Monitoring agricultural water use: challenges and solutions for sustainable water management

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Summary

As the largest sectoral user of water, agriculture is impacted by and a major driver of water scarcity globally. Monitoring of agricultural water use is essential to identify and design effective strategies to balance water demands with other sectors and the environment under future change. Yet, most countries face large gaps in their ability to identify where, when, how much, and for what purposes water is withdrawn or abstracted by farmers. This chapter provides a critical review of the current evidence about the technical, financial, social and political barriers to effective monitoring of agricultural water use, focusing on the twin challenges of abstraction permitting and water use quantification. We identify enablers and barriers for new technologies – specifically satellite remote sensing – to plug gaps in in-situ monitoring infrastructure, and the need to think beyond improved data collection to how such data is then used in design and enforcement of agricultural water resources management and planning policies.

Introduction

Water scarcity is a growing challenge facing many areas of the world, negatively impacting food security, economic development, human and ecosystem health (Dolan et al., 2021). As the largest sectoral user of water in most water scarce regions, agriculture is central to efforts to address the environmental and socio-economic challenges posed by water scarcity. Agricultural productivity is heavily dependent on access to reliable and affordable water supplies for irrigation. This dependence is expected to grow further in the coming decades as demands increase to intensify food production and warming temperatures simultaneously drive higher crop water requirements (Rosa, 2022). In parallel, there is also a growing recognition that continued unimpeded growth in agricultural water abstractions would have severe negative consequences for freshwater-dependent ecosystems and other human uses of water such as urban supplies, industry, rainfed agriculture and freshwater fisheries (McDermid et al., 2021; Schmitt et al., 2022; van Maanen et al., 2022).

Much of the academic and policy debates around agricultural water use have historically focused on how to mitigate water scarcity and conflicts through improved management. At the farm-level, narratives have centred around goals of improving agricultural water productivity to achieve 'more crop per drop' (Giordano et al., 2021). Proposed solutions include innovations to heuristics and technologies to better target how irrigation is applied and scheduled (McCarthy et al., 2020; Kelly et al., 2023), optimising crop choices (Beyer et al., 2022; Richter et al., 2023), or via development of more drought tolerant cultivars (Passioura, 2006). At larger catchment or landscape scales, extensive work has evaluated policies and strategies to sustainably and equitably manage trade-offs between agricultural and non-agricultural (environmental and human) water needs. These include the design of demand management instruments (including caps and economic instruments, such as water markets or charges) that reallocate water among alternative uses (Rey et al., 2019; Deines et al., 2021; Koebele et al., 2022), along with supply enhancement policies that rely on green or grey infrastructures to expand the water supply base available to both agricultural and non-agricultural users (van Vliet et al., 2021; Schmitt et al., 2022; Sun et al., 2023).

Central to all efforts to ensure food security, sustainability and economic efficiency under conditions of water scarcity is the ability to spatially and temporally monitor agricultural water use accurately and reliably (Foster et al., 2020). Information about where and how much water is used by agriculture is essential to accurately assess the sector's contribution to a region's water budget, to design or enforce policies to achieve more sustainable levels of agricultural abstractions, to guide or incentivise farmers on ways to improve on-farm water management practices and productivity, and to identify and plan investments to mitigate agricultural water insecurity. More broadly, monitoring is also essential to help ensure that policy interventions do not backfire in ways that ultimately end up further exacerbating scarcity and inter-sectoral conflicts over water. For example, shifts towards more efficient irrigation technologies have often been assumed by planners and policymakers to reduce water use when in fact monitoring reveals that they more commonly have had no impact on consumptive use or have led to increased water use through expansion of irrigated lands and/or switching to more water intensive crops (Pérez-Blanco et al., 2021).

While the value of monitoring agricultural water use is clearly apparent, attention given to this topic in policy and research has grown mostly in the last decade. Recent research has shown that even countries with highly developed systems of environmental regulation still lack robust and actionable monitoring of agricultural water use, while other regions collect little or no data at all on agricultural water use (Foster et al., 2020). The implications of these monitoring gaps for water management and policy are increasingly being recognised and highlighted. For example, monitoring gaps have been cited as a key enabler of illegal or unauthorised water use, which by some estimates account for up to 30-50% of total abstractions and are a key contributor to water scarcity pressures globally (Felbab-Brown, 2017; Loch et al., 2020). A lack of monitoring also limits the evidence base and can favour the consolidation of ill-informed systems of beliefs (e.g. that water availability can be increased through improvements to irrigation efficiency - Lankford et al., 2020) or failure to learn from past policies (e.g. failures of large-scale irrigation infrastructure development projects - Higginbottom et al., 2021). The need to strengthen monitoring of agricultural water use is also being acknowledged by governments and the agricultural industry, with growing interest in the potential for innovative monitoring solutions such as satellite remote sensing (Massari et al., 2021) and smart metering (Ouvrard et al., 2023) to support agricultural water management and stewardship.

In this chapter, we contribute to debates around agricultural water use management by reviewing the features, implementation, and innovations of irrigation monitoring systems and approaches globally. The following sections of this chapter focus on reviewing historic approaches for identifying and quantifying agricultural water use, followed by a critical discussion of the opportunities provided by recent innovations in satellite-based monitoring approaches. We then discuss the need to think beyond improvements in data collection and reporting to how agricultural water use policies are enacted and enforced if improvements in sustainability and efficiency of water use are to be achieved. The chapter draws on the authors' extensive experience in different irrigated regions across Europe, North America, and other parts of the world, drawing recommendations about the opportunities and challenges for strengthening agricultural water use monitoring and accounting globally.

Identifying and detecting where water is abstracted

An essential starting point for monitoring agricultural water use is knowledge and intelligence about the locations of agricultural abstractions, including where rights to water exist and how these change and evolve over time. Knowledge of where irrigation abstractions are permitted is an essential part of any water management system, both for understanding how agriculture is influencing catchment water budgets and for enforcing demand management policies and instruments.

To this end, many countries require farmers to register and obtain permission for abstraction before water can be taken for irrigation. Typically, this process involves a farmer making an application to the relevant environmental regulator or agency to obtain a permit or licence for a water right, before a new abstraction point is developed and made operational by a farmer. Based on local rules and environmental assessments (e.g. to determine that the abstraction won't negatively impact ecosystems or infringe existing abstraction rights of other users), an abstraction permit or right may then be granted. Abstraction licences may include stipulations about the water source, where, when and/or how much (including peak daily, monthly or annual rates) water can be abstracted. These conditions can be specified as hard limits on the rate or cumulative amount of abstraction in a given year, or may be linked to the hydrologic condition of the water source. For example, in the UK many agricultural licences specify the maximum volume of water that can be abstracted each year while also curtailing abstraction in the event that streamflow or groundwater levels drop below minimum thresholds, known as 'Hands off Flows" or "Hands off Levels" (Erfani et al., 2015). Alternatively, licences may instead restrict farmers' water use based on average levels of abstraction over multiple years, allowing irrigators to adjust water use from one year to the next in line with climate conditions and crop water needs. For example, in the Po River Basin in northern Italy the majority of water licences specify only the average water use restriction (Sanato et al., 2016), with similar rules also common in parts of the United States such as the states of Nebraska and Kansas (Young et al., 2021) where groundwater is the primary source of water for irrigation.

While abstraction registries are on paper an essential starting point for effective monitoring, the quality and completeness of official irrigation abstraction registries is highly variable in reality. Large data gaps often exist in abstraction registries even in countries with strong environmental compliance systems and laws. Farmers, for example, may decide to develop an abstraction point without registering or applying for an official licence to bypass costs associated with registration or subsequent fees for water access, where procedures are overly onerous or bureaucratic, or where moratoriums exist on registering new licences for water abstraction (ECA, 2021). These problems are especially pronounced for groundwater abstractions where the infrastructure (typically a pump and well) required to access water for irrigation is privately owned (Foster et al., 2020; Molle and Closas, 2020) as opposed to surface water irrigation that often depends in part on public or shared infrastructure such as canal networks. Indeed, challenges of identifying and deterring illegal groundwater well development have been widely reported around the world, including in countries such as Spain (Novo et al., 2015), Australia (Holley et al., 2020), and Mexico (Hoogesteger and Wester, 2017) to name only a select few examples.

The likelihood of abstractions not being officially registered is in part influenced by the extent to which a farmer expects non-compliance with permitting or registration requirements to be punished or penalised. Where consequences are expected to be below the returns from non-compliance, there are greater risks of unauthorised abstractions being developed. Over time, this may in turn serve to further delegitimize or undermine compliance with abstraction registration rules. This is especially common in countries or regions with weak environmental protection and governance systems. In countries such as India and Pakistan, for example, private groundwater well drilling for irrigation is now the de-facto standard practice with little expectation that these wells will be officially registered or permitted even though this may still be required on paper (Molle and Closas, 2020b). However, issues of non-compliance with abstraction permitting are also common in countries where strong environmental protections exist but which are inconsistently enforced. For example, in Doñana in Southern Spain 2,000 cases of illegal water abstractions were reported in the period 2003-2020. Yet, despite the scale of illegal use and its substantial human and ecological impacts, official data report 28 guilty verdicts for water theft equating to a prosecution rate of 2.2% (Loch et al., 2020) - a rate that is not unique to Doñana or Spain (Schmidt et al., 2020), highlighting the often limited costs of non-compliance with abstraction registration rules for farmers.

Nonetheless, it is important to recognise that incomplete abstraction registries are not purely due to farmers deliberately seeking to bypass official rules. Data gaps also reflect challenges and deficiencies in the institutions and processes of governance of agricultural water use. A common challenge is that responsibility for maintaining abstraction records often falls to different agencies depending on the source of water or when an abstraction point was first developed. In other cases, abstraction rights may be recorded but critical information may often fail to be captured (e.g. coordinates of an abstraction point), making it hard to track and monitor that water user in the future. This is especially common for older water rights for which requirements to register an abstraction may not have existed at the time the abstraction was originally developed, or for which records may only exist in paper form. In Spain, the 1985 Water Act aimed at transitioning from private to public ownership of groundwater, and created a "Public Water Registry" and a "Catalogue of Private Waters" to keep track of the ownership and water withdrawn. Yet, this database is far from complete almost 40 years after its creation–and thus the characteristics of some formal groundwater withdrawals are still essentially unknown (De Stefano et al., 2015). Similar challenges have been reported in California in the United States where implementation of a new Sustainable Groundwater Management Act (SGMA) has been complicated by an antiquated system of paper-based water rights (Kiparsky et al., 2021), which are difficult or impossible to access and use for water management decision-making.

This logistical challenge of maintaining accurate and complete abstraction records and registries is compounded by financial pressures faced by many regulatory agencies around the world, many of whom have experienced declining funding levels over recent years and decades. In the UK, for example, the Environment Agency who are the regulatory authority responsible for abstraction licensing and management have experienced budgets and staffing reductions of 80-90% in the past decade (NAO, 2022). Similarly, in the EU, over two-thirds of Member States cite lack of finance and staffing resources as a major barrier to the implementation of water resource management plans including systems of effective abstraction control and monitoring (EC, 2021). However, inadequate registries are also linked to institutional rigidities and often high transaction costs of reforming abstraction licensing. Further to the abatement costs faced by users who are constrained to relinquish (part of) their use, water allocation reforms also face nontrivial transaction costs related to the implementation, evaluation and monitoring of public policy programs, which can often represent up to 30% of total costs of the water allocation reform (Loch and Gregg, 2018). Lobbying, information gaps and asymmetries and policy dynamics can result in institutional rigidities that increase transaction costs and make policy reform expensive or even not feasible.

Finally, it is important to note that gaps in registries may occur intentionally, due to legal exemptions which mean that not all abstraction points are officially recorded and tracked. Exemptions are typically conditional on the intended volume of abstraction, purpose of water use, or in some cases even based on the type of infrastructure used to abstract water (Sanato et al., 2016; Molle and Closas, 2020a; Benson et al., 2022). These exemptions are often applied to limit burden on regulators and abstractors. While exemptions often mean that individual abstractions are small in nature - for example in the UK no licence is required if irrigation abstractions are less than 20 m^3/day (Benson et al., 2022) - collectively these users can amount to substantial volumes of agricultural water demand with significant potential impacts on water availability for licensed irrigators, other users, and the environment. The lack of need to register these types of abstractions also makes it hard to verify that actual abstraction practices remain within bounds of exemption rules. For example, an irrigator who on paper qualifies for an exemption to registration is therefore unlikely to have their abstraction rates monitored or metered to verify they do not exceed prescribed limits specified by the exemption policy.

Quantifying volumes and purposes of water use

Knowledge of where agricultural abstractions exist on its own is insufficient to support effective and sustainable management of agricultural water use. Additional information is also required about the volumes, application methods (e.g. irrigation technologies used), purposes (e.g. types of crops irrigated, and whether grown outdoors or under protected conditions such as polytunnels or glasshouses), locations, and associated costs and revenues of water use by farmers in order to support design and implementation of regulatory and non-regulatory water management policies. For example, without knowledge of the quantities of water abstracted it is impossible to assess and regulate levels of agricultural water demand to balance competing demands for scarce water. Similarly, without information on the expected returns from illegal water abstraction - which depend heavily on the volume of extraction and how water was used - it is challenging to design penalties that effectively deter this practice.

Monitoring of agricultural water use is typically achieved via on-farm metering in the form of a flow meter attached to the point of water abstraction. However, where metering exists, there are large differences in how data are collected and verified in different regions around the world. Most commonly, meter records are self-reported manually by farmers (Foster et al., 2020). This approach is relatively low cost for regulators whose staff and budgets are often stretched. However, self-reporting also poses risks to the quality and completeness of monitoring of agricultural water use (ECA, 2021). For example, farmers may be incentivised to misreport or fail to report water use and other required information if the likelihood of spot checks and penalties are low. Incidents of meter manipulation (e.g. reversing meters) and tampering (Griener et al., 2016; Al Naber and Molle, 2017; Sidhu et al., 2020; Molle and Closas, 2021) to falsify reporting of water use will also further degrade the quality of data collected from meters. Genuine or accidental reporting errors may also occur, remaining uncorrected if regulators lack capacity to properly scrutinise and follow up on potentially erroneous or spurious water use reports by farmers. Where meter records do exist, it is common for data to include records that appear spurious or outlier records, or for records to be incomplete or missing critical information for some abstraction rights even where otherwise robust metering systems are in place (Foster et al., 2019; Filippelli et al., 2022).

While metering of agricultural water use is accepted to be the gold standard for monitoring, levels of adoption and implementation of meters remain far from universal. There are still regions with significant water scarcity problems linked to agricultural abstractions where there remains no active metering (smart or otherwise) or reporting (self-reported or otherwise) of the amounts of water being abstracted by farmers for irrigation. In Middle East and North African countries land ownership is typically associated with the right to abstract groundwater, and several small and large water users have historically abstracted the resource without metering or formal reporting (Molle and Closas, 2021). Lebanon's National Water Sector Strategy, for example, approved in 2012 established the need to adopt demand-based policies such as metering and volumetric charging, but none of these policies have yet been implemented. Similar data gaps are also observed in countries such as Australia, where a report by the Murray-Darling Basin Commission found as little as 25% of total abstractions are metered in some parts of the basin (Hanemann & Young, 2020), while in the United States there is little official metering of groundwater abstractions in states such as California and Texas with large irrigated agricultural sectors (Foster et al., 2020).

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The reasons for a lack of adoption of meters are complex, and reflect a range of technical, economic, and socio-political barriers to implementation. First, installing and maintaining meters, including ensuring that these systems are not tampered with by farmers, is often a very expensive and time consuming task for regulators whose resources are already stretched (Foster et al., 2020; Molle and Closas, 2021). For example, Kinzelbach et al (2022) highlight the challenge facing a country such as China where metering would entail installing and maintaining infrastructure on millions of individual abstraction points. Financial and logistical challenges to implementation of metering are compounded by the fact that agricultural water use is typically composed of large numbers of individual abstractors, spread over wide and sometimes difficult to access rural areas. Metering has also frequently been opposed by farmers seeking to limit regulation or surveillance by the government. This opposition is often tolerated, or in some cases even enabled and supported, for political reasons or by businesses dependent on unmonitored and unregulated water use. All of this makes implementation of metering an often slow and laborious process, with the end result being that agricultural abstractions may often go unmetered until impacts on water resources become so severe that public pressure forces an increased focus on improving monitoring and data collection. The case of California in the United States is an exemplar of this pattern, where water metering has only recently received substantive focus in policy despite decades of prolonged unsustainable groundwater abstraction (Griggs, 2020; Bruno et al., 2022).

Metering alone - even when implemented reliably and robustly - is only sufficient to determine the volume of water abstracted. Collection and documenting of additional information about features such as the purpose or location of use is extremely uncommon, despite the fact that these may be important to assess compliance with the terms of a farmer's water right. In Spain, for example, it has been observed that farmers may sometimes use legally defined water rights to irrigate land in different locations than for which their permit or licence was not initially specified (Bea Martínez et al., 2021), creating challenges for tracking if and where water is being used legally and illegally for irrigation purposes. Similar challenges are also common in the context of water sharing and trading systems. In some regions, neighbouring farmers may share or pool water supplies between co-located farms as part of collective responses to drought and water scarcity. This makes attributions of metered volumes to specific users or land parcels challenging without additional data on water sharing practices (Chengot et al., 2021). Formal trading systems often specify that trading of abstraction licences must not alter levels of consumptive water use or return flows (Brozovic and Young, 2014) - yet both of these require additional data (e.g. on crop type or irrigation technology) that goes beyond the information provided by flow metering alone.

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Remote sensing – a tool to plug agricultural monitoring data gaps?

Previous sections of this chapter have highlighted that significant gaps remain in understanding of where, how much, and for what purposes water is used by farmers. It has been shown that many of these gaps are caused by technical, financial, social, and political challenges of implementing and maintaining reliable in-situ systems of agricultural water use monitoring. Given these challenges, there is growing interest in the potential of new technological solutions to help address data gaps in a cost effective and scalable manner. In particular, the potential of using satellite remote sensing to strengthen monitoring of agricultural water use has received growing attention from policymakers and researchers. This focus has been driven in large part by the explosion of increasingly high resolution and sophisticated satellite imagery and algorithms over recent years, which now offer the potential to monitor agricultural water and land use at unprecedented resolutions and scales.

Remote sensing can potentially support monitoring of agricultural water use in two main ways. First, analysis of satellite imagery can be used to detect where land is likely to have been irrigated or not (Deines et al., 2019; Dari et al., 2021; Higginbottom et al., 2023). If these estimates can be compared and contrasted with records of officially permitted abstractions, satellite data could therefore be used to identify errors or omissions in existing official abstraction registries or to pinpoint locations of potential illegal water use by farmers. Second, satellite data can also be used to generate estimates of rates of agricultural water use as a substitute or complement for in-situ metering of abstractions (Foster et al., 2020; Massari et al., 2021). The method through which water use is quantified varies depending on the type of satellite sensor. For example, thermal-infrared satellite such as the Landsat can be used to quantify crop water use through the solution of a surface energy balance (Vogels et al., 2020; Brookfield et al., 2023), radar sensors such as Sentinel-1 satellite seek to estimate irrigation water use events through detection of soil moisture anomalies (Modanesi et al., 2022; Dari et al., 2023), while optical sensors such as Sentinel-2 can support crop water budget estimates through monitoring of crop growth over the growing season (Foster et al., 2019; Garrido-Rubio et al., 2020).

Operational products and tools for satellite-based irrigation monitoring have recently been developed in several regions around the world. For example, in the United States the recently launched OpenET platform led by NASA operationalises satellite estimates of agricultural water use from six evapotranspiration models at field scales across the western United States (Melton et al., 2022). In Spain, the Mancha Oriental Central Irrigation Water Board (in Spanish: *Junta de Comunidades de Regantes de la Mancha Oriental*) has been using since 1996 remote sensing techniques for the management and monitoring of irrigation uses in its area, and since 2017 all this monitoring data is available free and open access via the SPIDERwebGIS system (http://maps.spiderwebgis.org/webgis/), allowing different users to study the temporal sequences of the different products generated, including water use (Garrido-Rubio et al., 2020). It is important to acknowledge, however, that such tools and platforms are not the norm globally. In general, developing and implementing satellite monitoring approaches requires substantial applied remote sensing and GIS technical skills, time, and finance, which must be considered in the context of the declining resources often available to many water managers and regulators.

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Satellite data and tools such as those described above undoubtedly have the potential to be a transformative solution for how agricultural water use is monitored and managed (Massari et al., 2021). However, it is important to recognise that satellite-based approaches will not be a perfect solution to regulatory challenges of identifying and tracking agricultural water use. One challenge is that errors in satellite-based estimates of agricultural water use can often be large, especially when being used to estimate rates of crop water use at field or farm scales (Foster et al., 2020). Even detecting locations of irrigated fields can be fraught with challenges, especially in regions with heterogeneous cropping patterns, high levels of cloud cover, or in humid and temperate regions where supplemental irrigation is small relative to rainfall during the growing season (Ozdogan et al., 2010; Xie et al., 2021). Moreover, some crops cannot be observed via remote sensing, notably greenhouses where incentives for illegal water use are often particularly high due to the high return they deliver to the farmer (Caparrós-Martínez et al., 2020). These uncertainties and omissions pose challenges for trust and acceptance of satellite-based monitoring, although evidence from countries where remote sensing use for monitoring is established within water management practice - such as Spain (Garrido-Rubio et al., 2020) - suggests that the perception of satellite estimates as ‘unbiased’ may help adoption and acceptance by irrigators.

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In addition, a further challenge is that the majority of satellite-based approaches provide estimates of consumptive water use (i.e. crop evapotranspiration). However, this emphasis creates a disconnect with the framing of abstraction rules and regulations, which often define rights or regulations based on the volumes or depths of water applied or abstracted by a farmer. Data derived satellite imagery may therefore have to be transformed into estimates of applied or abstracted water. This will introduce further uncertainties regarding irrigation efficiency and farmers irrigation management practices (Brookfield et al., 2023), with potential negative impacts for effectiveness of policies based on these derived estimates (Foster et al., 2020). Satellite data alone is also not able to determine the source of water used by crops, which is often an important requirement for management and policy. This presents further challenges in regions where farmers use irrigation to supplement rainfall, where multiple water rights serve individual fields or farms, or where different sources of water (e.g. groundwater and surface water) are used conjunctively but regulated independently.

Beyond these challenges, advances in satellite technologies do not remove the need for investment in in-situ monitoring. Estimation of crop water use from satellite imagery also depends on a range of additional data, including meteorological, soil, and land cover datasets that are often derived from in-situ monitoring. New data-driven satellite models of agricultural water use (Majumdar et al., 2020; Filipelli et al., 2022; Wei et al., 2022) may also require significant observations of actual water use or abstraction from in-situ monitoring to train algorithms so that they can be applied robustly to new locations. Furthermore, knowledge of the location of agricultural water abstractions and rights is also essential for satellite estimates to be used operationally in management and policy, yet as previously noted this data may not always be present. For example, using satellite data to distinguish legal from illegal farm water use can only be successful if satellite data advances occur alongside efforts to address gaps and deficiencies in abstraction registries and reporting discussed previously. Here, digitalisation of water rights presents opportunities, as shown by the approach of the Spanish Guadalquivir, Ebro and Duero river basin authorities which have included in their public geographical information system details about corresponding water rights, water sources and associated plots (GHC, 2023).

Given the various constraints around satellite based monitoring of agricultural water use in policy and management, there is arguably a need to focus on how the improvements in both approaches (satellite and in-situ) to monitoring can be leveraged to complement each other rather than satellite data being seen as a replacement for in-situ monitoring (Foster et al., 2020). For example, remote sensing could offer a powerful tool to target limited resources or staff conducting spot checks of low-cost self-reported water use estimates by helping to identify possible locations to check for illegal or unauthorized abstractions. Similarly, remote sensing could be used as a low cost tool for verifying abstraction levels in areas where the costs - environmental and economic - of failing to detect non-compliance are low, with metering prioritised in sensitive areas so that the quality of meter data that is collected can be maximised.

Beyond improved data to improved management

The previous sections of this chapter have highlighted the difficulties faced by regulators and water managers with regard to permitting and quantification of water abstraction by farmers, along with the potential for new technologies such as remote sensing to strengthen monitoring of agricultural water use. However, improved knowledge about where, how much, and for what purposes water is being abstracted does not automatically mean that agricultural water use will be managed more effectively, or that abstraction rules and regulations will be implemented as intended. For example, unregulated irrigation abstractions in water scarce regions has been visible and acknowledged for many years (Stava, 1946; Baird and Walters, 2020; Loch et al., 2020; Baird et al., 2021; Donna and Espín-Sánchez, 2021), but this has not necessarily led to substantial changes to the way those abstractions are managed in these regions. Moreover, given the technical, logistical, and economic challenges of monitoring large numbers of agricultural abstraction points distributed over large areas, no monitoring system will ever be perfect. For these reasons, improvements in monitoring systems and data – whether through greater in-situ data collection and/or derived from remote sensing and other technologies – must be accompanied by improvements to the way data is used in policy to control and enforce water use policies.

From a sustainability and equity perspective, one of the main concerns around gaps in agricultural water use monitoring is the potential to allow or encourage illegal or unregulated water use by farmers. In the absence of perfect monitoring, efforts therefore must be made to strengthen deterrents and penalties when farmers are found to have violated extraction rules or limits. For example, fines for illegal abstraction are often small in comparison to financial gains (Griener et al., 2016; Baird et al., 2021). Moreover, when illegal or unlicensed abstractions are detected, evidence indicates that legal prosecutions are frequently never fully enacted by regulators (Loch et al., 2020; ECA, 2021). Strengthening the severity or likelihood of these penalties being implemented could help to deter farmers from attempting to violate permitting or abstraction regulations (Castilla-Rho et al., 2019). Time lags also matter in this context. Long delays for implementation of enforcement action reduce deterrents to non-compliance, especially in a drought year where the value of water is high and/or where perceived likelihood of detection is low. For example, Loch et al (2020) document a case in the Doñana area in Southern Spain 77 illegal wells were detected in 2012 and an administrative procedure opened in 2014. This led to a sanction that was appealed to the Andalusian High Court of Justice, which finally ratified the sanctions in 2017-2018. This 6 year period from theft to implementation of sanctions provided substantial opportunity for the additional income obtained via illegal water abstraction to be leveraged to generate further financial returns, substantially reducing the severity of the original sanction.

Efforts to strengthen enforcement and compliance will only be achievable, however, if in parallel progress is also made to tackle the transaction costs that often constrain reforms to institutions and policies governing agricultural water use. Larger fines, for example, are politically costly; while supporting or siding with farmers, for example suggesting an amnesty and regularization of informal uses, can be seen as politically expedient especially at times of elections or where powerful farm lobby groups exist (Rijsberman, 2008; Grafton and Williams, 2020; Loch et al., 2020; Schmidt et al., 2020; Jacoby et al., 2021). Implementing penalties can also be a cumbersome and time consuming process for regulators. This is in part due to the significant under-resourcing of environmental compliance and regulation in many countries, along with the significant difficulties often faced in being able to detect and verify the occurrence of unregulated or unpermitted water use. In some cases, this can either extend to directly limiting ability of regulators to monitor and carryout enforcement action, as shown by examples in Donaña in southern Spain where lobbying has led some local municipalities to appeal against some fines imposed on irrigators for illegal abstraction or even pay fines through public money where water theft has occurred on land publicly owned and leased by the government (Loch et al., 2020).

Water scarcity and volatility in water supplies - driven in part by climate change - are likely to increase the need for and economic value of water for agriculture in many locations around the world (D'Odorico et al., 2020; Balasubramanya et al., 2022). Importantly, this may create increased incentives for non-compliance with abstraction regulations by farmers, especially those operating in regions where monitoring is patchy or limited and/or where there is limited support for farmers to mitigate the physical and financial impacts of water scarcity through other means. Given the infeasibility of perfect monitoring in practice, it is essential that efforts are therefore also made to address and mitigate the root causes and consequences of water scarcity for farmers. This could include measures such as insurance systems to financially protect farmers in the event of water allocations being curtailed in drought years, avoiding the need to abstract illegally to protect against economic and financial losses. Currently, most insurance schemes provide cover against drought primarily for rainfed crops (Abdi et al., 2022). Those which do provide cover for irrigated crops typically cover losses not related to water scarcity, or include stipulations that farmers must fully utilise all possible water sources (e.g., the US Federal crop insurance scheme - Suchato et al., 2022) which could incentivise inefficient or unregulated use of water. However, research has shown that provision of financial safety nets such as insurance could provide an important mechanism to protect irrigated agriculture against risks posed by physical and regulatory water scarcity (Gómez-Limón et al., 2020; Agudo-Domínguez et al., 2022), which may in turn help to incentivise compliance with abstraction regulations and restrictions.

Alongside support for dealing with the consequences of water scarcity, there are opportunities to strengthen resilience through interventions that aim to enhance supply reliability under drought and climate change. In some regions, this will require a greater focus on recognising the importance of water for agriculture - and of agriculture for food supply and economies - through changes to prioritisation rules around who gets water in times of scarcity. For example, in the UK agriculture is often the first sector to experience curtailments to water supply during droughts (Knox et al., 2018). Financial or technical support could also be used to enhance on-farm water supply and reduce the need for irrigation abstraction at times of scarcity or drought. Examples of interventions that could be used include development of new physical storage infrastructure such as on-farm reservoirs to smooth out hydrologic variability (Rey et al., 2017), nature-based solutions such as improved soil management or use of cover crops (Wens et al., 2020; Nouri et al., 2021) to retain water in soils in order to limit supplemental irrigation abstraction needs, or exploitation of non-conventional water sources such as treated wastewater for irrigation (Ricart et al., 2021). However, care must be taken that such measures do not exacerbate existing scarcity issues. For example, on-farm reservoir construction has been a source of controversy during recent droughts in Europe and elsewhere (Perin et al., 2021; Brown et al., 2022), due to the perception of withholding water from other downstream uses. Storage systems may themselves also be vulnerable to climate change (Gansah et al., 2022; Malerba et al., 2022), while also creating challenges for regulation when monitoring systems and infrastructure are insufficient to reliably and robustly track when and where reservoirs are actually being filled.

Beyond these interventions, there are also ways that the wider food supply chain and agribusiness market could more directly incentivise greater monitoring, collection and reporting of water use data. One promising area would be to more closely link farm subsidies and other forms of financial support, such as payments linked to product or supply chain certification, to requirements for farms and farmers to demonstrate robust accounting of water use data and compliance with water use regulations. Verifying the legality of water use and evidencing good water stewardship by growers is an increasingly relevant element for the certification of products, especially for water-intensive crops such as fresh fruits and vegetables. For example, the latest certification standards by GLOBAL G.A.P.'s Farm Sustainability Assessment (FSA) as well as the Sustainable Program for Irrigation and Groundwater Use (SPRING), the Alliance for Water Stewardship, Rainforest Alliance, and organic certification labels such as Naturland or CAAE have developed criteria and rules to validate the legal use of water at the farm level (Schmidt et al., 2020). However, some of these standards and frameworks still face challenges to widespread implementation gaps, in particular linked to the lack of baseline water metering and monitoring and the difficulties in linking monitoring data to specific users or plots in some farming systems.

Finally, on a broader level there is a need to move beyond thinking about monitoring and collection of agricultural water use data as a tool purely for regulation and demand management. Greater efforts should be made by both the public and private sector to support farmers to leverage monitoring data to enable positive changes in water management and stewardship that reduce exposure to scarcity and improve resilience of connected human-water systems. For example, at present, farmers' main incentive for monitoring and reporting water use is compliance with regulations. However, the value of water use data is arguably much greater than this. Opportunities exist for the agricultural sector to learn from monitoring by other sectors (e.g. domestic water use) and for other resources (e.g. energy), where monitoring of usage is used to enable better demand management. For example, greater sharing of agricultural water use data could be used to drive innovations in benchmarking (addressing performance ‘gaps’) and decision support that help farmers to learn and identify opportunities and pathways to improve their water management, in ways that in turn help to mitigate pressures posed by scarcity and drought.

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