www.water-alternatives.org Volume 17 | Issue 2

Kroepsch, A.C. 2024. Monitored but not metered: How groundwater pumping has evaded accounting (and accountability) in the western United States.
Water Alternatives 17(2): 348-368

Monitored but Not Metered: How Groundwater Pumping Has Evaded Accounting (and Accountability) in the Western United States

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ABSTRACT: The metering of individual groundwater use has become a common feature of recent interventions in groundwater governance in many parts of the world, though its actual implementation has been largely unsuccessful (Molle and Closas, 2021). Such metering efforts aim to curb groundwater over-extraction by quantifying – usually for the first time ever – who is pumping groundwater, how much, when, and where. This analysis takes a step back from these management interventions and asks how we got here. How did groundwater pumping become such a 'black box' and individual metering become the exception? And what are the consequences of this data gap? This paper explores these questions in the western United States where the close accounting of surface water diversions makes for a useful foil to largely unquantified individual groundwater pumping. I synthesise biophysical, political economic, and epistemic aspects of groundwater development to examine groundwater pumping's un-quantification and I argue that attention must be paid to all three of these categories if we are to understand why groundwater metering is not more prevalent. I elaborate on these three dimensions – groundwater materiality, knowledge production, and power/profit – as I trace how groundwater's un-metering has been produced, widened and maintained in the region over the last 140-plus years.

KEYWORDS: Groundwater, metering, politics of water quantification, inscrutable spaces and circulations, Western US

INTRODUCTION

The metering of individual groundwater use has become a common feature of recent interventions in groundwater governance in many parts of the world (Molle and Closas, 2021). These new metering efforts aim to curb groundwater over-extraction by quantifying – usually for the first time ever – who is pumping groundwater, how much, when, and where. Though groundwater metering is seen by many as "a self-evident best practice" of groundwater management, its actual implementation has been largely unsuccessful due to limited political support and rejection by groundwater users themselves (ibid: 18578). This analysis takes a step back from these groundwater metering interventions and asks how we got here. How did groundwater pumping become such a 'black box' and individual metering become the exception? More specifically, how did it become the case that groundwater use is typically quantified via wide-ranging networks of monitoring wells that capture general trends in aquifers rather than specific impacts at individual points of use? And what are the consequences of quantifying groundwater pumping in abstract versus individual terms?

This paper explores these questions in the western United States. This region is a good place to elaborate the selective ignorance of individual groundwater pumping because groundwater's status as a 'black box' stands in stark contrast to surface water monitoring. Western states have been in the business of quantifying individual surface water use since the late 1800s, when state engineers offices were created to administer individual water rights on rivers and streams (Best, 2009). Individual groundwater pumping, on the other hand, has yet to receive the same level of administrative attention. Private groundwater metering for the purpose of on-farm water management appears to be growing (USDA, 2018), but public groundwater metering for the purpose of reporting groundwater use to the state for aquifer management is still rare (though see the final section of this paper for some exceptions).

The absence of individual groundwater pumping data shows up in groundwater governance and scientific discourse in several ways. In the groundwater management literature, the topic of individual metering is absent or sparsely covered (Adkins et al., 2022; Ashley and Smith, 1999; Bennett et al., 2020). When it does come up, it is often because the concept is unpopular among well owners (d'Elgin, 2016; Walsh, 2022; Wölfle-Hazard, 2022) or because metering gaps are but one of many groundwater unknowns (Molle and Closas, 2019). In the hydrogeology literature, the lack of individual pumping data emerges in the form of complaints about metering data being problematically absent in the western United States (Castle et al., 2014; Famiglietti et al., 2011) and worldwide (Bierkens and Wada, 2019; Rodell et al., 2018; Taylor et al., 2013). The lack of individual pumping data is also evident in the differing estimates of pumping volumes that are achieved via different methods of approximation (see, for example, Cooley et al., 2021).

It isn't that groundwater is unimportant in the so-called American West. On the contrary, the use of groundwater has been critical to development in Western states for more than a century (Di Baldassarre et al., 2021; Konikow, 2013). Today, Western states withdraw approximately 71% of the groundwater extracted for irrigation nationally, they include about 10 million people who rely completely on their own wells for drinking and domestic uses, and they are home to millions more whose public water supply systems are sourced from groundwater (Dieter et al., 2018; Rojanasakul et al., 2023). Climate change and drought further amplify these trends, as a growing number of water users turn to aquifers to make up for fickle surface water supplies (Castle et al., 2014; Dieter et al., 2018). Nor does the region lack groundwater observers. American hydrogeology matured into a proper scientific field through investigations of groundwater resources in Western states in the late-1800s, plus the development of degrees in hydrogeology at universities in the region in the mid-1900s (Rosenshein and Moore, 2013). And yet, these things have not added up to widespread groundwater metering.

I interrogate this data gap in the analysis that follows. More specifically, I ask how the absence of individual groundwater metering was produced in the American West, how it has been maintained in most areas of groundwater use for over a hundred years, and what its consequences are for today's groundwater users and surrounding places/ecologies. To be clear, my goal is not to argue that individual metering of groundwater would have automatically led to more cautious groundwater management in Western states were it more broadly initiated. The literatures on environmental knowledge production and water governance caution against such a simplistic assertion (Anderson and Cantor, 2024; Birkenholtz, 2014; Birkenholtz, 2008; Loftus et al., 2016; Loftus, 2006; Nost and Goldstein, 2022). But other consequences of Western states' selective ignorance around individual groundwater pumping are clear. They come in the form of overlooked inequalities among pumpers and questions unasked by scientists and regulators, plus missed opportunities in groundwater management.

To guide my exploration of groundwater's non-metering, I leverage the "inscrutable spaces and circulations" analytic by Kroepsch and Clifford (2021). It encourages the analyst to tease apart the biophysical, epistemic and political economic aspects of the non-production of environmental knowledge for careful examination, and then to put them back together again, thinking about how they are co-produced and how they intertwine to create environments of not-knowing. The existing groundwater management literature rarely explores all of these dynamics or puts them in conversation. I argue that it is essential to acknowledge the biophysical, epistemic and political economic aspects of groundwater use in order to develop a meaningful account of how and why individual groundwater pumping has largely escaped accounting (and accountability). This advances theory in the politics of water quantification by making a case for examining this full slate of dynamics in our efforts to understand how and why water becomes quantified – or doesn't. The approach also reminds us to think about the minimal metering of groundwater pumping in hydrosocial terms – as not merely a problem for researchers or a policy failure, but also as a component of hydrosocial processes made up of biophysical, epistemic and political economic dynamics (Linton and Budds, 2014).

This paper proceeds in five parts. First, I explain my research methods alongside a review of the literature on studying absences in environmental knowledge production. Next, I develop three historical and chronological sections that offer explanations for how the groundwater metering gap has been produced, widened and maintained in the American West over time, respectively. For reasons that will be explained later, each of these sections is geographically situated in a place of intensive groundwater use (Colorado, the High Plains and California). The paper concludes with a discussion of the present-day consequences of not metering individual groundwater use.

EXAMINING GROUNDWATER AS AN INSCRUTABLE CIRCULATION

As scholars studying gaps in environmental knowledge production have shown, trying to understand why something did not happen is a tricky intellectual task (Frickel, 2014). It is also an important one because, just as presences in environmental measurement are not inevitable and have uneven consequences, absences in environmental measurement are not preordained and have their own impacts (Nost and Goldstein, 2022). To borrow Murphy's apt terminology, alongside every hydrologic "regime of perceptibility" is a "regime of imperceptibility" that is also actively being produced through particular eco-social relations (Murphy, 2006). This is especially true for water flows in today's era of "water datafication" – a time when there is a rush to quantify, track and disseminate information about water via remote sensing technologies, computational advances, and open-source platforms (Hoefsloot et al., 2023; Marston et al., 2022).

This analysis follows Frickel's (2014) exhortation that scholars of knowledge absences should work to derive explanations of their causes rather than merely describing their existence. In an effort to do so, I leverage the inscrutable spaces and circulations analytic by Kroepsch and Clifford (2021). This framework offers a geographical take on environmental un-knowing that asks the analyst to consider how the biophysical and spatial aspects of groundwater pumping factor into its status as an 'inscrutable circulation' and how these are intertwined with (and reinforced by) equally important epistemic and political economic dynamics. Along these lines, I examine how individual groundwater pumping became an inscrutable circulation by working through aspects of groundwater's materiality (biophysical factors), groundwater knowledge production (epistemic factors), and groundwater-related power and profit (political economic factors). None of these dynamics is given primacy; to show this, I assemble them in a different order in each section of the analysis that follows.

I leveraged mixed qualitative and archival methods to illuminate the absence of groundwater metering in Western states and explore its origins. I began with 13 interviews with groundwater managers and scientists, which helped me to see the metering gap from their perspectives. After they struggled to answer the question of how pumping has largely dodged quantification, I embarked on a synthesis of multiple literatures to develop my own argument. First, I turned to the literature on groundwater law and policy in Western states to gather descriptions of policy problems and, if available, explanations of how they emerged. Second, I read environmental histories, which added context to how groundwater use and governance unfolded in Western states. Third, I layered on literature from political ecology and decolonial water studies to better illuminate the capitalist political economic structures and settler colonial epistemologies that shape groundwater use in the western United States. Finally, I studied auto-ethnographies by writers who have turned a critical eye to groundwater use by their own families and communities. These accounts were so insightful that I chose to focus the synthesis that follows on three places of heavy groundwater use captured in these texts: the South Platte Valley in Colorado (d'Elgin, 2016), the High Plains, which span several states roughly along the 100th meridian line (Bessire, 2021), and California's Central Valley (Arax, 2019).

These specific groundwater literatures are not new but they are rarely put together, so synthesising them offered novel connections. In particular, studies that critically question groundwater political economies and epistemologies are not often cited by researchers in other domains, who focus on groundwater's biophysical dynamics or policy prescriptions. Bringing these literatures into conversation is important for theorising the politics of water quantification because doing so situates groundwater extraction within broader processes of "dispossession, colonization, capital investment, and commodity production" (Walsh, 2022: 3). In keeping, this analysis focuses on the rapidly expanding settler colonial uses of groundwater that occurred from about 1880 to the present in order to locate the absence of individual groundwater metering in Western states within the "constantly expanding irrigation frontier" of which it has been part (ibid). This is not to discount the longstanding Indigenous uses of groundwater that preceded this timeframe (Crown, 1987; Haynes, 1999). Rather, the starting point of 1880 is intended to emphasise the ways that groundwater extraction advanced the structure of settler colonialism in Western states – by producing private property at the edges of arable lands and a "vertical frontier" for capital accumulation (Underhill et al., 2022: 1), by establishing "colonial beachheads" that expanded power differences between colonisers and the colonised (Curley, 2021: 388), and by offering a "spatiotemporal fix" for agricultural and urban development that shifted water shortages to future times and landscapes (Bolin et al., 2008: 1498).

Within these diverse groundwater literatures, no studies took up the question of how groundwater pumping became so un-metered. This meant that I often had to look for reasons by reading between the lines. As I did so, a useful thought experiment – again recommended by Frickel (2014) – was to come up with a "strategic comparison" against which to juxtapose groundwater metering. Surface water monitoring made a productive foil. As will be explained in more detail below, surface water diversions are more closely scrutinised by Western states than groundwater pumping. This disparity enables questions such as how and why individualised water metering emerged in one of these circumstances but not the other. To my knowledge, this comparison has not been made before in the groundwater or surface water literatures.

PRODUCED: THE SOUTH PLATTE VALLEY, COLORADO, 1880-1930

The South Platte River Valley is a helpful place to examine how the groundwater metering gap was initially produced by settler colonial groundwater users because the river's vigorous use in the last 150 years has made it a laboratory for surface water and groundwater law and administration in Colorado. The South Platte River has the reputation of being Colorado's hardest working river as it extends eastward from the Rocky Mountains across the plains, flowing first through Denver and then the state's most productive agricultural region before crossing into Nebraska. Over-appropriated since 1879, the South Platte's waters are used six or seven times before they reach the state line (HDR, 2015). The ancient South Platte River established a broad alluvial aquifer beneath and beyond the present-day river channel that holds a volume of water many times greater than the stream's annual surface flows. The two 'rivers' – above ground and below – are hydrologically connected, with subsurface flows feeding the river and vice versa, depending on location (Bash and Young, 1994). Like many other areas of groundwater use in Western states, the South Platte Valley had only a handful of wells up to about 1930, after which the area experienced an unregulated boom in well drilling that lasted many decades (Kryloff, 2008). Eventually, in the late 1960s, pumpers' impacts to senior surface-water rights holders prompted the state to establish tighter regulations for groundwater users. These regulations led to controversial well shutdowns in the 2000s (d'Elgin, 2016).

Inexhaustible, individualised, and easy to ignore

Euro-American settlers believed groundwater supplies to be limitless when the first recorded irrigation well was dug in the South Platte River Valley in 1889 (Code, 1937). This conviction had its origin in scientific speculations of the time, which aligned neatly with broader mythologies of the American West's unlimited land and water resources (Brooks, 2017). The inexhaustible supply myth held that Western groundwater was fed by gigantic underground rivers that originated from distant sources (Green, 1973). In the words of d'Elgin (2016: 67), whose family farmed with surface and groundwater in the South Platte Valley for several generations, "Groundwater was like magic. You couldn't see it, yet you pumped and it appeared". The ease with which alluvial groundwater flowed made it so the inexhaustible supply myth appeared to actually materialise on the ground. Similarly, artesian wells that tapped the nearby Denver Basin aquifer system gushed forth in a seemingly limitless manner. In 1892, and for many decades afterwards, an artesian well powered five elevators in the fanciest downtown hotel in Denver (Singer, 2017).

After shallow wells and artesian pressures declined, steadily advancing pumping technologies kept the water coming for decades. Drilling activities advanced ahead of the modern science of hydrogeology in the U.S., though the scientific discipline matured and formalised amidst the West's widening pumping zones (Meinzer, 1923; Narisimhan, 2008). Among the region's leading scientific authorities was William E. Code, a state irrigation engineer who devoted his career to groundwater investigations, primarily along the South Platte, starting in 1928 (Kryloff, 2008). Code drove the valley's dirt roads, visiting with farmers and recording local groundwater levels. His inventory grew to include thousands of wells. The data he collected led him to form theories about groundwater over-drafting that later made him an advocate for state groundwater regulations, but in the decades before Code and others worked to illuminate subsurface flows much was left to be learned about the innerworkings of aquifers (Kryloff, 2008). At the time, there were few indications that it might someday be valuable to quantify how much groundwater was being pumped by each user and no institution stepped forward to suggest the idea.

Groundwater came as an afterthought to the West's biggest water developer – the U.S. Bureau of Reclamation, created in 1902. Reclamation was more interested in developing surface water by building reservoirs in mountain valleys than it was in drilling wells to access groundwater (Green, 1973). The absence of large institutional actors is a theme that appears in more ways than one in the political economy of groundwater extraction. In contrast to surface water development, groundwater development has been an individualised endeavour. Harnessing rivers for human use requires significant upfront capital investments in costly infrastructure, plus a water management system that ensures the expensive infrastructure will be worthwhile (Opie, 2000). In other words, institutions were necessary to finance surface water projects and then to protect those capital investments via water administration. Along the South Platte, surface water institutions started with utopian irrigation colonies led by social reformers and evolved into Reclamation-led trans-basin water projects (Tyler, 1992). Groundwater users did not have the same incentives to work together. The cost of well drilling could be borne by an individual, who then gained access to an abundant and predictable water supply that did not require administration – at least for a while (Schlager, 2006; Kryloff, 2008).

Additional factors encouraged the individualisation of groundwater development. The groundwater property rights regime that emerged in the settler colonial West, based in English law, assumed that the contents of aquifers belonged to overlying landowners under a doctrine called 'the absolute ownership rule' (Sax and Abrams, 1986). Surface water, by contrast, has usually been considered a public resource, though with designated rights to individual use (Narasimhan, 2008). In other words, as people tapped into groundwater systems, rights to subsurface waters were rolled into existing land-based property regimes, which reinforced the power of and value of land ownership (Ashley and Smith, 1999). The result: aquifers that were individualised, essentially privatised, and basically unregulated – both in practice and the minds of groundwater pumpers. With personal capital investments made in wells and pumps, plus access based on land ownership, groundwater users in the South Platte valley and elsewhere came to see aquifers "chains of individual investments" rather than larger hydrological systems (Kryloff, 2008: 59). The absolute ownership doctrine reinforced this view by giving no consideration to the fact that pumping by one landowner could impact that by another (Gardner et al., 1997). Because volumetric constraint did not make sense under such an approach, measuring individual volumes did not make sense either.

When it comes to groundwater development the category of the 'individual' is not as straightforward as it sounds, however. The individualized nature of groundwater development has always meant more power for private capital in the extraction of subsurface waters (Underhill et al., 2023), but this came in multiple forms. Tragedy of the commons arguments about groundwater typically assume that individual users are people (for example, a farming family), but private companies have always been on the forefront of groundwater development in the West, and states and international geopolitics served as important boosters, too. Early studies of artesian groundwater potential across Colorado's eastern plains report that private investors such as railroads and coal prospectors beat federally funded geologists to the area in the 1880s; they also had more luck with their initial groundwater finds (White, 1882). Later government reports also highlight the importance of early industrial users of South Platte groundwater, such as sugar beet factories and steam plants (Bjorklund and Brown, 1957). Eventually state and nation directly encouraged farmers to drill wells, and often subsidised the costs, as World War I boosted demand for wheat exports and integrated Western farmers into international markets (d'Elgin, 2016; Molle et al., 2018; Worster, 1992).

Groundwater's biophysical characteristics also worked against dedicated monitoring from the start. Subsurface flows are largely invisible to the eye, of course, which poses challenges to management, but there has always been more going on with groundwater's materiality than just its hidden location. Surface water administration in Colorado makes for an illustrative contrast. The monitoring of individual surface water diversions for the purpose of administering the state's prior appropriation system has a long history there. Among Western states, Colorado prides itself on measuring every drop of water diverted from the state's rivers and being the most rigorous enforcer of water rights in the region (Weiser and Mitchell, 2022; Hanemann, 2014). By law, every withdrawal of surface water from a river must be metered at its point of diversion and recorded by state water administrators so that they can ensure water users are taking the proper amount at the correct location and time (Grantham, 2011). When early water administrators set about this work in 1879 they did so by horseback (Smith, 2009). Today, measurements of water diversions from busy rivers such as the South Platte are collected in real-time via satellite telemetry and even made publicly available for all water users to see in on the internet (Smith, 2009). By contrast, Colorado water administrators collect groundwater pumping data only in a handful of specific scenarios (which are usually focused on protecting surface water rights holders). To manage subsurface waters, they rely more broadly on networks of monitoring wells, which capture general aquifer trends, and models, which estimate and simulate pumping.

According to Schlager (2006), three biophysical features of surface water – which groundwater does not share – have contributed to tighter state monitoring of diversions from rivers. First, surface water is more obviously finite than groundwater in that, for example, a diversion by an upstream user will immediately subtract from the water available to downstream users. Second, surface flows move quickly and flow rates can be relatively easily measured in volume per second. Third, surface flows vary a great deal from day to day and especially from season to season. A fourth potential reason for surface water's tighter administration is the way that rivers' geomorphologies have assisted state surveillance: for water rights administrators to track surface water diversions, they had only to travel river corridors and measure flows at headgates where water was being diverted away from the stream channel (Best, 2009). This was (and still is) no small feat, but the fact that the enforcement landscape could follow visible waterways made it at least somewhat spatially consolidated and predictable.

None of the above applied to groundwater pumping. Rather than being finite, fickle and fast-flowing, alluvial groundwater in the South Platte was abundant year-round and also moved slowly, which meant that individual pumpers did not immediately impact each other in the way that surface water diverters did. Importantly, if groundwater was present then it could be pumped from underground at the precise place and time of desired use (Kryloff, 2008). As a result, points of extraction (wells) were scattered across the landscape at the whims of geologic forces and groundwater users rather than being consolidated along a river corridor. In other words, the biophysical characteristics that made individual surface water diversions something that had to be tracked in order for the prior appropriation system to function did not cross over to groundwater pumping (except in situations of surface water-groundwater connectivity, which Colorado would acknowledge in the 1960s). Groundwater was, in many ways, surface water's biophysical opposite. The South Platte River made for an unruly subject that required close watch if it was to be parcelled out according to the 'first in time, first in right' prior appropriation logic, while the year-round availability of its alluvial groundwater at desired points of use across a dusty landscape that manifested pumping impacts only very slowly made the aquifer easy to overlook.

Summary: A data gap produced

Unregulated wells began to appear across Western states in the late 1800s and early 1900s. By the 1930s, an official tally was already impossible. South Platte Valley estimates put the total number of irrigation wells at 550, with many more household wells uncounted, plus a number of industries leveraging groundwater for production and small towns tapping subsurface flows for public supplies (Bjorklund and Brown, 1957; d'Elgin, 2016). These dynamics combined and co-produced each other to generate an absence of individual metering. Alluvial groundwater's material invisibility, abundance, spatial extent, and slow-moving nature combined easily with ways of knowing groundwater as inexhaustible. These physical traits also reinforced political economic notions of groundwater as an individual resource that belonged to overlying landowners and need not be conserved. In addition, the absolute ownership doctrine and the absence of larger water development institutions made groundwater development the domain of private entities without much of an oversight structure. As private capital was invested in wells and pumps, an ethos of private control came with it (d'Elgin, 2016). These dynamics would intensify in the coming decades with an influx of financial credit that put well drilling within reach of many more farmers (Opie, 2000).

WIDENED: THE SOUTHERN HIGH PLAINS, 1930-1980

The vast Ogallala Aquifer underlies much of the High Plains, stretching from Texas in the south to South Dakota in the north. In the decades between 1930 and 1980, the greatest increase in groundwater-irrigated agriculture in Western states occurred in the southern portion of the Ogallala – in northwest Texas, eastern New Mexico, the Oklahoma panhandle, and southwest Kansas. Pumping jumped from an estimated 1 million acre-feet (Maf)[1] per year in 1945 to 13 Maf in 1965, which was roughly a quarter of all groundwater extraction in the American West (Ashley and Smith, 1999). In western Kansas, wells tapping the Ogallala continued to grow in number until 1977, when they peaked at about 16,000 (ibid). Explanations for the dramatic rise in groundwater use on the southern High Plains typically cite the Dust Bowl of the 1930s, plus later droughts. Also prominent are narratives of technological advancement – rural electrification in the 1940s and 1950s, centre pivot irrigation in the 1970s, and the overall increase in farm mechanisation. All were important to the expansion of drilling and pumping on the High Plains, but none would have been possible without accompanying changes in financial credit systems and federal farming subsidies (Green, 1973; Opie, 2000).

Indebtedness, federal priorities, and conceptual confusion

When environmental historians write about the decades after the 1930s, they often use the term 'maximum production' to describe a shift in farmers' approach to groundwater (Green, 1973; Opie, 2000). As Green (1973: 141) explains, "Farmers developed attitudes toward the use of [groundwater] irrigation that stressed maximum production rather than a guarantee against failure. Before long, farmers shifted

[1] One acre-foot = 1234 m^3.

from pumping only as a last resort, to irrigating regularly (even on Sunday) and trying to become more efficient". This was far from inevitable. Groundwater irrigation got its start in the region by way of land speculators who bought inexpensive land, tapped groundwater in order to raise its value, and then sold it at a profit – mostly to city dwellers with no irrigation experience (Green, 1973). Many early farms did not last, but by the 1930s a changing agricultural political economy generated a groundwater irrigation boom that stuck.

Overproduction of staple crops was already a problem following the World War I expansion of American agriculture, leading to surpluses and low prices (Worster, 1992). Farmers responded by ramping up production in order to profit from economies of scale. Farm mechanisation was key to this. So was heavy groundwater pumping. Both were encouraged by a new kind of credit economy that emerged after the 1930s and enabled farmers to take on higher levels of debt (Opie, 2000).

The new credit economy had public and private origins (Green, 1973). In response to the Great Depression, the US federal government authorised a range of reconstruction funds, agricultural subsidies, and loan guarantees for farmers. Local bankers and pump companies then leveraged these new financial supports to extend credit to farmers for drilling wells and purchasing pump equipment. Together they created a market. On the High Plains, early customers of groundwater irrigation equipment on credit were the most desperate of farmers, trying to survive drought and economic depression by converting low-value dryland farms into higher-value irrigated farms (ibid). In the words of a local banker on the Texas High Plains in the mid-1930s, "A man who had money wouldn’t buy an irrigation well; you had to find a poor devil to buy one" (ibid: 139).

The groundwater irrigation frontier expanded, on credit. In the process, what farmers had initially seen as "free water" became "debt-producing water" (Opie, 2000: 249). The more money that farmers borrowed to drill, pump, irrigate, expand, and more thoroughly mechanise their operations, the more indebted they became, and the more they had to grow and pump. As Opie explains (2000), "Whether intentionally or not, federal commodity and credit policies drove virtually all farmers, large and small, into patterns of high water-consumption industrialized farming". This dynamic intensified with time. When World War II began, the US Department of Agriculture pressed for even higher production to boost agricultural exports to Europe (ibid). The related expansion in farm debt and pumping carried on through the 1940s despite good rainfall, illustrating that farmers’ switch to using groundwater was a means for increasing production rather than averting crop failure (Green, 1973). Today, 48% of corn farms in Kansas are indebted according to U.S. Department of Agriculture data (Bessire, 2021). According to Bessire (ibid: 42), this indebtedness compels both waste and "a perverse kind of stability" that perpetuates the overproduction of corn and keeps farmers coming back to the bank.

As the number of wells ballooned on the High Plains after the 1930s, the practicalities of individual metering became ever more daunting. More importantly, even the idea of individual metering became a potentially catastrophic form of oversight for farmers who carried heavy debts, plus a growing agricultural finance industry that was similarly invested in a non-metered status quo. By the time groundwater problems emerged – in the form of shrinking yields, disappearing rivers, land subsidence, and conflict among water users – significant private capital had been sunk into tens of thousands of Ogallala wells and big profits were being made. In 1959 on the Texas High Plains, the increase in annual farm income due to groundwater irrigation was estimated at US$74 million and the increase in annual profits to other types of businesses was about US$125 million (Green, 1973).

State efforts at tightening groundwater regulations in this timeframe did not tip circumstances in favour of metering. Several Western states responded to groundwater-related conflicts in mid-century by applying concepts from surface water law because they were generally accepted (Ashley and Smith, 1999). For the most part, that meant taking the prior appropriation doctrine and layering it awkwardly onto aquifers despite obvious hydrologic differences. Doing so did not necessarily reduce pumping, however. When the priority system is applied to a river, it limits water diversions in order to protect senior rights amidst fluctuating flows. In a groundwater basin, on the other hand, the prior appropriation doctrine is used to control the total number of pumpers, with mixed results for groundwater volumes. In non-renewable aquifers that are isolated from streams, 'reasonable' declines in water tables are allowed in many states and groundwater mining is even sanctioned at set rates (such as over 100 years) (Schlager, 2006). In aquifers that are connected to streams, groundwater pumping is limited to protect surface-water rights holders, which often means leaving significant quantities of groundwater in place (ibid). In other words, prior appropriation systems quantified groundwater *appropriators* and made them legible to the state (Birkenholtz, 2014), but without quantifying the volumes of groundwater that should (or should not) be left in the subsurface. As a result, metering – or any other form of 'volume control' (Cousins, 2016) – remained irrelevant.

Plenty of monitoring attention was being paid to surface water in this timeframe, however. The federal government supported major investments in federal, state and local surface water monitoring systems in Western states, but groundwater monitoring did not see a corresponding jump. Congress began appropriating money to the United States Geological Survey (USGS) for stream gaging in 1894, and it has done so every year since (Rabbitt, 1989). The total number of stream gages funded by the federal government (often with the help of state and local partners) has increased over time to more than 11,000, with a subnetwork of 3470 Federal Priority Streamgages supported exclusively by federal agencies to ensure national water management priorities (CRS, 2021). By contrast, the USGS National Ground-Water Monitoring Network was first funded in 2015 and does not include an equivalent subset of wells prioritised by the US government (USGS, 2023).

Disconnects between groundwater’s biophysical traits and nationalised systems of economic production partly explain the disparity. Surface water’s unruly materiality meant that it required careful measurement so that flows could be put in service of American priorities, while groundwater’s slow-moving and subterranean status did not compel the same level of control. Federal stream gaging began in Western states because, as discussed above, the federal government was intent on appraising rivers for irrigation infrastructure in the form of dams and reservoirs (USGS, 1998). From there the government’s list of development objectives expanded to include managing floods, producing hydropower, enabling transportation, administering international and interstate river compacts, and supporting military operations (CRS, 2021). With the passage of federal environmental laws in the 1960s and 1970s, stream gaging also became crucial to enforcing federal regulations related to streamflow for threatened wildlife and water quality (USGS, 1998).

Materially speaking, groundwater was economically useful in different ways, and without such close oversight. Aquifers do not pose the same sorts of hazards that rivers do; groundwater seeps rather than rages. Transboundary groundwater systems were not given the same level of political attention as international and interstate rivers, which commanded compacts and treaties long before shared aquifer systems were recognised. Heterogeneous and hidden groundwater resources also do not directly serve hydropower production or transportation in the ways that fluvial systems do. Finally, the ecological and water quality downsides of groundwater extraction are slower-moving and more difficult to decipher than they are for rivers, where interference is obvious and requires regulatory attention via a dredge or fill permit under the Clean Water Act (USEPA, 2023).

Federal expenditures built a backbone of federally managed stream gages and they also advanced stream gaging by state and local entities. With USGS-supported gages tracking general river flows in key locations, state water administrators and local water managers could focus their resources on measuring individual diversions from rivers to manage water rights. The multi-agency surface water monitoring partnerships and areas of specialisation that resulted built the larger surface water monitoring and administration system in the West, which grew steadily until funding cuts were imposed in the 1980s (USGS, 1998). Groundwater monitoring, on the other hand, lagged behind. Not until 1988, for example, did the USGS collaborate with state and local water resource agencies on the High Plains to systematically study groundwater decline (McGuire, 2009). Today, even one of the most advanced monitoring systems for aquifer decline in the region – the WIZARD database, which the state of Kansas uses to compile groundwater-level data from multiple sources – is still too sparse to effectively measure aquifer depletion (Bessire, 2021). The vague groundwater depletion averages that are produced in the absence of sufficient empirical data perform a 'trick', according to Bessire. Suggesting that the Ogallala is a "homogeneous unit of water" actually "prevents real conservation in the most threatened portions of the aquifer" by blending their dangerously low groundwater levels with results from areas that are in better shape (111).

Additional epistemic dynamics contributed to the widening of the metering gap. Hydrogeology formalised into a discipline in the 20th century, but the growing number of groundwater scientists did not translate into calls for closer measurement of pumping. This was partly because of dynamics within the field. To begin with, hydrogeologists of the early 20th century were driven by questions of empire building and maximum resource use, not hydrogeological constraint (Rosenshein and Moore, 2013). Field surveys of the High Plains focused on how much water could be tapped, where, and how (Johnson, 1901; Meinzer, 1923; Lohman, 1953). In the 1960s, when some hydrogeologists began to pursue questions of conservation, the conceptual transition was not a smooth one (Narisimhan, 2008). The big ideas that sought to guide groundwater protection were (and still are) contested. Both the idea of the 'water budget' and the concept of 'safe yield' – which aim to identify sustainable thresholds for human groundwater pumping – have been critiqued for ignoring the fact that groundwater provides baseflows to hydro-ecological systems such as wetlands. They have also been charged with overlooking the reality that aquifers are complex and constantly changing, depending on weather, climate and pumping (Molle, 2023; Devlin and Sophocleous, 2005; Alley and Leake, 2004). The ambiguity and/or contestability of the very hydrogeologic concepts that aim to constrain groundwater pumping have limited their influence.

Hydrogeologists kept busy anyway, especially around the High Plains. As they attempted to get a better handle on aquifer depletion, they looked first to fledgling groundwater monitoring efforts. In the High Plains, this meant making maps of estimated pre-development groundwater levels and superimposing them on maps of contemporary groundwater levels synthesised from state and academic studies (Luckey et al., 1981). These sorts of analyses offered broad characterisations of aquifer dynamics but were not detailed enough to empower the decisionmakers who might have played a role in circumscribing groundwater development during the boom years. In Western states, groundwater regulations typically put the burden of proof for rejecting a groundwater well permit onto state agencies (Ashley and Smith, 1999). In practice, those agencies lacked the staff, funding and tools to thoroughly characterise aquifer systems and closely monitor the impacts of pumping (Schlager, 2006). The outcome has been a circular logic that benefits further development (Clifford, 2022): state water regulators were (and still are) limited in their ability to regulate pumping because they do not have the data they need to make the case that pumping needs to be more closely regulated.

Summary: A data gap widened

The absence of individual groundwater metering widened in the Dust Bowl years through the 1970s. Tens of thousands of new groundwater wells were drilled on the High Plains and across Western states, with little regard for the volumes of groundwater they would extract. Farmers took on newly available credit to mechanise their farms and pursue an ethos of maximum groundwater extraction for maximum production in a political economy of overproduction. Regulations adopted in the mid-1900s tended to limit the number of groundwater users, but paid little attention to the volume of water they could pump. Burgeoning federal water monitoring networks disregarded groundwater because it lacked a clear link to national economic priorities such as flood prevention, hydropower production and river navigation. The science of hydrogeology went through a conceptual shift towards groundwater conservation that lacked a clear set of principles, and then attempted to work around the metering gap by studying broad trends in aquifer decline using data offered by fledgling groundwater monitoring networks. As time moved on, the erratic nature of groundwater depletion would maintain these dynamics.

MAINTAINED: CALIFORNIA'S CENTRAL VALLEY, 1980-PRESENT

If the High Plains are the 'grain basket' of the United States, then California's Central Valley is the nation's 'fruit and vegetable basket'. It is home to the production of more than 250 types of fruit, vegetable and nut crops (Scanlon et al., 2012). While these crops are not new to the Central Valley, their production has intensified since around 1980, when global agricultural capital increasingly shifted into growing high-value (often perennial/permanent) crops that benefit from the precision of groundwater irrigation (Arax, 2019; Zlolniski, 2018). In 2019, more than two-thirds of the fruits and nuts and one-third of the vegetables produced in the United States were grown in California (CDFA, 2020). Like the High Plains, the Central Valley is also one of the world's top hotspots of groundwater depletion (Hanasaki et al., 2018). That depletion is accelerating: the current pace of groundwater decline in the Central Valley is nearly five times the long-term average since 1960 (Liu et al., 2022). The valley has a long history of failed 'technofixes' for groundwater over-drafting, including massive surface water conveyance projects and, more recently, the application of drip irrigation, both of which have (counterintuitively) served to increase groundwater pumping (Arax, 2019). The ongoing intensification of groundwater extraction in the Central Valley makes it an insightful place to understand how the absence of groundwater metering is being maintained.

Heterogeneity of depletion, lumping of pumpers, and the price of subsurface expertise

The impacts of groundwater depletion are not uniform, in part because different users pump different amounts, but also because aquifers are physically heterogeneous, which means that groundwater declines patchily. It is common for people to imagine an aquifer in the shape of a bathtub – an empty vessel that can be similarly drained by anyone with a 'straw' – but aquifers are more likely to be shaped like irregular bowls or egg cartons (Blomquist, 2020). Aquifer heterogeneity influences groundwater depletion. In an aquifer that is shaped like a bowl, wells near the edges will go dry while wells towards the middle are still able to pump. In an aquifer that is shaped like an egg carton, with multiple deep pockets of groundwater separated by geologic features, well owners next to each other may face very different groundwater prospects and groundwater users in one area may not have much impact on those in another area. As Walsh (2022) reminds us, there is no such thing as singular, uniform 'groundwater'.

Unfortunately, across Western states, the first to face groundwater decline in biophysically uneven systems seem to be those who are also most precariously positioned in the uneven political economy of contemporary agriculture. A recent study of dry wells across the western US found that 1 in 30 of the groundwater wells drilled since 1950 was likely to have been dry by 2015; it also showed that in places such as California's Central Valley the wells that have gone dry tend to be shallow domestic wells that are being out-competed by deep agricultural wells (Perrone and Jasechko, 2017). Anecdotal evidence from the Central Valley and state-level inventories of self-reported dry wells aligns with these findings (CDWR, 2023). Poor rural agricultural workers are seeing their wells and shallow groundwater sources dry up and their related socio-economic precarity worsen as large farms nearby drill deeper, pump more, and increase their groundwater and land access in the process (Underhill et al., 2022). While access to groundwater has always been mediated by access to private capital, in the Central Valley it is increasingly "premised on having the capital to drill deeper and deeper" (ibid: 18). The need to drill deeper has pushed out smaller farmers and invited in larger ones. Some wealthy Central Valley growers have even purchased their own drilling rigs to get ahead of their neighbours and circumvent backlogged local drilling companies (Arax, 2019).

Groundwater access has therefore not been the great Central Valley equaliser that many hoped it would be. Instead, groundwater pumping has been "the means by which the valley has become one of the most unequal places on Earth" (Arax, 2019: 112). Rather than stirring broad-based political resistance, however, the uneven and haphazard nature of well dry-ups has been a barrier to collective action. As Arax (2019) explains, people with disappearing groundwater feel they have little recourse. This includes, for example, the residents of the town of Fairmead, California. Fairmead began during the Great

Migration as a town for former African American slaves who were kept out of nearby cities by racist housing covenants. From its founding, groundwater was the only water available to residents. This continued to be the case after federal surface water irrigation projects bypassed the town. Today, large nut farms around Fairmead are pumping groundwater intensely, which is drying up the town's domestic wells. As Arax (2015) reported,

> Two dozen homes in this community of fourteen hundred residents – those on private wells nearest to the nut orchards – have come up dry since summer. A few families have already left. Just packed up and walked away. No 'For Sale' signs. No goodbyes. Scores of others, black families (…), white and Latino ones, too, who share a fickle community well system, are thinking of doing the same.

While pumping's impacts have been decidedly localised and idiosyncratic, the scientific knowledge that has been produced about groundwater decline is not. On the contrary, scientific discourse about groundwater decline is typically produced at broad geographic scales that lump many groundwater users together, in the process blurring inequities in groundwater extraction. This is of course partly because individual pumping data are unavailable, but it is also because hydrogeologists' analytical workarounds for the absence of pumping data tend to generalise across aquifers. Contemporary methods for calculating groundwater depletion rely on generalised groundwater levels from monitoring wells and broad remotely sensed data (Bierkens and Wada, 2019). When more precise measurements are available – usually in the form of proxies such as well permits or electricity use – analysts then leverage models to synthesise and interpolate among them to make sense of broader groundwater trends (ibid). The results tend to illuminate groundwater decline at the scale of the aquifer, or larger.

In particular, the turn to remote sensing to assess groundwater depletion in the absence of empirical pumping data – especially the arrival of Gravity Recovery and Climate Experiment (GRACE) satellite data – has kept the scientific conversation about groundwater decline very big (Domínguez-Guzmán et al., 2023). GRACE is an ongoing international satellite mission that measures groundwater decline via changes in gravity. When GRACE-based studies were initially published around 2010, they vividly revealed persistent groundwater declines across large swathes of heavily irrigated areas around the globe; however, the findings were only accurate at scales of 200,000 km^2 or more. In high profile scientific articles that make arguments about groundwater management using GRACE data, the entire Central Valley of California is depicted as a single large red blot (Famiglietti and Rodell, 2013). Similarly so for the High Plains (Longuevergne et al., 2010) and the Colorado River Basin (Castle et al., 2014). The GRACE data show how extensively groundwater has been depleted, which is important – but with such a zoomed-out view, the data also suggest a universalised problem in which all groundwater users share the same degree of responsibility and precarity. Other methods for estimating groundwater decline in the absence of pumping data tend also to merge groundwater users. For example, the USGS's reports on water use in the United States, published every five years, provide estimates of groundwater withdrawals aggregated at the county level (Dieter et al., 2018).

Groundwater management efforts in California, and elsewhere, similarly merge pumpers into an aggregate that does not distinguish their very different rates of groundwater extraction. Writing about California, Brooks (2017) argues that the problem of universalising among groundwater pumpers stems in part from the operative definition of sustainability forwarded by groundwater governance regimes such as the state's Sustainable Groundwater Management Act (SGMA), passed in 2014. According to Brooks, the SGMA defines sustainability with a 'number narrative' that holds that groundwater extraction is sustainable if pumping and recharge are balanced at the aquifer scale. Brooks (2017: 49) argues that this number narrative "collapses all of the individual residents into one envirotechnical system balancing its total inflow and outflow" even though groundwater use and responsibilities "are not (and likely would not be) equally distributed". In sum, the analytical workarounds that have been developed in the absence of pumping data, and the groundwater management concepts that circulate with them, combine groundwater users into aquifer-scale (or larger) problem and solution framings. This further works against the idea of individual metering by making the individual pumper appear unimportant.

An individual metering requirement could bring some clarity to the uneven nature of groundwater access and decline in California, but the idea is "generally met with resistance" by growers who hope to extract as much groundwater as possible during the SGMA implementation period (Walsh, 2022: 8). Few institutional checks or balances exist that might change the dynamic. As in other Western states, SGMA generally devolves groundwater management to local water users in groundwater basins, requiring that they come up with plans to achieve groundwater sustainability (Hauge, 2016). While the law requires stakeholder involvement – and specifically the inclusion of 'disadvantaged communities' – public participation has thus far been dominated by large landowners and large growers (Dobbin, 2020; Dobbin and Lubell, 2021; Méndez-Barrientos et al., 2019). This group increasingly includes wealthy institutional investors that have bought into groundwater-irrigated farmland in California as an investment strategy (Arax, 2019; Fairbairn et al., 2021).

These influential groundwater users position themselves relative to groundwater uncertainty in ways that increase their leverage in SGMA-related deliberations. As Walsh (2022: 8) argues,

> While a great deal of information exists about critically over-drafted groundwater basins [in California], the idea of a lack of data is repeatedly deployed by those who benefit from unregulated access, and invisibility is actively produced by them through the withholding of, or self-reporting of, historical pumping records.

But there is even more going on by way of subsurface knowledge production in California. In addition to claiming uncertainty or trying to produce it, large landowners and growers are increasingly using SGMA-related technical processes to both secure physical access to groundwater and to cultivate the idea of plentiful groundwater as a financial asset for the future (Fairbairn et al., 2021; Sizek, 2023). Rather than shirking over-drafting as a financial risk, groundwater decline has become a source of potential profit for investors in California by making whatever groundwater currently remains (or at least the idea of it) an asset that will grow in value with time for those who have the most secure access (Fairbairn et al., 2021; Sizek, 2023).

Expert interpretations of the subsurface in regulatory processes are key means through which groundwater investors are claiming these actual and potential profits. This is demonstrated by two current controversial groundwater issues in southern California: a proposal to pump groundwater from the Mojave Desert to cities (Sizek, 2023) and, in the Cuyama Valley, a move to convert dry rangeland into groundwater-irrigated vineyards (Fairbairn et al., 2021). Both of these reveal groundwater investors' increasingly sophisticated use of scientific tools to create 'subsurface worlds' that align with their development goals (Kroepsch, 2018). In the desert-to-city water transfer case cited above, groundwater investors at Cadiz Inc. were able to build a conception of the water cycle that made their proposed project seem like common sense (Sizek, 2023). They did so by leveraging scientific uncertainties about recharge rates and the behaviour of geologic faults, as well as ideas of nature as being inefficient and wasteful (Sizek, 2023). In the vineyard example, the Harvard Management Company employed hydrogeologic consultants who used privately held well data to argue that the local water table could be drawn down twice as deep as planners had previously thought without harm (Fairbairn et al., 2021). In both instances, investors combined subsurface uncertainties with proprietary data, and they hired hydrogeologic experts to develop imaginaries of groundwater surplus that are privately profitable but difficult to publicly challenge (Fairbairn et al., 2021; Sizek, 2023). These dynamics are not simply examples of groundwater governance gone wrong, argues Sizek (2023: 16); rather, these processes of groundwater regulation are actually co-producing "science, profit, and the state" at the same time.

Summary: A data gap maintained

In sum, the anti-metering and heavy pumping status quo in the Central Valley and other parts of California is being maintained despite (or perhaps because of) regulatory processes such as the SGMA. Groundwater depletion hits users unevenly due to aquifer heterogeneity and the fact that highly capitalised growers can keep drilling deeper while precarious domestic well users cannot. This works against collective action, as do scientific and regulatory discourses that universalise groundwater problems and solutions and merge different pumpers together despite their disparate hydrogeologic impacts and financial resources. Moreover, large growers and landowners (and investors therein) have significant influence over local groundwater governance processes, particularly via their increasingly savvy participation in the production of subsurface knowledge.

CONSEQUENCES: ACCOUNTING AND ACCOUNTABILITY IN GROUNDWATER PUMPING

As detailed above, aspects of groundwater's materiality, groundwater knowledge production, and groundwater power and profit have coalesced and been co-produced to generate a metering gap that has widened over time and been maintained for more than a century in most of the western United States. Hotspots of groundwater use illustrate these trends, from Colorado's South Platte Valley, to the High Plains, to California's Central Valley (Table 1). The consequences of the non-metering of individual groundwater pumping come primarily in the form of overlooked inequalities among groundwater pumpers and questions unasked by groundwater scientists and regulators, as well as missed opportunities for more strategic and principled use of aquifers.

Table 1. The groundwater metering gap.

Phase	Biophysical, epistemic, political economic dynamics: Co-produced and intertwined in each phase		
Produced 1880-1930 (e.g.; South Platte Valley, Colorado)	Inexhaustible supply myth *epistemic*	Individualised development, investment *political economic*	Invisible to the eye, underground *biophysical*
Widened 1930-1980 (e.g.; Southern High Plains)	Farm debt grows, regulations are focused on pumpers more than pumping *political economic*	Groundwater lacks traits that advance surface water monitoring *biophysical*	Hydrogeologists' conservation concepts are fuzzy, contested *epistemic*
Maintained 1980-present (e.g.; Central Valley, California)	Groundwater decline is patchy and socially uneven *biophysical*	Scientific/regulatory discourse lumps pumpers together *epistemic*	Wealthy landowners/ investors shape local governance *political economic*

In the absence of empirical pumping data, contemporary understandings of groundwater decline are made via analytical workarounds that operate at large geographic scales. This has political consequences. Pumpers are aggregated and blurred even though they increasingly diverge when it comes to groundwater access and volumes of extraction. Conversely, precise understandings of groundwater dynamics and uses are developed on an ad hoc basis with the heavy influence of individual pumpers who aim to profit from future groundwater access (or the idea of it). These dynamics limit consideration of groundwater inequities in governance processes. The inability to distinguish pumping hierarchies leaves smaller pumpers facing drying wells with little recourse and enables larger pumpers to continue scaling up their extractive practices without scrutiny. In many ways, this is the outcome of how groundwater regulations have been designed in Western states. But it is also a product of groundwater's unique materiality and the progression of hydrogeological methods and expertise – plus the ways those dovetail with groundwater governance.

By ignoring individual groundwater pumping – exactly how much groundwater is being extracted in particular places by particular users – current groundwater monitoring regimes make it impossible to ask 'who', 'how', and 'why' questions, let alone the more obvious queries of 'how much' and 'where'. Instead inquiry gets stuck in the zone of abstract volumes. This prevents researchers, resource managers, and even the public from asking the kinds of questions that might illuminate inequalities and power dynamics in groundwater use.

Foregone or foreclosed questions (and answers) include those such as: Is there a relationship between different kinds of farm owners and groundwater pumping rates? Do agricultural sprawl and increased pumping go hand in hand, or not? Are agricultural producers changing their pumping behaviour in locations where groundwater regulations are tightening, or do they simply move their operations to less-regulated spaces and keep pumping at the same level? When the negative impacts of over-drafting are clear and broadly impactful (e.g.; the impacts of subsidence to highways and other infrastructure), who keeps on pumping, how much, and how do they justify their extraction? When it comes to stakeholder-driven groundwater governance, do groundwater metering and transparency make collaboration more or less likely (if so, by whom, and why)? How does groundwater-related discourse change with metering interventions, if at all? Would widespread and transparent groundwater metering democratise subsurface knowledge in productive ways, or would it merely be performative? How could groundwater metering be utilised within other regulatory regimes, such as endangered species protection or water quality management?

The rarity of well metering also limits some innovations in groundwater management, such as conjunctive groundwater – surface water management and aquifer storage and recovery. Conjunctive management aims to coordinate the use of groundwater and surface water by prioritising surface water use during wet periods and groundwater use during dry periods. Aquifer storage and recovery (ASR) takes this a step further by purposefully using aquifers as underground storage sites; surface water is actively pumped into aquifers for later use. Both of these management techniques have been widely advocated for many years, but still are not widely practiced. Where they have been implemented, it has been with mixed results (Blomquist et al., 2004). Among the major limiters of these groundwater management techniques is the absence of metered pumping (Sugg et al., 2016; Newman et al., 2018). Few water users are willing to delay their groundwater use or actively stockpile water in an aquifer when there is no way of knowing whether another water user might extract it and in what quantity. This raises additional research and regulatory questions, such as whether the allure of new management concepts is enough to tip groundwater basins toward metering? Or if metering, adopted for other reasons, might create the right socio-ecological conditions for practices like conjunctive use and ASR?

There are a few places where getting direct empirical answers to these questions might yet be possible. Though the non-metering of groundwater pumping is widespread in the western United States, as elaborated above, a handful of places have adopted the practice. For example, some groundwater management districts in Kansas began requiring metering and reporting by agricultural wells in the 1990s, with limited success, though the state strengthened those regulations in 2017 (Bessire, 2021). Recently in Colorado, annual metering and reporting became required of well users in four basins where pumping has threatened river flows that are promised to neighbouring states in interstate compacts (CDWR, n.d.).

In several areas of California outside the Central Valley, groundwater users in adjudicated groundwater basins and water districts have developed pumping rules that include metering stipulations (Langridge and Ansell, 2018; Langridge et al., 2016). Arizona requires metering and annual reporting by large wells in designated Active Management Areas (AMA); however, it has not kept up with data collection (Perry, 2019) and ignores the significant pumping underway outside AMAs (James, 2020). Future research could explore how and why well metering emerged in these cases and others, and to what effect, with an emphasis on the role of biophysical, epistemic, and political economic dynamics in these basins.

In today's world of remotely sensed data and increasingly sophisticated computational techniques, it is increasingly difficult to make the case for a data-gathering practice that is as cumbersome and expensive as individual metering (Bracken, 2012) – especially when it is also politically unpopular and tamper-prone. As we have seen, however, that will not limit the making of claims to subsurface waters or the uneven impacts of those claims. Ultimately, the non-metering of groundwater use in the American West demands that we continually note the presence of an absence and evaluate its contours. Further, we should continue to ask how that absence came to be, how it continues to persist, and what it means for hydrosocial relations.

ACKNOWLEDGEMENTS

I am grateful for the insights and encouragement of several colleagues who have shaped my thinking about groundwater metering, in particular Katie Clifford, Marc Tadaki and Steven Smith. Thanks also to the three anonymous reviewers whose feedback strengthened this manuscript. Any errors are mine alone. This research was supported by a grant from the US National Science Foundation and National Institute of Food and Agriculture (INFEWS #2021-607020-34178).

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