs" as the broader categorization of incentive-based management tools. Trading can be executed through a wide range of exchange vehicles, including short- and long-term leases, permanent transfers, and other more advanced or unique arrangements, such as inter-annual water exchanges or dry-year options contracts.

The paper was informed by interviews with over two dozen experts in California water policy, law, and management. While the individuals represent a diversity of backgrounds and perspectives, several common themes emerged from the interviews: namely, the need to

1. develop trust in groundwater management through an inclusive and transparent process
2. ensure efficient and accurate collection of appropriate data
3. devise a fair groundwater allocation
4. carefully craft trading programs to reflect local hydrologic conditions
5. address concerns over funding management activities.

Water trading has been an important water management tool in California for decades, which has helped agricultural, municipal, industrial, and environmental uses alike (Hanak and Jezdimirovic, 2016). Trading reduces the impact of water scarcity by creating voluntary mechanisms for water users to reallocate water to higher-value needs. While trading is not a new management tool for surface water or in several of California's adjudicated groundwater basins, there remain many opportunities to develop local groundwater trading programs to assist GSAs and their constituents in cost-effectively achieving the goals of SGMA.

Appropriately constructed, groundwater trading offers enormous potential to encourage and reward groundwater conservation. This is not to imply trading programs are a panacea; instead, they must function in parallel with, and often hinge upon, other groundwater management efforts, such as monitoring, modeling, and implementing best management practices.

This paper is intended for GSA managers and board members, groundwater users, and practitioners who are interested in learning about groundwater trading programs. Our intention is to demystify trading programs by providing an overview of groundwater trading, the basic elements of setting up a trading program, and some remaining challenges or questions for consideration. The paper also discusses groundwater allocations and other management tools that could be useful to GSAs with or without trading. This paper is not intended to be an instructional manual or step-by-step guide for establishing a trading program. For those interested in further exploring groundwater trading programs, appropriate technical and legal advice is essential.

Challenges of groundwater management and the opportunities of trading

While there are natural similarities between managing surface and groundwater, there are also substantial differences. Some of the most difficult challenges to groundwater management include developing pumping allocations in a manner acceptable to users and consistent with groundwater rights law, monitoring and enforcement of groundwater use on private lands, understanding the complex nature of groundwater behavior, and addressing the delayed effects of management actions.

The geophysical relationships of groundwater flow and pumping are complex. Adequate modeling support requires monitoring and data collection of groundwater variables and properties that are often difficult to accurately measure. For example, groundwater is largely extracted from and conveyed over privately owned lands, a challenge for quantifying or monitoring groundwater use. Further, the delayed effects of groundwater pumping mean that the consequences of pumping today may ripple into the future for years or decades depending on the hydrology of the system. As a result, corrective actions may take years or decades to be fully realized. In some instances, the consequences of overdraft are irreversible, as is the case for inelastic land subsidence. Because of these and other factors, groundwater management must be approached with a long time horizon in mind.

The case for groundwater trading

Groundwater is a critical resource for the rural communities and individual well owners who rely on groundwater as a primary source of drinking water and is a highly valuable water supply for agricultural, industrial, and municipal purposes alike. Groundwater is also essential for supporting groundwater-dependent ecosystems (GDEs), including both habitats and species. Like all shared resources, there are limits to how much groundwater can be safely withdrawn, and one use can impact the use of others. Accordingly, effective management of the shared resource requires methods of allocating groundwater use, sometimes to shift withdrawals in space and time, to avoid unhealthy increases in withdrawals, and to achieve overall reductions in groundwater pumping. Shifts or cutbacks in pumping could require scaling back production, changing operations, or investing in new conservation technology. Such activities could result in high costs to individual groundwater users with ripple effects to the local economy, tax revenues, and labor market. There are valid concerns that pumping restrictions could lead to significant private and public costs in the near-term. However, in the long-term, failing to regulate pumping could be far more costly.

Groundwater trading can be a cost-effective tool to shift pumping patterns or curb pumping to help achieve groundwater sustainability goals. In simple terms, under a trading program, an aggregate pumping limit is set based on an analysis of acceptable pumping levels and individuals are assigned some portion of the total, called an allocation.[1] They can choose to use up to all of their allocation without penalty. If they use only some, they can lease or permanently sell the remainder to another user; if they exceed their allocation, they can lease or purchase from another user who has not used all of their allocation. Trading provides groundwater users with opportunities to move[2] groundwater from activities that can more easily be interrupted (e.g. annual crops) or that generate comparatively less revenue to ones that require uninterrupted water supplies or generate higher revenues (e.g. municipal use, industrial processes, or higher net-revenue crops). For example, once allowcations are assigned, growers could redistribute groundwater allocations between their own fields, moving allocations to fields with more water-intensive or higher-net-revenue crops from fields with lower water use or lower net-revenue crops, or trade allocations with other growers. In essence, trading enhances the range of options available to groundwater users.

Trading provides flexibility to groundwater users to move groundwater to where and when it is most needed both now and in the future. As conditions or needs for groundwater change, users have the opportunity to effectively reallocate groundwater through trading. Compared to top-down regulatory approaches, the nature of trading programs provides groundwater users with more choices and flexibility on a voluntary basis to meet groundwater management objectives. Further, the ability to monetize groundwater in a trading program can reward individuals for conservation and improved management practices.

Trading programs are only as good as their governance systems and rules. Strong governance requires transparency, oversight, monitoring, enforcement, and protections for third parties, which includes existing water rights holders, disadvantaged communities (DACs), and groundwater-dependent ecosystems. Since DACs and GDEs often lack the purchasing power or representation to acquire water, ensuring sufficient supplies and protections for each is essential. Sufficient quantities of groundwater should be allocated up front to such uses when a trading program is developed, or alternatively, management or trading rules may be developed to protect such groundwater uses.

Groundwater trading under the Sustainable Groundwater Management Act

Consistent with the local flexibility in SGMA, robust trading rules must incorporate appropriate hydrologic relationships, legal obligations, and community-specific needs. No two groundwater trading programs are identical, and each must be tailored to meet the specific objectives and needs of the local groundwater basin. While trading programs may function across GSA boundaries, the rules and regulations governing them should appropriately reflect both local hydrologic relationships and socioeconomic and ecosystem needs.

1 Typically, trades are subject to certain regulations aimed at protecting third parties from harmful effects of trades (e.g. well interference, stream depletion).

2 Trading groundwater does not necessarily mean physically conveying it from the seller to the buyer; in fact, most groundwater trades do not physically transfer groundwater, but rather the permits or allocation to pump it.

TABLE 1

Questions to inform the development of groundwater trading programs

Category	Questions
Objectives and outcomes	• What is the purpose of the trading program? • What performance metrics are needed?
Data and support	• What data and reporting requirements are necessary to support trading? • How will transfers of allocations be tracked? • What administrative support will be required? • How much will it cost to develop a trading program? How will the startup and ongoing costs be funded?
Third-party impacts	• What social, economic, or environmental concerns might arise from trading, and how can these be addressed? • If trading could lead to increases in consumptive use or pumping "cones of depression", what mitigating strategies can be used? • What constraints are needed to protect existing surface water and groundwater users, including DACs and GDEs, from impacts of trade? • How should groundwater trading integrate with surface water?
Adjustments over time	• How might the trading program need to evolve over time, including the need to adjust to management actions, reduced allocations, or the improved understanding of the hydrology of the groundwater basin? • How might the groundwater manager need to adjust the trading parameters to accomplish basin objectives?
Participation and process	• Will the allocation and trading program conflict with groundwater rights? • How can confidence and trust be instilled in the trading program? How can fairness, sustainability, and creation of value be ensured? • How would a GSA need to coordinate with counties or other GSAs to be successful? • Should a trading program include both leasing and permanent transfers? • How would buyers and sellers participate in the process? How would participants identify other interested parties, navigate trading compliance, and negotiate price? • Who would approve trades? Would trades be subject to public comment? • How can timely action on pending trades be ensured?

Clear objectives and outcomes

An essential underpinning for a healthy trading program is an inclusive and transparent process of stakeholder engagement. The GSA should consider its groundwater users and their roles, including DACs and GDEs, in defining the vision for the basin. An inclusive starting point can reduce conflicts as well as necessary adjustments after a trading program is in place, when addressing issues is likely to be much more expensive and problematic. Defining clear objectives and outcomes will inform the development of groundwater trading programs, including rules for trading. A selection of useful questions to inform the design of a groundwater trading program is available in Table 1. For a more comprehensive list, see Green Nylen et al. (2017).

Defining and tracking the allocation

There is a popular saying among water trading professionals: "You can't trade what you don't measure." Setting and enforcing groundwater allocations are important first steps to developing trading programs. Many GSAs will need to provide allocations and mechanisms to manage, monitor, and enforce groundwater use, regardless of whether a trading program exists. Transparent governance and enforcement become particularly important in the presence of a trading program, where there are additional financial incentives to disobey the rules. For instance, in the Murray-Darling Basin in Australia, home to the most active water trading globally, a water official recently came under scrutiny for allegations of corruption and theft (Matthews, 2017). Building public trust in the governance institutions and compliance mechanisms is important for successful implementation of groundwater management and trading alike.

Under SGMA, groundwater allocations are to be developed locally through GSAs or through the courts if local administrative solutions are unattainable. While GSAs have the authority to determine allocations within their boundaries, they do not have the authority to determine or change groundwater rights. Allocations should be informed by groundwater rights law as well as local needs, though striking this balance could be challenging. Considerations in developing allocations include landowner (e.g., agricultural, domestic, industrial), non-landowner (e.g., municipal, industrial), and GDE uses. Further, the requirements to monitor and enforce the allocation play an important role in deciding how to quantify individual groundwater use.

Groundwater rights and allocations

One of the primary challenges of developing allocations under SGMA is that there exists little to no guidance on how to develop the allocation in a way that is consistent with California groundwater rights doctrine. The State's groundwater law was developed through common law, or court decisions, in contrast with surface water law, which was largely developed through statute (Nylen Green et al., 2017). California groundwater rights can primarily be claimed through overlying, appropriative, or prescriptive rights, although new prescription was effectively ended at least for a period of time following the passage of SGMA. We discuss the main features of overlying and appropriative rights, though the discussion is neither comprehensive nor intended to substitute legal advice. For a more thorough history and explanation of California groundwater rights, we recommend Cannon Leahy (2016) and Nylen Green et al., (2017).

Overlying groundwater rights are based on the riparian and correlative water rights doctrines. Overlying rights are used by the landowner for beneficial uses on overlying land from which the groundwater is pumped. An overlying rights system is not necessarily quantifiable, though rights holders must use groundwater for reasonable and beneficial use. However, to allocate groundwater consistent with groundwater rights, a GSA could divide the native groundwater between landowners proportionate to property size. For example, a GSA could set a volume of groundwater pumping allowed per acre (e.g., 1 acre-foot per acre per year) regardless of how much each landowner has used in the past. In theory, this system is indifferent to which landowners have already developed groundwater resources, treating all landowners equally. It is perceived as being fair to landowners who have not yet used groundwater but might wish to in the future. However, there has been debate around whether landowners with dormant, or unused, groundwater rights should be on the same footing as existing rights holders, overlying or appropriative. The streamlined adjudication statutes implemented through AB 1390 (Alejo) and SB 226 (Pavley) provide that within a comprehensive adjudication, a court may "consider applying the principals established In re Waters of LongValley Creek System," which is the principal case sanctioning subordination of dormant riparian rights in the surface water context (Wat. Code § 830(b)(7)). The prospect of subordination of overlying rights could have consequences to property values for lands without developed groundwater use. In the Chino Basin, an over-appropriated basin, dormant groundwater rights were essentially lost or forfeited to other uses (Nylen Green et al., 2017). Additionally, case law recognizes that an importer of foreign waters (foreign from the watershed or "foreign in time") should receive some credit for foreign water stored in the groundwater basin. This will further complicate allocations by GSAs.

Appropriative groundwater rights are based on prior appropriation, or "first in time, first in right". Importantly, appropriative rights in California are junior to overlying rights (unless an appropriator has obtained a prescriptive right),[3] so that even the most senior appropriative right remains junior to groundwater uses on overlying lands. Groundwater rights are only available for appropriation so long as there is surplus groundwater after the overlying needs are met. Appropriative rights are generally not acquired by overlying landowners, such as municipal water purveyors for use within or outside of the groundwater basin. If a groundwater basin comes into a state of overdraft, California groundwater law would require shorting supplies to appropriators in reverse order of seniority, from most junior to most senior. While it might be perceived as being fair to overlyers and senior appropriators, this system tends to result in disproportionate economic impacts. Further, as municipalities do not have overlying groundwater rights but appropriative rights, the system creates challenges for municipal water suppliers and other appropriators that would suffer greatly from curtailment.

Developing allocations consistent with state law and community needs is not straightforward and may be challenging for GSAs. Several of our interviewees recommended an inclusive, transparent, and well-documented process for comparing potential allocation strategies, discussing the winners and losers under each scenario, and devising a strategy that works best for the stakeholders. Several interviewees also suggested developing allocations in a way that approximates what might happen in a court adjudication or according to groundwater rights doctrine. If compromise is not achievable or if stakeholders prefer the security of the court process, a GSA could enter into a streamlined adjudication. Adjudications can provide more certainty around allocations as well as positively alter

3 Prescriptive groundwater rights are acquired by pumping in an overdrafted basin to the detriment of overlying right holders in an open and notorious fashion for a period of years without objection. Many municipal water providers have acquired prescriptive rights in overdrafted basins. These rights have been recognized by the courts as very secure.

aspects of groundwater rights. Two examples of court-altered groundwater rights are discussed in "Adjudication as a means of altering groundwater rights," below.

Irrespective of the allocation formula, the total of all allocations must be determined to align with basin management objectives that achieve sustainability under SGMA. In other words, aggregate allocations must reflect the basin's "sustainable yield." The sustainable yield should be periodically reviewed based on monitoring and/or modeling of basin conditions against target conditions.

Allocations can be developed with more or less flexibility to address inter-annual variability in hydrologic conditions or water demands. Two common forms of providing flexibility in an allocation are carryover provisions or allowing multi-year pumping averages. For example, a GSA with a single-year allocation of 12 acre-inches per acre could allow unused allocation to be carried over into the following year for use or develop an equivalent five-year allocation period allowing up to 60 acre-inches per acre. The inter-annual flexibility could be useful to agricultural producers who could then change cropping patterns across the years, pump more in drought years, or, for those with surface water rights or allotments, switch between water sources depending on availability. Carryover and multi-year allocations provide more flexibility, though there exists some risk that extreme drought could induce exceptionally high pumping in a single year. During its 2012 drought, the average groundwater user in the Upper Republican Natural Resources District (NRD) in Nebraska pumped approximately 1.5 times the annual allocation in a single year, leading to acute groundwater and stream depletion.

Adjudication as a means of altering groundwater rights

Under California law, court adjudication is the only process that can definitively determine groundwater rights. Through adjudication, the priority distinction between overlying and appropriative rights can be removed or the transferability of overlying rights clarified and improved. Accordingly, an adjudication could be desirable for some GSAs.

Priority system

Many adjudicated basins in California and other western states have established allocations with equal priority (e.g. Mojave Basin), blurring the distinction between overlying and appropriative rights, while other allocation systems maintain some aspects of the underlying priority system (e.g. Chino and Seaside Basins). In most cases this was achieved through court blessing of a consent decree negotiated by the parties to the adjudication. Future allocation systems may even include some opportunities to obtain an allocation for dormant rights (e.g. a proposal under consideration in the Las Posas Basin).

Transferability

There is debate over whether overlying rights are at all transferrable or limited to use only on the particular property with which the right is associated (Nylen Green et al., 2017). Since appropriative rights are not restricted to use on overlying lands, they are more transferrable. Adjudication allowed basins like Chino, Mojave, Seaside, and Tehachapi to have transferrable overlying rights. Some basins, such as Chino, only allow overlyers to trade with other overlyers while other basins, such as Tehachapi, allow overlyers and appropriators to trade between one another (Nylen Green et al., 2017).

Tracking groundwater use

There are several methods to quantify groundwater use, each with their own advantages and disadvantages (see Table 2, page 8), and a GSA will have to weigh the costs and benefits of an appropriate quantification and enforcement scheme not only for trading, but management more broadly. Notably, irrespective of the measuring system selected, limiting tradable water to the volume of water lost from the system through consumptive use is important in avoiding a net impact to the area from which the traded water originates.

When selecting the method by which groundwater use is measured, a GSA must consider the time and costs to monitor and enforce the allocation, the uncertainties and limitations of the method, and the method's comparative advantages and disadvantages for management. Given that many municipal and industrial water users are already metered, we focus here on the quantification methodology for agricultural groundwater use. Quantification methods for agricultural use include certified irrigated acreage, crop coefficient models, calibrated energy records, flow meters, and remote sensing-based methods.

The choice for how groundwater use is measured determines the unit of allocations within a groundwater trading program. Importantly, the quantification scheme does not need to be perfect to work well, though it can influence some groundwater trading or management decisions. For example, area-based trading would allow producers to exchange irrigated acres, but would not necessarily encourage deficit irrigation or strategies to reduce water use per acre. Area-based trading does not itself reward field-level improvements to water management because there is no ability to quantify and sell conserved water on irrigated land. Volume-based trading would allow water users to trade acre-feet of water and incentivize reductions in water use per acre, as unused allocations are

TABLE 2

Comparison of groundwater quantification methods

Quantification method	Units	Description and enforcement method
Irrigated area	Irrigated area (acres)	**Description:** Certifying irrigated area is a coarse measurement for groundwater use, as it does not capture field-level variation in water use due to differences in crops, soils, technologies, practices, or other characteristics. **Enforcement:** Aerial flyovers or remote sensing
Irrigated area hybrid	Irrigated area (acres); Crop coefficients (acre-feet/acre)	**Description:** Irrigated acreage can be combined with crop coefficients, which more closely approximates field-level water use. This approach still cannot capture differences between irrigation strategies and technology, best management practices, soil types, and other field-level characteristics that influence water use. **Enforcement:** Annual crop survey alongside aerial flyovers or remote sensing
Calibrated energy records	Meter calibration (acre-feet/kWh); Energy use (kWh)	**Description:** Uses energy-use of pumps to estimate the volume pumped. Energy records by themselves can lead to large errors in estimating groundwater use, but can be improved with calibration. They also require that all groundwater pumps be hooked up to electricity, which is often not the case. **Enforcement:** Energy records and meter calibrations
Flow meters	Applied water (acre-feet)	**Description:** Flow meters are fairly straightforward, though are costly in terms of the equipment and, if not telemetered, the time spent for staff to conduct meter readings and periodic calibrations. Some flow meters are not tamper-proof. Use of pumped volume, through flow meters or other methods, does not account for the portion of applied water that may return to the groundwater through deep percolation. **Enforcement:** Meter readings
Remote Sensing	Evapotranspiration (acre-feet)	**Description:** Quantification of consumptive use, as a surrogate for actual pumping, can be done through methods that combine satellite imagery with ground-based weather data. Such methods are used routinely in some locations and may provide a viable mechanism for quantifying groundwater use. Some remote sensing platforms assume the full crop water requirement is met, which may lead to errors. If a field uses both surface water and groundwater, surface water volumes must be known to estimate groundwater use. **Enforcement:** Remote sensing

quantifiable and of monetary value. While there are several advantages of volumetric trading, both the equipment and resources to monitor and enforce volumetric allocations and transactions are expensive.[4] Only one in four wells in California is estimated to have a volumetric flow meter (National Agricultural Statistics Service, 2014). While it may be ideal to use only one method for tracking the allocation, pragmatically it may be easier to use a combination of methods depending on what is feasible for groundwater users. For example, the Mojave Water Agency uses different methods, including both flow and energy meters, to track allocations. Another combined approach includes self-reporting with some level of verification through remote sensing (i.e., evapotranspiration).

Remote-sensing-based methods of measuring water use have become more accessible in recent years. These methods measure the net water use—the volume of water lost from the system through consumptive use—rather than the gross water use, such as the volume pumped. One of the challenges of strictly measuring the volume pumped is that not all of the pumped water is consumptively used; a portion of it returns to the local system through processes such as deep percolation, runoff, or evaporation. Measuring

4 Self-reporting may seem attractive for reducing time and costs for meter readings, but it creates incentives for misreporting. If there are penalties for allocation overages or the ability to sell unused allocation on a trading program, some individuals may under-report their groundwater use in order to avoid a penalty or generate revenue from a sale that does not result in groundwater use reduction.

net water use, and using this as the unit of allocation, can be preferred, since it incentivizes water saving measures independent of irrigation methods and automatically accounts for return flows.

Enforcing the allocation is challenging but of utmost importance, particularly under a trading program where there are financial incentives to cheat or misreport use. In the Upper Republican NRD in Nebraska, groundwater users were caught bypassing their meters to pump more than their allocations. The District stripped their pumping rights, equivalent to a $3 million loss in property value (Brozović and Young, 2014). Developing a strong system of monitoring and enforcement, with steep penalties for violations, will discourage cheating. Implementing strong and transparent accounting and enforcement mechanisms is critical to the success of groundwater trading and management as a whole.

Tools to handle over-allocation

Setting the allocation accurately can be challenging, particularly absent historical pumping data. Further, current levels of pumping may be unsustainable in the long term, and so it may be necessary to adjust allocations over time. Ramp-downs, adjustable allocations, and trading offsets are useful tools to handle such issues.

A ramp-down is a gradual decrease of allocation over time, helping users adjust to pumping reductions that may be necessary to achieve sustainability. The Mojave Basin was over-allocated during its adjudication, but its allocations are subject to ramp-downs depending on aquifer conditions. Every year, the Mojave Water Agency's watermaster can evaluate conditions and recommend to the court overseeing the adjudication to reduce the allocation up to five percent from the previous year's allocation. A GSA could consider a similar method for making the adjustments needed to gradually reduce allocations to sustainable levels.

Understanding of the pumping rates and aquifer conditions will improve over time and a GSA will need mechanisms for updating allocations as needed. An adjustable allocation could allow for refinements in the pumping rates in case the original estimate of aquifer imbalance was too high or too low.

An offset, or a percentage of water taken off of a trade, may also be incorporated to reduce over-allocation or to hedge against uncertainty of spatial or temporal impacts. For example, if a 10 percent offset exists and 100 acre-feet of water is sold, 10 acre-feet would be held back for the aquifer and the remaining 90 acre-feet transferred to the buyer. Offsets can assist in meeting management goals, though the level of the offset must be carefully considered. If too high, the offset can make trading arbitrarily expensive and unduly place the burden of reducing over-allocation on trading participants. This was evident when the Central Kansas Water Bank charged a minimum of 23 percent through multiple conservation offsets on water leases; over five years, the Bank facilitated only one lease (Kansas Water Office, 2011). Large offsets can limit trading activity and therefore the effectiveness of the offset itself. It may be desirable to have a more modest offset and encourage more trading activity. For example, Colorado's lease fallow tool implements a 10 to 12 percent offset to jointly protect third parties and reduce the time and effort individuals would normally spend for costly engineering evaluations and legal proceedings. In this case, the offset simplified an otherwise complicated and costly process and encouraged more trading.

Trading rules under SGMA

In this section, we cover considerations for trading rules under SGMA: tools to integrate hydrologic connectivity into the trading rules; developing recharge credit schemes; and transfers between GSAs and across basin boundaries. To increase the likelihood of long-term viability and reduce the likelihood of conflict, rules governing trade, like the allocation method, should be developed through active and transparent stakeholder engagement and informed by the best available data and science.

Hydrologic connectivity

Understanding the aquifer dynamics through monitoring and groundwater modeling is crucial to designing a well-functioning trading program. The dynamics will inform rules concerning who may trade with whom (e.g. sub-basin boundaries), whether any adjustments are needed to account for spatial differences (e.g. stream depletion, seawater intrusion), in which directions trades may occur, and whether a trade will cause localized drawdown or well interference for existing users. Groundwater trading programs should be developed to both reflect the hydrologic relationships and protect existing users, which may require rules related to basin boundaries, zoning, spatial buffering (e.g. around municipal wells), minimum well spacing, trading ratios and adjustments, and offsets.

In regions where groundwater pumping induces a spatial effect, such as stream depletion, impacts to GDEs, or seawater intrusion, trading rules must account for and correct any consequences of groundwater trading between different locations. For example, the Twin Platte NRD in Nebraska manages groundwater that induces stream depletion on the Platte River. Each well location uniquely induces stream depletion, some at higher rates and some at lower rates. Parties trading groundwater in the Twin Platte have to make proportionate changes in groundwater pumping depending on the comparative values of their stream depletion factors. For example, a buyer with a stream depletion factor twice as high as a seller's would have to reduce pumping by half; in other words, the buyer would only be able to use half of the seller's allocation. This practice is referred to as "ratio trading", which can be used to account for any number of spatial differences: consumptive use, crop coefficients, soil types, seawater intrusion, and stream depletion, among others. Ratio trading is a mechanism to demonstrate impact equivalency in a trade.

Trading programs often include rules to limit impacts or well interference on existing users, particularly those with domestic or shallow wells. There might be well spacing requirements or allocation density constraints to limit the effect of a new well's cone of depression on existing neighboring wells. Municipalities or ecologically sensitive areas might have a spatial buffer inside of which new groundwater pumping is disallowed or limited.

Conjunctive use schemes: recharge and recycling

The nature of California's variable surface water supply has and will continue to give rise to innovation in conjunctive water use and trading programs. In years of high surface water flows, excess flows can and have been used to recharge groundwater. Recharge may be accomplished through direct recharge or in-lieu recharge, in which groundwater pumpers forego groundwater pumping and use available surface water instead of the forgone groundwater. To provide incentives to individual landowners to recharge on their own land or to temporarily switch to surface water, GSAs could devise a credit scheme for recharged groundwater. The credits could be applied to the individual's allocation or transferred and sold to another user in accordance with the trading rules.

Groundwater recharge projects will be a key tool to meet the goals of SGMA, particularly in years of high flows; however, any recharge credit scheme would have to comply with State water law. The State Water Resources Control Board (SWRCB) treats groundwater storage as it would reservoir storage, meaning that the storage of surface water underground must have a recognized beneficial use beyond storage. In other words, while the SWRCB does not recognize recharge as a beneficial use in and of itself, the Board allows for recharge as a medium through which water may be put to beneficial uses. For example, the Kern Water Bank recharges excess surface flows for urban, agricultural, and environmental purposes alike. Legislation to recognize recharge itself as a beneficial use has been controversial, as there are concerns that recharged water could be hoarded among some water users to the detriment of surface water users downstream. Further, peak surface water flows generate environmental benefits, requiring a balanced approach between diverting surface water for recharge and leaving it for instream or downstream uses.

Water recycling is another opportunity for conjunctive use. For example, a city's treated wastewater could be used for irrigation in an in-lieu program or for direct recharge. Water recycling programs should consider any water quality and downstream effects, such as decreased effluent. As with other augmentation options, incentives could be included in a trading program to encourage water recycling.

Trading between GSAs and across basin boundaries

In order to generate the most opportunities to trade sustainably, developing a trading program across GSAs at the sub-basin or basin level may be desirable. SGMA requires coordination agreements among GSAs within a basin (California Water Code Sections 10727 and 10727.6), though there is debate whether trading across GSA boundaries is allowed (see Green Nylen et al., 2017). A wider geography would create more opportunities for groundwater users to trade,[5] but could also create more localized impacts, such as cones of depression. Sub-basin or zonal trading could be optimal.

It is important to note that allocation transfer between nearby GSAs does not necessarily mean a physical transfer of water, through pipelines or canals. Within a sub-basin or basin, groundwater trading would most likely be comprised of individual groundwater users transferring allocations, but not physically conveying groundwater between one another. This common characteristic of groundwater trading may help avoid some of the complications associated with surface water trading, such as conveyance and capacity constraints.

Participating in the trading program

Understanding and developing the process for participating in groundwater trading is particularly important for groundwater users. The process includes the workflow of trading: how to identify interested parties, how to value water, how to obtain regulatory approval, and how to execute the transaction legally and financially.

Trading structures

A trading structure is the mechanism participants use to identify and match with trading partners. Some are informal, such as "coffee shop" markets or bilateral contracts; others are slightly more formalized such as brokerage and bulletin boards; and still others are much more sophisticated such as auctions and electronic clearinghouses. Trading structures

5 Most rural counties have ordinances prohibiting groundwater transfers outside of county boundaries. Some ordinances as written may only restrict the physical transfer and conveyance of groundwater, while others may be broadly written to also restrict the transfer of allocations. Such an ordinance would be potentially problematic for a trading program, as county boundaries do not reflect hydrologic boundaries. As a result, some GSAs may need to coordinate with their local counties to revise ordinances.

are not mutually exclusive; several active trading programs have multiple structures existing simultaneously. For example, groundwater trading in western Nebraska actively happens through bilateral contracts, real estate brokers and auctions, the electronic bulletin board of Craigslist, and electronic clearinghouses. Each trading structure has its own benefits and costs, which are summarized in Table 3. Trading structures are less important from the regulatory perspective and more important for the participants, who face different transaction costs and levels of convenience and flexibility under each.

Pricing and confidentiality

Because the value of water changes over space and time, it is important not to overly-constrain prices through regulation or to expect uniformity of prices. Fixed pricing can be a significant limiting factor in trading participation, as it is can be set too high for buyers or too low for sellers. For several years, the Central Platte NRD in Nebraska set the price for groundwater-irrigated acres and chronically suffered from low participation. Generally speaking, prices are allowed to adjust dynamically through negotiation or within the trading program and are allowed to flexibly change not only year to

TABLE 3

Comparison of trading structures

Trading structure	Description	Administrator	Advantages and disadvantages	Participant costs
Bilateral contracts or "coffee shop" markets	The most common form of water transactions worldwide, no formal trading mechanism exists. Participants largely learn of one another by word of mouth.	None; informal and decentralized	**Advantages** • Costless to agency to implement **Disadvantages** • Difficulty identifying an interested party • Difficulty in price negotiation • Difficulty in regulatory compliance	No third-party fees; high search and transactions costs
Brokerage	Representation of a buyer or seller in a water rights transaction.	Private sector	**Advantages** • Helps identify interested parties • Helps to negotiate price • Specialized agents help in regulatory compliance **Disadvantages** • Still somewhat decentralized • Pricing often favors the represented party	Brokerage fee
Bulletin boards	A physical or electronic board where interested parties can list information about their water rights for others to get in contact with them.	Private sector, regulatory agencies	**Advantages** • Centralizes trading activity to a degree **Disadvantages** • Difficulty in price negotiation • Difficulty in regulatory compliance	No third-party fees; moderate search and transactions costs
Auctions and reverse auctions	A physical or electronic system in which buyers outbid one another (auction) or sellers undercut one another (reverse auction) to trade water.	Private sector, regulatory agencies	**Advantages** • Centralizes trading activity to a degree **Disadvantages** • Asymmetric pricing: One side reaps the benefits or gains of trade • Difficulty in regulatory compliance	Auction fee if privately run
Electronic clearing-houses or "smart markets"	Leverages the power of computer optimization and a tailor-made algorithm to match participants within the trading rules and by price points.	Private sector, regulatory agencies	Advantages: • Centralizes trading activity • Automates regulatory compliance • Includes price discovery mechanism Disadvantages: • Intensive startup costs to develop	Trading fee, if privately run

TABLE 4

Regulatory and financial roles of trading programs

Regulatory role	Financial role
• Monitoring, enforcement, and verification • Maintaining groundwater rights database • Setting rules and regulations for allocations and trading • Review and approval of trades	• Matching and brokerage • Water valuation • Price negotiation and discovery • Execute transaction: File applications, transfer funds, file legal paperwork with GSAs and courthouses

year, but within an irrigation season. Each trade has its own characteristics, including timing, use and soil type, infrastructure and technology considerations, and input costs, and therefore its own unique value of water.

A trading program can be conceptualized as having two distinct aspects: the regulatory and financial roles (see Table 4). Some groundwater trading programs have separated the regulatory and financial roles between the public and private sectors, respectively (e.g., Edwards Aquifer Authority, TX; South Platte and Twin Platte NRDs, NE; Mojave Water Agency, CA), while others have integrated them (e.g. Central Platte NRD, NE; Fox Canyon Groundwater Management Agency, CA).

Limiting conflicts of interest

There are potential conflicts of interest that arise when an entity both regulates groundwater trading and administers the trading platform, which could open doors to match trades or share information in a way that is advantageous to the GSA, board members, or staff. If the GSA plans to participate in the trading program and buy back groundwater rights, this is even more problematic, as the GSA would have both insider information on pricing and could potentially give itself first access to purchase groundwater ahead of other participants.

A GSA could keep separate the financial and regulatory aspects of the trading program, where setting and enforcing rules is within the regulatory role and the matching and pricing of trades within the role of a financial overseer, which can be served by a number of entities, including private sector partners. Separating the matching and pricing from its regulatory responsibilities will likely help GSAs to limit liabilities and the potential for conflict regarding unfair trading activities, and accordingly, can help to build trust in the overall trading system. This separation of duties allows regulatory agencies to participate on trading platforms if interested in buying back allocations while giving themselves protection from claims of mismanagement, favorable trading, or sharing of or using insider information.

Is public price disclosure necessary?

The tendency in starting a trading program is to require public disclosure of price information, but participants may resist sharing what is perceived as sensitive and confidential financial information. In many successful trading programs, the price information for individual transactions is not disclosed. Publicly sharing pricing data is not necessary for trading or conducting the regulatory aspects of a trading program, and could actually discourage activity amongst individuals who distrust the motivations behind its collection. As trading programs become more active, broader, or accepted, comfort around sharing price data may evolve. Reporting aggregated data (e.g. average price, average volume of groundwater traded) and anonymizing individual transactions data can provide information on the performance of the program while maintaining a layer of confidentiality to specific participants.

Approving and executing trades

To the extent possible, developing a set of transparent and formulaic rules around trading will help to treat individuals fairly and expedite the process while still preventing third party impacts. Otherwise, evaluating trades on a case-by-case basis, without clear rules and guidance for approval, can unnecessarily prolong approval processes and potentially generate concerns of bias around the GSA's decisions. If the rules are transparent and procedural, the decision-making around a transfer is clear. Further, formulaic rules will shorten approval times for trade, which will not bog down participants, staff, and board members in the review of trades.

Approval of trades can be an administrative responsibility for GSA staff or that of the GSA board. Placing transfers for approval on a board agenda improves transparency, as trades are noticed on a public agenda that is subject to the Brown Act and open to public comment. The Mojave Water Agency places transfers on its board's consent agenda to protect both its board and groundwater users from perceptions of favoritism. If the trade complies with the Agency's rules, it is simply approved.

All accounting of groundwater transfers is held within the regulatory agency, including the changes in locations of pumping, the landowners involved, and the duration of transfer (e.g. one year, multi-year, or permanent). The changes in allocations will be important for enforcement and assessments alike. The transfer of funds for the lease or sale is usually handled privately, such as between individual landowners or through an escrow account, and not through the regulator. In some groundwater trading programs, though not all, a permanent transfer requires recording a deed with the county clerk to provide more transparency in real estate transactions. The Santa Paula Groundwater Basin, for example, requires all transfers be recorded (United Water Conservation District vs. City of San Buenaventura, 2010). Otherwise, there is no recorded information on the property's title with respect to its access to groundwater. Lack of title information concerning transfers can be a problem, especially in California where overlying groundwater rights are inherent in land ownership.

Practical advice for getting started

Given the complex nature of groundwater trading programs, rules will need to be adjusted over time, as new information and improved data become available. Well-designed trading programs evolve through regular evaluation and adjustment to inform improvement of their program over time. Because any agency is unlikely to design the rules perfectly at the outset, it may be prudent to start a trading program with leases only—no permanent transfers—and using informal trading mechanisms. Testing trading rules with a handful of single-year transfers can help the GSA learn, better understand the incentives and effects of their rules, and troubleshoot any issues that arise. Prematurely transitioning to a permanent and formalized system (e.g. electronic clearinghouse) potentially robs the GSA of the chance to learn and iterate on the trading rules and could result in permanent, rather than temporary, unforeseen consequences.

Developing a groundwater trading program can be costly and time intensive. Between stakeholder engagement, designing trading rules, modeling and evaluation, funding ongoing administrative support, and monitoring, enforcement, and verification, the costs add up. However, implementing a program that provides long-term risk management for groundwater users can help to reduce the economic burden of new groundwater regulations, dramatically reduce the long-term cost of water management, and provide a range of benefits and reduced risk to the water users over time.

Conclusions

Groundwater management presents an opportunity to work towards greater water security. While new pumping restrictions or shifts in use to achieve sustainability under SGMA can result in near-term economic hardships, groundwater management in the long term can secure the resiliency of the resource and the livelihoods, communities, ecosystems, and economies that depend on groundwater. Well-designed trading programs that account for social, economic, and environmental concerns, can help ease the transition to reduced pumping levels and changes in use and can reward individuals for improved groundwater management practices. Trading programs, as well as complementary programs such as water banking or recharge, can create

Glossary

Allocation: A unit of groundwater use that has been defined and quantified through acceptable methods that can be assigned or distributed to specific users. Conjunctive management: The strategic practice of managing different sources of water supplies, such as surface water and groundwater, to improve long-term reliability. Natural or artificial recharge (e.g. aquifer storage and recovery), in-lieu groundwater banking, or reclamation and recycling are examples of conjunctive management.

Disadvantaged community (DAC): The entire area of a water system or community where the median household income is less than 80 percent of the statewide median annual household income or, in the case of severely disadvantaged communities, less than 60 percent of the State's median household income (Title 22 of the California Code of Regulations, § 64300(a) and California Public Resources Code, Section 75021).

Groundwater-dependent ecosystems (GDEs): The "species and ecosystems that depend on groundwater for some or all of their water needs" (Rohde et al., 2017).

Sustainable yield: The "maximum quantity of water, calculated over a base period representative of long-term conditions in the basin and including any temporary surplus, that can be withdrawn annually from a groundwater supply without causing an undesirable result" (DWR, 2017).

Third-party impacts: The negative consequences of a transaction to an external party, who could be a surface water rights holder, groundwater user, or groundwater-dependent ecosystem. Negative consequences could include well interference, lowering of groundwater levels, degradation of water quality, stream depletion, seawater intrusion, land subsidence, or reduction of groundwater storage.

Trading program: An incentive-based policy tool that allows individuals to buy, trade, exchange, or sell some aspect of the right to pump and use groundwater (e.g., an allocation), usually for monetary compensation.

new revenue streams and risk management tools that previously had not existed. If individuals understand that they can be rewarded and compensated for implementing water-saving strategies, it should help smooth the transition to sustainable groundwater governance.

One of the most important aspects of developing groundwater management programs, including trading programs, is establishing trust. Across the United States, where new groundwater management regimes have been initiated, early actions have started as controversial, but eventually, as trust develops, the management has transitioned to an accepted, largely administrative function. Building trust relies on making concerted efforts to engage the variety of stakeholders, ensuring transparency throughout the process, and building meaningful collaborations.

Trading programs should be developed with the utmost thought and care for the local conditions: social, economic, and environmental alike. The importance of tailoring a trading program to local hydrologic relationships and community concerns cannot be overstated. To achieve this, a GSA will need to be intentional in creating a transparent process that includes engaging with stakeholders, building relationships and trust, developing and managing the data, modeling, and support tools, and recruiting technical expertise as needed.

There is a wealth of information available about existing groundwater trading programs and groundwater management under SGMA. A selected list of those resources is available for reference in "Additional resources," page 15.

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