

## Exploring a water data, evidence, and governance theory

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# 1 Exploring a water data, evidence, and governance theory

2

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15

## 16 **Abstract**

17

18 The hydrological evidence on which water resource management and broader governance

19 decisions are based is often very limited. This issue is especially pronounced in lower- and

20 middle-income countries, where not only data are scarce but where pressure on water

21 resources is often already very high and increasing. Historically, several governance theories

22 have been put forward to examine water resource management. One of the more influential is

23 Elinor Ostrom's theory of common-pool resources. However while used very widely, the

24 underlying principles of Ostrom's approach make pronounced implicit assumptions about the

25 role of data and evidence in common-pool resource systems. We argue here this overlooks how  
26 power relations, user characteristics, system arrangements, and technological advances  
27 modulate fundamental associations between data, evidence, and governance, which we  
28 contend need to be considered explicitly. Examining the case of water allocations in Quito,  
29 Ecuador, we develop a set of concrete criteria to inform the ways in which Ostrom's principles  
30 can be applied in a data-scarce, institutionally complex, polycentric context. By highlighting the  
31 variable impact of data availability on subsequent evidence generation, these criteria have the  
32 potential to test the applicability of common assumptions about how to achieve water security in  
33 a developmental context, and hence offer the possibility of developing a more encompassing  
34 theory about the interactions between water data, evidence, and governance.

35

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

38

### 39 **Highlights**

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

43

### 44 **1. Introduction**

45

46 The lack of knowledge about the physical state of water resources due to limited  
47 measurements, and a lack of institutional and technical capacity, are exacerbating the multitude  
48 of challenges faced by water managers across the globe (Hannah et al., 2011; Garrick et al.,  
49 2017). In light of this situation, current presumptions about water resources governance –in

50 particular, the relationship between data, evidence, and decision-making in this process— should  
51 be re-examined. Within a decision-making context, *data* can be considered as the result of an  
52 observational process, supported by in-situ or remote sensing technologies. These data are  
53 shaped by stakeholders into *evidence*, i.e., a body of facts and information supporting the  
54 validity of an idea. The process of shaping data into evidence is heavily dependent on the  
55 broader governance arrangements within a given context that service a particular objective.  
56 Such arrangements define rules surrounding data generation, collection, ownership, storage  
57 and dissemination followed by use in decision-making.

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

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

74 These assumptions are not always tenable in view of the endemic data scarcity in many natural  
75 resources systems. In addition, the need for advanced technologies for data collection and

76 processing may also lead to imbalances in access, and hijacking of technologies by certain  
77 actors. At the same time, advances in technologies, such as low-cost sensing, public domain  
78 datasets and new Information and Communication Technologies (ICTs) can be leveraged to  
79 democratize data access and evidence generation. These evolutions warrant a critical re-  
80 examination of these assumptions and their implications for water resources governance, as a  
81 first step towards a more comprehensive theory that links water data, evidence, and governance  
82 explicitly.

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

93

94

## 95 **2. Paradigms of Water Resources Governance**

96

### 97 **2.1 State-led approaches**

98 Following Hardin (1968)'s seminal analysis of the 'tragedy of the commons', by the end of the  
99 20<sup>th</sup> century it was well accepted that the governance of natural resources used by a common  
100 group of individuals led to the conclusion that in the absence of state or clear private control,

101 human beings would by nature overuse and eventually deplete a given resource to maximise  
102 their own individual utility (Gardner et al., 1990; Ostrom and Nagendra, 2006).

103 Since Hardin's assertions, a host of governance approaches have been put forward that  
104 challenge his view. A consensus seemed to emerge amongst decision-makers and donor  
105 communities worldwide on the need to adopt an integrated, catchment-based approach as per  
106 the Dublin Principles of 1992 (Rogers et al., 2003). This consensus, building upon earlier work,  
107 led to the advocacy of the concept of Integrated Water Resources Management (IWRM),  
108 defined as a "*process which promotes the coordinated development and management of water,*  
109 *land and related resources, to maximise the resultant economic and social welfare in an*  
110 *equitable manner without compromising the sustainability of vital eco-systems*" (GWP, 2000).  
111 Based on this definition, IWRM foresees the need for multiple (often competing) water resource  
112 users to be overseen by a state-sanctioned organization; for instance, a water users'  
113 association or a catchment management board. Such organizations set rules, entry barriers and  
114 thresholds, conflict resolution mechanisms, and determine water allocation shares in addition to  
115 conducting all necessary monitoring and evaluation activities. Since its conception, the IWRM  
116 approach has been challenged by available and emerging evidence: it has been argued, for  
117 instance, that its top-down, expensive and unsustainable design makes IWRM insufficiently  
118 flexible to deal with the institutional and financial capabilities of developing countries (Merrey,  
119 2009; Molle et al., 2010).

120 Privatisation has been advocated as the answer to remove the common-pool component of  
121 natural resource use, rendering each individual owner responsible for their own share  
122 (Demsetz, 1974). This process requires a centralised authority to regulate, monitor and ensure  
123 equity between all stakeholders, including the environment, which would in turn lead to better  
124 cost recovery and increased efficiency (Bakker, 2010). However, the privatisation of water  
125 resources has a mixed record, particularly in the water supply sector. One of the main issues is  
126 the limited applicability of free market rules to the water sector, as basic water demand does not

127 strongly respond to price changes. Therefore, as the cost recovery principle is enacted and  
128 customers are unable to pay fees, water theft may increase (van der Bruggen et al., 2010). As  
129 water scarcity increases across the globe, market-based approaches to the allocation of water  
130 have been promoted in which water is priced as an economic good and water rights are traded  
131 between competing players (Garrick et al., 2009; Wang, 2018). Similar to carbon pricing tools  
132 such as cap-and-trade or revenue-neutral taxation, it is suggested that various water pricing  
133 methods could incentivise users to apply more sustainable approaches (Grafton, 2017). A well-  
134 known water market example that has created controversy is the Murray-Darling basin of  
135 Australia, set up within an IWRM context (Grafton et al., 2016; Grafton and Wheeler, 2018).

136

## 137 2.2 Ostrom and the ‘tragedy of the commons’

138 Ostrom (1990) presented evidence that has since been invoked to challenge top-down, state-  
139 led approaches. She found that under a certain set of conditions, users of a given resource can  
140 successfully self-organise and manage resources more sustainably. Drawing from a large set of  
141 practical cases, Ostrom (1990) and Tang (1992) examined over 47 irrigation systems, of which  
142 22 were government-managed and the remaining 25 farmer-managed. Whereas only 40% of  
143 government-managed irrigation systems had qualitatively high performance, over 70% of the  
144 farmer-managed systems were considered “well managed”. Underlying highly performing cases,  
145 certain major design principles or best practices were found to be in use by the relevant  
146 stakeholders (Table 1; Wilson et al., 2013; Fleischman et al., 2014). Many studies have  
147 attempted to evaluate the applicability of these principles. Cox et al. (2010) reviewed 91 studies  
148 and found the design principles to be supported well by the empirical evidence. Here we explore  
149 each of the principles in turn, and the associated implicit assumptions on data availability that  
150 are needed for their successful application.

151

152

153 Table 1: Design principles in local common-pool resource systems and major underlying data  
 154 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 tribunals 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)

155

156



157 Principle 1 entails a clear definition of who has the right to abstract a given resource, as well as  
158 delimiting the boundaries of the resource system. It requires the ability to set, and, more  
159 importantly, to enforce barriers-to-entry. In a water resources system, achieving this aim  
160 involves continuously and reliably monitoring both boundaries to prevent access to non-  
161 members. Principle 2 implies the establishment of locally relevant rules that regulate benefits  
162 and costs to users, i.e. rules reflecting locally specific characteristics of a resource. For  
163 example, setting sluice gate opening times on a tertiary canal of an irrigation system to  
164 correspond to periods of high human labour availability on the dependent fields. Transparent  
165 and reliable data and information flows are key for successful coordination between users.  
166 Principle 3 refers to the inclusivity of the operational decision-making process. In order for users  
167 to comply with rules voluntarily, they must have the ability to shape them; and in order for policy-  
168 making and enforcement tribunals and mechanisms to be effective, users must be able to  
169 assimilate relevant information and interpret the data adequately, to transform it into usable and  
170 applicable evidence. Principle 4 is a key factor: Ostrom (1990) found that in most successful  
171 systems, monitors were either users or were accountable to them. Moreover, she observed a  
172 tendency to make the detection of cheating as inexpensive and as visible as possible. Ensuring  
173 that the monitoring process uses techniques (e.g. equipment types, models, precision, and  
174 accuracy) and standards acceptable to users is important to foster a sense of trust and  
175 compliance. Principles 5 and 6 are vital to design accountability structures and measures, by  
176 both sanctioning cheaters in proportion to the magnitude of their infraction, and also by creating  
177 spaces to resolve disputes effectively and efficiently. They assume that transparent monitoring  
178 tools and techniques are available that are able to detect the frequency of cheating and  
179 responsibilities, in addition to using unified database tools and standards to resolve disputes  
180 objectively. Principle 7 refers to scenarios where relevant government authorities grant minimal  
181 recognition of self-organisation rights. This principle is also presumed to include the right to  
182 monitor, access, and use data. Principle 8 has been invoked when attempting to design a large-

183 scale, distinct governance arrangement under the banner of polycentric governance. The  
184 concept of polycentric governance refers to a scenario in which multiple interacting independent  
185 decision-making centres with different purposes, organisations, locations, at various scales  
186 cooperate for the effective and efficient management of a given resource (Andersson and  
187 Ostrom, 2008; Pahl-Wostl, 2009; Cole, 2015). In other words, a polycentric system is one in  
188 which management and governance are de facto distributed across a broad group of  
189 independent stakeholders pursuing sometimes differing and competing objectives. In such a  
190 context, well-defined information pathways, acceptable generation and collection tools and  
191 storage and transmission standards are vital. Attempts have been made to formalise this  
192 concept in water resources, although experimental in nature, via a catchment-wide polycentric  
193 governance approach (Lankford and Hepworth, 2010).

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

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

204

205

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

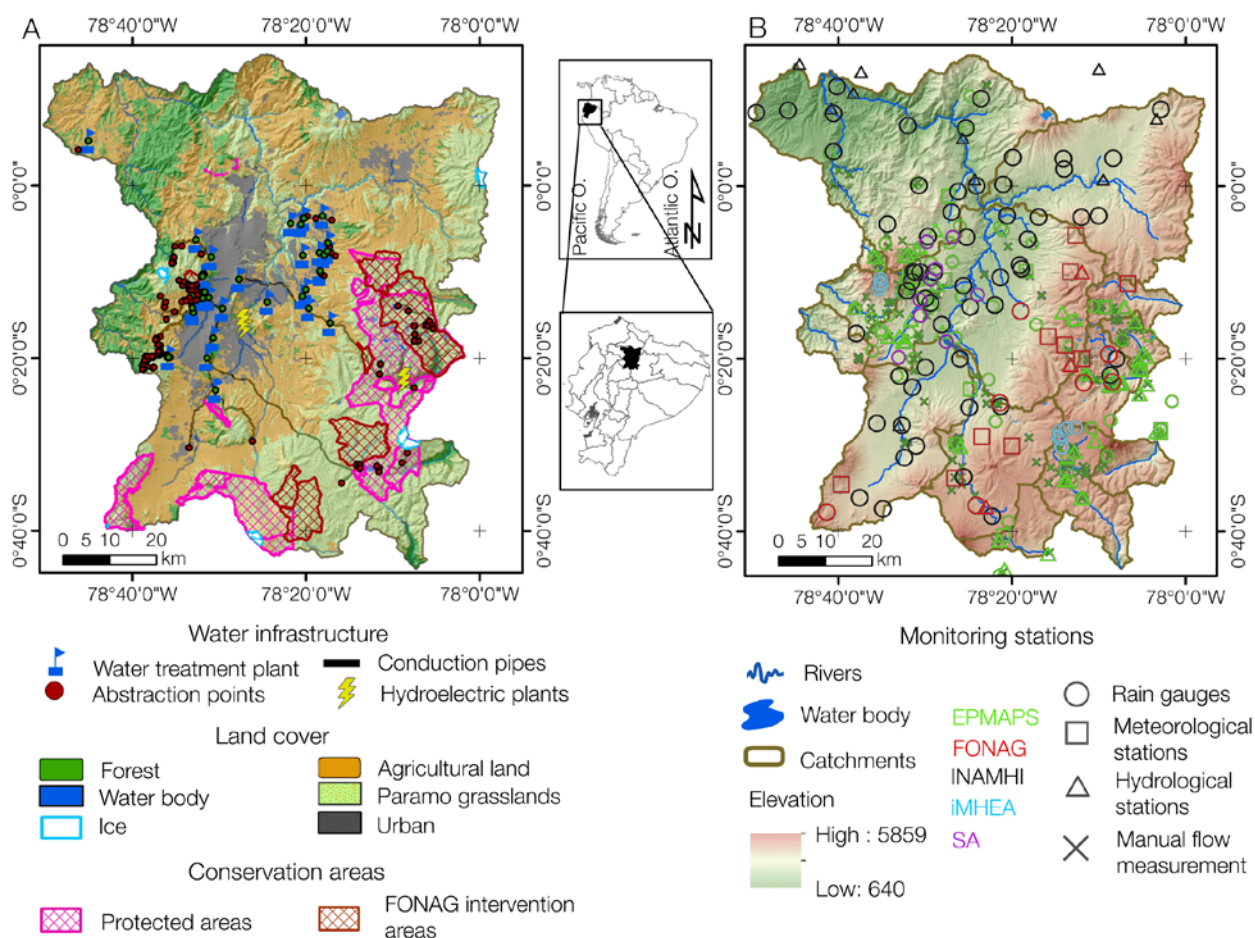
207

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

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

234 200 km<sup>2</sup> has been acquired by EPMAPS for conservation purposes. EPMAPS is part of a water  
 235 fund, Fondo para la protección del Agua (FONAG), devised as a long-term financial mechanism  
 236 that receives public and private funds from several institutional water users including  
 237 hydropower generators, bottling companies, and environmental NGOs (Echavarría and Arroyo,  
 238 2012). FONAG protects the upstream water sources of the QMD by intervening in 1551 km<sup>2</sup> of  
 239 land via conservation and restoration measures such as grazing control and wetland  
 240 rehabilitation.

241



242 Figure 1: Polycentric system of Quito Metropolitan District (QMD) area. (A) Several institutions  
 243 manage the land and water resources, where the water supply company EPMAPS is one of the  
 244 main actors. (B) The hydrometeorological monitoring network in the area is one of the densest  
 245

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

248

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

264 Hydrometeorological monitoring and data generation is, similarly, complex (Figure 1B). FONAG  
265 manages its own monitoring network, including dozens of weather stations, hydrometric and  
266 water quality monitoring points, biodiversity observational areas, and experimental plots. The  
267 Environment Secretary of the QMD local government (SA) also operates a set of stations mainly  
268 in the urban area, whereas EPMAPS monitor water resources affecting their abstractions.  
269 These monitoring networks have been operating in parallel with that of the National Institute for  
270 Hydrology and Meteorology (INAMHI). INAMHI is responsible for national-scale

271 hydrometeorological monitoring to inform water resources management, climate change  
272 adaptation, and disaster risk management. INAMHI's data, although important, are not  
273 particularly useful to evaluate ecosystem services nor to analyse the impacts of interventions  
274 such as restoration, conservation, or natural infrastructure implementation. The monitoring  
275 network in the studied area comprises 44 meteorological stations, 90 rain gauge stations, 60  
276 hydrological stations, and 226 manual hydrometric measurement points, making it one of the  
277 densest networks in the Andean region. FONAG has set up an independent network for impact  
278 evaluation as part of the Regional Initiative for Hydrological Monitoring of Andean Ecosystems  
279 (iMHEA: Ochoa-Tocachi et al., 2018). This impact monitoring constitutes the core of a  
280 programme aimed at establishing a scientific station in coordination with several local, national  
281 and international universities to measure and quantify the hydrological impact of their activities  
282 on available water quantity and quality. Many other independent institutions, such as NGOs and  
283 universities, have established short-term monitoring for small and time-limited projects. Although  
284 data generation and access are complex, there are no clear mechanisms to coordinate efforts  
285 and foster collaboration. In recent years, the aforementioned institutions coordinate their  
286 monitoring efforts more closely.

287 As a result of this institutional complexity, quantifying and enforcing surface and groundwater  
288 allocations, as well as implementing water efficiency measures appropriately in the QMD, faces  
289 many obstacles that could be less pronounced in a more centralised, IWRM system. In order for  
290 Ostrom's principles to apply to the QMD water resources system, the aforementioned data  
291 implications ought to be satisfied; however, there are several challenges. As stated previously,  
292 rigorously understanding the demand side of the system is a key priority; in particular, the  
293 quantification and enforcement of water abstractions by users in the QMD. To this end,  
294 SENAGUA is required to provide full accounts of the country's water availability under a new  
295 Water Resources Law passed in 2014 (AN Ecuador, 2014). Data about the natural hydrological  
296 system are already scarce; but irrigation water demand, in particular, is lacking. Abstraction

297 licences are generally granted from user-based estimations of demand requirements and a  
298 yearly averaged streamflow value. This procedure is problematic: it does not reflect seasonal  
299 variations and precise estimations of actual water requirements developed using thorough water  
300 balance assessments.

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

322 unifying the data format, spatio-temporal coverage and reliability is challenging (Karpouzoglou  
323 et al., 2016).

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

329

330

#### 331 **4. Exploring a water data, evidence, and governance theory**

332

##### 333 **4.1 The role of hydrological data in governance**

334 The Quito case is a clear example of a water resources system with the characteristics of a  
335 socio-hydrological systems (Sivapalan et al., 2012; Blair and Buytaert, 2016; Mao et al., 2017).

336 Governing and managing such systems sustainably requires objective and independent  
337 monitoring of the major variables that define supply and demand, such as precipitation,  
338 discharge and bulk abstractions. Measuring these parameters has historically required  
339 expensive and technologically sophisticated equipment (Buytaert et al., 2016). The emergence  
340 of alternative, low-cost options, for example devices connected to the Internet of Things, could  
341 empower a broader range of stakeholders to conduct such measurements much more  
342 extensively (Gubbi et al., 2013).

343 In a polycentric scenario, implementing each of Ostrom's principles implicitly relies on a series  
344 of key assumptions about the monitoring process (Table 1). These assumptions can be divided  
345 into five facets: data generation, collection, storage, transmission and communication, use and  
346 application as evidence (Mol, 2006). Enforcing resource and user boundaries in the case of a  
347 non-exclusive resource such as water is challenging, requiring at minimum a highly robust



348 abstraction monitoring network. In addition, devising locally compatible usage rules requires a  
349 good understanding of system processes and trends, which may in turn necessitate the  
350 presence of continuous, long-term monitoring. Implementing user and resource monitoring in a  
351 polycentric system is more complex. In the case of IWRM, the catchment-wide regulator  
352 typically has a clear legal responsibility to conduct all monitoring activities; for instance, to  
353 enforce water allocation shares and to characterise the overall water resource state for  
354 infrastructure planning and system optimisation purposes (Buytaert et al., 2016). Hence, data  
355 are usually concentrated amongst a few select institutions, which may negatively affect the flow,  
356 availability, and quality of knowledge amongst stakeholders. However, where multiple  
357 governance layers starting from the self-organised systems interact independently, it is often  
358 unclear how the legal right to monitor is attributed to given institutions or entities. In addition,  
359 hydrological evidence may play a different role; for instance, to support informal ad-hoc  
360 negotiation process in conflict resolution mechanisms. In such systems, the decentralised  
361 nature of decision-making renders data highly distributed amongst stakeholders (Lankford and  
362 Hepworth, 2010). Therefore, properties such as access to information and the trust and  
363 credibility of information sources play a much more prominent role in the decision-making  
364 process. However, as a consequence of this data distribution, multiple databases may be  
365 formed, with varying levels of technical reliability and completeness (e.g. format, spatio-temporal  
366 scale, measurement methods, accuracy, precision, collection, storage, and transmission  
367 protocols). In such a context, unless clear information dissemination incentives and pathways  
368 are in place to unify and standardise these databases, a number of different perceptions of the  
369 human-water system state may emerge. Furthermore, data quality and reliability can also be  
370 highly variable: additional data does not necessarily imply better outcomes in a scenario where  
371 actors do not hold sufficient trust in the evidence presented to them. Also, in relation to the  
372 aforementioned dynamics, stakeholder topologies in water resource systems are generally  
373 highly heterogeneous: stakeholders have varying interests and socio-economic incentives,

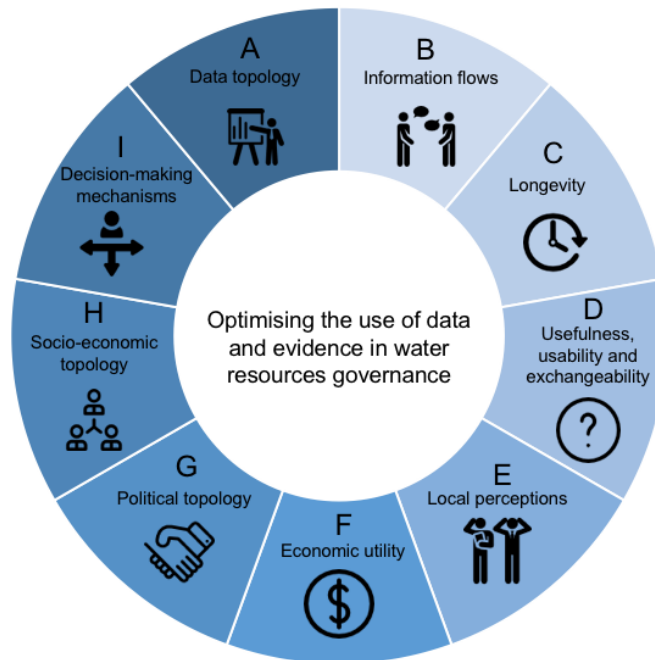
374 depending on the importance of their water abstraction allocation volume as a proportion of their  
375 total income. Political imbalances between stakeholders could greatly affect the effectiveness of  
376 any monitoring activity, by skewing the results to a specific agenda and disrupting the  
377 applicability of general governance procedures. In addition, increased monitoring in order to  
378 ensure rule compliance, transparency and accountability by making cheating 'visible' to other  
379 stakeholders is inherently difficult in water resources (Cox, 2010). Surface water over-  
380 abstraction, for instance, is not easily observable and attributable.

381

#### 382 4.2 Criteria to assess the water data, evidence and governance dynamic

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

393



394

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

397

398 A. Data topology:

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

402

403 B. Information flows and communication channels in place:

404 A clear set of pathways to disseminate and potentially merge generated data is required.  
 405 Also, emerging monitoring technologies increasingly have a wide variety of generation,  
 406 collection, storage and dissemination protocols. A set of agreed-upon database  
 407 standards is therefore needed, including measurement techniques, minimal acceptable  
 408 formats and standards. These standards are needed to prevent the potential divergence

409 in perceptions of the state and dynamics of the water resource system and subsequent  
410 strategies.

411

412 C. Longevity of hydrological data:

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

417

418 D. Usefulness, usability, and exchangeability of data:

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

422

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

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

430

431 F. Economic and financial utility of monitoring:

432 Being able to calculate the return-on-investment obtained from a given monitoring  
433 activity allows stakeholders to direct financial resources strategically for relevant

434 purposes. Furthermore, presenting quantified benefits helps users to accept such  
435 activities.

436

437 G. Political topology:

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

443

444 H. Socio-economic topology:

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

452

453 I. Decision-making mechanisms in place:

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

458

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

475

476

## 477 **5. Conclusions and Outlook**

478

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

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

493

494

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508

509

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