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Executive summary

Reliable and effective monitoring of water use and availability is essential for the design and implementation of sustainable, equitable, and efficient water management policies; in particular as pressures on water resources grow as a result of climate change, population growth, and socio-economic development. Yet, in almost every area around the world, large gaps exist in infrastructure and capacity to monitor natural and human components of the water cycle. In this paper, we discuss and review the causes and consequences of water monitoring gaps. We show that deficiencies and gaps in the monitoring of water usage and availability arise for a variety of technical, socio-economic, and political reasons, ranging from chronic underfunding of monitoring infrastructures and agencies by governments to direct opposition to and attempts to circumvent data collection by water users. Resulting gaps in knowledge about water usage and availability increase the likelihood that water will be used or allocated in ways that unsustainable and inefficient, with the burden of water risks resulting from poor water management often falling disproportionately on the environment and marginalised user groups. To address these challenges, we argue that there is a fundamental need for governments, donors, and water managers to drastically increase the prioritisation – and financial investment – committed to both collecting water data and enforcing policies around water use. Agencies responsible for monitoring water use and availability must also explore and develop capacity to exploit new approaches to strengthen monitoring within their constrained budgets and capacity, including through use of digital technologies such as satellite remote sensing and IoT, citizen involvement in water data collection and management, and partnerships with private sector. Finally, there is a need for recognition that perfect monitoring will never be feasible or practical in the real world, and, as such, policy design should seek to explicitly embed and consider uncertainties in our ability to monitor water use and availability. This must include efforts to incentivise compliance with water use regulations by users, in particular in the agricultural sector, through a combination of rewards and penalties that are grounded in improved understanding of water user compliance behavior. Only with these innovations will technical advances in water management plans and policies be likely to succeed in their objectives, and societies be able to address growing water risks in the years to come.

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1. Introduction

Water scarcity poses a significant threat to the functioning and health of societies, economies, and ecosystems globally. It is estimated that approximately 4 billion people (~50% of global population) live in areas of severe water scarcity (Mekonnen and Hoekstra, 2016), while health of freshwater ecosystems is being heavily impacted by human competition and conflict over limited freshwater resources (Albert et al., 2021; Vanhamasd et al., 2022; Wu et al., 2023). Human and ecological exposure to water scarcity is expected to rise further in the coming decades as a result of increases in water demand and more volatile supplies caused by a combination of climate change, population growth, and other socio-economic changes (Gleick and Iceland, 2018; Xu and Famigletti, 2023). Indeed, it is estimated that over 6 million people may live in regions of severe water scarcity by 2050 (UN, 2018; Boretti and Rosa, 2019) if changes to water management and policy are not made to adapt to growing water supply-demand imbalances.

An extensive research and policy literature exists that evaluates solutions to achieve more efficient, sustainable, and equitable management of limited freshwater resources, including under future climatic, hydrologic, and socio-economic changes. Proposed policy responses to address water scarcity vary substantially between regions and catchments due to the heterogeneity of their hydrologic, socio-economic, and political contexts. In countries with already well-developed supply and storage infrastructure, focus is more heavily on demand-side (e.g. using water more efficiently and/or using less water) policy options for managing scarcity. These include water use quotas (Young et al., 2021), changes to pricing or taxation (Mitra et al., 2022), water markets and trading (Garrick et al., 2023), and insurance (Agudo-Domínguez, 2022). However, demand management also exists alongside efforts to enhance supply (making more water available and/or at lower cost to users) through construction of new storage and transfer infrastructure (Basheer et al., 2021; He et al., 2021), pumping wells and conjunctive use schemes (Marques et al., 2022), investment in remediation of existing supply systems (Ho et al., 2017; Perera et al., 2021), and the exploitation of novel/unconventional supply sources such as desalination, rainwater harvesting and greywater reuse amongst others (Berbel & Esteban, 2019; Ricart et al., 2021; van Vliet et al., 2021; Karimidastenaei et al., 2022). Supply enhancement measures receive significant investment in both higher and lower income countries. However, supply enhancement is a particularly important role in policy debates in regions where there are large economic and technical constraints underpinning water scarcity (Rosa et al., 2020), or, in the case of storage infrastructure, where there is increasing temporal volatility in water supply due to climate change (World Bank, 2023).

Common to all demand- and supply-side policies, wherever or not they are implemented, is the need for reliable and accurate data to quantify and track water use and availability at scales and resolutions consistent with policy goals and objectives (Foster et al., 2020). Limited or ineffective monitoring can have significant negative impacts on effectiveness of water policies, both in terms of how policies are designed and how they are implemented – as the often-cited phrase states "*you can't manage what you don't measure*". For example, without monitoring of water abstractions it is impossible to assess demand reductions needed to improve water sustainability (Bohling et al., 2021), or to implement, enforce, or verify reductions on water usage as part of demand-management policies (Foster et al., 2020; Loch et al., 2020). Furthermore, inaccurate or incomplete data on water availability poses further challenges for policy and management, including by constraining ability to assess available water resources to be allocated between competing uses (Josset et al., 2019), limiting the ability to effectively identify and assess drivers of scarcity and ex-post hydrologic and environmental impacts of policy changes (Deines et al., 2019; van Loon et al., 2022), and reducing overall trust in water management planning (Lin et al., 2023).

While the importance of monitoring is widely acknowledged, capacity and systems to adequately monitor both water use and supply are often limited in regions with high current or projected future water scarcity. For example, research has shown that only a small proportion of water abstractions volumes and locations are metered and officially verified, with the issue afflicting both higher-income and lower-income countries alike (De Stefano and Lopez-Gunn, 2012; OECD, 2015; Felbab-Brown, 2017; Foster et al., 2020; Loch et al., 2020; Schmidt et al., 2020). Where abstraction data are collected, data are often of variable quality or completeness, in particular due to a reliance on self-reporting of meter records and a lack of public transparency on data sharing that creates potential for false or erroneous reporting in absence of extensive spot checks (Averyt et al., 2013; Castilla-Rho et al., 2019; Foster et al., 2020). Gaps in monitoring of water use are especially pronounced for groundwater use and abstractions from agriculture (Molle and Closas, 2020). This reflects the fact that groundwater irrigation abstractions are highly dispersed over space, and often depend solely on privately-owned pumps and wells that may be installed and operated outside of legal and regulatory systems (Foster et al., 2020; Rouillard et al., 2021).

Monitoring challenges are not restricted to water abstractions and use. Infrastructure and systems for monitoring availability of water over space and time within river basins and aquifers are also rarely adequate or complete. For example, widespread disparities have been documented in the spatial distribution of stream gauge stations, with large disparities and biases in the density of streamflow gauging both between and within river basins and countries (Krabbenhoft et al., 2022). Even more significant gaps also exist in monitoring of other stores and flows in the water cycle. In particular, precipitation and groundwater level data, which depend on networks of point-based monitoring systems, are often inadequate to reliably characterise spatial complexities and deterioration in water availability and resource status including hydrologically-complex surfacewater-groundwater interactions (Xu et al., 2013; Gibson et al., 2017; Hora et al., 2019; Joshi et al., 2021; de Felipe et al., 2013). These issues are especially pronounced in lower income countries with lower historic and current capacity to invest in monitoring infrastructure (Tramblay et al., 2021). However, evidence also suggests that investment in maintaining and expanding hydrologic monitoring has also declined in many higher income countries over recent years (Ruhi et al., 2018; Josset et al., 2019) with negative implications for ability to support water management and policy.

Despite significant known gaps and deficiencies in monitoring of water use and supply, these issues are frequently ignored in research and practice efforts focused on developing policy solutions to water scarcity. With very few exceptions, models and decision support tools used in water management and policy evaluation and design (e.g. Siderius et al., 2021; Zeff et al., 2021; Sapino et al., 2022) assume that simulated water demands and supplies are known with certainty at the spatio-temporal scale of interest in the real world. Where uncertainties are introduced into policy assessments, these typically relate to assumptions about future system drivers (e.g. climate or socio-economic scenarios – Basheer et al., 2023) or user decision-making (e.g. rules or heuristics governing demand choices – Giuliani et al., 2016). In contrast, uncertainties caused by gaps or inaccuracies in monitoring of water availability and demand are rarely considered as part of assessments of expected policy outcomes, including sustainability and robustness. Examples of these simplifications include the assumption of perfect compliance with demand-management policies such as water quotas (Young et al., 2021), the inability to consider unofficial uses of water (e.g. informal irrigators – Venot et al., 2021) in water policy design and assessment, and the obscuring of uncertainties related to sectoral water use (e.g. irrigated agriculture – Puy et al., 2022).

In the context of these issues, this white paper first provides an overview of how gaps in monitoring of water demands and supplies influence the outcomes of water management and policy for people, economies, and the environment. Then, we identify and discuss key drivers contributing to limited monitoring infrastructure, capacity, and practices, using these insights to identify opportunities and challenges for how monitoring of water availability and demand can be strengthened including through new technologies and data (e.g. Earth Observation, IOT) that are increasingly being leveraged to fill gaps in traditional monitoring systems and infrastructure. Finally, we highlight some of the challenges that may exist with moving from improved data and monitoring to improvements in the sustainability, equity, and efficiency of water management, in particular contextualising broader changes that will be needed if better data are to lead to better water management outcomes.

2. Consequences of monitoring gaps

Before exploring the causes and solutions to limited water monitoring, it is important to first consider how lack of reliable data on water availability and/or use may impact the efficacy of water management and policy.

When extraction and use are not accurately monitored, it is impossible to reliably design, implement, or enforce rules and regulations around water access and allocation. Without knowledge of how much water is currently, or has historically, been extracted by users, planners lack the necessary information to assess how much water demands need to be reduced to achieve desired management goals. Butler et al. (2020) highlight the importance of water abstraction data as a means of determining pumping reduction targets for aquifer stabilization, drawing on insights from the High Plains aquifer system in the United States. A lack of data on current water uses and abstraction volumes also makes it hard for planners to effectively target or design interventions to limit or reduce water use in response to water scarcity or sustainability challenges. Garrick et al. (2023) note the need for greater monitoring of water abstraction trading to improve market design and regulation. Similarly, the Spanish Special Plan for the Upper Guadiana (SPUG) budgeted EUR 810m to buy back 200 MCM (million cubic meters) of water to restore the balance in the underlying aquifer (4.05 EUR/m^3), but ended up reacquiring 13.3-13.6 MCM of unused “paper rights” and 2 MCM of actual water rights (33 EUR/m^3) due to lack of data on actual water uses (Pérez-Blanco, C. D., & Gutiérrez-Martín, 2017).

A lack of capacity to monitor locations and quantities of water extraction further impacts efforts to tackle water scarcity by providing enabling conditions for illegal water use to occur via reduced likelihood of detection (Schmidt et al., 2020) which, following Becker’s (1968) rational choice model, reduces the real cost of theft and may lead to expected gains from illegal behaviour that encourage theft (Loch et al., 2020). Illegal or unregulated water use temporarily or permanently reduces the availability of water for other users and sectors, either by exacerbating hydrologic constraints or increasing the economic costs of water access. These externalities of illegal water use can drastically alter the intended outcomes of water management policies and allocation regulations for legal users and the wider environment, in particular during periods of drought when water supply-demand imbalances are already strained. Illegal abstractions by irrigated agriculture have been cited as a key cause of reduced inflows impacting aquatic ecosystems in several areas around the world including the Doñana wetland world heritage in Spain (Loch et al., 2020; Green et al., 2023), Lake Urmia in Iran (Parsinejad et al., 2022), and Pacific Northwest of the United States (Zipper et al., 2019; Bustic et al., 2023). Furthermore, illegal abstractions have also been identified as both driving and exacerbating drought vulnerability, including by reducing the effectiveness of demand management responses to periods of acute water shortfalls (Stone, 2015; Schmidt et al., 2020; Rejón, 2023, Schlembach, 2023).

Illegal water use enabled through ineffective monitoring of water use also has broader negative economic impacts. In Australia, for example, illegal and unlicensed water abstractions have been cited as key causes of inefficiencies in water markets designed to support water allocation and environmental protection, for example due to reductions in reliability and therefore value of legally defined rights (Schmidt et al., 2020). More broadly, illegal water use – whether directly by individuals or through informal water supply networks and systems – by its nature reduces funds received by governments for official water supply. This contributes to lower capacity to invest in maintenance and refurbishment of water supply infrastructure that over time can reduce supply capacity to users, a problem that is especially pronounced in large, rapidly expanding urban centres in the Global South (Felbab-Brown, 2017). It is important to note that reliance on informal or unregulated supply systems in these contexts is often driven by inequities in official service provision and ability to pay costs of water access (Cawood et al., 2022). On the other hand, lenient institutional responses to theft may be interpreted as an implicit subsidy that offloads the financial burden of addressing these inequities onto the environment, while at the same time hindering sustainability of official supply infrastructure networks and systems and reducing system resilience and its ability to cope with drought events (due to declining water stocks).

As in the cases of water use monitoring, where water availability is inadequately quantified, this can also create significant challenges for water management and policy. If governments and regulators do not know how much water is available for sustainable use in a catchment or aquifer, it is impossible to robustly define sustainable limits on water extraction and use. Together with inaccurate information about the status and quantities of existing water usage, this can lead to over-licensing of water and over-allocation of water – where defined rights to water exceed available supplies. Over-allocation is a common occurrence and driver of water scarcity pressures in many areas around the world, contributing to unsustainable abstraction rates and greater volatility in supply reliability for users (Le Quense et al., 2007; Grantham and Viers, 2014; OECD, 2015; Moore et al., 2020). These issues are especially pertinent for groundwater due to the invisible nature of the resource, a consequence of which is that unsustainability of over-allocation may be underappreciated until severe depletion has already occurred at which point storage may only recover with large cutbacks or even permanent cessation of abstraction (Lall et al., 2020).

Even where advances in hydrologic information and data subsequently enable improved characterization of water availability, implementing changes to previously defined licensing and rights can be extremely difficult, time consuming, and politically sensitive, thus increasing the transaction costs of water allocation reform (Garrick, 2015). This can 'lock-in' historic over-allocation of water rights, limiting or delaying innovation in water management policy and adaptation to future climate and socio-economic change. For example, many catchments in the south and east of England are heavily over-licensed, which has contributed to constraining reforms to water abstraction management (including proposals to introduce formal water markets and trading systems) in part due to risks of re-activating currently unused 'sleeper' or 'paper' licenses (Raffensberger and Harou, 2012; Ofwat, 2015). Similar issues exist in other countries, including the Po River Basin in northern Italy (Santato et al., 2016) and in the Colorado river basin in the United States (Kuhn and Fleck, 2019) where pressures have been magnified by recent drought periods and events, while in some basins in Southern Spain "paper water" is even more abundant than real water due to the overallocation of water rights, lack of control of water uses, and decreasing water resources under climate change and anthropogenic pressures. This issue compromises compliance with environmental flow conditions, requiring the implementation of demand control measures and instruments to stimulate the temporal exchange of water rights (Sanchis-Ibor et al., 2022) or, as in the case of Australia, substantial investments to buy-back excess water rights (Wheeler et al., 2014; Wheeler et al.,2022).

Gaps in water availability monitoring also limit the ability to dynamically adapt and adjust water policies in response to changing hydrologic conditions in ways that may improve the efficiency of water allocation, mitigate conflicts between water users, and preserve freshwater ecosystems during periods of supply constraints. For example, in parts of the Murray-Darling basin allocations are defined conditional water availability in a given year (Grafton et al., 2014) while in the UK and other countries in Europe it is common for abstraction licenses to include restrictions linked to hydrologic conditions (Richter et al., 2012). Similarly, research has shown the ability to improve efficiency of water management through integration of near real-time monitoring and future forecasts, for example to support reservoir operation (Turner et al., 2020) or triggering adjustments to regulations based on observed hydrologic changes (Kinzelbach et al., 2022). None of these can be implemented or enforced without the ability to reliably monitor and track water availability changes over space and time. As a result, in locations where hydrology is poorly or inadequately gauged, policy design will be limited making it harder to ensure limited water resources are used efficiently or to adapt allocation approaches to future changes in water supply and/or demand.

Additionally, the consequences of monitoring gaps extend beyond the design and implementation of water management policies. Where monitoring is limited, our ability to learn from outcomes of implemented water management policies and projects is also constrained and opportunities to trigger adaptations or corrective action to enhance water management performance are reduced. Large-scale dams and canal-based irrigation projects, for example, have for several decades been a key mechanism through which donors and governments have sought to reduce agricultural water insecurity in Sub-Saharan Africa. Yet, their outcomes are rarely monitored, with research suggesting that these projects consistently underperform in part due to a failure to collect data that would have shown that these projects commonly over-estimate expected improvements in water use, access, and productivity (Higginbottom et al., 2021; Redicker et al., 2022). Moreover, lack of ex-post monitoring has facilitated the survival of widespread myths such as the idea that irrigation modernization saves water—where scientific theoretical and empirical research has consistently shown that the opposite is the case (Grafton et al., 2018; Pérez-Blanco et al., 2021). Comparable issues occur where water infrastructure defects go undetected due to monitoring gaps. For example, delays in fixing or remedying maintenance issues with water supply infrastructure increase scarcity for users and costs of remedial action for government, a challenge that is likely to grow due to ageing and deterioration of water infrastructure in many locations (Perera et al., 2021).

3. Causes of monitoring gaps

Gaps in the monitoring of water usage and availability arise for a variety of technical, socio-economic, and political reasons. Understanding the drivers and root causes of monitoring gaps is critical for designing and developing solutions to strengthen monitoring of water supply and use, and for effective utilisation of these data in policymaking and water management practice. In the following sections, we discuss key drivers and causes of data gaps related to monitoring of water demand and supply in turn while noting common overlapping challenges between the two.

3.1. Water abstractions and use

An essential requirement for effective monitoring of water usage is knowledge of where abstractions occur and how these locations change over time. However, tracking and maintaining databases on the locations of water abstraction is logistically more complex than monitoring hydrologic conditions such as streamflow or groundwater levels. While regulations exist in many countries that require users to register and report abstraction locations, rules are often difficult or even impossible to enforce in practice. For example, evidence from around the world shows that significant numbers of abstraction points often exist that are not captured by official water rights registries (EASAC, 2010; De Stefano and Lopez-Gunn, 2012; Schmidt et al., 2020). These issues are especially pronounced in regions where groundwater is a major source of water supply and where abstractions are dominated by large numbers of distributed individual users (commonly agricultural), keeping track of which is an enormous (arguably impossible) financial and logistical challenge for often under-resourced regulators (Molle and Closas, 2020).

Incomplete water rights inventories represent a major blindspot for policymaking and management. A common framing is that gaps in water rights inventories reflect the presence of illegal abstractions where users are circumventing official regulations to take water they are not entitled to or to avoid payment for water access and use. While this may be true in some contexts (e.g. an unlicensed abstraction for commercial or agricultural activities in a country with a well-defined water rights system – Novo et al., 2015; Loch et al., 2020), causes of gaps in water abstraction and rights databases are often more complex. Procedures for formally registering and legalizing registration of abstractions can be complex, time consuming, and expensive. Foster et al. (2021) discuss how the majority of groundwater wells in Nepal – and the wider South Asia – are drilled by private operators and rarely officially registered due to long delays in official permitting and drilling procedures, while Komakech and de Bont (2018) note that costs of government drilled wells in Tanzania can often be several times that of those drilled privately. These factors often act to disincentivise registration, especially where penalties for non-reporting are limited or there is tacit official acceptance of 'unauthorised' abstractions for logistical, financial, or political reasons (Molle and Closas, 2020). Moreover, barriers to registration and formalisation are often borne disproportionately by certain groups of users – often those with lower income or education levels – potentially contributing to exclusion of these groups from official water management and allocation (Al Naber and Molle, 2017; van Koppen and Schreiner, 2019).

Official water rights registries may also by their design ignore certain categories of water user. This can take the form of official exemptions designed to ease the administrative burden on both users and regulations. For example, some countries only require water abstractions to be officially licensed or registered if the volume of water being abstracted or characteristics of the abstraction system exceed certain minimum thresholds. In the UK, abstraction licenses are not needed if the volume of water abstracted is less than 20 m^3/day (UK Government, 2017), with similar types of volumetric lower limits or thresholds used in other countries for determining licensing requirements for both surface water and groundwater abstractions (Molle and Closas, 2020). In these cases, locations of exempt abstractions are often unknown to those designing water management policies or plans, nor is this information readily available to those tasked with ensuring that abstraction exemptions are being adhered to.

Registers of 'official' water users may also implicitly exclude certain categories of user due to a desire to not recognise or support those users. Illegal users of water – especially rural agricultural users – may be officially 'ignored', due to an implicit desire to not regulate low-income users or to avoid being burdened with requirements to support users to improve access to water or efficiency of water use (De Stefano and Lopez-Gunn, 2012; Molle and Closas, 2020). In some cases, perceptions about the quality or value of water use may also influence recognition in official water registries. Venot et al. (2021) and de Bont et al. (2019) both highlight that small-scale irrigation abstractions in parts of sub-Saharan Africa are sometimes deliberately not included in water use registries due to perceptions that use is wasteful that, if acknowledged, would go against official development narratives that emphasise large-scale 'formalised' and state-controlled irrigation infrastructure. In other cases, gaps in registries of water use may reflect outdated or poorly managed systems of water governance. For example, water allocation in Italy is managed by regional authorities, which may share a common basin. This results in poor coordination efforts and asymmetries in water resources management with upstream water abundant regions having little incentives to monitor water, which in turn negatively impacts the ability of the overall basin authority to establish an objective register of water uses.

Maintaining official registers of water abstraction locations is only one component of an effective system of water demand monitoring and management. Additional information must also be reported and collected about the quantities and timing of water being abstracted and for what purposes water is being abstracted. Here, a major common challenge affecting water systems around the world is the systematic low levels of water metering including those with significant current or project water scarcity. As for registration of abstraction locations, gaps in water metering are most severe for agricultural abstractions and those linked with private groundwater wells. Foster et al., (2020) show in the United States that the majority of agricultural wells are not metered including in depletion hotspots such as California and Texas, while in countries such as China and India the sheer number of private wells makes direct metering an almost impossible task to implement and maintain (Shah, 2014; Wang et al., 2020). Aggregated monitoring of urban domestic and industrial water abstractions is more commonplace, especially in higher income countries, but metering at disaggregated levels still remains absent in many parts of the world (Di Mauro et al., 2021). Irrespective of use or location, a lack of metering creates a major challenge for water planning and management, both in terms of reconciling demands for scarce water and implementing policy solutions that seek to limit (e.g. quotas) or incentivise (e.g. pricing) reductions in water demand (Rey et al., 2019).

One of the key drivers for low levels of metering is the economic costs of purchasing and installing flow meters, which sometimes creats a financial barrier or disincentive for users and authorities. For example, Sanz et al. (2016) highlight that Upper Guadiana Plan in Spain has a total investment budget of nearly 100 million Euros for flow metering, while in the United States flow meter costs can run into several thousand dollars per device requiring government subsidies or cost sharing to support rollout (e.g. LENRD, 2016). Costs are increased by requirements to maintain and repair metering systems, both due to wear and tear (e.g. in rural settings where water quality is often variable) and as a result of deliberate tampering and vandalism by users is commonplace (Baird et al., 2021; Molle and Closas, 2021; Kinzelbach et al., 2022). Where these costs are borne by regulators they can place a significant strain on budgets, or where borne by users, these costs raise the likelihood of users opposing implementation. Financial concerns are often magnified by the fact that the value of meter data is commonly not fully appreciated until a region is experiencing significant water management pressures, and changes to policy – including around monitoring – may not be actioned once periods of acute drought or scarcity abate (Nohrstedt et al., 2021). Groundwater management in California in the United States is a textbook example of this problem, where metering has only recently become central to debates and discourses around policy reform despite decades of significant aquifer depletion (Griggs, 2020).

Attempts to expand or enhance metering may be impeded by pushback from users, including though different forms of legal and illegal political pressure. Users – in particular agriculture and industry – often view metering as a precursor to regulation that will lead to charges or restrictions be increased or imposed that negatively impact their businesses and livelihoods (Molle and Closas, 2021). Farmer and agricultural groups – through both legal and illegal lobbying – have been central to stymying or delaying rollouts of water metering even in the face of severe water scarcity and drought in several countries including Spain (De Stefano and Llamas, 2013), Australia (Bell, 2022), United States (Foster et al., 2020), Mexico (Hoogesteger, 2018), and Pakistan (Schmidt et al., 2020) to name just a selection of examples. Injuries to public officers tracking illegal water abstractions due to booby traps or physical assaults have also been reported in areas like California illegal marijuana fields and Doñana (Loch et al., 2020). Pushback from users may also plays into broader socio-political opposition to mandatory involvement of the state in private decisions and property (Niles and Wagner, 2019). However, opposition to water metering often does not come solely from water users themselves. Wider sectors and supply chains are often dependent on unregulated water use, and there may be a desire to not shine a light on these issues as this could create reputational risks or financial costs (e.g. if unregulated users are penalised and new sources of supply must then be found). Similarly, policymakers may have concerns around the impacts of metering on users and the wider economy, which may be seen as a reason to delay or even actively lobby against metering. For example, Doñana is a major exporter of berries to several European markets, and putting an end to water theft may constrain the supply of these commodities, increase prices, and reduce market income both locally (through reduced employment, income, and demand) and abroad (Parrado et al., 2020).

Finally, where water abstraction locations are known and metered it is important to note that this does not necessarily equate to the collection of reliable and actionable data. While smart metering and automated data collection are expanding for domestic and industrial water use in some parts of the world (Cominola et al., 2015), the overwhelming majority of water meter data – especially for rural agricultural uses – is self-reported by users (Foster et al., 2020). The US state of Kansas, for example, has one of the world's most extensive network of metered groundwater wells, but relies almost entirely on self-reporting of data by users (Riley et al., 2019; Zwickle et al., 2021). Self-reporting creates opportunities for deliberate or accidental false reporting, which are logistically challenging to detect given spot-checking capabilities of most regulators are often extremely limited, with many faced with limited or even declining budgets for enforcement of water and other environmental regulations (e.g. Benami et al., 2020; NAO, 2022). Bypass and tampering with meters have also been widely reported as causes of low-quality meter data, while bribery of meter recorders can also be used to distort records (Molle and Closas, 2021).

3.2. Water supplies and availability

Monitoring of water supplies and availability is typically more widespread than that of water abstractions, in part because data such as streamflow records are socially and politically less contentious than data related to users' water abstraction and usage. Nonetheless, large variability exists in the density, completeness, and quality of hydrological monitoring infrastructure and data around the world (Condon et al., 2021; Krabbenhoft et al., 2022). The density of global hydrologic monitoring networks has been shown closely correlated with economic status of countries and regions, with largest monitoring gaps unsurprisingly found in regions with lower economic, technical, and institutional capacity to invest in and maintain high-quality monitoring networks (Krabbenhoft et al., 2022). Spatial discrepancies in hydrologic monitoring infrastructure also reflect broader societal challenges that constrain ability to effectively collect and maintain hydrologic data records, including greater vulnerability to conflicts and disasters, challenges accessing remote locations that are exacerbated by poor infrastructure, and ineffective governance (Hannah et al., 2011; Cho et al., 2017; Haile et al., 2022). Most alarmingly, many 'blind spots' in hydrologic monitoring exist in regions with substantial projected future increases in water scarcity and/or high levels of water supply variability, such as Sub-Saharan Africa and Southeast Asia.

Regions with historically dense hydrologic networks are also experiencing declining numbers of active monitoring stations due to cutbacks to funding and financial support. Again, a concerning trend is that many areas of the areas of declining monitoring are located in regions with high current or projected water risks. For example, Ruhi et al. (2022) show a decline in stream gauging globally over past decades driven by funding and other pressures, with hotspots of declining monitoring in catchments with significant flood and/or drought risk exposure or sensitive freshwater ecosystems. Even for well-resourced and effectively managed hydrologic monitoring systems, there remain major economic and logistical challenges that limit the ability to collect data with sufficient detail and resolution needed to respond to rapidly evolving hydrological change and water scarcity pressures. For example, the ability to characterize the status or changes in groundwater storage is challenging even in those regions (e.g. North America, Europe) with the most extensive monitoring systems, with data gaps leading to differing assessments of water resource availability and sustainable abstraction limits needed to protect the environment and economies (Custodio et al., 2016; Rusli et al., 2021; Bohling et al., 2021).

A further driver of gaps in monitoring of water availability arises because instrumenting and collecting hydrologic data does not by default translate into making this data accessible and usable by those involved in water management. It is not uncommon for different types of hydrologic monitoring in a given catchment to be held by different local, regional, or national government agencies and departments, as well as by other groups such as international agencies or community organisations (Josset et al., 2019; Barker et al., 2022). Datasets may be presented, and need to be accessed and processed, in different ways depending on the source or provider, making information challenging to interpret and integrate (Addor et al., 2020; Lall et al., 2020; Brunner et al., 2021). For time and resource constrained users, such as policymakers and water managers, this can be enough to render these data infeasible to access and utilise. User trust in data may also be affected by the fact that different data portals can sometimes provide very different values for water availability and scarcity metrics depending underlying dataset and processing choices (Mueller et al., 2015).

Alongside this, the majority of hydrologic monitoring systems also contain little if any objective information on uncertainties in the data provided. For example, Josset et al. (2019) found that none of the current state-level hydrologic monitoring datasets in the United States quantify or document observational data uncertainty, with comparable information gaps observed for hydrologic monitoring systems globally (Wilby et al., 2017; Condon et al., 2021). In more extreme scenarios, there may even be deliberate attempts to limit sharing of data and obscure transparency. For example, sharing of hydrologic data has shown to be restricted due to political, security, and privacy concerns, in particular for transboundary rivers with contestations of water allocation between different countries and actors (IWMI, 2021; Donchyts et al., 2022; Sarafaraz et al., 2022; Lin et al., 2023). All of these factors reduce the quantity and quality of available data to characterise and quantify water availability, introducing biases to water management planning (Wilby et al., 2017) while also creating inequities in who has access to different forms of data and information to support negotiations over management of water resources.

Finally, it may be argued that hydrologic monitoring systems are not only spatially and temporally lacking, but in some cases may also not actually collect the kinds of information needed to enable effective and innovative policy and management responses to water scarcity. Groundwater monitoring networks, for example, focus on monitoring changes in aquifer water levels or storage, but typically do not collect any information about changes in other important hydrogeological properties. For example, well or pumping yields have been shown to be a more significant predictor of impacts of aquifer depletion on groundwater users but are not monitored directly – in part due to challenges of metering mentioned previously – nor can they be easily derived from water level or storage observations (Foster et al., 2015; Foster et al., 2017). These types of data or information 'gaps' are characteristic of broader disconnects that exist between those responsible for designing and implementing hydrologic monitoring systems, and the policymakers and managers who are the end users of these data.

4. Pathways for improved monitoring

Strengthening monitoring capabilities and data, as well as the ability to enforce rules and regulations based on this information, is essential for achieving sustainable, equitable, and efficient management of scarce water resources. Without effective monitoring, technically sound water management plans and policies are unlikely to succeed in their objectives and at worst risk exacerbating existing water risks and scarcity. Drawing on insights about the drivers and consequences of monitoring gaps from water scarce regions globally, we have identified several recommendations – and associated challenges – for how gaps in monitoring of water demand and supply could be addressed in order to support water management planning and policy.

4.1. Recognise monitoring as integral to the design, implementation, and success of water policies

Our analysis has highlighted that gaps in capacity, resources, and infrastructure are a major underlying driver of limited monitoring of water use and availability in many parts of the world. Given this, we argue that there is an urgent need for governments, donors, and water managers to drastically increase the prioritisation of investment in enhancing and maintaining monitoring infrastructure, without which planners will be operating blind (or at best with impaired vision) in attempts to design solutions to growing water scarcity challenges.

In this context, there is some positive evidence of growing recognition around the world of the importance of investing in monitoring capabilities to enable more effective and sustainable responses to water scarcity pressures and challenges. Examples include efforts in Spain and Australia to develop improved registries of water rights and uses to address scarcity pressures and illegal water use (Schmidt et al., 2020), along with investments in the US state of California to expand groundwater level monitoring networks to support implementation of the state's Sustainable Groundwater Management Act (SGMA) (Babbitt et al., 2018). However, much remains to be done, in particular with regard to empowering agencies responsible for monitoring with the capacity and funds to maintain systems and ensure quality assurance of any data collected. For example, the Environment Agency – the regulatory body responsible for water management in England and Wales – has seen large cutbacks in funding and staffing for policy enforcement (NAO, 2022) limiting its ability to respond to emerging water risks (Wentworth, 2012; The Guardian, 2022). Similar trends of declining funding for environmental compliance and enforcement reported in other higher-income countries (OECD, 2005; EIP, 2019; Escriva-Bou et al., 2020), while limited budgets and prior infrastructure investment in lower-income countries mean that funding for enforcing water (and other environmental) policies is often non-existent.

Achieving proactive support for and investment in monitoring will likely require efforts to educate and debias assumptions amongst policymakers around the perceived low need for monitoring and benefits of investing in infrastructure and capacity. Monitoring of water resources is typically wholly or primarily financed through national budgets and taxation, and hence a case must be made for the benefits of investing in hydrologic monitoring as opposed to other environmental and non-environmental priorities (OECD, 2005). Here, scientific research has a key role to play in demonstrating the value of monitoring for users and wider society in adaptation to water scarcity (e.g. through reduced water risks), including identifying where, when, and what types of monitoring should be prioritised given limited available capacity and resources (Hino et al., 2018; Foster et al., 2020; Kampf et al., 2020; Krabbenhoft et al., 2022). In parallel, in some regions, there will be a need to address regulatory capture by groups with vested interests, such as illegal users and the industries and legal communities that benefit from the activity (Perez-Blanco et al., 2021). Lobbying by these groups can increase transaction costs, which, in turn, will deter investment in improving monitoring even where the political will and financing may otherwise have been available.

Alongside efforts to champion the value of monitoring in policymaking and environmental budgets, there are also opportunities for government agencies traditionally tasked with hydrologic monitoring to work more closely with users and the private sector to enhance data collection and availability (Sarni et al., 2022). Amongst water intensive users in agriculture and industry, there are pressures and attempts to demonstrate that water is being used productively and efficiently (CDP, 2017; WWF, 2018;

Reig et al., 2019). Here, there is an opportunity to reframe monitoring as not only a tool for regulatory control, but also as something that can add value to farmers and businesses operations and bottom lines (Foster et al., 2020). For example, emerging business models and financial markets for water stewardship are demonstrating ways that growers water use data can be used to reward good practice (e.g. payments linked to reductions in water usage or improved water management practices) rather than simply as a tool for regulators to impose restrictions on usage (e.g. Common Good Water programme for alfalfa water credits in California – https://commongoodwater.com; Annheuser-Busch partnership with USA Rice to improve water efficiency in rice production in SE United States – https://www.anheuser-busch.com/newsroom/anheuser-busch-and-usa-rice-partner-to-support-sustainable-rice-farming) Similar opportunities exist for partnerships to enhance monitoring of water availability, in particular through exploiting linkages with private sector monitoring networks and technology innovation (e.g., Deines et al., 2023). However, care is required to ensure data quality and comparability, including when there is potential for reported data to be manipulated in order to influence subsequent policy enforcement (Athey, 2017) or where assymetries in data access may be created (Zipper et al., 2019).

Recognising the challenges of overcoming severe technical, financial, and capacity constraints faced by many water monitoring and regulatory agencies, there will also be a need to consider supporting new and innovative solutions for enhancing data collection on both water usage and availability. These include exploiting digital monitoring technologies that enable regulators to collect and analyse more data at lower cost (discussed in detail under Recommendation 2 below), but also include empowering citizens and communities to be more involved in the processes of monitoring and managing water. Citizen science has contributed to reinforce public engagement and improve the knowledge and awareness of citizens (Brouwer et al., 2013). Yet, the level of involvement of citizens has often been limited to data gathering (e.g. Little et al., 2016; Nath and Kitechen, 2023), below the true potential of citizen science to co-create knowledge (Buytaert et al, 2014). Recent developments on ICTs facilitate information acquisition and its use, boosting opportunities for the successful development of citizen science projects (Hecker et al, 2018) to support improved monitoring of both water availability and use for river basin planning. However, it is also important to recognise that data gathered by citizens are also uncertain, and this uncertainty must be acknowledged and accounted for when used to support planning and management of water use or availability (Etter et al., 2018).

4.2. Embrace digital solutions to fill monitoring gaps, but beware seeing them as 'quick fixes'

Deploying traditional monitoring technologies (e.g. flow meters, stream gauges, etc) and approaches (e.g. manual field verification of water use reports) everywhere is unlikely to ever be technically, economically, or socially feasible, for reasons discussed earlier in this paper. Given this, there is a need to consider opportunities to leverage new digital technologies as a means of complementing existing monitoring infrastructure and filling gaps in data needed to support design, implementation, and enforcement of water management policies.

Satellite remote sensing, for example, offers a promising solution for monitoring and detecting distributed agricultural water abstractions across large areas at low costs, which are currently only sparsely captured by in-situ abstraction monitoring. Examples of initiatives leveraging satellite data to support water management policy include the OpenET data platform developed by NASA and other partners to provides easy access to satellite-based evapotranspiration data (Melton et al., 2022), along with the use of remote sensing to track and monitor irrigated cropland areas for water rights enforcement in countries such as Spain and Italy (Calera et al., 2017). Similarly, earth observation also offers an invaluable source of information to plug gaps in water availability monitoring, especially in areas with limited or missing in-situ gauging. Novel examples of applications linked to policy and management including quantification of streamflows using new NASA SWOT satellite (Riggs et al., 2023), high-resolution quantification of groundwater storage changes using GRACE and InSAR data (Castellazzi et al., 2018), and the monitoring of soil moisture with SMAP satellite data to support drought monitoring and detection (Vergopolan et al., 2022)

Digital innovation opportunities to strengthen monitoring exist not only through earth observation. Digitilisation can support integration of currently disparate datasets, helping to enhance and add value to already existing monitoring infrastructure and systems. Kinzelbach et al. (2022) demonstrate how integration of hydrologic data and models can be used to enable more dynamic and responsive management of groundwater resources in parts of the North China Plain, while Hino et al. (2018) show how machine learning methods can be used to analyse water pollution reports to develop more targeted allocation of inspection effort. In addition, digitilisation can also simplify and lower costs for collecting and reporting water data robustly. For example, digital verification and automated reporting of meter records and hydrologic data linked to low-cost sensors has potential to enhance accuracy, resolution, and cost effectiveness of water data collection compared with traditional field investigations and infrastructure (Zekri et al., 2017; Paul et al., 2018; Calderwood et al., 2020; Koech et al., 2021). More broadly, digitalisation has additional benefits of making data more open and accessible to users and the wider public, including facilitating and simplifying opportunities for citizen involvement in monitoring through mobile apps and technologies (e.g. citizen science solutions as part of eGroundwater project etc). For example, the Guadalquivir River Basin Authority has developed an online Geographical Information System which includes complementary GDPR-compliant information about locations and characteristics of water rights for irrigation (GHC, 2023).

Caution must be taken, however, to ensure digital technologies and data are not viewed as panacea solutions that replace the need for in-situ monitoring. Digital technologies are not error free, and some digital monitoring approaches may suffer from high levels of uncertainty especially where what is measured is a proxy rather than a direct measure of water use or availability. These issues are especially relevant in the context of Earth Observation data, where estimates of water use or hydrology are derived based on relationships with spectral information captured by satellite sensors. EO estimates of agricultural water use, for example, have been shown to differ substantially from the on the ground reality, in particular when seeking to estimate levels of applied or abstracted water at fine spatial and/or temporal scales often required for policy design and enforcement (Foster et al., 2019; Foster et al., 2020). Failure to acknowledge and recognise these issues poses risks for water management, in particular where it creates a false sense of confidence amongst end users that leads to maladaptive choices about how to manage scarce water resources.

Given these constraints, we suggest digital technologies should be viewed as means to further support — and ideally enhance — rather than replace existing or conventional monitoring approaches. For example, uncertain but detailed EO data could be used as a tool for targeting on the ground spot checks, or to allow in-situ gauging or metering resources to be focused on areas where water risks or environmental sensitivity is greatest (Foster et al., 2020; Filippelli et al., 2022) and has been successfully employed in New South Wales by the water regulator (Barnes, pers. comm., 2023). In doing so, remote sensing and other digital monitoring technologies could play an important role in helping to address the logistical and financial constraints that underpin monitoring gaps faced by many regulators and water management agencies (Schmidt et al., 2020; Massari et al., 2021). However, it must also be recognised that deploying, validating, and maintaining digital monitoring solutions also requires time, finance, and staff with appropriate technical skills (Pritchard et al., 2022), all of which as previously noted are often in short supply in agencies responsible for monitoring water use and availability. Training and capacity building are thus critical requirements to ensure the long-term success and impact of digital solutions as part of monitoring of water management policies.

More broadly, there is also a need to consider the social and ethical risks that may be posed by increasing emphasis on digitalisation of monitoring as part of water management policy. For example, while use for detection of illegal uses of water may be desirable in many contexts, in lower income countries these data may be used to surveil and ultimately exclude informal users of water who currently operate outside of official government systems in ways that ultimately exacerbate inequalities in access (e.g. Venot et al., 2021). Power imbalances also exist in who gets to access, use, and ultimately benefit from new digital technologies – for example wealthier or more powerful water users may be more able to challenge data uncertainties, or manipulate what is included in data systems to benefit their own interests. Surveillance of water use via increasingly high-resolution satellite data also brings with it critical questions around individual privacy (Purdy and Leung, 2012), many of which are increasingly recognised in broader debates around conservation and natural resource management (York et al., 2023) but have been inadequately explored in the context of water management.

4.3. Design management policies to ensure robustness in the absence of perfect monitoring

It is important to recognise that we will never achieve ‘perfect’ data or monitoring systems with no ‘gaps’, while innovations described above often take substantial time to be implemented and adopted in policy and practice. Given this, there is a need to design and assess water management policies with imperfect monitoring in mind, in particular to ensure robustness where the hydrologic reality differs from what was anticipated in the planning process. Recent advances in methods for decision-making under uncertainty, such as the use of global sensitivity analysis (Kryston et al., 2022; Rodrigues-Flores et al., 2022) and AI-based robust search algorithms (Smith et al., 2019; Arnold et al., 2023; Basheer et al., 2023), hold promise in this area. However, there is a need for greater focus and analysis of the applications of these methods in the context of water monitoring gaps, including uncertainties related to both physical hydrology and human water use behaviors which have typically been neglected in research and policy focused on robust water management planning.

For water usage specifically, acknowledging constraints to monitoring also means that efforts must be made to ensure that effective support (‘carrots’) and penalties (‘sticks’) are in place to incentivise users to comply with water demand management policies even where monitoring is imperfect or incomplete in reality. Incentives to encourage compliance with water abstraction management policies can take several forms. Illegal or unregulated water use is driven in part by pressures posed by acute scarcity and drought (Schmidt et al., 2022). As a result, compliance could be strengthened through interventions that help users to reduce exposure to water scarcity and drought risks. In the UK and several other countries this includes providing grants to support farmers to build on-farm reservoirs to enable storage of winter high flows as buffer against potential summer abstraction restrictions (Hess et al., 2022), while provision of advisories and decision-support tools are also used to help farmers to comply with more water use restrictions (Chengot et al., 2023; Schipanski et al., 2023). However, caution is needed to ensure these measures do not generate unintended maladaptive consequences that exacerbate water scarcity or inequities. For example, the ability to verify that farm reservoir filling occurs during legal months in the absence of reliable water abstraction monitoring is challenging, while there has been controversy over hydrologic sustainability and social justice implications of reservoir water capture in some regions (Rouillard, 2020; Brown et al., 2022).

Alongside physical interventions to reduce exposure to scarcity, support can be targeted to mitigate or buffer users against the economic or financial impacts of scarcity. A common example are insurance programmes, such as crop insurance programmes that provides payouts to farmers in the event of crop loss due to a variety of factors including drought and water shortfalls (Reyes et al., 2020; Agudo-Domínguez et al., 2022; Bucheli et al., 2023). Alongside risk transfer measures such as insurance, compliance can also be encouraged through other positive financial incentives, such as linking to subsidies or certification standards. For example, the European cross-compliance ties direct agricultural payments (and some other CAP payments) to certain environmental obligations. One of the cross-compliance conditions (GAEC 2) covers water abstraction authorisation procedures set by the Member States. National/regional authorities check 1 % of specified groups of farmers who irrigate their fields, and impose penalties (typically a 3 % reduction in their subsidy under BPS or SAPS) for those who do not comply with national/regional water abstraction authorisation procedures However, its effectiveness is severely hampered by implementation gaps, with cross-compliance having little or no impact where there is weak authorisation procedures or users that fall outside of payment regimes. Only three of the assessed eleven Member States and regions check for the presence of meters - Belgium (Flanders), France (Centre-Val de Loire), Cyprus; and ten of the 11 did not check the content of authorisations, such as maximum abstraction volume and time of irrigation (ECA, 2021). Certification schema – such as GLOBALGAP-SPRING and others – are increasingly using control points to assess whether the product has been grown using a legal water source. However, implementation requires training of certifiers on the ground, reliable water metering on the farm, and a high-level ranking in the certification schema to properly exclude products from the supply chain which have not been irrigated legally (Schmidt et al., 2020).

Incentives alone are unlikely to be sufficient to robustly deter illegal water use practices, and, in parallel, there is therefore a need to strengthen deterrents to rule-breaking. Enhancing capacity for regulators to detect illegal water use (e.g. through more resources for spot checks combined with use of digital technologies) can help to make illegal abstraction a riskier proposition for users (Loch et al., 2020). However, when illegal use is detected, significant penalties also need to be in place to deter other offenders. These include levying of fines for non-compliance at levels that exceed the value gained from illegally abstracted water, imposition of legal penalties such as criminal prosecutions, temporary or permanent removal of water rights, or even leveraging community peer pressure to deter offenders. Whatever the type of penalty imposed, it is crucial to ensure that penalties are accompanied by awareness raising about the consequences of illegal water use along with significant resourcing of agencies responsible for implementing penalties. Indeed, financial and legal penalties exist on paper in many countries experiencing illegal water use pressures, but implementation is often limited in practice due to lack of political will, administrative and judicial capacity, and strong pushback from user communities (Schmidt et al., 2020).

To support efforts to tackle illegal or unregulated water use, there is also a broader need to better understand the drivers of non-compliance, including the potential responses of users to increases risks posed by climate change and growing inter-sectoral competition over water, in order to design more effective regulatory response strategies. Little research exists that documents the conditions under which illegal water use occurs, or the effectiveness of different potential incentives and deterrents in practice. Moreover, there is a need to better understand how compliance with water policies and regulations is influenced by different modalities of governance involving state and/or users in management of scarce freshwater resources. Recent examples have demonstrated the importance of stakeholder involvement in water management design and implementation for ultimate acceptance of policy reforms (e.g. Molle and Closas, 2020; Rouillard et al., 2021; Marston et al., 2022). However, user/stakeholder involvement can only be effective if there is accountability, transparency, and trust about drivers of scarcity and how policies will be enforced, which is predicated on existence of water availability and water use monitoring systems and data.

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