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<u>Abstract</u>

The hydrological evidence on which water resource management and broader governance decisions are based is often very limited. This issue is especially pronounced in lower- and middle-income countries, where not only data are scarce but where pressure on water resources is often already very high and increasing. Historically, several governance theories have been put forward to examine water resource management. One of the more influential is Elinor Ostrom's theory of common-pool resources. However while used very widely, the underlying principles of Ostrom's approach make pronounced implicit assumptions about the role of data and evidence in common-pool resource systems. We argue here this overlooks how power relations, user characteristics, system arrangements, and technological advances modulate fundamental associations between data, evidence, and governance, which we contend need to be considered explicitly. Examining the case of water allocations in Quito, Ecuador, we develop a set of concrete criteria to inform the ways in which Ostrom's principles can be applied in a data-scarce, institutionally complex, polycentric context. By highlighting the variable impact of data availability on subsequent evidence generation, these criteria have the potential to test the applicability of common assumptions about how to achieve water security in a developmental context, and hence offer the possibility of developing a more encompassing theory about the interactions between water data, evidence, and governance.

Keywords: water resources governance | data scarcity | monitoring | data collection | hydrological evidence | polycentric governance

Highlights

- Ostrom's governance principles rely on strong assumptions related to data and evidence
- Changes in data availability will impact these assumptions
- We provide criteria to assess the impact of such changes on those principles

1. Introduction

The lack of knowledge about the physical state of water resources due to limited measurements, and a lack of institutional and technical capacity, are exacerbating the multitude of challenges faced by water managers across the globe (Hannah et al., 2011; Garrick et al., 2017). In light of this situation, current presumptions about water resources governance –in particular, the relationship between data, evidence, and decision-making in this process– should be re-examined. Within a decision-making context, *data* can be considered as the result of an observational process, supported by in-situ or remote sensing technologies. These data are shaped by stakeholders into *evidence*, i.e., a body of facts and information supporting the validity of an idea. The process of shaping data into evidence is heavily dependent on the broader governance arrangements within a given context that service a particular objective. Such arrangements define rules surrounding data generation, collection, ownership, storage and dissemination followed by use in decision-making.

Water is typically considered a common-pool resource (CPR). A CPR is defined as a natural or human-made resource system where the exclusion of potential beneficiaries is costly but not impossible (Ostrom et al., 1994). Governing a CPR was viewed historically through the 'tragedy of the commons' lens enunciated by Hardin (1968), where individual utility maximisation would lead to overuse and, thus, resource depletion. A possible solution to this inherent challenge in the water resources domain is thought to reside in top-down approaches such as Integrated Water Resources Management (IWRM) or private ownership (Pahl-Wostl, 2009).

In disputing these traditional top-down CPR governance assumptions, Ostrom (1990), based on empirical evidence, articulated a list of principles in use in successfully self-organised CPR systems. She emphasised the underlying socio-political dynamics of a given system, which manifests itself in elements such as agreed-upon conflict resolution and sanction mechanisms, clearly defined user and resource boundaries, and appropriation rules tailored to local conditions. However, these principles are strongly based on the necessary evidence to support the identification of these boundaries, the formulation of rules, and resolution of conflicts. In its turn, this assumes implicitly the availability and universality of data generation and collection, visualisation capabilities, and application (Coleman and Steed, 2009; Cox et al., 2010).

These assumptions are not always tenable in view of the endemic data scarcity in many natural resources systems. In addition, the need for advanced technologies for data collection and processing may also lead to imbalances in access, and hijacking of technologies by certain actors. At the same time, advances in technologies, such as low-cost sensing, public domain datasets and new Information and Communication Technologies (ICTs) can be leveraged to democratize data access and evidence generation. These evolutions warrant a critical re-examination of these assumptions and their implications for water resources governance, as a first step towards a more comprehensive theory that links water data, evidence, and governance explicitly.

Here, we do so by reviewing the historical evolution of water resources governance and understanding its co-evolution along with data collection and generation practices, and developing a set of criteria to be considered when evaluating the applicability of Ostrom's principles to a water resources system in which data shortages and limited institutional capacity co-exist. We introduce the case of Quito, Ecuador as an example of this challenge, especially in the area of water allocation. By highlighting the variable impact of data availability on subsequent evidence generation, these criteria will help redefine common assumptions about how to achieve water security in a developmental context, and will support the development of a more comprehensive theory about the relationships between water data, evidence, and governance.

2. Paradigms of Water Resources Governance

2.1 State-led approaches

Following Hardin (1968)'s seminal analysis of the 'tragedy of the commons', by the end of the 20th century it was well accepted that the governance of natural resources used by a common group of individuals led to the conclusion that in the absence of state or clear private control, human beings would by nature overuse and eventually deplete a given resource to maximise their own individual utility (Gardner et al., 1990; Ostrom and Nagendra, 2006).

Since Hardin's assertions, a host of governance approaches have been put forward that challenge his view. A consensus seemed to emerge amongst decision-makers and donor communities worldwide on the need to adopt an integrated, catchment-based approach as per the Dublin Principles of 1992 (Rogers et al., 2003). This consensus, building upon earlier work, led to the advocacy of the concept of Integrated Water Resources Management (IWRM), defined as a *"process which promotes the coordinated development and management of water, land and related resources, to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems"* (GWP, 2000). Based on this definition, IWRM foresees the need for multiple (often competing) water resource users to be overseen by a state-sanctioned organization; for instance, a water users' association or a catchment management board. Such organizations set rules, entry barriers and thresholds, conflict resolution mechanisms, and determine water allocation shares in addition to conducting all necessary monitoring and evaluation activities. Since its conception, the IWRM approach has been challenged by available and emerging evidence: it has been argued, for instance, that its top-down, expensive and unsustainable design makes IWRM insufficiently flexible to deal with the institutional and financial capabilities of developing countries (Merrey, 2009; Molle et al., 2010).

Privatisation has been advocated as the answer to remove the common-pool component of natural resource use, rendering each individual owner responsible for their own share (Demsetz, 1974). This process requires a centralised authority to regulate, monitor and ensure equity between all stakeholders, including the environment, which would in turn lead to better cost recovery and increased efficiency (Bakker, 2010). However, the privatisation of water resources has a mixed record, particularly in the water supply sector. One of the main issues is the limited applicability of free market rules to the water sector, as basic water demand does not strongly respond to price changes. Therefore, as the cost recovery principle is enacted and customers are unable to pay fees, water theft may increase (van der Bruggen et al., 2010). As water scarcity increases across the globe, market-based approaches to the allocation of water have been promoted in which water is priced as an economic good and water rights are traded between competing players (Garrick et al., 2009; Wang, 2018). Similar to carbon pricing tools such as cap-and-trade or revenue-neutral taxation, it is suggested that various water pricing methods could incentivise users to apply more sustainable approaches (Grafton, 2017). A well-known water market example that has created controversy is the Murray-Darling basin of Australia, set up within an IWRM context (Grafton et al., 2016; Grafton and Wheeler, 2018).

2.2 Ostrom and the 'tragedy of the commons'

Ostrom (1990) presented evidence that has since been invoked to challenge top-down, state-led approaches. She found that under a certain set of conditions, users of a given resource can successfully self-organise and manage resources more sustainably. Drawing from a large set of practical cases, Ostrom (1990) and Tang (1992) examined over 47 irrigation systems, of which 22 were government-managed and the remaining 25 farmer-managed. Whereas only 40% of government-managed irrigation systems had qualitatively high performance, over 70% of the farmer-managed systems were considered "well managed". Underlying highly performing cases, certain major design principles or best practices were found to be in use by the relevant stakeholders (Table 1; Wilson et al., 2013; Fleischman et al., 2014). Many studies have attempted to evaluate the applicability of these principles. Cox et al. (2010) reviewed 91 studies and found the design principles to be supported well by the empirical evidence. Here we explore each of the principles in turn, and the associated implicit assumptions on data availability that are needed for their successful application.

Table 1: Design principles in local common-pool resource systems and major underlying data assumptions applied to the case of water resources systems, after Ostrom (1990).

Principle	Description	Underlying data requirements
1A. User boundaries	Clear limits between non-users and users and well-defined barriers-to-entry	Technological robustness: continuous and reliable monitoring
1B. Resource boundaries	Clear physical limits to the shared resource	
2. Congruence between appropriation and provision rules and local conditions	Local settings are accounted for in the distribution of costs and benefits	Reliable monitoring Well-defined information pathways
3. Collective choice arrangements	Decision-making mechanisms and tribunes open to all users	Accessible data visualisation and translation tools
4A. Monitoring of users and resource	Monitoring of user allocation shares and provision levels at relatively low-cost	Technological robustness: continuous and reliable monitoring
4B. Local monitors	Monitors are accountable to or are the resource users	Agreement on monitoring techniques and standards
5. Graduated sanctions	Agreed-upon graduated sanctions regime to ensure accountability	Monitoring techniques able to detect cheating: amount, responsibility
6. Conflict resolution mechanisms	Agreed-upon effective and efficient conflict resolution mechanisms	Unified database standards (format, scale, measurement methods) to objectively assign responsibilities
7. Minimal recognition of right to organize	Legal recognition of right to self-organise	Legal recognition of right to monitor, access, and use data
8. Nested enterprises	Coordination between all relevant local groups situated within a broader socio-economic system	Well-defined information pathways Compatible databases (format, scale, measurement methods)

Principle 1 entails a clear definition of who has the right to abstract a given resource, as well as delimiting the boundaries of the resource system. It requires the ability to set, and, more importantly, to enforce barriers-to-entry. In a water resources system, achieving this aim involves continuously and reliably monitoring both boundaries to prevent access to non-members. Principle 2 implies the establishment of locally relevant rules that regulate benefits and costs to users, i.e. rules reflecting locally specific characteristics of a resource. For example, setting sluice gate opening times on a tertiary canal of an irrigation system to correspond to periods of high human labour availability on the dependent fields. Transparent and reliable data and information flows are key for successful coordination between users. Principle 3 refers to the inclusivity of the operational decision-making process. In order for users to comply with rules voluntarily, they must have the ability to shape them; and in order for policy-making and enforcement tribunes and mechanisms to be effective, users must be able to assimilate relevant information and interpret the data adequately, to transform it into usable and applicable evidence. Principle 4 is a key factor: Ostrom (1990) found that in most successful systems, monitors were either users or were accountable to them. Moreover, she observed a tendency to make the detection of cheating as inexpensive and as visible as possible. Ensuring that the monitoring process uses techniques (e.g. equipment types, models, precision, and accuracy) and standards acceptable to users is important to foster a sense of trust and compliance. Principles 5 and 6 are vital to design accountability structures and measures, by both sanctioning cheaters in proportion to the magnitude of their infraction, and also by creating spaces to resolve disputes effectively and efficiently. They assume that transparent monitoring tools and techniques are available that are able to detect the frequency of cheating and responsibilities, in addition to using unified database tools and standards to resolve disputes objectively. Principle 7 refers to scenarios where relevant government authorities grant minimal recognition of self-organisation rights. This principle is also presumed to include the right to monitor, access, and use data. Principle 8 has been invoked when attempting to design a large-scale, distinct governance arrangement under the banner of polycentric governance. The concept of polycentric governance refers to a scenario in which multiple interacting independent decision-making centres with different purposes, organisations, locations, at various scales cooperate for the effective and efficient management of a given resource (Andersson and Ostrom, 2008; Pahl-Wostl, 2009; Cole, 2015). In other words, a polycentric system is one in which management and governance are de facto distributed across a broad group of independent stakeholders pursuing sometimes differing and competing objectives. In such a context, well-defined information pathways, acceptable generation and collection tools and storage and transmission standards are vital. Attempts have been made to formalise this concept in water resources, although experimental in nature, via a catchment-wide polycentric governance approach (Lankford and Hepworth, 2010).

In summary, data play a vital part in any CPR governance arrangement by defining and enforcing rules around use. Ostrom's principles depend on a series of key assumptions about data availability, from generation and collection, all the way to storage and dissemination. Water resources management in Quito, Ecuador, is a typical example of a polycentric system facing a multitude of data-related challenges, especially in the area of water allocation.

While Ostrom's principles have been typically applied to smaller-scale systems, there have been attempts to generalise Ostrom's principles formally (Wilson et al., 2013) and to assess their applicability to large systems (Fleischman et al., 2014). We take this work forward here by considering the empirical case of Quito, where a multitude of actors operate independently and across scales to influence local water resources governance arrangements.

3. Case study: water allocations in the water supply system of Quito, Ecuador

Ecuador is located in the tropical Andes with approximately 16 million inhabitants, located in large part in the mountainous region of the country, where water resources face the most severe challenges (Buytaert and De Bièvre, 2012). Under United Nations (UN) population growth scenarios, the country is projected to grow by 37.7% by 2050 (United Nations, 2013). Moreover, a significantly negative impact, albeit with a very high degree of uncertainty, of climate change on mountain regions is predicted along with degradation typical of such areas such as deforestation and erosion (Viviroli et al., 2011; Gonzalez-Zeas et al., 2018). These effects are reflected in the capital city of Quito, located at roughly 2,850 m above sea level in a narrow inter-Andean valley as part of the Quito Metropolitan District (QMD). Due to the complex and steep terrain on which it was built, the city is highly vulnerable to water supply changes. Exacerbating this situation, Quito relies on water transfers from the neighbouring Amazon catchment to cover 62%, or approximately 4.5 m^3/s, of its domestic water use (Buytaert and De Bièvre, 2012). On the demand side, hydropower, water-intensive irrigation and domestic water use constitute the major water uses in and around the QMD. Surface water abstractions account for the overwhelming majority (>95%) of water use in the QMD. In the face of a highly vulnerable and uncertain supply side, there is an acute need to understand and control water demand adequately across all sectors, from appropriately quantifying and enforcing surface and groundwater allocations to implementing water efficiency measures.

The polycentric nature of the water governance arrangements in place around the QMD is manifest in the various interacting and nested layers of institutions with independence in decision making, covering a total area of approximately 6847 km^2 (Figure 1A). They range from local water resources organisations such as irrigation systems with the ability to formulate their own management rules, to high level government institutions with national decision power. The public water company of Quito (EPMAPS) manages 151 abstraction points that transmit water to 34 water treatment plants. The upstream area that provides water to these abstraction points is 2366 km^2, from which 815 km^2 are part of the National System of Protected Areas; a further

200 km^2 has been acquired by EPMAPS for conservation purposes. EPMAPS is part of a water fund, Fondo para la protección del Agua (FONAG), devised as a long-term financial mechanism that receives public and private funds from several institutional water users including hydropower generators, bottling companies, and environmental NGOs (Echavarria and Arroyo, 2012). FONAG protects the upstream water sources of the QMD by intervening in 1551 km^2 of land via conservation and restoration measures such as grazing control and wetland rehabilitation.

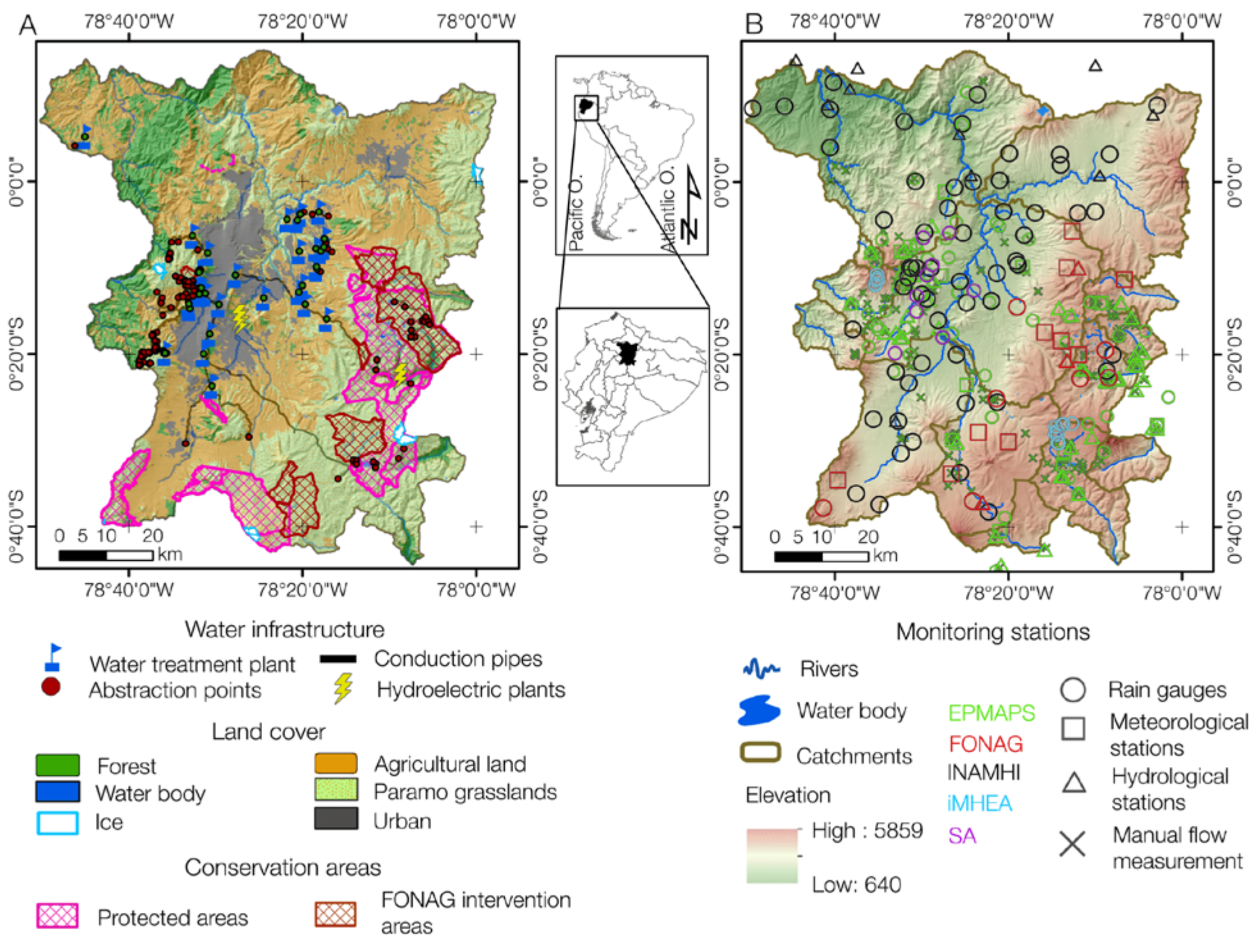

Figure 1: Polycentric system of Quito Metropolitan District (QMD) area. (A) Several institutions manage the land and water resources, where the water supply company EPMAPS is one of the main actors. (B) The hydrometeorological monitoring network in the area is one of the densest

in the Andean region, with at least five official networks and several other independent data generators.

A highly important group of users – farmers – is not involved in FONAG and is instead grouped within a large number of local self-governing water boards. Irrigation systems are clearly defined, both in spatial extent and membership, with significant room to manoeuvre in various management and governance aspects. The National Water Secretariat of Ecuador (SENAGUA) has allocated 8045 water abstraction points in the QMD; however, at present, there is no clear and sustainable methodology to enforce allocations, optimise water use, and comply with regulations such as sustaining environmental flows. SENAGUA grants each irrigation system a water allocation – typically a single value of permitted discharge into the primary canal. The water supply ratios, timings and frequencies of flows into secondary and tertiary canals both at the head and tail of the system are left to the self-governance structures that are in place. EPMAPS has the ability to enforce water abstractions unilaterally, whereby it can for example fine upstream users for exceeding their legally defined limits. Other users such as the Quito electricity company (EEQ), which depends overwhelmingly on hydropower, are also capable of monitoring user abstractions in a catchment of interest where power production requirements are at risk of not being met.

Hydrometeorological monitoring and data generation is, similarly, complex (Figure 1B). FONAG manages its own monitoring network, including dozens of weather stations, hydrometric and water quality monitoring points, biodiversity observational areas, and experimental plots. The Environment Secretary of the QMD local government (SA) also operates a set of stations mainly in the urban area, whereas EPMAPS monitor water resources affecting their abstractions. These monitoring networks have been operating in parallel with that of the National Institute for Hydrology and Meteorology (INAMHI). INAMHI is responsible for national-scale hydrometeorological monitoring to inform water resources management, climate change adaptation, and disaster risk management. INAMHI's data, although important, are not particularly useful to evaluate ecosystem services nor to analyse the impacts of interventions such as restoration, conservation, or natural infrastructure implementation. The monitoring network in the studied area comprises 44 meteorological stations, 90 rain gauge stations, 60 hydrological stations, and 226 manual hydrometric measurement points, making it one of the densest networks in the Andean region. FONAG has set up an independent network for impact evaluation as part of the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA: Ochoa-Tocachi et al., 2018). This impact monitoring constitutes the core of a programme aimed at establishing a scientific station in coordination with several local, national and international universities to measure and quantify the hydrological impact of their activities on available water quantity and quality. Many other independent institutions, such as NGOs and universities, have established short-term monitoring for small and time-limited projects. Although data generation and access are complex, there are no clear mechanisms to coordinate efforts and foster collaboration. In recent years, the aforementioned institutions coordinate their monitoring efforts more closely.

As a result of this institutional complexity, quantifying and enforcing surface and groundwater allocations, as well as implementing water efficiency measures appropriately in the QMD, faces many obstacles that could be less pronounced in a more centralised, IWRM system. In order for Ostrom's principles to apply to the QMD water resources system, the aforementioned data implications ought to be satisfied; however, there are several challenges. As stated previously, rigorously understanding the demand side of the system is a key priority; in particular, the quantification and enforcement of water abstractions by users in the QMD. To this end, SENAGUA is required to provide full accounts of the country's water availability under a new Water Resources Law passed in 2014 (AN Ecuador, 2014). Data about the natural hydrological system are already scarce; but irrigation water demand, in particular, is lacking. Abstraction licences are generally granted from user-based estimations of demand requirements and a yearly averaged streamflow value. This procedure is problematic: it does not reflect seasonal variations and precise estimations of actual water requirements developed using thorough water balance assessments.

The logistics and costs involved in monitoring and enforcing surface water and groundwater allocations adequately, as well as domestic consumption by users, pose several challenges for SENAGUA. Installing and maintaining a robust monitoring network is difficult and costly in mountain environments. Moreover, EPMAPS and the various irrigation systems in the QMD do not have the same benchmarks and procedures on collecting on water abstraction data. These problems could lead to potential judicial proceedings that challenge SENAGUA's abstraction data. Also, the dissemination of abstraction data to users is problematic, as there is no permanent ground staff, and contact with inspectors takes place only every few months in the best-case scenario. Allocation enforcement and monitoring need to happen constantly, not only over an entire hydrological season to assess availability, but over a much longer period to enforce amounts and possibly trigger behavioural change. There are multiple logistical and financial drawbacks to achieving this end. Enforcing and sanctioning of cheating is difficult due to the multiplicity of rules applicable to various systems such as upstream irrigation schemes, as well as the difficulty in clearly appropriating responsibilities for over-abstractions. In addition, certain users, such as local farmers whose entire livelihoods are dependent on agriculture, might not be amenable to the use of monitoring as a rule enforcement measure, and in certain cases have tampered with measurements to obfuscate the actual abstraction rates. In addition, SENAGUA currently do not have clear mechanisms to incorporate abstraction data adequately in their decision-making process; for instance, they do not incorporate water demand sources in the routing module of their hydrological models. Furthermore, in a polycentric system where a multitude of actors is able to conduct monitoring activities, reconciling existing databases by unifying the data format, spatio-temporal coverage and reliability is challenging (Karpouzoglou et al., 2016).

Responding to these challenges effectively involves a clear need for additional data concerning major elements in the water cycle; in particular, water allocations and actual abstractions. The applicability of Ostrom's principles to the QMD context is increasingly uncertain, as it relies on a set of implicit assumptions about the availability and use of these data, which may not always be satisfied.

4. Exploring a water data, evidence, and governance theory

4.1 The role of hydrological data in governance

The Quito case is a clear example of a water resources system with the characteristics of a socio-hydrological systems (Sivapalan et al., 2012; Blair and Buytaert, 2016; Mao et al., 2017). Governing and managing such systems sustainably requires objective and independent monitoring of the major variables that define supply and demand, such as precipitation, discharge and bulk abstractions. Measuring these parameters has historically required expensive and technologically sophisticated equipment (Buytaert et al., 2016). The emergence of alternative, low-cost options, for example devices connected to the Internet of Things, could empower a broader range of stakeholders to conduct such measurements much more extensively (Gubbi et al., 2013).

In a polycentric scenario, implementing each of Ostrom's principles implicitly relies on a series of key assumptions about the monitoring process (Table 1). These assumptions can be divided into five facets: data generation, collection, storage, transmission and communication, use and application as evidence (Mol, 2006). Enforcing resource and user boundaries in the case of a non-exclusive resource such as water is challenging, requiring at minimum a highly robust abstraction monitoring network. In addition, devising locally compatible usage rules requires a good understanding of system processes and trends, which may in turn necessitate the presence of continuous, long-term monitoring. Implementing user and resource monitoring in a polycentric system is more complex. In the case of IWRM, the catchment-wide regulator typically has a clear legal responsibility to conduct all monitoring activities; for instance, to enforce water allocation shares and to characterise the overall water resource state for infrastructure planning and system optimisation purposes (Buytaert et al., 2016). Hence, data are usually concentrated amongst a few select institutions, which may negatively affect the flow, availability, and quality of knowledge amongst stakeholders. However, where multiple governance layers starting from the self-organised systems interact independently, it is often unclear how the legal right to monitor is attributed to given institutions or entities. In addition, hydrological evidence may play a different role; for instance, to support informal ad-hoc negotiation process in conflict resolution mechanisms. In such systems, the decentralised nature of decision-making renders data highly distributed amongst stakeholders (Lankford and Hepworth, 2010). Therefore, properties such as access to information and the trust and credibility of information sources play a much more prominent role in the decision-making process. However, as a consequence of this data distribution, multiple databases may be formed, with varying levels of technical reliability and completeness (e.g. format, spatio-temporal scale, measurement methods, accuracy, precision, collection, storage, and transmission protocols). In such a context, unless clear information dissemination incentives and pathways are in place to unify and standardise these databases, a number of different perceptions of the human-water system state may emerge. Furthermore, data quality and reliability can also be highly variable: additional data does not necessarily imply better outcomes in a scenario where actors do not hold sufficient trust in the evidence presented to them. Also, in relation to the aforementioned dynamics, stakeholder topologies in water resource systems are generally highly heterogeneous: stakeholders have varying interests and socio-economic incentives, depending on the importance of their water abstraction allocation volume as a proportion of their total income. Political imbalances between stakeholders could greatly affect the effectiveness of any monitoring activity, by skewing the results to a specific agenda and disrupting the applicability of general governance procedures. In addition, increased monitoring in order to ensure rule compliance, transparency and accountability by making cheating 'visible' to other stakeholders is inherently difficult in water resources (Cox, 2010). Surface water over-abstraction, for instance, is not easily observable and attributable.

4.2 Criteria to assess the water data, evidence and governance dynamic

While water data management and governance have been examined previously and best practice guidelines developed (Australia Bureau of Meteorology, 2017), such evaluations and recommendations have not been conducted as far as the broader role of data within the governance process is concerned. By combining our review of governance paradigms with our analysis of the case study of Quito, we now attempt to generalise our findings into a set of generic criteria that support an explicit analysis and assessment of the potentially complex and multi-layered relationship between Ostrom's governance principles, data and evidence in a given water resources system. The criteria are intended as a best-practice guide of how to integrate data within existing water resources governance arrangements and processes in a specific case study. The criteria are visually summarised in Figure 2.

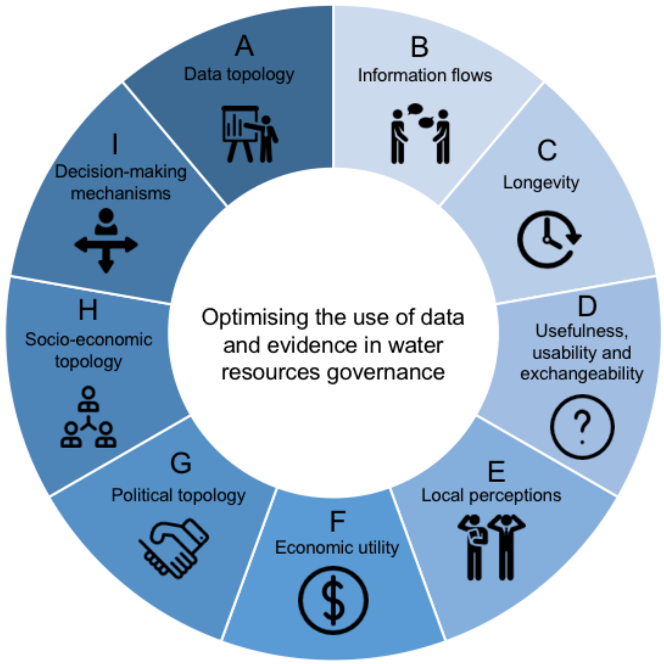

Figure 2: Criteria identified in this study to optimise the use of observational data and scientific evidence in water resources governance.

A. Data topology:

A transparent topology of the monitoring process is needed to understand the dynamics of how data are generated, collected, stored, and applied. This process is necessary to make stakeholders aware of their rights and responsibilities.

B. Information flows and communication channels in place:

A clear set of pathways to disseminate and potentially merge generated data is required. Also, emerging monitoring technologies increasingly have a wide variety of generation, collection, storage and dissemination protocols. A set of agreed-upon database standards is therefore needed, including measurement techniques, minimal acceptable formats and standards. These standards are needed to prevent the potential divergence in perceptions of the state and dynamics of the water resource system and subsequent strategies.

C. Longevity of hydrological data:

As hydrological processes often involve long timescales, monitoring activities and maintenance of databases both need to be sustainable. As factors such as climate and demographic change become more pronounced, temporal stationarity cannot be assumed (Milly et al., 2008).

D. Usefulness, usability, and exchangeability of data:

It is desirable to maintain monitoring networks in line with the needs of the local communities involved in the water resource system. Stakeholders should be able to assimilate, visualise, and exchange the collected data.

E. Understanding actual data gaps as perceived by system stakeholders:

Even though technology will allow increasing monitoring efforts to take place, any such activity should be in line with a clearly defined and agreed-upon strategy and objectives amongst stakeholders. Moreover, understanding local perceptions, even if unjustified, is key to fostering trust and capturing varying narratives about the functioning of the system, which in turn is important to understand the way in which data are mobilised in the process of evidence generation.

F. Economic and financial utility of monitoring:

Being able to calculate the return-on-investment obtained from a given monitoring activity allows stakeholders to direct financial resources strategically for relevant purposes. Furthermore, presenting quantified benefits helps users to accept such activities.

G. Political topology:

Accounting for broader political forces and power distributions is evidently key when considering the general dynamic of data and governance. In water resource systems, stakeholders should set and independently enforce transparent and well-defined legal constraints on the right to monitor, access, and use data in the midst of technological changes.

H. Socio-economic topology:

The inclusion of broader socio-economic forces is desirable to capture potential discrepancies in the incentives of various stakeholders to participate in a given governance system. Whilst Ostrom (1990) assumed socio-economically homogeneous users in the systems she observed, disparities may appear and be exacerbated by increased data generation capabilities. For instance, a user whose livelihood depends entirely on water abstractions might, given more readily available sensing techniques, pursue a contingent strategy, contrary to group interests.

I. Decision-making mechanisms in place:

Finally, as stated previously, the monitoring process is comprised of data generation, collection, storage, dissemination, and use as evidence. In the final step, it is vital to describe both the technical methods, e.g. computer software, and the policy tools, e.g. user group meetings, to understand the way in which evidence is utilised.

The impact of technology on governance is having and will continue to have profound repercussions across all sectors of society, which are embedded in the general notion of informational governance, where this new topology of data access can shape, and potentially transform, broader and deeper societal arrangements (Mol, 2006). In the area of natural resource governance, technology is increasingly enabling a wider range of users to conduct their own monitoring activities. Data enable the understanding of impacts, internal processes, and outcomes within any system. The monitoring process makes it possible to use data as evidence to provide a factual basis for the best possible decision to be made. However, increased data can either lead to exclusive management and control, or chaos and incoherence in extreme cases, as users mobilise the resulting evidence in service of a specific agenda. The implications of this dynamic on the applicability of Ostrom's polycentric governance principles therefore need to be interrogated. Potentially large discrepancies and disparities between users as a result of increased but unequal technological access could affect socio-economic and political balances within a water resource system of interest. The development of traditional water resource governance theories to accompany these trends is needed for an all-encompassing data, evidence, and governance theory.

5. Conclusions and Outlook

Understanding and characterising the traditional relationships between data, evidence, and governance are critical to achieving sustainable water resource use. Nowhere is this more relevant than in polycentric water resource systems. Characterising the water cycle is becoming more critical than ever, as water scarcity increases and more optimal and sustainable use is pursued.

Hydrological data remain limited across the globe, but various technological developments and low-cost tools are changing these limitations, encouraging greater non-scientist participation in data collection and analysis (Paul et al., 2018). Given these developments, a critical re-examination of the underlying data implications of Ostrom's CPR governance principles is vitally important. Using the example of a polycentric water resource system in Quito, Ecuador, we have shown how several factors, including but not limited to technological changes, are placing strain upon this relationship. In order to overcome such potential limitations, we have developed and described a set of criteria to be used when assessing the broader implications of monitoring on the governance dynamics of a given water resource system.

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