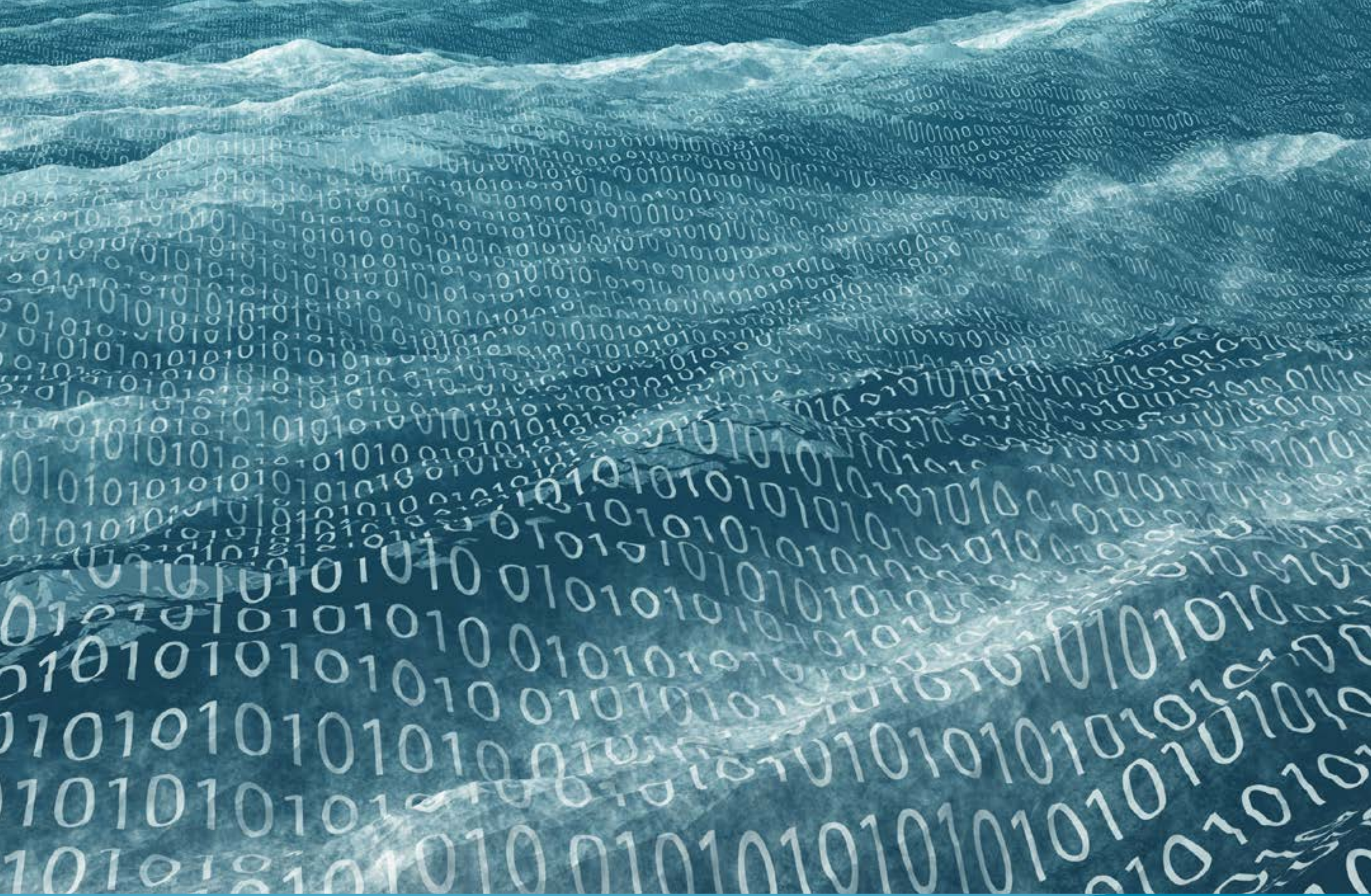

The Value of Water Information

OVERCOMING THE GLOBAL DATA DROUGHT

xylem
Let's Solve Water

Acknowledgements

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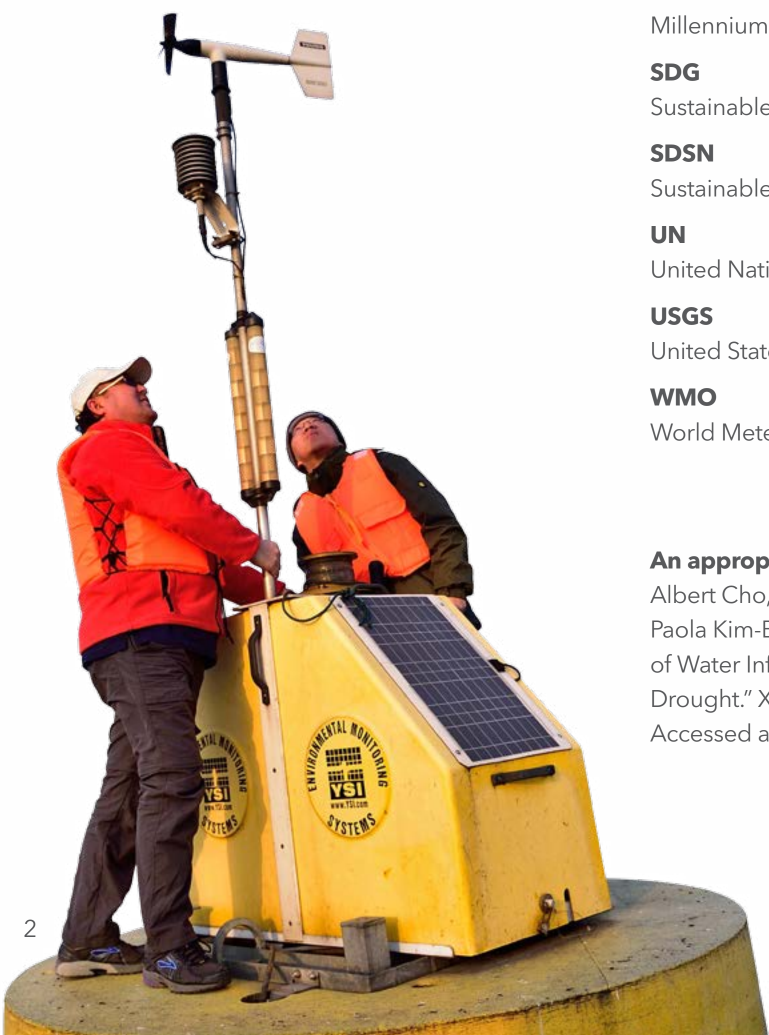

Abbreviations

CIESIN
Center for International Earth Science Information Network

GEMS
Global Environmental Monitoring System

GRDC
Global Runoff Data Center

NASA
National Aeronautics and Space Agency

NOAA
National Oceanic and Atmospheric Administration

MDG
Millennium Development Goals

SDG
Sustainable Development Goals

SDSN
Sustainable Development Solutions Network

UN
United Nations

USGS
United States Geological Service

WMO
World Meteorological Organization

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There is a troubling mismatch in the world of water data. On the one hand, the global need for information about water is immense and growing. Rising demand for fresh water, coupled with increased volatility in global climate patterns, means that robust and timely information to support decisions about allocating and managing water resources is more valuable than ever. Meanwhile, the digital revolution has made collecting and analyzing large datasets ever cheaper, and the application and use of these data more powerful.

Despite the growing need and the increasingly actionable opportunity to address it, the backbone of the global water monitoring system – made up of publicly available, scientifically validated networks of sensors, communications equipment, and data centers that support a wide number of uses – is struggling just when it is needed and used most. As our analysis below will suggest, this decline represents a significant lost economic opportunity for the world.

This paper is a call to action for data users, data providers, and global decision-makers concerned about water resources, climate resilience and sustainable development. It provides an overview of hydrological monitoring systems and explains the importance of public water data to national governance, resource management, planning, and efforts to achieve global objectives such as the Sustainable Development Goals. This paper also finds significant declines in the number of hydrological monitoring stations reporting in the public water data systems responsible for sharing hydrological information globally, with highly inconsistent temporal coverage and insufficient spatial coverage. These findings are particularly concerning given our review of economic literature indicating that hydrologic information is a sound and attractive investment that provides a 4-to-1 return with direct and indirect benefits to private actors and the general public. These findings provide a call to action to increase public and private sector support for these vital public goods – and suggest a number of recommendations to reverse the growing ‘data drought’ facing a changing world.

Hydrological monitoring systems

This document focuses on hydrological monitoring systems that collect water data in situ through the design, installation, operation and maintenance of networks of sensors and research stations. While remote sensing (e.g. satellite-derived imagery) is a very important complement to in situ data, it has different operational and research characteristics beyond the scope of this assessment. In situ networks are operated by a variety of public and private actors, including government agencies, such as the United States Geological Survey, non-profit organizations, and private sector companies.

There is no single global hydrological monitoring system, but rather a proliferation of networks designed and operated by their respective owners for specific uses and at different spatial scales. These systems take measurements of many different parameters and data types, including source measurements of atmospheric water (e.g. precipitation), surface water (e.g. streamflow and lakes), groundwater, and oceans and coastal water resources. On the demand side, data related to agricultural, industrial, municipal, domestic and environmental uses of water are also used to support decision-making.

These monitoring networks support vital decisions related to the management of water resources. The US Geological Survey (USGS), for example, identified nine different categories of uses for its national water monitoring network, including assessment of general hydrological conditions, statistical modeling of streamflow to support regional planning, support for users' daily operational decision-making, hydrologic forecasting, water quality monitoring, planning and design for specific infrastructure projects, scientific research, and other applications, including recreational decision support for uses such as fishing and watersports (Wahl et al. 1995). Others have grouped these benefits into three core categories: planning and design-related benefits, flood and storm management, and resource optimization (Azar, Sellars, and Schroeter 2003). All of these uses are likely to expand as global macro drivers, such as a growing population, urbanization, economic development and climate change, intensify the need for water information delivered with higher density (more parameters measured at higher spatial and temporal resolution), continuity over long periods, and availability (i.e. discoverability, access, machine readability).

Because water touches nearly every aspect of human lives, water information systems are important to the Sustainable Development Goals (SDGs) agreed by the United Nations in 2015. The SDGs include a specific goal (SDG 6) devoted to ensuring the "availability and sustainable management of water and sanitation for all," but data about water are vital to the achievement of nearly all 17 of the Sustainable Development Goals (UN Water 2016). Lack of access to clean water and sanitation spreads diseases that kill millions every year (SDG 3), and the burden of obtaining water and sanitation falls disproportionately on women and children, exacerbating gender inequality (SDG 5) and educational challenges (SDG 4). Water management is a vital driver of food security (SDG 2); sustainable energy (SDG 7); resilient infrastructure (SDG 9); safe and resilient human settlements (SDG 11); sustainable production and consumption patterns (SDG 12); climate resilience (SDG 13); conservation and sustainable use of oceans (SDG 14); sustainable management of terrestrial ecosystems (SDG 15); and promotion of peace – as water scarcity is a driver of conflict (SDG 16). Table 1 maps various categories of water information, ranging from streamflow information to data on water consumption, to decision-making across various policy domains.

For example, local, state and national governments use real-time streamflow readings to generate flood warnings; without these data, flood warnings would have much lower accuracy, and potentially lead to the public ignoring warnings to evacuate areas in advance of a flood. In addition, infrastructure planners use these data to plan highways and bridges capable of withstanding changes in water level and flow rates. Insurance companies depend on accurate floodplain mapping, which depends on streamflow and precipitation data (USGS 2006). Energy companies depend on hydrological data to predict river flows for projects such as sustainable run-of-river hydropower projects. However, despite the relevance of water information to the achievement of important development objectives, as the next section outlines, many countries lack robust water information systems, and the trend lines are not positive. As it is difficult to manage what goes unmeasured, gaps in public water data systems do not bode well for our collective ability to achieve sustainable water resources management.

Table 1
Water data are used across a variety of critical decisions.

	Water Supply				Water Demand			
	1	2	3	4	5	6	7	8
Energy production	■	■			■			
Food production	■	■	■		■			■
Flood protection	■	■		■	■	■		
Insurance		■	■	■	■	■	■	
Water storage planning	■	■	■		■	■	■	■
Climate resilience	■	■	■	■	■	■	■	■
Water quality for human health		■	■		■	■	■	
Water quality for ecosystem health		■	■	■	■	■		■
Wastewater treatment		■				■	■	■
Infrastructure design	■	■	■	■	■	■	■	■

Targets for SDG 6	Water Supply				Water Demand			
	1	2	3	4	5	6	7	8
6.1: universal and equitable access to safe and affordable drinking water for all							■	
6.2: access to adequate and equitable sanitation and hygiene for all							■	
6.3: improve water quality globally		■	■	■				■
6.4: substantially increase water-use efficiency across all sectors		■			■	■	■	
6.5: implement integrated water resources management at all levels	■	■	■	■	■	■	■	■
6.6: protect and restore water-related ecosystems		■	■	■				■
6.a: expand international cooperation and capacity building support	■	■	■	■	■	■	■	■
6.b: strengthen local communities for improving water and sanitation management	■	■	■	■	■	■	■	■

Legend:
1. Atmospheric, 2. Surface water, 3. Subterranean, 4. Oceanic, 5. Agricultural, 6. Industrial, 7. Domestic, 8. Environment

The data drought

Scientists, industry experts, and policymakers recognize that the existing reach of water monitoring systems is insufficient to support the global need for water data. According to a 2012 industry survey of over 700 water professionals, including hydrologists, engineers, and utility managers, 72% reported that they need data from more monitoring stations to meet program goals (Aquatic Informatics 2015). Academic studies support this conventional wisdom (Gleick et al. 2013). Several studies have documented an overall decline in in-situ monitoring systems across the world (Fekete and Robarts 2015). This decline includes a diminishing number of precipitation gauges (Stokstad 1999), water quality monitoring systems (Zhulidov et al. 2000), and river discharge sensors (Fekete et al. 2012).

While there will always be a gap between the nearly infinite desire for more data and the finite resources available to supply it in any given domain, the "data drought" facing hydrological information is particularly concerning given the social benefits and vital importance of water resources. This paper gauges the extent of monitoring gaps by examining public, globally standardized data sets and station density targets recommended by the United Nations World Meteorological Organization (WMO). The databases in this analysis rely on voluntary reporting by national statistics and environment agencies and are aggregated either by a United Nations center or by a United States government agency.

To estimate the scale of the monitoring gaps, information from these data sets was compared to the WMO framework for minimum network density as outlined in its "Guide to Hydrological Practices: From Measurement to Hydrologic Information" (WMO 2008), which provides the best-available approach to discuss generalized adequacy of in-situ stations. The framework outlines benchmark levels of minimum network density for hydrological monitoring stations to deliver appropriate levels of hydrological information services, disaggregated by physiographic area (terrain and climatic considerations), such as mountainous, coastal, arid/polar, interior plains, hilly and small islands (Kundzewicz 1997; Mishra and Coulibaly 2009; WMO 2008). These reference levels are used in this analysis to estimate the number of sensors that "should be" in place in a given physiographic area (Table 2 outlines the minimum benchmark station density for each physiographic area).

Table 2
WMO's recommended minimum densities of hydrological stations

Physiographic unit	Description	Precipitation (Area in km² per station)	Streamflow (Area in km² per station)
Small islands	Island states or territories with area 500km² or less.	250	300
Coastal	Areas within 100km from the coastline.	9,000	2,750
Arid / Polar	Areas classified as 'Dry system' or 'Polar system' by the Köppen-Geiger climate classification system	100,000	20,000
Mountainous	Areas with elevation of 1,500m or greater.	2,500	1,000
Interior plains	Areas with elevation of 200m or less.	5,750	1,875
Hilly / Undulating	Total area not classified as Coastal, Mountainous, or Interior plains.	5,750	1,875

Source: WMO 2008.

The assessment also draws a distinction between reporting gaps and measurements gaps. We defined the 'reporting gap' as the difference between the number of stations reported to global databases and the recommended station density standards defined by the WMO. We defined the 'measurement gap' as the difference between the recommended station density standards defined by the WMO and the estimated number of active stations, which we assessed using a statistical model. Both metrics are imperfect. The reporting gap could be due to a lack of physical stations or to gaps in reporting practices for extant stations; at the limit, a country could have a high-density, active monitoring network that is not reporting data to global public databases. The measurement gap is not directly observable because it is difficult to quantify the number of extant stations, especially for stations that are not reporting data.

We have therefore chosen to quantify the reporting gap based on objective standards and observable data, and to estimate the measurement gap based on statistical analysis. Both metrics are relevant to decision-makers interested in ensuring access to hydrological data, but their use requires careful interpretation.

The gap analysis based on this approach suggests some common themes. First, there are significant gaps in the water monitoring system between current reporting of station data and reference coverage levels established by technical experts. Moreover, these gaps are most pronounced in developing countries, and have widened over the past 20 years around the world. The analysis is summarized in the following table:

Table 3
Reporting gap analysis of water data by type of monitoring system

	Station Reporting	**Country Reporting**	**Reporting Gap[1]**
Streamflow (GRDC)	By 2010, stations decline 40% since peak reporting in 1979	Declined from 142 countries in 1979 to less than 40 after 2010	Gap of 30,938 to 52,057 in current global database
Precipitation (NOAA)	By 2010, stations decline 31% since peak reporting in early 1980s	Over 180 countries reporting since the mid-1800s	Gap of 6,416 to 14,773 in current aggregated database
Water Quality Stations (GEMS)	By 2010, stations decline 41% since peak reporting in 1993	Total of 83 countries reporting since 1965, but only 16 after 2010	Not calculated as no targets by parameter.

[1] Reporting gaps are defined as the WMO recommended number of stations minus the number of reported stations in the specific database since 2010.

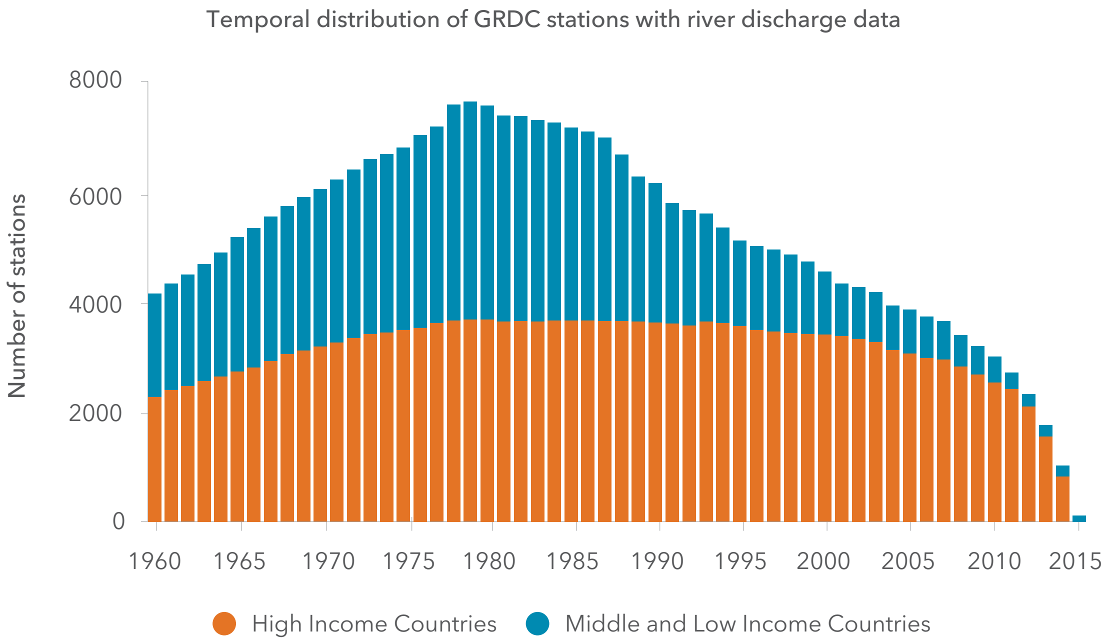
Streamflow analysis

Streamflow monitoring stations provide critical information about the spatial distribution and seasonal variation of surface-water resources, including flooding and indicators of droughts.

The Global Runoff Database maintained by the UN Global Runoff Discharge Center (GRDC) is the most comprehensive aggregator of streamflow data with geo-located stations (GRDC 2015). As seen in Figure 1, records show a peak in number of stations in the 1980s, a short-lived era of global concern around environmental health impacts and resource constraints that resulted in greater public spending and reporting on monitoring systems (Hannah et al. 2011). While the number of stations reporting in high-income countries was generally adequate for minimum benchmarking, this was not the case for middle and lower income countries and certain specific spatially defined topographies (Fekete et al. 2012; Hannah et al. 2011). Moreover, even at peak coverage of streamflow in the 1980s, coverage was still significantly short of the recommended number of stations. Using the WMO station density guidelines and CIESIN's Population, Landscape and Climate Estimates spatial data (CIESIN 2012), we assessed the gap between the number of stations recommended and those actually reporting (Table 4).

Figure 1

Active reported streamflow stations peaked in 1979 and have declined over 40% from this peak[2]



Source: GRDC 2015 Database; CIESIN analysis.

To understand the global station coverage and determine if there are any gaps, we combined the WMO station density guidelines with country-level aggregations of terrain types (CIESIN 2012). This calculated lower and upper estimates of required stations, the variation being due to definitions of mountainous terrain. This method yields a global reporting gap of roughly 31,000 – 52,000 stations.

This reporting gap could be significantly closed by making more station data publicly available.

[2]The data from GRDC was provided and analyzed in June-November 2015 and was not reflective of the most recent inventories in the database.

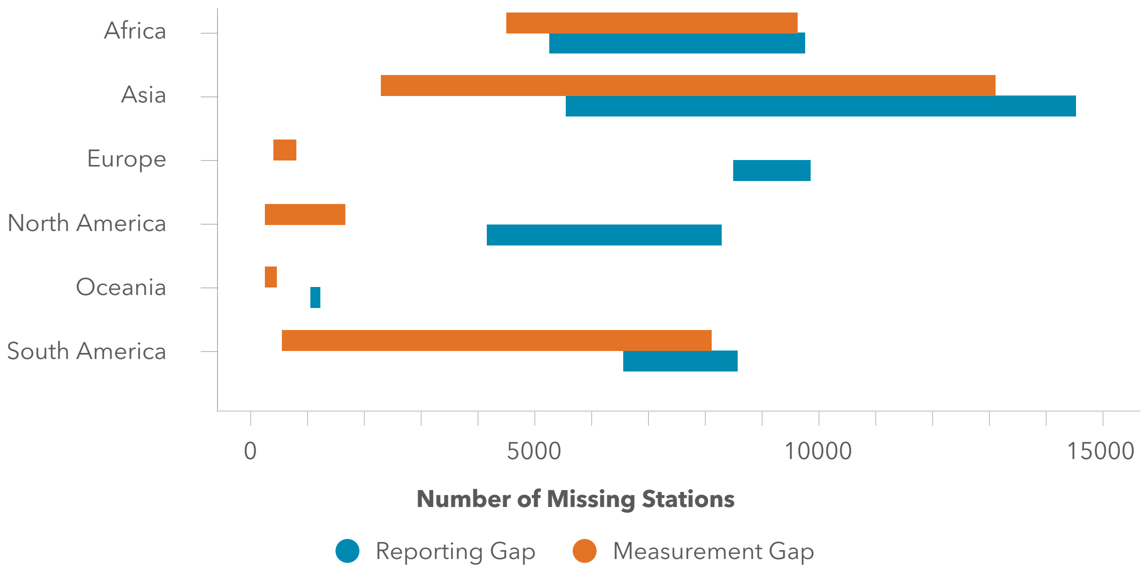
But precisely because reporting is so limited, it is difficult to accurately assess the more critical measurement gaps. Experts generally agree that high-income countries meet minimum standards for monitoring networks, but that many other countries — especially those in Africa and Central Asia — have deficient coverage of monitoring stations (Fekete et al. 2012; Hannah et al. 2011).

To provide indicative estimates on the potential measurement gaps, we developed a statistical model to estimate the underlying density of measurement stations using the assumption, based on expert input, that national levels of income per capita are correlated with the completeness of hydrological monitoring networks. Using these models, we estimated a global 'measurement gap' of about 8,500-33,600 stations.

Table 4

Gap analysis for reported streamflow stations

Regional Clusters	Number of stations recommended using WMO density guidelines		Number of unique stations reported in GRDC since 2010	Reporting Gap Analysis		Measurement Gap Analysis	
	Min -	Max		Lower estimate	Upper estimate	Lower estimate	Upper estimate
Africa	5,570 -	10,060	251	5,319	9,809	4,673 -	9,728
Asia	5,423 -	14,579	6	5,417	14,573	2,523 -	13,131
Europe	9,390 -	10,812	917	8,473	9,895	353 -	736
North America	5,592 -	9,778	1,567	4,025	8,211	211 -	1,695
Oceania	1,129-	1,257	99	1,158	1,030	202 -	310
South America	6,705 -	8,698	159	6,546	8,539	578 -	8,045
World	**33,937 -**	**55,057**	**2,999**	**30,938**	**52,057**	**8,540 -**	**33,645**



Note: *The range of recommended stations represents variation in the interpretation of mountainous areas, which have the highest density of recommended stations. The measurement gap analysis was calculated using income-based inferences for all countries, regardless of previous reporting to GRDC. The model assumes that countries who have surpassed defined wealth levels have installed the minimum WMO benchmarking stations. If countries already report equal or more stations, they are automatically included. Running these scenarios at two different wealth levels provides the upper and lower bound of the potential number of in-situ stations. This method was meant to circumvent the challenges of inconsistent reporting and provide a second modeled estimate of measurement gaps.*

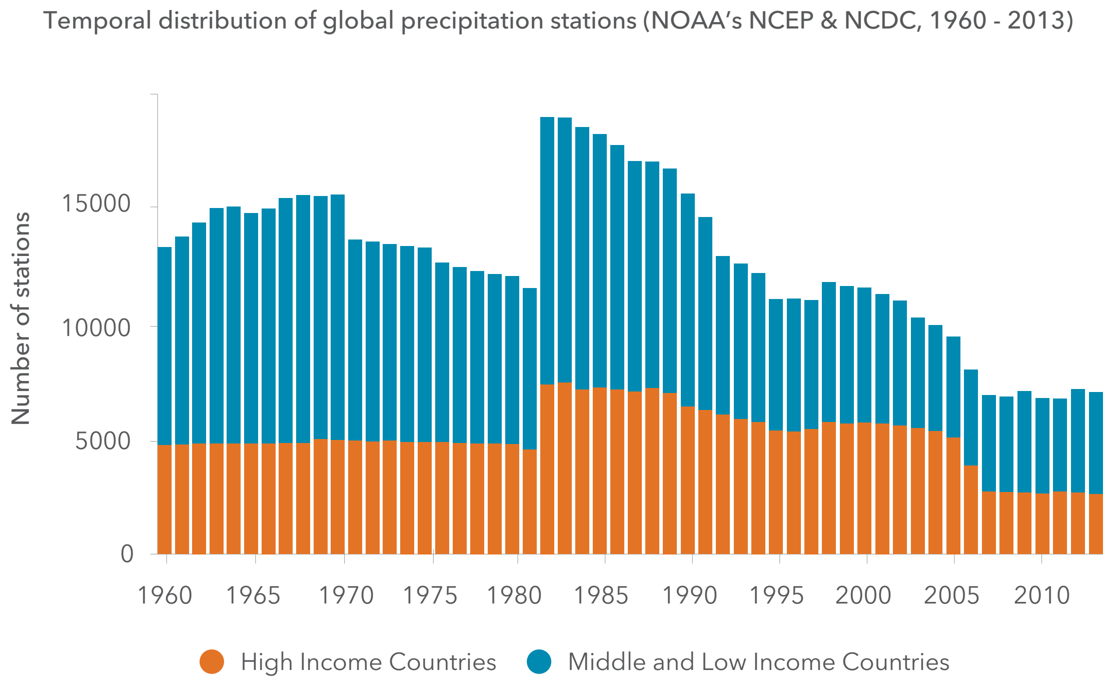
Source: Global Runoff Data Center (GRDC) 2015; WMO 2008; CIESIN analysis.

Precipitation analysis

Precipitation measurement stations are used by multiple water resource users, ranging from city planners managing drinking water reservoirs to farmers optimizing their use of stored irrigation water to climate scientists trying to predict likelihood of future droughts. As with streamflow, the public reporting of rainfall and climate monitoring stations also appears to be declining. Two historical datasets from the National Oceanic and Atmospheric Administration (NOAA) were combined to provide an estimate of the global coverage of known and aggregated publicly available rain gauges (Ropelewski, Janowiak, and Halpert 1985; Vose et al. 1992). These data sets, initially aggregated by the United States NOAA and hosted in the online Climate Data Library at the International Research Institute on Climate and Society, provide historic records from multiple government agencies. This includes over 180 countries with over 140,000 station-years, dispersed across 175 years of records, including some stations updated hourly (Menne et al. 2012). Similar to streamflow reporting, there was a significant spike in number of recorded precipitation stations in the 1980s with approximately 18,750 stations at the peak, and a decline in subsequent years to the lowest level of reported stations since 1960 (Figure 2). Today, there are fewer than 12,900 stations that have actively logged data since the year 2000; a 31% decrease from the peak number of stations. Unlike streamflow measurement, the peak coverage of recorded precipitation stations in the 1980s was greater than the recommended amount, but has recently fallen to levels that are slightly below the recommended coverage. Based on WMO guidelines, the number of stations needed globally is between 10,000 – 20,000 stations (Table 5). The reporting gap is smaller but still significant, between 6,500 – 15,000 precipitation stations.

Figure 2

Active precipitation stations peaked in 1983 and have declined over 30% from this peak[3]



Source: Ropelewski, Janowiak, and Halpert 1985; Vose et al. 1992, CIESIN analysis.

[3]The data from NOAA was provided and analyzed in June-November 2015 and was not reflective of the most recent inventories in the database.

Table 5
Gap analysis for reported rainfall and climate stations

Region	Number of Stations Based on WMO Density Guidelines		Number of Stations in NOAA after 2010	Reporting Gap Analysis	
	Low	High		Low	High
Africa	1,683	3,654	845	1,012	2,910
Asia	1,634	5,442	1,548	661	4,157
Europe	3,015	3,601	1,254	2,390	2,871
Americas	1,744	3,485	1,282	580	2,229
Oceania	360	369	253	172	181
South America	2,149	2,977	552	1,601	2,425
Total	**10,585**	**19,528**	**5,734**	**6,416**	**14,773**

Note: *All numbers are rounded to the nearest ten; small island estimates are rounded to the nearest 5. As a result, totals do not always sum.*

Source: CIESIN analysis.

Water quality analysis

Water quality measurement helps decision-makers understand and respond to risks related to public and ecosystem health by measuring the physical properties, chemical components, and organic and microbial variables of various types of water resources. Since 1978 the UN Global Environmental Monitoring System (GEMS/Water) has aggregated the ongoing status of global water quality data related to inland water bodies (UNEP 2017). Country-level reporting, as in other databases, remains voluntary. This database includes a range of 176 water quality parameters varying across station and country (UNEP 2014), with a total of 3,631 station-level points.

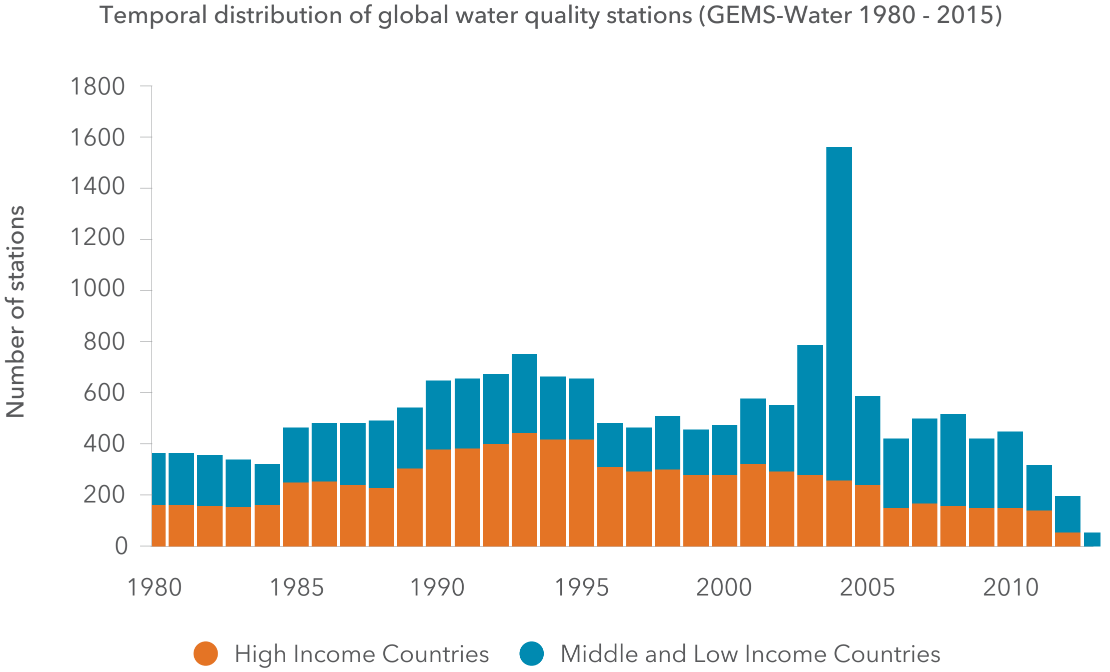
The historic analysis of stations, unlike the other databases, continues to increase until the mid-1990s, when it declines to a relatively stable number until 2010, when reporting declines sharply[4]. One large data transfer from Brazil created a large spike in the number of reporting stations in 2004, after which further data were not reported. Therefore, while the total number of reporting stations reached 1,568 in 2004, the annual average remains below 800 input points[5] (see Figure 3). A significant portion of the 3,600 stations provide only geo-location information of the station, not reporting actual water quality data. This practice explains the discrepancy in total numbers between the total stations and number reported each year. This data set shows another key trend: inconsistent reporting of individual stations from year-to-year. Only 35% of all the stations have submitted more than 5 years of data, although this is skewed by the large submission from Brazil. In sum, despite the lack of a reference level for water quality network density, public water quality reporting is sparse and inconsistent relative to flow and precipitation monitoring despite the obvious importance of water quality parameters for public health and environmental sustainability.

[4] This post-2010 decline in reporting is attributable to the recent transition of hosting responsibilities for the GEMS/Water Data Center from Environment Canada to the International Centre for Water Resources and Global Change at the Federal Institute of Hydrology in Germany, and is currently being addressed.

[5] We did not calculate gap analysis for this database as each water source type (river, lake, stream, groundwater) has different requirements for benchmarking and water quality parameters.

Figure 3

Summary of reported stations in GEMS-Water database



Source: UNEP 2017; CIESIN Analysis

Discussion and analysis

It is important to reiterate that in each case, these analyses reflect the number of stations that are reported in public databases, not the underlying number of extant stations. There are likely to be stations and sensors in place that are not being reported, which may be a result of malfunctioning equipment, lack of institutional capacity to report the station, not meeting technical collection standards or quality, or unwillingness to openly share data. Academic and policy research papers have repeatedly identified this challenge of obtaining reliable and continuous multi-year and high frequency data from many countries. For example, Dinku et al inventoried over 140 stations in Ethiopia, (vs. 29 reported in the NOAA collection); 60 stations in Zimbabwe (vs. 30); and 400 in Colombia (vs. 57). All four barriers need to be addressed but the result is the same: data that are not recorded and shared can be difficult to access and are likely to generate less social benefit than data that are openly shared and easily discoverable.

We addressed these reporting gaps by running several scenario analyses using varying national wealth thresholds to provide estimates of potential measurement density of streamflow stations. This assessment of the 'measurement gap' suggested that for streamflow data, about 50% of the 'reported data gap' is likely driven by the absence of physical monitoring stations, and thus requires expansion of the in situ monitoring station network.

Regardless of the cause of the reporting and measurement gap, this analysis reveals three important findings of concern. First, levels of publicly reported data are well below established benchmarks for station coverage. Second, there is a growing gap in reported data in three of the most widely available and globally comprehensive public water data sets. Third, these gaps are most severe in the developing countries of Africa, Asia and South America. Finally, there are reasons to believe that a significant proportion of the "missing data" in the gap analysis is attributable to the absence of stations, not just the absence of public reporting.

Estimating returns on investment

Clearly there is a gap between optimal levels of station density and actual reporting stations in global hydrological data systems, but that does not necessarily indicate a problem. After all, measurement costs money, as it requires designing, installing, operating, and maintaining a network of environmental sensors and research stations as well as further investments in technology, data management, and training to clean, verify and disseminate data. Decision-makers inevitably need to make choices about which parameters to monitor to support a broad range of uses, how to monitor these parameters using scientifically robust methods, and how to collect, manage and share the resulting data in a cost-effective way.

The question is whether decision-makers are wisely avoiding investments that do not yield adequate returns, or whether there is a market failure leading to sub-optimal provision of public access to hydrological data. After all, water information is a public, non-rivalrous and non-excludable good, which in economic theory suggests the potential for sub-optimal levels of investment absent adequate public investment. To explore this question, Xylem partnered with the Nicholas Institute for Environmental Policy Solutions at Duke University to conduct a detailed review of economic literature assessing the returns on investment from hydrological monitoring programs (Gardner, Doyle, and Patterson 2017).

Research databases were scanned for academic and peer-reviewed studies that quantified a benefit-cost ratio for public water data; this yielded 29 estimates benefit-cost ratios from 21 articles, ranging from the academic literature, government (e.g. USGS, OMB), inter-governmental agencies (e.g. World Bank), and NGOs that account for both costs and benefits of water information.

While many of the studies faced methodological limitations related to the measurement of costs and benefits, the picture that emerges from this synthesis of the analytic literature is striking. The median benefit-cost ratio of water information was 4, with a range of 0.04 to 33 (Figure 4), suggesting that a dollar of investment in public water data systems generates, at the median, four dollars in social benefit. In 86% of the analyses, authors reported that the benefits of water information are greater than the costs. There are also reasons to believe that this benefit-to-cost ratio is understated as most studies focused on a limited subset of the potential beneficiaries from a given public hydrological dataset.

Though the methodological limitations of the underlying studies suggest a degree of caution is warranted, this analysis suggests that the world is leaving significant value 'on the table' by under-investing in public water data infrastructure. These invisible losses take the form of inefficient infrastructure investment decisions, sub-optimal operational decision-making by water users, and avoided losses from adverse water conditions that might have been anticipated with better, dense, more accessible water data. By contrast, making renewed investments in such data infrastructure could unlock significant benefits that are difficult to measure because they are difficult to specify ex ante; once datasets exist and are freely available, they become a powerful foundation for innovation and a diversity of use cases that may create substantial social benefit.

Figure 4

Benefit-cost ratio of public water data, from synthesis in Gardner et al. (2017). Median benefit-cost ratio is ~4. Red line indicates benefit-cost ratio of 1.

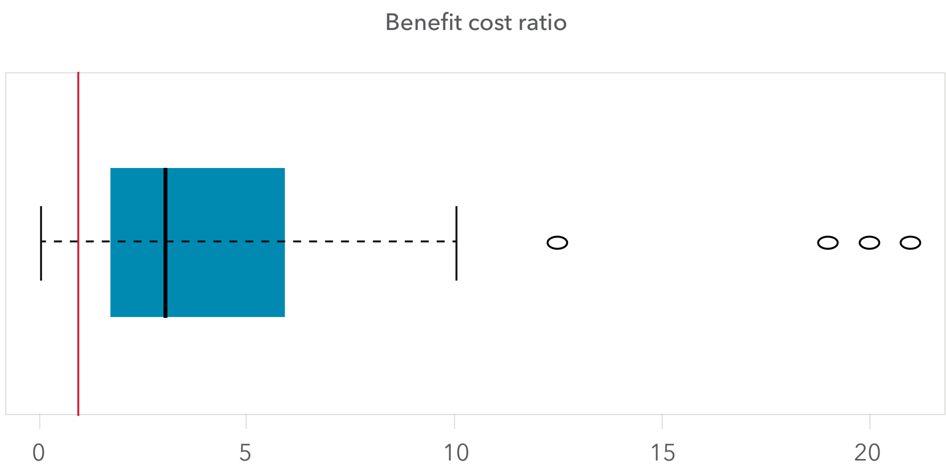
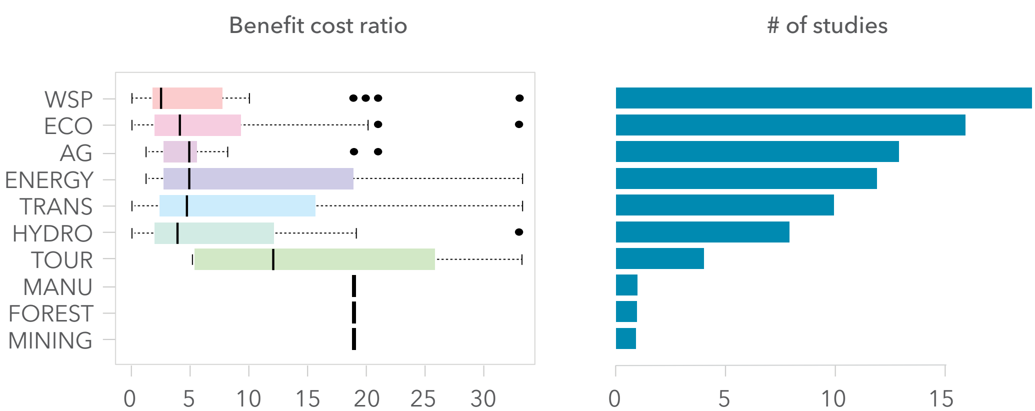


Figure 5

Benefit-cost ratio across sectors (left) and number of benefit-cost estimates within each sector (right). Many values are counted multiple times because estimates for multiple sectors were aggregated at the same study.



Conclusions and recommendations

Several conclusions emerge from this analysis:

- Demand for public water data will continue to increase as demand-driven scarcity and supply-driven variability both increase with macro trends such as population growth, urbanization and climate change. A robust network of continuously reported in-situ monitoring stations is fundamental to manage the present and underpin models of the future.
- Public water data systems serve a broad variety of needs vital to many users and objectives, including framing within the Sustainable Development Goals. Yet they are not currently available at levels and in platforms considered satisfactory by their users.
- Public water data infrastructure is not delivering water data with information density (either spatial or temporal) consistent with the expectations that technical experts (e.g., the World Meteorological Organization) have established as an appropriate standard.
- Moreover, public water data infrastructure has been declining in coverage over time across a number of critical parameters and organizations.
- The current gap and declining trend line are both concerning because public water data infrastructure tends to have highly positive benefit-cost ratios. The world is leaving money on the table by failing to invest at appropriate levels.
- Benefit-cost literature demonstrates an approximate 4-to-1 return on investment for public water data, cutting across themes and applications.
- Recent activity since this report was first drafted, related to ongoing mobilization around monitoring the Sustainable Development Goals, gives hope that more resources and attention will be given to providing hydrological data as a global public good.

To address these issues, decision-makers can take the following actions:

- **Conduct a national-level assessment of hydrological monitoring capacity to feed into global data sets.** Data sets on the current state of hydrological monitoring systems are sparse. Reframing monitoring around minimum reporting standards could motivate a more comprehensive inventory and analysis of national monitoring systems, with efforts to document and understand the root causes of declining coverage. This may be occurring already under the various UN Water initiatives related to monitoring SDGs. Findings should engage public and private stakeholders to support filling identified gaps.
- **Commit sufficient resources.** Although we did not perform a detailed analysis of current funding levels for water monitoring systems, it is clear that the declines in monitoring stations cannot be reversed without incremental funding. This gap analysis methodology could help refine earlier costing work by the United Nations Sustainable Development Solutions Network (SDSN) by providing an indicative basis for the investment needs at a country or regional scale for both increased sensor systems and improved data aggregation. (Espey et al. 2015) Human resources and institutional capacity will also need to be built in order to ensure that countries have the ability to share and analyze the data they collect. Finally, there is an often-overlooked cost to making data publicly available that needs equal advocacy from the international policy and scientific communities.
- **Explore new models for data sharing that reinforce existing validated databases.** Recognizing that substantial data exists beyond the spreadsheets of government-validated sources, but often not easily discoverable or available to public users, seek new models for data sharing that are supported or endorsed by international forums.

Conclusions and recommendations (continued)

- **Elevate monitoring from technical to principal negotiating forums.** Establishing a robust water data infrastructure is vital to the achievement of the Sustainable Development Goals and climate resilience. Reversing declines in hydrological monitoring data collection and data sharing should be the subject of discussion by principals at negotiating forums, such as the UN Framework Convention on Climate Change, not confined to discussions in subsidiary technical bodies. This could include more formal mechanisms for annual accountability for reporting by data producers to the database platforms.
- **Continue to develop standard frameworks to ensure comparability and quality of water monitoring systems.** The lack of standardized data reporting frameworks and tools for implementing and managing the water monitoring system results in a heterogeneous global system that is impossible to benchmark, improve, and manage. Continuing to standardize frameworks for reporting and integrating data will be not only useful, but necessary if (and when) efforts are made to link to non-governmental data, including academic, private sector or citizen-science data. The goal should be a minimum density of stations that have standardized protocols to also ensure data quality and comparability.
- **Automate data reporting through new real-time monitoring technologies.** Many in-situ sensors are now available to provide automated transfer of data to cloud services. This has been done most effectively in the climate and precipitation monitoring systems and reduces transaction costs of data processing and transmission; water quality sensors are increasingly available and should be integrated into cloud services as well.
- **Prioritize critical gaps, including streamflow stations and under-covered regions.** Our analysis found that streamflow monitoring represents a significant gap between current coverage and good practice, even though streamflow monitoring is among the most valuable components of the water monitoring system. Investments should also be targeted toward improving coverage in developing countries, specifically in Asia, Africa, and South America.
- **Combine data technologies to increase cost-benefit ratios.** Design information systems so that integration of data technologies is mutually beneficial, such as satellite imagery and in-situ monitoring. This approach sees each marginal investment in data technologies as complementary towards the total potential of other data technologies if efficiently combined and reconciled. This could greatly increase the cost-benefit ratios (Levy 2017).

Water data can play a vital role in helping stakeholders solve many of today's most important global challenges. Without these data, decision-makers are 'flying blind' into a world of greater scarcity, variability and climate risk. By investing to reverse the global "data drought" in public water data infrastructure, decision-makers can establish greater certainty, unlock innovation, and create significant social, economic and environmental value in support of the Sustainable Development Goals.

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2) a leading global water technology company.

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