Can a Water Smart Grid Help Society Achieve the Sustainable Development Goal of Water as a Human Right?

A-A D. Jones, III[a,*]

[a] *Department of Chemical Engineering, Northeastern University, Boston, MA 02115, USA*

Abstract

In the spirit of measuring what we care about, the UN Sustainable Development Goals (SDGs) provide guidelines to measure "universal and equitable access to safe and affordable drinking water for all." In this work, I show where permanent or semi-permanent, autonomous or semi-autonomous technologies (objects, not processes) can measure and induce progress toward those goals and where they cannot. To do this, I apply the Institutional Analysis and Development Framework to each of the seven normative definitions from the SDGs as "action arenas." For each normative definition, I examine if technologies exist or can be created to effect a positive outcome for consumers in that particular action arena using nine evaluative criteria. This analysis is applied to the United States as a case study considering its physical systems, regulations, and governance structures. This work, combined with efforts to translate the United States' systems and structures, can lead to multinational applicability. This paper examines how and when a water smart grid can and cannot be used effectively. I conclude that the material artifacts of a water smart grid can advance the SDG of safety and affordability. However, technology alone cannot assign people to jurisdictions, limiting its ability to advance goals of universal and equitable access.

Keywords: Water Smart Grid, UN Sustainable Development Goals, Sensor Technology

*Corresponding author
Email address: A.Jones@Northeastern.edu (A-A D. Jones, III)

1. Introduction

A human right is an essential thing that needs to be protected and guaranteed, though not necessarily provided, by the state [1]. If our global society ambitions are reflected by the actions of the United Nations, we have declared water a human right [2]. In other words, we care about water. We should measure what we care about to induce positive outcomes [3]. In the spirit of caring about human rights, the United Nations has put forth Millennium and Sustainable Development Goals (MDGs and SDGs) providing guidelines to measure "universal and equitable access to safe and affordable drinking water for all."[4] While 147 countries achieved the MDG for drinking water, the SDGs are designed to set goals for human rights in all countries [5]. SDGs address problems of providing safe drinking water at a global scale, applicable in the cases of water issues in Flint, Michigan in the United States and around the world [6]. Thus, policy makers and providers will have to design, implement, maintain, and improve water sourcing, treatment, delivery, and payment specific to every location to meet the SDGs, a particular challenge in the face of changing climate and economics. During design, is it possible to "measure twice and cut once" to create these systems as efficiently and in as timely a fashion as possible?

The guidelines for measuring progress toward the SDG goal for water recommend using household or institutional surveys [4]. Surveys report an individual's "perception of service", which can over or under estimate "performance of service" [7, 8, 9]. Furthermore, surveys are limited in geographic and chronographic scope: surveys measure where a user interacted with the service at the time the survey was taken rather than overall state of the service. For example, the United States Geological Services (USGS) survey of US water systems comes out once every 5 years and is missing data from many public water suppliers in addition to data from domestic self-suppliers [10]. Increasing geographic and chronographic scope is limited by the cost of increasing survey frequency; labor required to take and adminster surveys; costs of designing surveys; incentives and other methods of increasing response; and by willingness of participants to respond [11]. Responses to survey questions are influenced by the membership of the surveyor, the phrasing of the question, and interpretation of response [12, 13].

However, surveys also assess what matters in the provision of a necessity like water: fundamentally, whether a person's needs are being met. The medical profession is coming to terms with the idea that the patient can significantly contribute to the diagnostic process [14]. At present, water consumers and health care providers can be aware that something is wrong in a water system, in real time [15]. People and surveys may continue to have a use beyond what technology can achieve. Furthermore, surveys provide room for interpretation, nuance, and variability in response, which, while a technical challenge to interpret and compare across time, can provide valuable insight to needs that may otherwise go unmet.

Technological solutions are alternative options or strong complements to traditional surveys that increase reporting frequency, reduce manpower, reduce costs, and bypass the limitations of human observational skills and willingness. Technology would be deployed in a water smart grid which is proposed as a necessary solution to water shortages in the United States [16]. It is hypothesized that by following the example of electrical smart grids, water provision could develop similar distribution efficiency. Electrical smart grids are proposed solutions including but not limited to smart meters, distributed production, sensors and controls, and machine learning that can dynamically adjust electrical production and transmission to dynamically reduce stress and downtime on the grid [17]. However, there are crucial differences between water and electricity. Water is a human right and faces provision requirements, regulations, and public pressures unseen by electricity; water is generally not a distributed resource; and water generally cannot be "shut-off or shunted" for safety reasons [18]. The "smart" in smart grid refers to autonomous engineered systems that provide two-way information flow, allowing consumers to adjust use to costs and failures in the system; for example, water meters that give hourly usage data to consumers and providers, instead of monthly meter reading by a human. Furthermore, it refers to systems that can learn, adjust, and alert; for example, suites of pressure and flow sensors that can determine when heavy flow is a leak and not simply heavy use and reroute flow automatically [19]. Similar to the electrical smart grid, the water smart grid is also far from being employed, both due to the absence of technology and, more significantly, the absence of appropriate field testing environments for testing components of these critical infrastructures [19, 16].

For the purposes of this study, the term "technology" will be used to describe permanent or semi-permanent, engineered, autonomous or semi-autonomous systems. The terms permanent or semi-permanent are used to distinguish devices designed to be deployed and later recovered for a study period from those designed to be left in the field until they need to be replaced. Autonomous and semi-autonomous are defined as manmade devices that interact with a part of their environment without the interaction of a human aside from infrequent maintenance. This definition focuses on the material artifact, not the "operational sequences, verbal and non-verbal skills" that make up a technique or the sociotechnical systems [20]. This definition is in line with common use and evoked imagery of the word. This will hopefully skirt confusion and misuse found even in critique of the word's use in academic literature [20]. I separate the material artifact aspect of technology from its institutional knowledge and behavioral aspects in order to analyze the notion that "it is easier to change technology than to change behavior, and it is more difficult to determine cultural acceptability than technical feasibility" [21]. Furthermore, technology is one of the four dimensions of water identified by the UN Centre for Human Settlements, along with administration, financial, and economic management.

I will analyze if existing and developing technology can accurately measure and induce progress toward the SDGs as compared to traditional survey methods. Furthermore, in this investigation I aim to determine whether technology can effectuate sustainability outcomes. The physical systems, regulations, and governance structures that constrain this study are domestic systems in the United States. The analysis, framework, and conclusions may apply to a wider range of systems.

2. Theoretical Framework

I will perform a theoretical analysis using the Institutional Analysis and Development Framework (Figure 1) to analyze whether existing and developing technology can accurately measure and induce progress toward the SDGs[22]. The action arenas will cover interactions within the home, neighborhood, local, regional, and national levels. The participants in this action arena are stakeholders who move in and out of positions as consumers, providers, regulators, activists, elected officials, engineers, economists, and health care providers. For example, a stakeholder can both consume and provide water via a well on their land using a system they engineered themselves. The technologies are the linkages between participants and the SDG of providing "universal and equitable access to safe and affordable drinking water for all." The action situations are the normative definitions of the SDG, as shown in Table 1.

Table 1: Reprinted in Entirety from SDG Methodological Note Target 6.1[4]

Target language	Normative definitions of target elements
6.1 - By 2030, achieve	
universal	Implies all exposures and settings, including households, schools, health facilities, workplaces, etc.
and equitable	Implies progressive reduction and elimination of inequalities between population subgroups
access	Implies sufficient water to meet domestic needs is reliably available close to home
to safe	Safe drinking water is free from pathogens and elevated levels of toxic chemicals at all times
and affordable	Payment for services does not present a barrier to access or prevent people meeting other basic human needs
drinking water	Water used for drinking, cooking, food preparation, and personal hygiene
for all.	Suitable for use by men, women, girls, and boys of all ages, including people living with disabilities

For each normative definition, I will examine if technologies exist or can be made to effect a positive outcome for consumers in that particular action situation. Exogenous variables to this analysis include the overall existence of water and climate change. These two variables are linked, since climate change induces shifts in total water available at low energy cost, and as water becomes less available at low energy, extraction using energy-intensive means may impact human-induced climate change [23, 24]. The political-economic landscape, structure of providers, and geopolitical locations of water resources, are exogenous variables that I show are critical to the use of technology to address the SDGs. Social norms like privacy and perceptions over what information is fixed or variable or hidden or explicit are considered as exogenous variables that may encourage or discourage the use of technology. The designation of infrastructure as a communal pool resource is an exogenous variable that may provide opportunity or difficulty for implementation of the technology to achieve the "for all" action situation of the SDGs. For the United States case study, the 1974 Safe Drinking Water Act (SDWA)

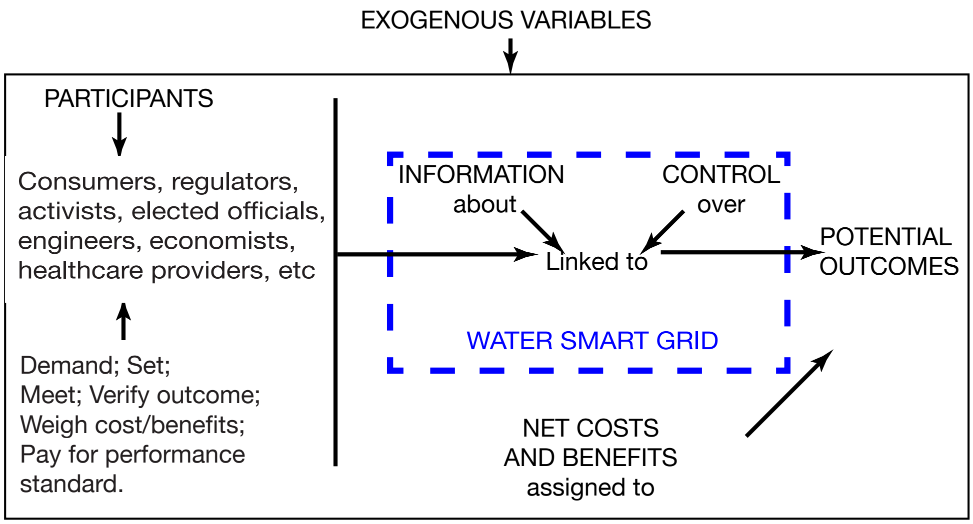

Figure 1: Institutional Analysis and Development Framework as applied to the UN SDG of providing "universal and equitable access to safe and affordable drinking water for all."

and its 1986 and 1996 amendments are exogenous variables. Property and water rights, in addition to the SDWA, are considered as exogenous variables to this analysis.

For each action situation and each technology, there exists a series of evaluative criteria that I will ask and assess via existing research and news reports.

- What can be done with the information gathered from a given technology in the action situation?
- Can the information present an accurate picture of the action situation?
- Can accuracy be defined?
- What is the tolerance for frequency?
- What is the tolerance for false positives or failure of the device?
- Will action on the information gathered positively or negatively impact the outcome?

- Will the technology expose or obscure problems?
- Who will benefit and who will be harmed from the use and information provided from the technology?
- Can technology be used to drive progress toward an outcome?

I leave a benefit-cost analysis to the end, assuming that all parts of the water smart grid can be implemented and will address each action area as explored. I theoretically analyze which questions can and cannot be asked with technology and whether those questions will lead to or away from a desired outcome, in this case the SDG for water. This analysis will assume it is given that governments are ultimately responsible for guaranteeing the human right to water. It will not hold in situations where neither the people nor the governments are capable of seeking redress and reform through procedural accountability [25]. Systems that gather and distribute information to all levels, command and control physical resources, and monitor and prevent contamination of those resources are hampered in the absence of regulators, regulations, adjudicators, systems of tort, and electoral capacity to induce change by one party on another [26, 27]. This analysis will not address corruption and explicit maleficence that supplant the legal frameworks above. I will not address actions of war and international disputes that move discourse of water away from local impact and control. I will not emphasize the right to water for corporations or farming. While these issues are important, especially in water markets, the standards for quality and quantity in corporate and agriculture operations are vastly different, sometimes necessitating completely different systems. Lastly, the subjective nature of taste, which cannot be ameliorated with technologies for monitoring or treatment, will not be considered in this analysis [28].

3. Universal Water

Universal water provision "implies [provision in] all exposures and settings including households, schools, health facilities, workplaces, etc." [4]. "Universal" is accurately described by enumerating everyone who wants water and their connection to a water supply. A connection includes both self-supply and public water supply. Currently, national-level estimates of universal water provision in the United States are combinations of self-reported sales numbers from public water suppliers, Environmental Protection Agency

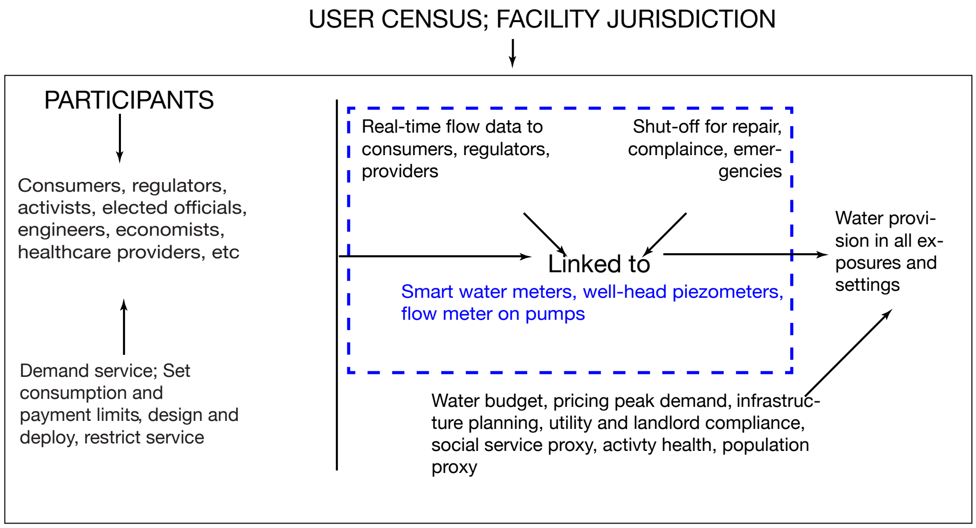

Figure 2: Technology to measure "Universal." Meters should be designed to measure usage and automatically provide usage data and location accessibly both onsite and at centralized databases at every facility where people use drinking water for all participants [29].

(EPA) Safe Drinking Water Information System (SDWIS) information, and United States Census data [10].

An accurate picture of water usage and water coverage is important in producing a water budget [30]. Accuracy cannot be achieved for this situation without a consensus of who is supposed to provide, maintain, and aggregate data from these meters and for whom. Furthermore, meters would not address homeless populations that do not participate in shelters and are not covered by any census [31, 32, 33]. Additional technologies like public showers, toilets, and water fountains, if not homes – while not part of a smart grid – could then be connected to the public water systems, to address those populations. Populations with private wells should be accounted for, though private wells are not regulated in most states.

In the event consensus is reached on who covers whom, measurement frequency can weight a number of factors based on the tolerance for missed readings. For example, if the meter measures a cumulative volume per day, it could miss times when the water is not flowing at all. If the device is being used to detect breaks, low pressure, excess use, or even cumulative use, hourly measurements may miss the desired outcome. Less than daily measurements may not provide the benefits of a smart meter, because a day without water can disrupt meals, employment, and hygiene. Error tolerance (e.g. , false positives for leaks) is low in this area if resources are being deployed to fix service based on device readings or water is shut off due to device error.

Will action on usage and connectivity information positively or negatively impact the outcome of universal water provision? This information could be used to restrict activities that have a quality of life benefit only to those who can afford it. Pricing and affordability will be addressed later (Section 7), but it is worth noting that the ability of a "smart water meter" to shut off water in nonpayment scenarios goes against the SDG for water. Furthermore, data from smart meters has been used to distinguish how water is being used by an individual household: for example, between running a washer machine versus bathing. While this has implications for water pricing, it also presents an unacceptable invasion of privacy for some [34]. Though more of an equity issue, continuous monitoring of water for immigrants without legal status may be more harmful than beneficial to these populations. Comparative data leading to competition has worked for some environmental goals, yet doing better than average in terms of water use can create false appearances of water security.

Can technology drive progress toward the goal of "universal" water provision? In instances where jurisdictions have outdated databases, where present costs of gathering data obscures future benefits of identifying cost savings, technology in the form of a smart meter can indeed drive progress toward the goal of universal provision [35]. Technology can bridge the gap in data missing for many public water systems in the US SDWIS. However, technology cannot bridge the problems of jurisdiction, property rights, privacy rights, and trust without necessary regulatory frameworks and institution building.

4. Equitable Water

Equitable water "implies progressive reduction and elimination of inequalities between population subgroups," in access, safety, and affordability of water [4]. An accurate picture of "equitable" includes describing the state of water provision to marginalized groups that are traditionally underserved by public provision in quality, quantity, or regularity. Some of the groups highlighted here will be poor living in mobile homes, Native American com-

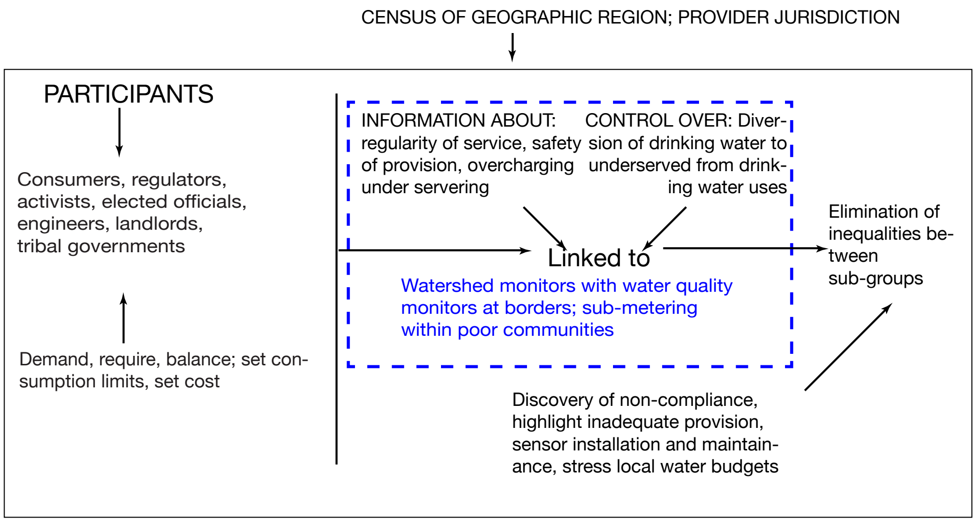

Figure 3: Technology to measure "Equitable." Technology should be deployed to measure safety, availability, and regularity of water provision to marginalized groups.

munities living on tribal land, and communities that are not supported by a public water system as defined by the SDWA. At the federal level, there are no provisions within the SDWA to protect water rights for these groups other than Native American communities. Communities not supported by public water systems must provide their own water via wells. The Clean Water Act has protections from contaminants that can offer protection for well users.

An accurate picture of equitable water provision would rapidly and continuously measure instances of water disconnection and contamination, along with inadequacies in both. For example, water provision has been difficult for people who live in apartments and mobile home parks where water meters are not submetered (nor considered a public water system by the SDWA [36]). Unless the legal framework is structured to ensure submetered billing, billing for such residences is variable (see, for example, [37]) A systematic analysis of water survey data showing that water shut-offs were higher for residents of mobile home parks in 2015 was prompted by news reports of the same [38]. Providing information during use to all parties is the most effective way to incite behavioral change. For example, providing regular usage data to an owner convinces them to install low flow meters [39].

While US tribal lands are sovereign, they share physical connection with the United States. While allocation of physical water between tribal land and the United States has occurred, physical water connections are limited [40]. To ensure water is transferred adequately and safely across borders, monitoring frequencies need to mirror usage and recharge rates (see Section 5). Similar to addressing the problem of universal provision to homeless populations, the transfer of existing technologies not part of the smart grid to tribal land must be part of any technology suite. Any absence of this transfer will lead to further inequality. This is exemplified by legislative creep of state regulations into and reduced water quality of tribal land due to either an absence of tribal regulatory infrastructure – the kind the federal government subsidized for the states – or courts narrow interpretation of what is within the purview of a tribal government [41].

As in the "universal" action scenario, water smart grid technology cannot overcome many issues related to "equity" without an accurate census. Unlike the "universal" action scenario, information from technology can highlight jurisdictional challenges to equitable water provision. If groups are not connected with the technological solution, the very absence of coverage in relation to an accurate census shows that they are being underserved. However, investment in these technologies for high-income communities can stress local budgets and further leave out low-income communities.

5. Access to Water

Access to water "implies sufficient water to meet domestic needs is reliably available close to home" [4]. An accurate picture of access to water includes knowing water availability for a given community, by which the means the community gets that water (piped or well, public or self), and the provision reliability. "Universal" is distinguished from "access" noting that the focus in the action arena of "universal" is on the people whereas the focus in the action arena of "access" is on the resource.

Current methods of determining availability include piezometers utilizing shut-in pressures, as well as acoustic, electrochemical, and seismic sensors. Freshwater resources like groundwater aquifers can be measured using dedicated satellite data [42]. These methods are currently conducted through geographically sparse site studies that are limited in temporal resolution [43]. A system of technology to conduct the same studies would include making robust and low-power sensors that can operate in the field permanently and

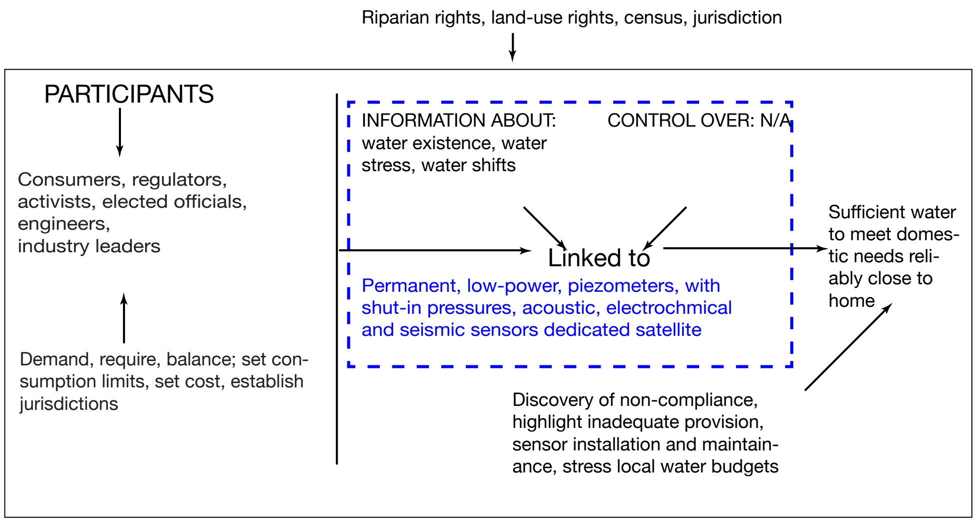

Figure 4: Technology to measure “Access.” Determining access is important to developing dynamic and accurate water budgets.

report readings automatically. The USGS public-supply database currently gives estimates on water use at the county and state level by aggregating data from public water system intakes and census data [44]. These sensors, combined with smart meters on buildings and on public water system intakes, make a smart grid.

Combining water use with water availability along with filling spatial and temporal gaps in water availability and water stress models, increases water security [30]. Furthermore, integrating control can prevent waste and abuse of water. The data presented in real time can bring water stress above-ground for users, planners, activists, economists, and engineers. For example, elected officials and economists can weigh costs and benefits for paying landowners of high-recharge lands [45]. Real-time water stress data presented to users can bring water conservation efforts into the home, displaying how a home’s water use stresses a given aquifer.

However, accuracy is difficult to define in this action arena for a number of reasons. Primarily, while the current state of water stress can be modeled in a given area, changes in availability take time to propagate through aquifers [46]. Additionally, water recharge through precipitation will change on a monthly basis [45]. Yearly measurement will not capture seasonal variation. The measurement frequency of water availability can be low for the aforementioned reason, though not as infrequently as the USGS five year inventory.

Knowing how much water is available can assist in long-term planning. This can be beneficial for conservation and planning efforts. However, this additional knowledge can also encourage industries that need freshwater for other reasons to relocate to regions of high water availability and outspend smaller users to capture that water, disrupting established patterns of water use [47].

How users are connected to the public water system after the water leaves the treatment plant is also useful information. Engineers can use a well-distributed, continuous two-way data flow network to identify leaks between measurement points. This part of the water smart grid might include pressure sensors and flow sensors placed at regular intervals within pipes, not simply at mains connections. Furthermore, combining pressure and flow data across a system with models of how the system should function can provide feedback to determine excessive usage, monitor reliability, and so on in real time. Activists, elected officials, and economists can use a system to identify insufficient provision through poorly covered regions in linked networks. This information can bring to light areas of frequent failure.

Accuracy in water delivery can be defined for a given jurisdiction and an accurate census. An accurate map of piping networks, flow and pressure profiles, loss, leaks, and total connections addresses access. These systems can be monitored on a much more frequent basis than "availability" because these systems are under constant use, as well as different stages of repair, stress, and strain. The tolerance for false positives is not as high as for measuring "availability". If data is misrepresented rarely, it is likely still better than the current system, and fail-safes such as the state of flow at a water treatment plant and the state of flow at someone's house are known entities. The data collected from these sensors at the local level can automatically be integrated into national databases.

Data and information uniformity can enable action at all levels. At the household level, comparing anonymized usage against a neighbor's can encourage competition and suggest opportunities for savings. At the neighborhood level, there are opportunities to compare with other neighborhoods to ensure equitable service and response times to issues. Still, uniform information can ignore extremes and does not provide political momentum like single catastrophic events [48].

Riparian and land-use rights can cause property owners to be wary of technological monitoring by government agencies [49]. This issue can be partially overcome through incentives [45]. Populations may object to remote monitoring of private use [34]. Determining who is served by a given source is a current problem that will not be solved by implementing a smart grid. Additionally, when a given population exists in either an overlapping or exclusionary zone, the smart grid may be difficult to implement.

6. Safe Water

"Safe drinking water is free from pathogens and elevated levels of toxic chemicals at all times" [4]. An accurate portrait of safe drinking water would capture the total amount of a specific contaminant over time individuals are exposed to, in accordance with age and other medical risks (see section 9). This requirement is currently met in the United States by setting levels and sampling frequencies at reasonably achievable levels to protect large portions of the population [36]. Detecting bacterial contamination is currently dependent on culturing the bacteria and looking for specific indicator organisms for treatment efficacy or source of contamination [50]. Detecting toxic chemicals is currently achieved using mass spectroscopy almost exclusively in laboratory settings due to capital cost of equipment and technical expertise in interpreting results [51].

The data gathered from these technologies can be used by a consumer to decide whether to trust tap water. If two-way feedback is implemented, as desired by smart grid advocates, then water utilities can provide consumers with boil water orders immediately. Engineers can compare data taken from a collection of neighborhood sensors to household, as well as schools or health care facilities, sensors to determine if consumer-reported problems are the consumers' or utilities' responsibility. Activists and elected officials can use the information to push for equity of service quality. Higher-resolution data in both space and time can assist economists in studying the effects of investment (or lack thereof) on water quality, and vice versa.

Challenges with creating an accurate portrait of safety include the regular identification of new chemicals discovered to have toxic effects [51]. In addition, technology does not exist that can individually identify most bacteria. The latter is not as relevant, since our methods for disinfection are targeted to eliminate the most recalcitrant bacteria, though determining viability of

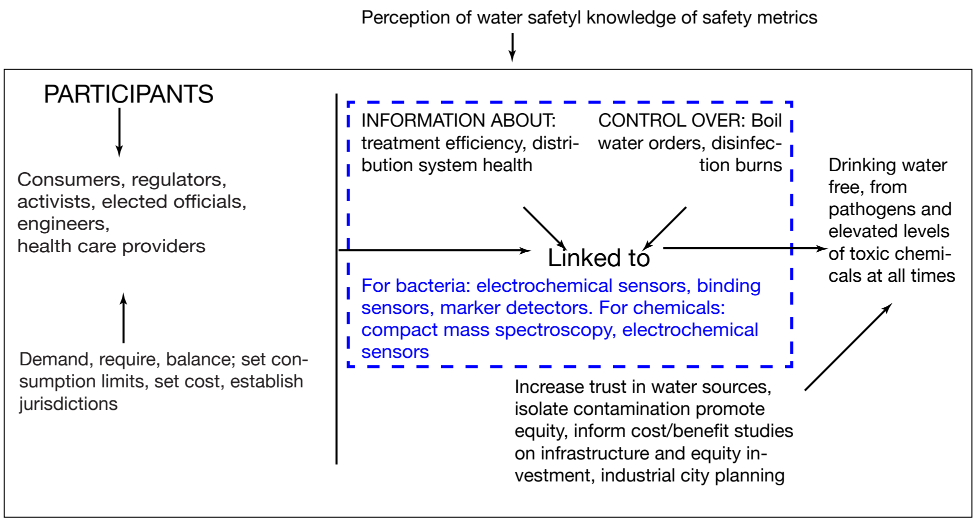

Figure 5: Technology to measure "safe." Compact methods for detecting bacterial and chemical contaminants are being developed [52, 53].

screened microbes would be. If these technologies can be created, there is no reason to set a limit on frequency. Since water safety can be affected intermittently by changes in source water quality that may take time to propagate, or rapidly by leaks, or knowingly by chlorine burns, sampling at higher frequencies can only capture more data about water quality. False-negatives are less tolerable in this action arena than in others because failures in safety can lead to irreversible harm.

The data provided from biosensors can be used to impose standards from outside or inside a jurisdiction that cannot be met immediately. Furthermore, stringent standards may not allow for the flexibility necessary to provide adequate water during a water crises. Stringent standards can be used to evict communities that cannot afford to meet those standards and replace them with those that can, thus directly working against the SDGs. In this way, among others, standards can disrupt local economies [54]. Once existing standards are in place, it is difficult to raise them for a number of reasons. Nevertheless, as mentioned earlier, safety is a moving target, and what we know about how novel engineered chemicals affect the developing or elderly body is always increasing. Therefore, having technologies in place to determine and ensure safety can be used to reinforce and make those standards harder to change. Having sensors can also benefit activists. It was only through the collaboration of health care professionals diagnosing and regular testing of waters by an outside engineer that elevated lead levels were exposed in Flint, Michigan [15].

Overall, sensors that measure chemical and biological safety can be used to drive forward the goal of safety. Even in the case of self-supplied water, knowing more – in terms of total metrics and temporal and geographic frequency – about water quality can provide benefits to the consumer, engineer, activist, elected official, and economist. A challenge exists when high standards are used to evict users from areas deemed "unsafe" in exchange for users who can afford to repair those unsafe conditions.

7. Affordable Water

Affordable water implies that "payment for services does not present a barrier to access or prevent people meeting other basic human needs" [4]. An accurate picture of water affordability would involve determining how people pay for water, why they may forgo paying for water, if water is the reason they forgo paying for other things, and what they do when they cannot pay for water. Furthermore, it involves determining if water charges are being applied to meet the goals of universal, equitable, accessible, and safe access. If not, are those costs being made up for in some other way? Affordability may also involve challenging or changing viewpoints on how much water should cost. The present situation for providing affordable access to water varies by state and service. Programs to make water affordable in the United States, for example, are established by private providers in the states of New Jersey and Pennsylvania, and public utilities in California. Water pricing is not enough to meet maintenance demands or encourage sustainable use [55]. Feedback mechanisms on water pricing are too far removed removed to be measured accurately.

Accuracy is difficult to define and achieve in the action situation of affordability. Affordability is also partially determined by an individual's relative ability to prioritize paying for water as opposed to other household costs. Difficulties exist in determining affordability with state-of-the-art willingness to pay surveys and studies [56]. Additionally, it is beyond the scope of this paper to discuss how people perceive paying for water. However, technology as a linkage can increase survey geographic scope and frequency by placing surveys at the point of use. Furthermore, real-time usage versus cost data may reveal behaviors over the long term. Correlating median household income with water costs may also reveal affordability issues.

These measurements and, more specifically, providing costs to the consumer must be done frequently enough for those budgeting to discover trends and make adjustments. For example, policy makers may only need monthly data to determine seasonal fluctuations and set yearly budget allocations. Consumers may need daily numbers to adjust leisure activities that require large amounts of money or identify costly leaks. Activists and economists may need both to determine the behavioral patterns that making water affordable seeks to achieve. Survey data will have to be taken frequently high enough to be relevant but low enough so people respond.

Action on this data is identical to action on pricing and payment data, which has had mixed success. The data collected can be used to affect pricing and payment. Aggregate data can be presented to consumers to show where their payment is going adn to demonstrate the value added: to delivery, testing, maintenance, and land acquisition. Furthermore, policy makers, economists, and activists can use aggregate data to determine if pricing is fair and that the percentages of taxpayers' budgets and providers' budgets are reasonably aligned with goals of universal, equitable, accessible, and safe access. Because technology is not human, people may be more or less likely to report financial difficulties to a machine [57, 13]. A more real-time monitoring system can provide better data to determine pricing, influence usage, and determine when affordability is altering water use. Water pricing has a significant impact on water consumption in apartments as opposed to water consumption being impacted by moral obligation in houses [39]. It follows that behavioral patterns can potentially be analyzed to increase provision in times of financial hardship noting water usage decreases versus total cost.

Technology that collects survey and usage data can be incorporated into advocacy for "affordability." It can be used to micro-target reduced pricing to low-income households and neighborhoods. When these technologies are combined with technologies that will improve operating health of the system (e.g. the technologies used to meet the "universal", "access" and "safety" elements of the SDG), overall water prices may drop. When combined with transparent data for all users, not only households, the implementation of fair water pricing can be advocated. Making water affordable will not be possible without defining what is fair water pricing for which population.

8. Drinking Water

Drinking water is “water used for drinking, cooking, food preparation and personal hygiene” [4]. An accurate picture of “drinking water” would separate water usage by type both within a building and between buildings. Currently there is no physical separation and thus little data exists distinguishing these uses from nondrinking uses. However, data analysis has been used to approximately separate usages based on household surveys on time of use. Technologies that could be used to address this would include flow sensors deployed inside a building on specific appliances and faucets. In addition, introducing physical separation between drinking and nondrinking (nonpotable) water usages should be introduced from an efficiency standpoint [58].

An accurate picture of water usage can inspire alternative technologies for treatment, delivery, and maintenance. Knowledge of drinking water uses versus non-drinking water uses can also encourage infrastructure investment in alternative sources and delivery methods to separate out uses that require high-quality water from those that do not. For example, treated wastewater that is high in nitrates could be used to water lawns in lieu of fertilizing and watering lawns with drinking water [58]. Or, recognizing that certain pipes deliver water for nondrinking (non-potable) uses could alter the use of corrosion and contamination control chemicals in certain waters over others.

Accuracy in this arena is defined as capturing usage and guaranteeing provision of high quality drinking water in an adequate amount. This number may underestimate or overestimtate the minimum daily estimate noted in literature depending on an individual’s health status, local climate, food quality, diet, and employment. Therefore, what is “adequate” may vary from household to household and person to person.

Usage data can be used to increase or decrease pricing for “valued” uses which may inadvertently discourage flexible usage of water by those that cannot afford it. For example, by increasing pricing of residential water used for watering lawns, those who used that water to farm and supplement household food budgets may be discouraged. Additionally, companies that use water other than for drinking can be made to pay more for “drinking water” or encouraged to create onsite water treatment for high-quality water. Such flexibility will not be known until it is clearer where and how much water is being used for drinking.

9. Water for All

Water for all implies that water is "suitable for use by men, women, girls, and boys of all ages, including people living with disabilities." An accurate picture of "water for all" would capture the specific needs of individuals, since water-related health issues can cut across any segment of society and are coupled to an individual's health status. Currently under the SDWA and amendments, public water systems are required to sample water as directed by their state for chemical contaminants. Many states require random sampling of sites in a given service area at fixed intervals, while any home, office, or school level data must be gathered by the property owner. Biological contaminants are required to be tested in a fixed number of samples per month by population. The EPA administrator is required to take into account specific vulnerable populations when setting safety standards [36].

Technologies that could address this have been mentioned earlier in sections 3, 5, 6. Furthermore, these technologies would have to be coupled to accurate health data and vulnerabilities of all populations being served. The aggregation of data – for example, water usage by a neighborhood – will look completely different from water usage of a city or a state, and policy decisions made at each of these levels will have a less complete picture than a coordinated effort [27]. Even when the maximum contaminate load is set for the most vulnerable population, the absence of knowledge at the residence or school level, for example, can expose these populations to contamination exceeding that. Vulnerable populations may be hard to single out with limited manpower for manual sampling. Autonomous systems can increase sampling frequency spatially and temporally. Water safety meters can be installed in schools, senior centers, hospitals, and other locations where vulnerable populations gather to ensure they are covered, in addition to increasing the number of random sample points. Furthermore, empowering local citizens with data on water usage may enhance "scale capabilities" lacking at lower levels of scale [27].

10. Discussion and Conclusion

I applied the institutional analysis and development framework to analyze whether technology (the material artifact), as a linkage in the IAD framework, could support a positive outcome in the action scenarios defined by the SDG for "universal and equitable access to safe and affordable drinking water for all." Table 2 summarizes the primary method by which technology as a linkage can encourage a positive outcome in each action scenario defined by the UN SDG for water as well as the primary challenge to that technology's implementation.

Table 2: Summary of IAD Analysis

Action Scenario	Can Tech Encourage Positive Outcome?	Primary Methodology	Primary Challenge
Universal	No	N/A	Jurisdictional
Equitable	Yes	Highlighting gaps in provision	Jurisdictional
Access	Yes	Quantifying availability	
Safety	Yes	Quantifying contaminants	Technological
Affordability	Yes	Increasing geographical and temporal scope of surveys	Behavioral
Drinking water	Yes	Separation of use	Privacy
Water for all	No	N/A	Privacy, health care infrastructure

Water smart grids promise transparency of quality, quantity, and sustainability metrics. Water providers showed quality improvements and violation drops after the SDWA required a to be report sent to consumers [59]. Water smart grid technology can provide reporting at the point of use – for example, by displaying real-time safety data on a faucet. This may instill trust in the source as continued positive readings will show consistency and negative readings will show honesty. Still, 40% of New Jersey residents continued to believe that bottled water was safer than tap after the SDWA required water reports [60].

Consumers, providers, and regulators can ignore provided information. For example, only 9% of people surveyed understood they were able to receive a water report as required by the Safe Drinking Water Act Amendments of 1996 [61]. Furthermore, people view health departments to be responsible for health information about health as opposed to water departments [61]. Additionally, negative data can be averaged out with more positive data, while outlying data may show of systemic problems.Technology cannot absolve providers, activists, users, or elected officials of the responsibility to monitor water.

In attempting to adapt the principles of the electrical smart grid to water, a number of questions, both technical and sociotechnical, must be asked. For safety, in particular, would water providers invest in technologies that will lose relevance? Would consumers accept a technologies' safety report that will soon be out of date? Would regulators sanction devices that are out of date before they are deployed? How would consumer protection agencies and environmental agencies coordinate on rapidly developing technology? Additionally, what are the technological solutions and regulatory frameworks for distributive water production through home rain water, grey water, wastewater collection, treatment, and reuse [58]? How would economic efficiency of water treatment be achieved without economies of scale in water treatment? Who is responsible for safety, maintenance, and reporting of distributed water tanks and treatment centers [62]? Is it socially acceptable to return to distributed water? Furthermore, as is often asked in distributing electricity generation, is it possible to maintain both a distributed system and a centralized system specifically for those who cannot afford capital and maintenance costs associated with self-generation?

Now that it is clear which questions can be answered with technology, a benefit cost analysis of answering these questions can be undertaken. A smart-grid targeting universal water provision could reduce census taking cost. Specifically, with a more detailed population proxy, like knowing how many individuals are connected to given public water systems, would reduce the cost of determining if a housing unit is vacant easier and improve census modeling and testing [63]. The US census in 2020 is estimated to cost $12.5 billion, with the majority of this cost attributed to canvasing non-responsive housing units, vacant or not, and with $\sim 10\%$ of housing units vacant, at most $1.2 billion could be saved [64, 65]. A smart grid would eliminate questions regarding how people get their water in the American Community Survey. While the length of the questionnaire is not assumed to effect cost of giving the survey, in 2013 it was estimated to cost respondents $58 million or $0.56 million per question annually [66]. Moreover, collecting this data where at the local levels where it is needed would reduce reliance of state and local governments and private business firms on the census, dissemination of which cost the US Census Bureau \$114 million in 1990 [64]. Reducing water related health care issues may save up to \$250 million annually, through increased income, reduced illness related absenteeism and reduced death [67, 68, 69]. If 14 – 18% of drinking water is wasted due to leaks annually and the US dedicated $\sim$ \$19 billion to the state revolving loan fund each year from 2013-2016, then a 10% reduction could lead to an annual \$1.9 billion savings.[70, 71] If a water smart grid can automate the creation of a water budget it could reduce border disputes. This has cost, for example, Florida \$71 million over sixteen years fighting Georgia, which spent \$30 million over two years, over water budgets and subsequent appropriations [72, 73]. The biggest benefit touted by proponents of smart grid technology is accurate pricing of water though it is difficult to say whether people would be willing to pay those cost. The largest benefit may be renewed faith in public drinking water systems and potentially an increased willingness to pay [8, 28].

There would have to be 1.2 – 2.4 million sensors on a per mile or 1/2 mile of water pipe. An additional 133.5 million sensors in households, multiplied by the number of sensors per house. Invasive sensors would have to last as long as the pipe $\sim$ 80 years. The biggest cost savings coming from a reduction in surveying vacant property and leaks of \$3.1 billion. Onsite sensors would have to cost than \$10 annually less to run and build while in pipe sensors would have to cost less than $\sim$ \$800 over 80 years or \$64,000 per device. Cost of new, wide-spread, technology is likely to be less costly than existing due to innovative solutions [74]. Furthermore, even the cost of existing technologies, like the mass spectrophotometer which is currently a lab tool, have been known to drop dramatically when retooled for mass consumption.

Russel Train (EPA administrator 1973-1977) once commented "in controlling pollution, whether by establishing discharge standards for new sources or compliance schedules for existing facilities, improvements in technology must and will be a driving force in achieving our environmental goals." I found that the strongest use case for technology is in the specific action situation of safety. However, the strongest challenge found to using a water smart grid to achieve our SDG for water is the inclusion of land use rights and property rights similar to Bakker, et al., (2008) [75].

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