The Value of Water Monitoring

AQUATIC Informatics

eBook

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Contents

Executive Summary

The benefits of hydrological information vastly outweigh investments made in water monitoring. Whereas investment in monitoring is tightly constrained by administrative processes, hydrological information supports the beneficial resolution of many water issues providing unbounded value.

Hydrological information is the *lingua franca* for communicating the capacity of a watershed to accommodate diverse demands. Many social, economic, and environmental decisions hinge on the weight of evidence provided by water monitoring. Do we have enough relevant and trustworthy information to tip those decisions toward a high return on investment in managing our water resources to ensure our collective water security?

This eBook proposes that additional funding is required to close the growing gap between water monitoring capability and the rapidly evolving need for evidence-based policies, planning, and engineering design. An in-depth look at the public benefits of water monitoring and the value of hydrological information in informing better decisions, as well as a review of published economic studies on environmental monitoring, together provide the basis for forming persuasive arguments that are sensitive to local politics and priorities to address this global deficit in funding.

Who needs to read "The Value of Water Monitoring" and why?

- Water resource managers — to build a compelling business case in support of their water monitoring programs.
- Public administrators — to learn how to evaluate the return on investment in water monitoring for optimizing the public good achieved from public expenditures.
- Water monitoring specialists — to learn how to efficiently and effectively manage their water data in order to maximize potential value and return the highest possible benefit.
- Hydrologists, biologists, health professionals, and water resource engineers — to influence the design and development of water monitoring programs in order to enable continuous improvement in their ability to solve present and future problems.
- Taxpayers — to inform politicians of the need to avoid having to pay, in perpetuity, for the inevitable harm resulting ignorance of the condition of shared watershed resources.
- Environmentalists and indigenous watershed stewards — to ensure that the health of their watersheds are provided for with sufficient monitoring to enable a sustainable future.
- Socially responsible individuals — to ensure that the pre-conditions for fair play in the sharing of our most valuable common-pool resource are in place.
- Investors — to learn how the risks, profitability, and security of their investments in industry, natural resources, and major capital projects are sensitive to the assumption that the water that these investments depend on is secure and well managed.

Water monitoring is an essential public service. The resulting hydrological information enables evidence-based decisions about water. Public safety, food supply, energy production, social justice, the environment, health, and prosperity all have high inter-dependency on the water within any watershed. Policies, planning, adaptive management, and engineering decisions need reliable information about the variability of water quantity and water quality over time and in space. The role of the watershed — in the context of the sum of the impacts of human activities — must be understood in order to learn from the past, manage the present, and create a secure water future.

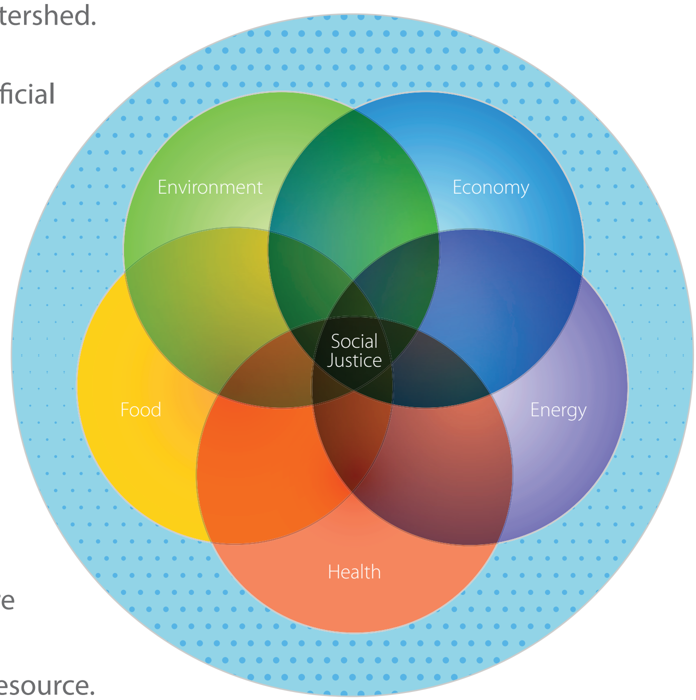
Providing for a safe and secure source of water to support all requirements is expensive. Protecting people, property, and transportation infrastructure from floods is expensive. Developing sufficient capacity to survive periods of drought is expensive. Making wrongful assumptions about the quality and/or the quantity of water in providing for these essential public services is expensive. Given the high cost of hydrological ignorance, a sustainable supply of relevant, reliable, and trustworthy hydrological information is essential to ensure the wise use of public funds.

Water is a versatile resource. At each point along its path to the ocean, water serves some essential function: transforming the landscape; transporting substances by flotation, in suspension, or in solution; giving life; and providing energy. Each of these functions alters the water in some way, changing its quality and/or its availability to fulfil its role at downstream locations. These functions are extensively exploited for human benefits with a sum of impacts that affect fundamental environmental services and the security of all stakeholders in the watershed.

Beneficiaries sharing a common source of water can co-exist largely unaware of each other when clean freshwater is abundant. However, as the abundance — or quality — of water becomes limited, even if only during certain periods of time or in certain locations in a watershed, then any one use can be detrimental from the perspective of foregone benefits for other purposes. For this reason, water must be managed as a common-pool resource.

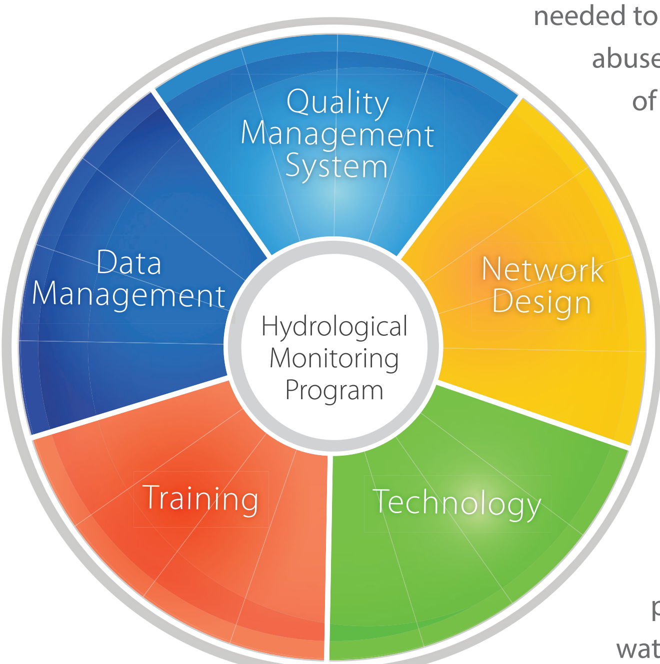
A common-pool resource is prone to over-use, misuse, even abuse. Over-use occurs when independent beneficiaries wrongly assume that there is an over-abundant supply resulting in more usage than the source can support. Misuse occurs when unintentional harm is done to the common-pool as a result of ignorance of the harm being done. Abuse occurs when a beneficiary of the common-pool knowingly exceeds their "fair" share, or otherwise causes harm to the common-pool, in the certainty that the transgression is undetectable.

Relevant, reliable, and trustworthy hydrological information is needed to prevent over-use, misuse, or abuse of water in any watershed.



Within a common-pool the degree of overlap of beneficial uses is a function of both the number and extent of special interests. Overlap is only possible because of the ability of water to be used, returned to the environment, and then re-used at a downstream location for the same, or a different, purpose. Re-usability, hence the potential for optimizing net benefit, is severely limited by over-use, misuse, and abuse of shared water.

It is relatively easy to identify the objective requirements of a few major beneficiaries (e.g. hydropower, agriculture, and drinking water) to ensure their needs are met. Less apparent are the objective requirements of all other beneficiaries of the shared resource. Social justice is at the intersection of all uses of water, making this value highly dependent on the existence of relevant, reliable, shared, and trusted hydrological information.



A well-conceived water monitoring network provides the information needed to protect against over-use, prevent misuse, and detect abuse of the common-pool. Open, transparent monitoring of the common-pool breeds trust amongst stakeholders. Trust in each other, trust in the process, and trust in the data are the foundational building blocks for fair and sustainable allocation of benefits from the common-pool.

Impatience with the growing disparity between publicly available supply and demand for relevant, reliable, and trustworthy hydrological information is fueling an industry full of technological solutions. An extensive array of water monitoring devices is emerging to collect more raw water data, for more parameters, at higher frequency. And the collection of water data is being ever more distributed as public budgets decline and private organizations invest to fill gaps in the water data they require.

Paradoxically, the gap between supply and demand for actionable hydrologic information continues to grow in spite of unprecedented growth in the volume of raw water data. Public environmental monitoring agencies need additional funding. Watershed monitoring needs to be strategically planned and coordinated in order to be efficient and cost effective. In some cases, the most trusted agency needs to expand their station density; in other cases, it is better to devolve the responsibility for monitoring to local levels of government. If devolution is the solution, then the level of funding must be adequate to support the implementation of a trusted quality management framework. Agencies that are relatively new to the role of water monitoring are often data rich but information poor as a result of investing in water monitoring technology without sufficient investment in a proper data management system.

In order to inform decisions and influence meaningful change, water data must be processed into hydrologic information that is relevant, reliable, and trusted. This information must be shared to enable the highest resolution view of a watershed, and to be effectively used it must be inter-operable. Expectations of new insight and understanding of the state of the watershed are shattered as spreadsheets become increasingly bloated with uninterpretable data that are isolated and out of context from all of the other data in the watershed.

The standards of practice used by the most trusted water monitoring agencies in the world can be used to produce highly-valued hydrological information relevant to any watershed — information that is inter-operable and usable across agencies. These standards of practice are being incorporated into commercial off-the-shelf (COTS) water data management software, as leading agencies around the world adopt these solutions and influence the software development roadmaps.

Conformance with data management best practices that facilitate efficient and effective workflows and data sharing will help close the global hydrologic information gap. The production of high quality hydrological information from water data is no longer the exclusive realm of national-scale data providers. More gauges and better data management are both important. Investment is needed to get more boots on the ground, complete with better monitoring equipment. Making the most of this data investment requires software and systems to transform water data into valuable hydrologic information.

The return on investment on proper water data management is unbounded. Regrettably, data collected with disregard for widely accepted standard of practice can be disinformative (i.e. indicating watershed response characteristics that are not true), resulting in disbenefit (i.e. resulting in wrongful decisions). Fortunately, the benefits from hydrological information — complete with properly managed metadata to make it searchable, discoverable, and accessible — perpetually increase in value.

The costs of a complete water monitoring program — including network design, station installations, field operations, and data management — can be evaluated in relation to the benefits resulting from use of the hydrological information it generates. Studies have been designed to look at the benefit/cost of incremental adjustments to the size of a network as well as incremental adjustments to the length of period of record. A review of these studies reveals a consistently positive return on investment, which varies in value depending on how the hydrological information is applied.

Despite showing a positive return, all investigations of benefit/cost are limited in scope. The costs of operating a stream gauge are tangible and immediate, but many of the benefits are either intangible or deferred. The value of water monitoring for social justice or environmental sustainability has never been evaluated. Most studies are limited to investigating the benefit of data for informing engineering decisions for the design of specified water infrastructure. This means the economics of water monitoring are even more positive than the published studies indicate.

The need for evidence-based engineering decisions is greater now than it has ever been as we face climate uncertainty, increased pollution of our limited fresh water resources, and the increasing demands of our growing world population. It is increasingly the case that engineers have to study available hydrological information even more closely to be able to detect change — and to call on information from varied monitoring sources to correctly attribute cause — in order to design infrastructure that is robust to new and emerging watershed response characteristics.

However, it is increasingly the case that the primary motivation for water monitoring has little, or nothing, to do with the end-use purpose of engineering design. The design of water infrastructure ultimately benefits from all relevant, trusted, and accessible hydrological information, even if collected and managed for other purposes, so these benefit/cost ratios remain relevant as justification for investments in water monitoring. These ratios are a lower boundary of value while the benefits for social justice and environmental sustainability wait to be discovered. Disconnect between the distribution of benefits and the responsibility for costs means that a high benefit/cost ratio does not necessarily ensure that water monitoring will be adequately funded.

The benefits of water monitoring are widely distributed, whereas the costs are highly concentrated, usually within an agency that has limited access to sufficient resources. Gaps in funding for water monitoring result in gaps in hydrological information which, in turn, result in critical gaps in our ability to control our own destiny. A secure water future is dependent on closing these gaps. We must close the funding gap.

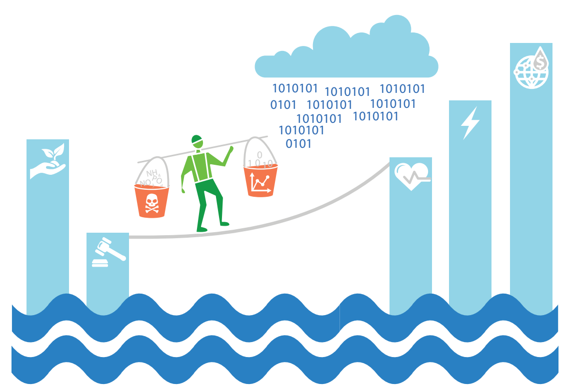
It is a truism that "you don't get what you deserve, you only get what you negotiate." People actively engaged in water monitoring are not naturally inclined to negotiate. We are drawn to a career in the field, not by our skill as communicators, but by our skill in solving complex problems in varied, and sometimes difficult, environmental conditions. We have an underlying faith in the process of empirical science for resolving essential truth. The evidence we produce should speak for itself.

In practice, the business case for water monitoring is often not enough. There are several open-ended arguments that speak against the use of public resources for funding water monitoring. The security of our water future should not be put at risk because of flawed logic, obscured in semantic confusion. This confusion must be answered with articulate, evidence-based, unambiguous statements about the public good served by public investment in water monitoring.

The sum of benefits from the many and varied uses of hydrological information exceeds quantification. A qualitative understanding of the net value can support a more holistic evaluation of the true benefits of water monitoring. As such, it is useful to consider water monitoring in a country where responsibility for water monitoring is closely aligned with an ethic of watershed stewardship.

The Tasman District on the north end of the south island of New Zealand has an abundance of clean, freshwater. It could be argued that, apart from the threat of flooding, such abundance would mean there is little need for investment in water monitoring. In fact, investments in water monitoring infrastructure are healthy and sustainable.

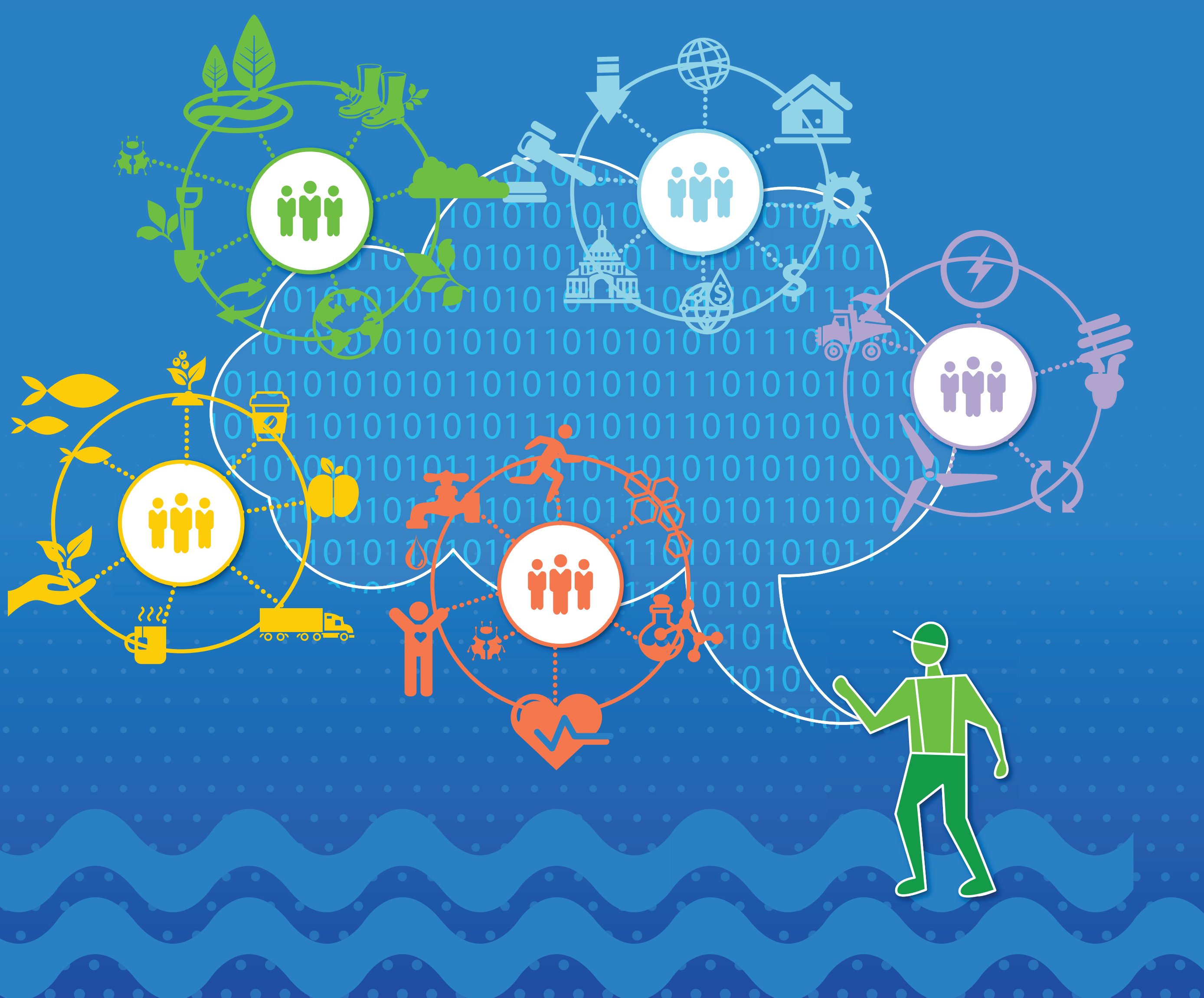
The value of water monitoring as the connection between diverse social, environmental, and economic interests is inestimable. Hydrological information bridges all differences in the objectives of the many and various beneficiaries of the common-pool resource.



This eBook is intended to help water resource professionals around the world frame locally meaningful discussions on how to best prepare for a secure water future. Wise, fair, and sustainable use of our water resources is dependent on wise, fair, and sustainable funding for water monitoring. The supply of relevant, reliable, and trusted hydrological information is constrained by bureaucratic processes that control the disbursement of public funding. Many jurisdictions around the world are poorly informed of the essential public service provided by water monitoring resulting in inadequate allocation of public funds. Solutions to many of the most pressing problems of the 21st century will require alignment of the priority for funding of water monitoring activities with the critical importance of water to our collective security.

Chapter 1: Hydrological Information Is a Public Service

The public is served by activities that ensure harmony, security, and well-being. Our dependency on a reliable supply of clean freshwater is one of the greatest threats to our economy, our food supply, our health, our environment, and our willingness to share water. Hydrological information brings these threats under our control.



Water monitoring creates hydrological information that is central to many inter-connecting activities that are vital to our economy, our health, our safety, and our environment. Too often, existing water monitoring networks produce insufficient information to ensure that water resource decisions are adequately supported by physical evidence (Hannah et al. 2011, Grabs 2009). These critical gaps in available hydrological information can be substantially reduced by additional investment in monitoring (UNU-IWEH 2015, Marsh 2002). Clearly, an increase in funding for water monitoring will close these knowledge gaps, improving outcomes for all aspects of water management.

In most cases, water monitoring networks are, and must be, publicly funded (Cordery and Cloke 2010). A clear and coherent understanding of the public good served by water monitoring is essential to support the wise allocation of public capital and operating budgets.

Water has an important influence on national economies, yet its economic impact is largely unaccounted for (UNESCO 2012a). The Auditor General of Canada, for example, reports that the measurable contribution of water to the Canadian economy is in the range of C$7.5 to $23 billion annually and recommends that the amount invested in monitoring should reflect this economic value (Environment Canada 2010). However, the reality is that "new" money for water monitoring is very hard to come by.

There is intense competition for spending on public goods and services. Public demand for obvious services (e.g. security, highways, schools, and hospitals) must be balanced against the importance of less directly obvious services such as water monitoring. The connection between the role of water in public affairs (e.g. public safety, energy security, and food security) and the role of water monitoring in ensuring public security has not been well explained. Indeed, Cordery and Cloke (2010) and Grabs (2009) attribute inadequate funding for water monitoring to insufficient awareness of the value of hydrological information.

This poor understanding in the value of hydrological information results in a heavily discounted perception of the role of water monitoring as a public service. This lack of understanding is deeply institutionalized, creating a fundamental disconnect between the authority for monitoring and accountability for the consequences of decisions made without adequate information. In fact, Brown and Dick (2001) determined that the supply-demand imbalance exists because users of information have no direct influence on the supply of that information. Furthermore, monitoring requires ongoing, long-term, and disciplined commitment that does not fit well with the cyclical nature of political priorities and associated budget allocations. These deeply entrenched characteristics of funding within the public service help to explain why funding for water monitoring has not kept up with the need for a more accurate, reliable, and complete picture of the state of our watersheds.

In a threat matrix of societal risks (Figure 1 on the following page) water crises are more impactful — and more likely to occur — than any other imminent threat (WEF 2015). Furthermore, the trajectory of this threat does not bode well for the future. High impact water events are in the popular news almost every day, yet absent from public discussion is the role that further investment in the infrastructure for water data, information, and knowledge will have for our collective security in a changing world. Governments invest in

“Military Intelligence” to protect their nations from threats of conflict. Addressing the life-critical threats from water will require an equivalent role and investment in “Environmental Intelligence.”

Figure 1. Threat matrix of the vector of impact and likelihood of Societal Risks (WEF 2015)

Ironically, threats to sustainable water resources are often an unintended consequence of deliberate planning and foresight. Inconveniently, solutions for one threat to society (e.g. energy security) can exacerbate a threat to another aspect of society (e.g. food security) whenever water is the connecting element. The impacts of dams, reservoirs, flow regulation, diversions, export, urban development, manufacturing, thermal energy, agriculture, forestry, mining, and petroleum production are integrated and cumulative (NWRI 2004). Adverse, unanticipated consequences are, too often, an unwelcome result of inadequate hydrological guidance in support of integrated planning, policy development, and multi-objective decision-making.

Sustainability requires planning over long time-scales. The life-cycle of water infrastructure can span decades to centuries. There is a substantial cost of ownership for water management infrastructure. For example, the American Society of Civil Engineers estimates that US$21 billion in funding will be required to repair or replace 14,000 high-hazard dams and US$1 trillion will be required to repair or replace aging drinking water infrastructure (ASCE 2013). The consequences of deferring investments in water infrastructure can be highly impactful on the tax base. Deferring investment in water monitoring means there will be too little information, too late, for the wise use of major capital budgets (NHWC 2006).

Water monitoring is an essential component of evidence-based decision-making for managing present, and preventing future, water crises (Grabs 2009). Hydrological information supports the continuous advancement of hydrologic science (Hannah et al. 2011, Spence et al. 2007). Hydrological information reduces risk exposure to extreme events (Archer 2010, Barbetta et al. 2009, Sweet 2008, NHWC 2006, Black and Tavendale 2004, Bayliss and Reed 2001, Walker 2000, Cordery and Cloke 1994).

Hydrological information is required for resource assessments, regulatory purposes, and river management, and to direct policy by helping draft legislation (Marsh 2002, Sutcliffe and Lazenby 1990). Hydrological information supports the achievement of balance for multi-objective, multi-stakeholder decision-making.

> "Without high-quality data providing the right information on the right things at the right time; designing, monitoring and evaluating effective policies becomes almost impossible."
>
> "Data are the lifeblood of decision-making and the raw material for accountability."
>
> — A World That Counts: Mobilising the Data Revolution for Sustainable Development, United Nations 2014

Hydrological information is the result of systematic water monitoring. Unfortunately, the role of water monitoring as a public service is poorly understood. Threats from water, and to water, are competing for a greater share of public spending in many jurisdictions around the world. **The cost of robust and reliable water monitoring may be less than the rounding error in the public spending needed to address many neglected, as well as new and emerging, water priorities.** Funding for water monitoring is an ethical requirement of responsible governments to ensure that public investments result in critical water infrastructure that is capable — and sustainable — within the context of the water sources and limitations within all watersheds.

Water is a shared resource, whereas the responsibility for water management is often highly compartmentalized with overlapping and/or abutting jurisdictions within any watershed. One critical role for the public service is to ensure harmony in the sharing of this common-pool resource. Reliable, trusted hydrological information shared openly within any watershed is the basis for harmonious governance.

Chapter 2: Water Is a Common-Pool Resource

Water enables. Water destroys. Most importantly, water connects. It is as if everything we care about is in a state of suspension, dependent on the water that can enable, or destroy, our economy, our environment, our health, safety, and well-being. The point of saturation is reached when no further demands can be made of the watershed without losing something that we have always taken for granted. What are we willing to give up first? How long do we have before we have to make those hard choices?

First and foremost, we must strive to ensure that there is enough clean water available to everyone, everywhere, and all of the time to meet basic human needs. Paradoxically, we also depend on water to dispose of all manner of substances toxic to our very existence. Water allocation has to be managed in a cumulative effects framework to achieve balance amongst such competing priorities.

> "It is now universally accepted that water is an essential primary natural resource upon which nearly all social and economic activities and ecosystem functions depend." — UNESCO 2015

Past history of water demand is not a good predictor of future stress on our water sources. For example, the cost of adapting to a 2 °C rise in temperature is estimated to require expenditures between US$70 to $100 billion per year, of which 15 to 20% will be for water supply and flood management (World Bank 2010). These new investments must be managed in the context of competing demands for energy, food, industry, human settlements, ecosystems, and security.

More water from the common-pool will be needed for the energy sector. Universal energy security for basic human needs and productive uses will need to include an additional 2 to 3 billion people by 2030. Mitigation of the carbon footprint for such growth in the energy sector will require lowering global energy intensity by 40% (United Nations 2010). Hydropower has the lowest carbon emissions of any of the conventional energy sources. It is highly likely that hydropower expansion will have to contribute clean energy to meet the expected 60% increase in energy demand over the next 3 decades (Steer 2010).

Water is required for almost all energy production, not just hydropower. Extraction of most forms of non-conventional oil and gas (e.g. oil sands, shale deposits) is intensely water consumptive. Thermal and nuclear power plants require large volumes of cooling water. Bioenergy consumes and alters water through forestry or agricultural practices. Moreover, producing enough biofuel for 5% of global road transport would consume at least 20% of the total quantity of water now used for agriculture (WEF 2011). Clean wind and solar energy sources are made economically viable only if their intermittency can be mitigated by reliable and dispatchable hydroelectric sources.

If clean energy is in limited supply, desalination for future water supply is much less attractive than water importation. Stokes and Horvath (2009) estimate that meeting the water demand for California using desalination would require 52% of the state's electricity and more than double greenhouse gas emissions relative to water importation.

Food security is perhaps most increasingly dependent on water from the common-pool. Water for food production already accounts for about 70% of global freshwater withdrawals (UNESCO 2012b). Steer (2010) estimates that 45% more agricultural water will be required by 2030 to feed 8 billion people.

Water for irrigation is sourced from rivers, lakes, reservoirs, and groundwater. Inadequacy in supply from rainwater or surface water sources is often compensated by groundwater extractions. The cumulative depletion of groundwater in the United States since 1900 is about 1,000 km^3. Most of this depletion has occurred in the last few decades with a 25 km^3/yr rate observed for the period from 2000 to 2008 (Konikow 2013). Groundwater extraction has negative impacts on the availability of surface water, aquatic ecosystems, and the water quality and aesthetic quality of streams and rivers (Barlow and Leake 2012).

Agricultural production in both irrigated and rain-fed systems affects water flow in the landscape (NWRI 2004). The combination of changes in surface infiltration and patterns of surface and sub-surface flow can result in increases in both peak runoff and silt load and decreases in both base flow and groundwater recharge. Food processing plants use tremendous quantities of water to ensure a safe food chain. The quality of surface water and groundwater downstream of agricultural uses is deteriorating as a result of increased loadings of sediments, nutrients, pesticides, and pathogens. These effects of agriculture are creating a growing need for hydrological information at much finer temporal and spatial scale than is routinely available (Lins 2008).

The right to use surface water for irrigation varies by jurisdiction. For example, the principle of prior apportionment (i.e. first in time, first in right) is prevalent in western North America, whereas the principle of riparian water rights (i.e. landowner frontage rights) is prevalent in eastern North America. In either case, the rights of any one individual are conditional on the rights of others. It is increasingly the case that archaic laws, confounded by a long history of complex legal precedents, are resulting in over-allocation of scarce water. Timely and reliable hydrological information is needed to keep farmers productive in their fields and out of the courtrooms.

Economic prosperity is dependent on water from the common-pool. Economic security depends not only on energy and food, but it also requires raw materials, manufacturing, and reliable transportation systems. Forest management activities control wildfires and insects for the benefit of timber harvesting, all of which alter streamflow quality and quantity. Mining and manufacturing activities require large volumes of water for extraction, concentration, processing, and waste containment or disposal. Vital transportation corridors for roads, railways, pipelines, and telecommunications are vulnerable with respect to their alignment with flood plains and innumerable stream crossings. Water from the common-pool enables a growing economy, and economies of scale are changing the distribution of people around the world.

Global economic expansion is driving an unprecedented migration from rural to urban communities. The resulting urban development interferes with the hydrological cycle degrading the aquatic environment, water quality, and groundwater (American Rivers 2002). Urban growth is intensifying demand for clean water and wastewater disposal, both of which are essential for human health.

Public health is dependent on water from the common-pool. The World Health Organization (WHO) estimates 3.5 million deaths per year (including over 1900 children deaths per day!) result from inadequate water supply, sanitation, and hygiene. The total burden of disease could be reduced by 10% by solving these issues with better management of water resources (WHO 2008). Reliable hydrological information is badly needed to improve access to safe drinking water and basic sanitation. Critical gaps in monitoring is highlighted as a key challenge by the World Health Organization (WHO 2014). The rate of urban growth has outstripped the capacity of aging water infrastructure. Innovative solutions for infrastructure renewal are urgently needed, and these solutions will depend on our knowledge about the quantity and quality of all available water sources.

Public safety is dependent on the management of water in the common-pool. Urban density is highly concentrated in, and near, floodplains, deltas, and river confluences for historic reasons (e.g. transportation nexus, food, and water supply), increasing exposure to flood risk. There are many manifestations of floods, some which should be prevented (e.g. dam failure), some which should be avoided (e.g. flash flood), some which should be directed (e.g. levee or floodway), and some which should be accommodated (e.g. for vital in-channel maintenance, floodplain rejuvenation). In all cases, even when in excess of immediate requirements, water needs to be monitored and understood in order to be better managed (Archer 2010, Sweet 2008, NHWC 2006, Black and Tavendale 2004, Bayliss and Reed 2001, Walker 2000, Cordery and Cloke 1994). The state of the watershed upstream of these regions of high flood-risk exposure is increasingly important.

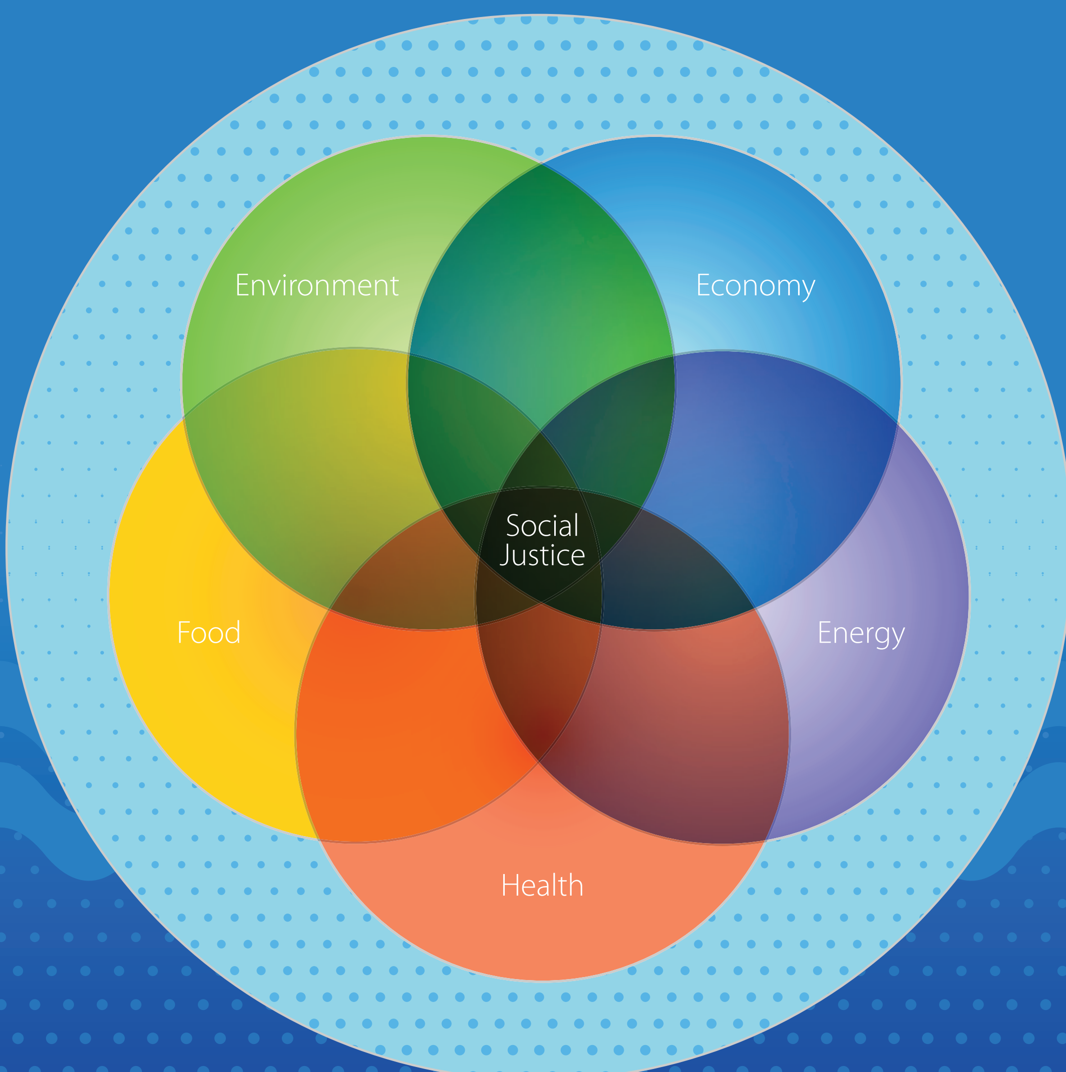
> "Water's role in underpinning all aspects of sustainable development has become widely recognized." — UNESCO 2015

A sustainable environment is highly dependent on water in the common-pool. Human interference with the hydrologic cycle is at the expense of flows that enable healthy ecosystem form and function. Freshwater systems and aquatic habitats are sensitive to changes in quantity, quality, and timing of streamflow. The most certain path to a future that has drinkable, swimmable, and fishable water is to avoid doing harm to the geophysical and biological integrity of our water sources. Sustainable development requires hydrological information (UNESCO 2015, Cordery 2001).

When water is sufficiently abundant, many distinct activities can co-exist in the common-pool with little direct interaction or need for cooperation. However, it is increasingly the case that watersheds are reaching a point of saturation, where any change in water use has deleterious consequences for existing uses. As the demands we make of the common-pool increase, our dependency on hydrological information increases. Relevant, credible, and timely hydrological information is needed to ensure fair and sustainable use of water as our common-pool resource.

Chapter 3: Multi-Objective Decision-Making for Justice & Sustainability

Social justice is the "fairness" of all decisions made about the common pool and is thus best managed in the context of competing uses of water. Water does not respect political boundaries and there are downstream impacts resulting from every water use. The distribution of costs and benefits as a result of water management decisions can have profound social effect (UNESCO 2015). Bullock et al. (2009) explicitly link the Millennium Development Goals — addressing extreme poverty, gender equality, education, and environmental sustainability — to investments in water.



Water monitoring requirements are deeply entrenched in most inter-jurisdictional water treaties because hydrological information is essential to avoid, or resolve, conflict when water resources are shared across political boundaries. The countries of central and South Asia lack consistent and comparable data on water supply, flow, and usage creating unnecessary tension and risk of conflict. Better water resource information is proposed as the first essential step in reducing this risk (UNESCO 2012a). Water provides reasons for transboundary cooperation rather than war (UNESCO 2009). Open, trustworthy, and reliable hydrological information is the basis for secure neighboring societies.

Outside of the realm of negotiated treaties, the absence of binding requirements for water monitoring is resulting in a widening gap between water data availability and competing demands for water. Water over-use, misuse, and abuse are inevitable consequences of ignorance of the spatial and temporal distribution of water quantity and quality. Objective evidence about water availability and quality is essential for both social and environmental justice.

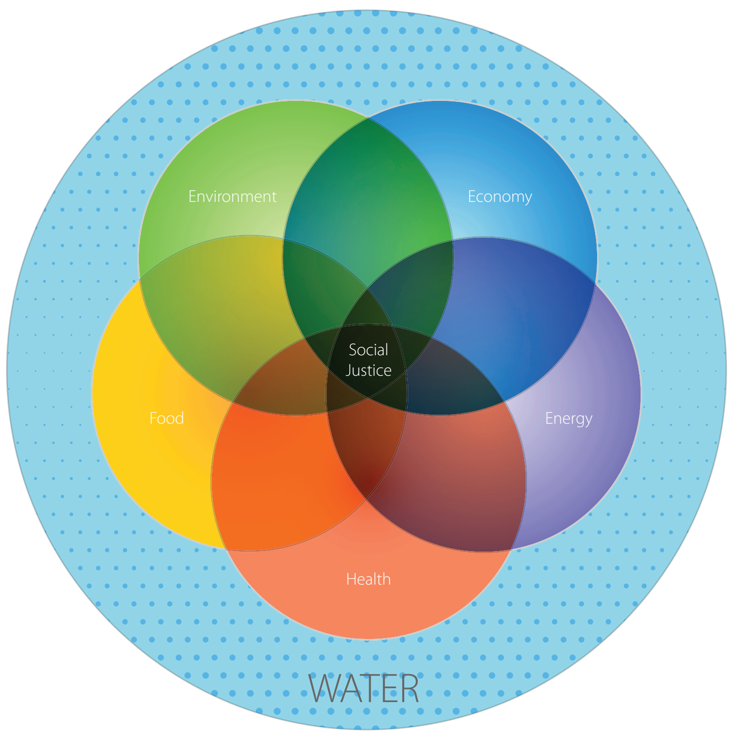


Figure 2. Diagram illustrating inter-dependencies of water management in a common-pool resource framework.

Present needs for water must be balanced against future risks for a sustainable environment and secure society (Witter and Raats 2001). Monitoring of water in excess of immediate human requirements (i.e. the blue area in Figure 2) improves base-line knowledge: in anticipation of future needs; for risk assessment; for the calibration of the extent of harm in similar but impacted systems; for informing design and development of mitigating and restorative strategies for those impacted systems; for calibrating remote sensing data and climate models; and for identifying climate driven trends (Whitfield et al. 2012, Burn et al. 2012).

Within the domain of human requirements (intersecting circles in Figure 2) there are many valid but competing uses for water. The actual quantity and quality of water — as revealed by credible and defensible monitoring — is the foundation for agreement amongst all stakeholders.

Moreover, all of these competing uses for water must be managed in the context of an uncertain climate future (Wright and Irving 2010, UNESCO 2009). Water use policy, planning, and management must be resilient to both historic and emerging risks in water supply. Global climate models can provide an outlook over time-scales that are aligned with the life-cycle-management of major water infrastructure investments. However, the uncertainty inherent in these predictions must be managed adaptively by continuous evaluation against ground truth (Miles 2003).

It is now more important than ever to use empirical evidence to understand the predicted outcomes, complete with uncertainties, in our models of the future (Montanari and Koutsoyiannis 2014, Hamilton and Whitfield 2008). It is increasingly important to be able to systematically track the departure between the water futures that are predicted against those which are realized. Early detection of significant departure from historic patterns of streamflow frequency distributions require strategic and systematic monitoring to correctly inform development of planning and policies for water in a changing world (Whitfield et al. 2012, Burn et al. 2012).

> "One cannot predict future events exactly if one cannot even measure the present state of the universe exactly." — Stephen Hawking
>
> "One planet, one experiment." — E.O. Wilson

Water monitoring must provide factual evidence that is timely, independent, objective, and relevant. The facts of water supply — and impacts of water demand — are fundamental for understanding, building consensus, and determining appropriate action to resolve, or preferably avoid, social conflict and environmental degradation.

In 2009, Elinor Ostrom earned the Nobel Prize in Economic Science for demonstrating that common property could be successfully managed by groups using it. The key to Ostrom's theory is simple communication, which increases joint payoffs (Ostrom 2010). Trust is the most efficient mechanism to enhance transactional outcomes. Trusted hydrological information about how much water there is, where, when, and at what quality is therefore essential in a framework of collective management of water resources.

Hydrological information is the primary line of defense against water security threats. The use of stream gauges can be equated with the use of instrument gauges in an airplane. Gauges are used for monitoring current state and trajectory in order to identify departures from a desired status and trajectory.

We would not design commercial aircraft without instrument gauges and we should not design infrastructure for a highly water dependent society without stream gauges. In aircraft operations undesired states and trajectories can be identified/mitigated, exacerbated, or result in a failure to respond (Helmreich 1999). The first option is not available in ungauged basins because there is no information about current status or trajectory for early detection and mitigation of problems before they become consequential.

Environmental sustainability requires that enough water is reserved for ecosystem function. Social justice is a function of fair use of water from the common-pool. All demands on the watershed have the potential to have a negative impact of environmental sustainability and social justice. Water monitoring is required to know the effects of all alterations of flow and water quality in the context of the capacity of the common-pool. Multi-objective decisions are highly dependent on relevant, timely, and trusted hydrological information.

Chapter 4: Transforming Water Data into Hydrological Information

Water is measurable at a location at a certain time, but it is constantly on the move. Meaningful metadata for water data are needed to create the hydrological information needed to put the point-scale observations into a larger context.

Hydrological information is the result of strategic and systematic network design, technology, training, and data management in the context of a credible and trusted quality management system. Hydrological information is resolved when water data are systematically processed into a state, ensuring relevance, integrity, inter-comparability, validity, and accessibility.

Water is able to flow to where it is needed, when it is needed, at a quality that is needed because of decisions taken by highly trained professionals. The vast majority of people can take their clean water supply for granted because these decisions are made on their behalf. Wise use of water is a result of hydrological information combined with the knowledge of how to interpret that information to inform water resources decisions (Bloschl 2006, Cordery 2001, Burn 1997).

Hydrology is a place-based science. The pathways for water movement within a watershed are many, complex, and highly variable. Processes that transform inputs of precipitation and snowmelt into a steady stream of water occur out of sight, through complex pathways, over many time-scales, with many geophysical, geochemical, and biological interactions (UNESCO 2009, Bloschl 2006). These interactions control water flow, its state (e.g. temperature), and its constituents (e.g. in suspension and in solution).

Hydrology is a global science. Water passes through the atmosphere, biosphere, lithosphere, hydrosphere, and cryosphere in completion of the hydrological cycle. All time-scales are relevant. In some cases we are mining groundwater that was sourced as meltwater from the last glacial epoch. Such water is only renewable if we are willing to wait for another ice age. We depend on hydrological information to inform where the water has come from and how long we will need to wait for reversal of the cumulative effects of over-use, misuse, or abuse.

Hydrology is a complex science. Chemical and biological water data are increasingly integral to hydrological information systems (Lins 2008). Whereas flow data tell where water is at a point in time, water chemistry and aquatic ecology tell the story of where the water has been, what it has been doing, and what services it can continue to provide. The current status and trajectory of stream health is revealed by coordinated, systematic, hydrological information.

The net effect of watershed-scale structure and process dynamics can be best understood by inference of watershed-scale response characteristics. A stream discharge hydrograph and the chemical and physical signature of water represent a synthesis of all upstream sources and their interactions.

The response characteristics of a watershed are sensitive to change in land cover, land-use, water-use, and macro-, meso-, micro-, and miso-scale weather patterns. Interactions of dynamic processes with heterogeneous land surface properties can result in system behavior that does not scale as simple linear functions of input intensities and drainage area. For these reasons hydrological science is wholly dependent on the production of hydrological information.

"Our present satisfaction [with our state of understanding] may reflect the paucity of data rather than the excellence of the theory." — Martin Rees

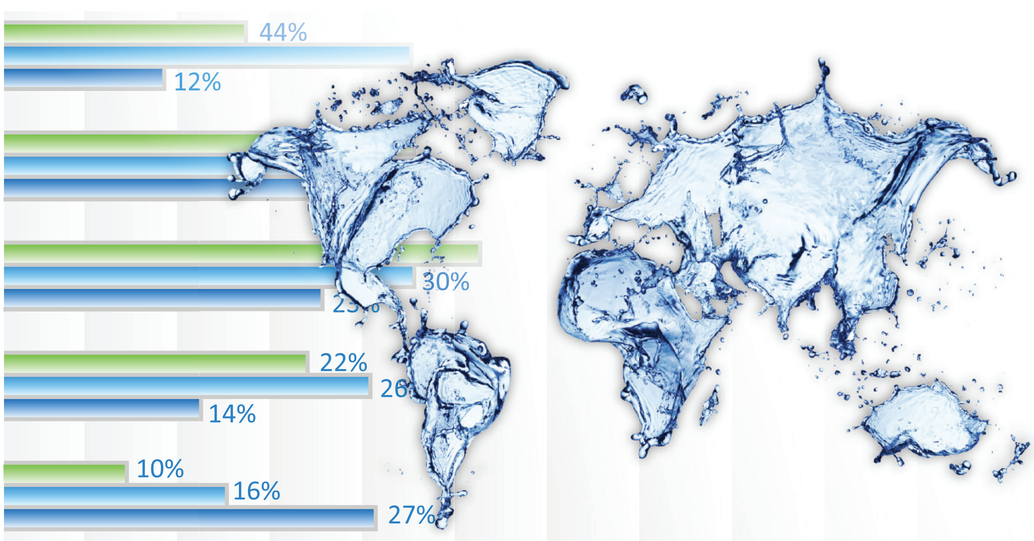
Hydrology is an evidence-driven science. The need for more hydrological information is acute. Recent advances in water monitoring technology are resulting in more water data being collected, about more things, at more places, at higher frequency than ever before. Unfortunately, field monitoring technology is out-pacing the adoption of modern data management software. The result: valuable hydrological information remains hidden in spreadsheets that are increasingly bloated with isolated, uninterpretable, water data.

Inferences made from hydrological information are a revelation of the true condition of the watershed and must not be misinformed by artefact of monitoring methods or technology (Whitfield 2012). An effective data management system is required to establish the trustworthiness of water data (Dixon et al. 2013).

Modern hydrological data management systems are designed to efficiently provide centralized data management; evidence based analysis; automated real-time data processing; auditable documentation of compliance with authoritative standards and procedures; and effective reporting and data dissemination (Aquatic Informatics 2013a). Careful management of the provenance of data provides confidence that the specifications for the technology used, the training of the hydrographers, and the design of the network are compliant with the service objectives of the quality management system (Aquatic Informatics 2012).

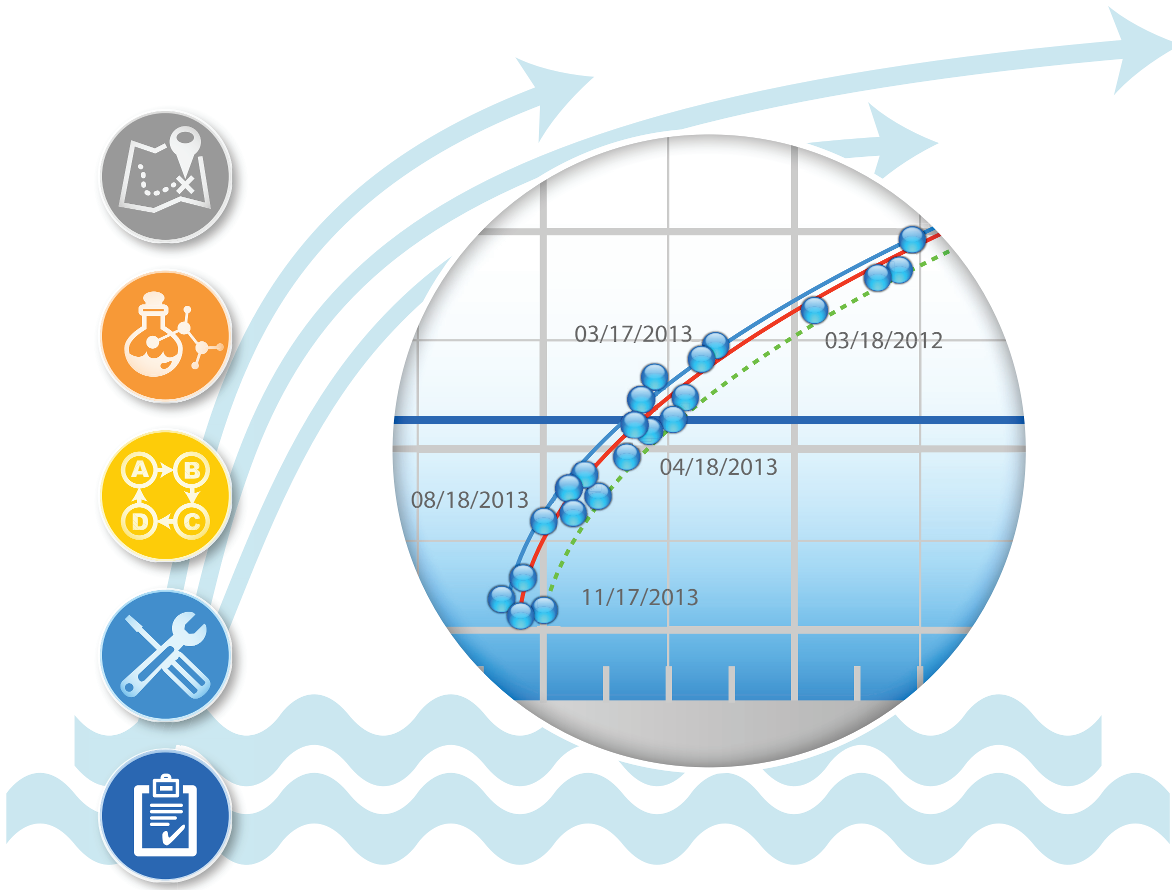
"Before, we used to process water data using basic spreadsheets. Three people were permanently assigned to do this job and just for only 14 stations. Today, we use AQUARIUS Time-Series to manage data from more than 100 stations in real-time, not only for stream flow data, but also for soil moisture, temperature, solar radiation, precipitation, and ten more meteorological parameters. Only two technicians are doing this job and we have time to do more in the office and in the field!"
— Roberto A. Cerón, Hydrologist of Dirección General del Observatorio Ambiental, Ministerio de Medio Ambiente y Recursos Naturales, El Salvador (Aquatic Informatics 2015)

Today, over 28% of water monitoring professionals use commercial hydrological data management systems (Report: Global Hydrological Monitoring Industry Trends, Aquatic Informatics 2012). They report being able to better meet evolving stakeholder expectations for real-time data products and services, metadata availability, higher level analysis, and timely reporting and publishing. In comparison to the use of spreadsheets, water monitoring professionals using actively licensed commercial software reported higher satisfaction with their data management system in areas such as system responsiveness to emerging technologies, performance, reliability, data security, and breadth of features.



The rich features of modern hydrological data management systems collectively support attribution of fitness for purpose, by combining data with meaningful metadata and thereby transforming water data into valuable hydrological information. Water data collected for any one purpose can be transformed, curated, and managed as hydrological information serving many diverse purposes now and into the future. The result of prudent data management is actionable information, and that information grows in value over time as it is used to support decisions beyond its original intended purpose.

Stream discharge is required for effective economic and environmental management of our watersheds. It is also one of the most difficult variables to monitor on a continuous basis. The key to accurate monitoring of stream discharge is the derivation and ongoing adjustment of stage-discharge rating curves. Highly effective rating curves accurately predict into extrapolated zones and hold shape as the density of rating measurements increase. Residuals make intuitive sense and alternate interpretations have been investigated and found lacking. Effective rating curves are the result of a well-executed monitoring plan; good understanding of the underlying science; systematic application of knowledge; strategic control of variance; and objective qualification of the results enabled with modern water data management systems (Aquatic Informatics 2013b).



Modern hydrological data management systems also simplify data sharing between organizations to help fill information gaps. Relevant, reliable, and trustworthy hydrological information must be freely shared in order to realize a world where:

- Impactful water resource decisions are made in a timely manner with high confidence;
- Decisions never result in unintended, needlessly adverse, consequences;
- Negotiations are focused on trusted data rather than historical grievances;
- Collective consensus is undiminished by uninformed debate about uncertainties;
- Governance is based on relevant and timely evidence; and
- Planning and policies arise from robust analysis of relevant and trustworthy data.

Communication of hydrological information must include communication of the data quality indicators that ensure that the information is fit for purpose (Aquatic Informatics 2014, Lins 2008).

The value of water data collected for a single purpose is finite. The value of hydrological information that is shared, complete with its provenance, is unbounded. Realization of the potential value in hydrological information (Figure 3) requires management of the time dimension, the quality dimension, and the communication dimension.

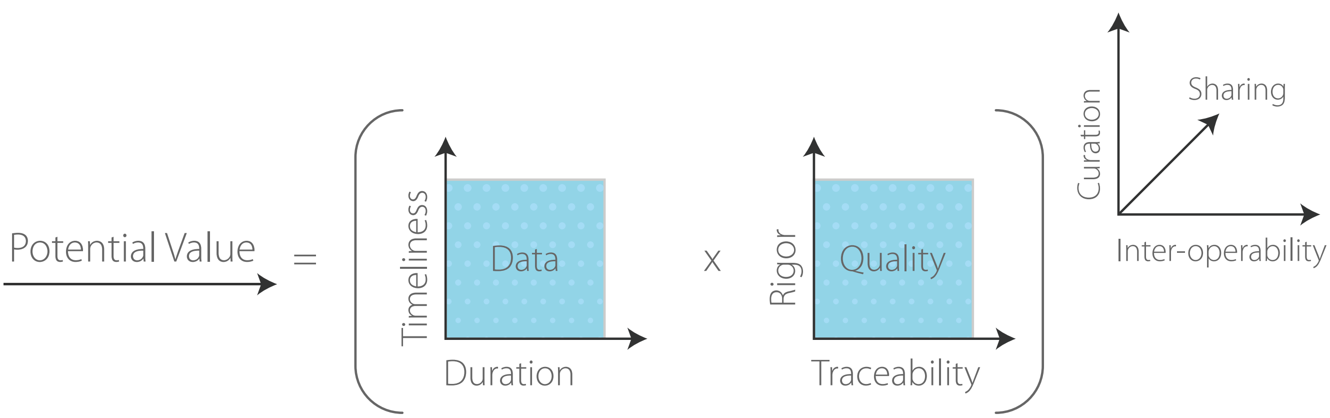


Figure 3. The potential value of hydrological information is a function of its timeliness and the length of record; the rigor and traceability of data quality; the life-cycle management of historic data; and the use of standards such as OGC WaterML 2.0 for ensuring inter-operability.

The relevant time-scales include immediacy and longevity. Information must be timely in order to be useful (Aquatic Informatics 2013c). The information must also correctly represent relevant trends, cycles, and transients in order to be correctly interpreted. In many cases, the temporal variability of hydrological information is only revealed after decades of record collection (Cordery and Cloke 1994).

Quality must be managed with sufficient rigor to be fully defensible and the provenance of the data must be traceable to establish credibility. Compliance with internationally recognized standards ensures rigor, and the use of modern data management systems are required to ensure and automate auditable traceability.

Curation of data requires the use of a data management system that write-protects the data once compliance with the quality management framework has been assured. Quality management is required to ensure the coherence and integrity of long time-series.

Modern data management systems make hydrological information searchable (i.e. its existence can be identified by independent 3rd parties), discoverable (i.e. its fitness for purpose can be validated by independent 3rd parties), and accessible (i.e. it can be used by authorized 3rd parties). Hydrological information should be shared using a common information model, data format, interface, and semantics to enable interoperability integrated across geographic and organizational scales. Open Geospatial Consortium standards (e.g. OGC 2014) for exchange of hydrological time series data are designed to ensure highly efficient and effective re-usability and re-purposing of valuable hydrological information.

As more data are freely available and shared on the Internet, it is important to remember that not all instruments create water data equal in quality. Modern hydrological data management systems make it easier to centralize and process data produced by the increasing array of water data sensors available in the market (Aquatic Informatics 2013c). By tracking data quality and fitness for purpose, these systems inform better decisions. New sensors and dataloggers provide many new options and, in many cases, make it easier and cheaper to collect water data. Some devices are built to exacting performance specifications, whereas other devices sacrifice quality for a low price. It is frequently the case that specialized training is required to correctly configure the deployment of these instruments so that their function is not compromised by local conditions.

It is relatively easy to deploy a sensor in a stream to collect continuous water data. However, what is really needed is reliable and relevant hydrological information. Raw water data has dubious value for any purpose other than as a raw material to generate useful hydrological information. Value is found in the work that transforms water data into useful hydrological information and therefore establishes the fitness for purpose of the result. In some cases data collection technologies are deployed with little understanding of how to convert the data into useful hydrological information. Water data without proper data management have little demonstrable value because a distinct possibility exists that the data result from the use of inappropriate technology that has been unskillfully deployed.

Value in hydrological information is strongly influenced by the trustworthiness of the source, and the data accuracy, representativeness, length of record, timeliness, and accessibility. Relevance is location-specific; the details about the monitoring point in the context of the feature of interest need to be associated with the data. Collectively, these attributes are referred to as "fitness for purpose." In order for data to have value it must be useful, and in order to be useful it must be fit for purpose (Hannah et al. 2012). Therefore the management of data — for what it adds in security, quality control, quality assurance, quality coding, reporting, and communications — can be as valuable as the data itself.

Hydrological information is required to detect hydrological change in space and time (Munday et al. 2013, Burn 1994), attribution of causal forcing, identification of processes and their interactions, and predictions at ungauged sites (Hannah et al. 2011). Hydrological models require hydrological information for calibration, initialization, validation, and characterization of uncertainty (Hamilton and Whitfield 2008, Spence et al. 2009, Spence et al. 2007). The value of the hydrological knowledge generated from hydrological information is priceless.

Hydrological information is required for engineering design. The design specifications for waterway crossings, water reservoirs, hydropower facilities, urban drainage, and flood protection works are highly sensitive to the magnitude, frequency, and duration of hydrological events. An under-specified design will fail prematurely. Premature design failures can be catastrophic. An over-specified design is costly. Unnecessary costs expended for a single large project can exceed the cost of funding an entire water monitoring network. Yet, the value of the hydrological information generated by that monitoring network grows over time as it informs additional projects, supports social justice, and protects environmental sustainability.

The benefits of hydrological information for engineering design purposes can be quantified using economic analysis techniques. Benefit/cost ratio greater than unity can be used to justify public expenditures for water monitoring, even if the hydrological information is used for no purpose other than engineering design.

Chapter 5: The Benefit/Cost of Water Monitoring

Water infrastructure must be designed to provide specified functionality during all extremes in water variability over the expected life of any project. All existing global water infrastructure, worth trillions of dollars, is supported by hydrological information provided by water monitoring. It is a titanic task to provide enough hydrological information to ensure that all water projects are well designed (not over- nor under-designed) and optimally maintained.

As previously discussed, there is a growing cacophony of water data of varying credibility resulting from deployments of a wide variety of new water monitoring devices. Water data can actually be disinformative (Beven and Westerberg 2011) resulting in dis-benefits. Engineering design is dependent on hydrological information that is meaningful in context as identified by fitness for purpose. Whereas the benefit/cost of simply collecting water data cannot be evaluated, there are several approaches for evaluating the value of hydrological information that is fit for specified purposes.

Conventional business economic models are inadequate to explain the value of hydrological information. Hydrological information is not exchanged in a true marketplace environment, therefore it is not possible to use "willingness to pay" (WTP) as an indicator of the value of water monitoring (Walker 2000). Vigilone et al. (2010) report that selling water data for cost recovery is a major barrier to data sharing in Europe. Even nominal cost recovery will result in by-pass of the authoritative data source in favour of data exchange amongst colleagues who have versions of data to share (even if outdated, corrupt, or incomplete). Commercialization of water supply in South America has resulted in expansion of water monitoring, but an overall decrease in public data availability (Hannah et al. 2012).

A low WTP for water monitoring may best be explained by a high willingness to accept (WTA) the consequences of inadequate stream gauging. The costs of hydrological ignorance are readily accepted as a result of climate change, or simply bad luck, rather than as a largely unnecessary cost due to a structural deficiency in the delivery of hydrological information. We must stop the long, sad, history of catastrophic results from under-design.

While conventional business models fall short, a review of published industry reports on the benefit/cost of water monitoring provides the evidence needed to secure the additional funding to modernize and expand environmental monitoring networks. There are several economic analysis methods that are useful for measuring the benefit of ensuring that the right people have the right hydrological information at the right time to make the right decisions. Dawdy (1979) defined an optimal network as one that has the maximum value for a given budget or is designed such that marginal value is equal to marginal cost. In a data void the first station has the greatest value but also has the greatest marginal cost. Each additional station adds marginally less value but at marginally less cost. The methods reviewed by Dawdy for establishing value are summarized in Table 1.

It should be noted that alternate classifications of methods are equally valid. For example, McMahon et al. (1994) classified the methods used to estimate value of benefits as the case study approach, the Bayesian approach, the empirical approach, and the assessment of incremental values approach. The incremental value approach is further sub-divided into: analytical approach; sampling from historical record; and sampling from synthetic sequences. The much simpler Dawdy (1979) classification of methods is adequate for this high level review of benefit/cost studies and investigations.

Table 1. Methods for evaluating the worth of data

Method	Summary
Information-Variance Approach	The strength of correlation amongst stations is evaluated to determine the transferability of information. The need for new data at ungauged sites or cost saving from discontinuing an existing site is determined by partitioning the standard error into components attributable to sampling in time versus sampling in space.
Transfer Function Variance Approach	The response characteristics of the physical system are associated with high frequency variance in the observations of the system. The need for higher density sampling (i.e. identify need for new sites) or any over-sampling (i.e. to discontinue redundant sites) of the physical system can be inferred from spectral analysis.
Economic Framework Approach	The worth of data is defined as a function of benefits foregone as a result of not having the data. Foregone benefits, in turn, are associated with uncertainties in the estimates of parameters needed for project design resulting in either over- or under-design. Benefits foregone also include decisions to postpone a potential development in order to collect more data.
Decision Theory and Bayesian Analysis	The relative worth of data is explained in terms of the loss to be expected as a result of data uncertainty. Various sources of uncertainty are considered for their marginal effect on value. Every source of uncertainty adds a dimension to the Bayesian framework. Decision theory is use-specific. Most studies focus on the fitness of the data for a specific purpose.

The methods summarized in Table 1 are typically applied with respect to evaluating an entire network of stream gauges that are used for a single purpose. However, it will almost always be the case that some of the gauges within a network are entirely irrelevant to any one purpose even though they might be highly valuable for a different purpose. Hence, the result of a network scale analysis for a single purpose should be interpreted as a lower boundary on value, with a much higher expected total value.

Simpson and Cordery (1987) demonstrate that benefit/cost of a purpose-specific gauge varies with record length. This time-dependency must be understood to answer questions such as "how long should a gauging station be maintained?" and "how long should a project be delayed while data are collected?" Several studies that help to define the sensitivity of benefit/cost to length of record are identified in Table 2 where benefit/cost ratios are evaluated as a function of time. In these studies, it is assumed that no "new" uses for the data accumulate through time, but that is rarely the case. The most precious data in any archive are from gauges with the longest period of consistent, reliable record. Any economic argument for additional funding to maintain or add stations should then include a qualitative analysis of the expected additional value generated by additional applications of the hydrological information.

Davis et al. (2010) evaluated the relatively dense network of stream gauges in England and Wales and confirmed that value grows over time. The gauges with the highest value were identified as established stations with natural flow regime and long period of record. They also found the data quality tends to be higher at stations fitting this profile. The analysis revealed that greater investment is needed for some gauges to improve data quality, particularly for extreme values.

As can be seen in Table 2 there is high variance in the benefit/cost ratios that can be attributed to water monitoring, from 0.1 to over 30 depending on any single application. It is apparent that there is no single benefit/cost ratio that applies for all regions for all purposes. Interpretation of these results requires consideration of the region, method, purpose, and scale of the investigation. The selection of a benefit/cost ratio to use in justification of water monitoring should either be based on a dedicated investigation or by careful consideration of which of these studies is most meaningful in a local context. Applying multiple studies to represent multi-applications of the hydrological information helps generative a more comprehensive, compelling, and truthful case for funding.

Table 2. Quantification the value of hydrological information using benefit/cost ratio methods.

Source	Region	Method	Purpose	Scale	Benefit/Cost
McMahon and Cronin 1980	Canada	Economic Framework Approach	Dams and reservoirs	Network	1.3
			Culverts and bridges		
			Spillways		
			Hydropower		
Fontaine et al. 1984	Maine, USA	Decision Theory and Bayesian Analysis Approach	Optimization of network operations	Network	N/A
Engel et al 1984	Nebraska, USA	Decision Theory and Bayesian Analysis Approach	Optimization of network operations	Network	N/A
Cordery and Simpson 1986	New South Wales, Australia	Economic Framework Approach	Flood damage reduction	Gauge	Length of record dependent
			Levee design		
Cordery and Cloke 1990	New South Wales, Australia	Economic Framework Approach	Small stream crossings	Network	20
			Water supply storages	Gauge	5
			Overall	Network	>30
Cordery and Cloke 1992a and Cordery and Cloke 1992b	New South Wales, Australia	Economic Framework Approach	Minor waterway crossings	Network	0.8
			Flood mitigation		0.1
			Water supply storages		1.7
			Urban drainage design		2
			Design of major structures		>4
			Minimum total		9
Cloke and Cordery 1993	New South Wales, Australia	Economic Framework Approach	Storage design	Network	Length of record dependent
Cloke et al. 1993	New South Wales, Australia	Economic Framework Approach	Small stream crossings	Network	Length of record dependent
Cordery and Cloke 1994	New South Wales, Australia	Economic Framework Approach	Flood protection design	Gauge	Length of record dependent

Source	Region	Method	Purpose	Scale	Benefit/Cost
Stewart 1994	Brisbane, Australia	Literature review — various methods	Flood forecast warning	Unspecified	6.6
	Australia		Reservoir capacity		>1
	Developing countries		Single use reservoir		>1
	Unspecified		Unspecified		2.81 to 21.2
Walker 2000	UK	Economic Framework Approach	Public water supply	Network	10
			Irrigation		8
			Flood alleviation		0.8
			Flood warning		1.7
Azar et al. 2003	British Columbia, Canada	Economic Framework Approach	Multi-purpose	Network	>20

There are several limitations to conventional methods of benefit/cost analysis. In most cases, these limitations result in the estimate of benefit/cost having a low bias. Evaluating asynchronous costs and benefits is particularly challenging. For example, specific future uses of the data are most often not known (e.g. the design of many hydroelectric projects depends on records collected prior to the need for project development). Furthermore, all methods of benefit/cost analysis assume stationarity of the populations being sampled and thus don't take into account the value of identifying trends and shifts in hydrological processes. Despite these limitations, the conventional methods of benefit/cost analysis provide evidence to support additional funding.

The value of data for prudent stewardship of water resources is difficult to assess relative to alternate investment of available resources. Benefits are shared over long periods and by many beneficiaries, whereas data collection costs are immediately payable. Pretto et al. (1996) recommend: identification of data uses, modelling reduction in uncertainty, estimation of economic costs, and linking reduced uncertainty with economic benefits.

Stewart (1994) noted that there is a lack of studies on the benefit/cost of hydrological information with respect to ecologically sustainable development. Most benefit/cost studies are with respect to an easily identified beneficiary of the data. Water is integral to each of the three dimensions (poverty and social equity, economic development, and ecosystems) of sustainable development (UNESCO 2015) and hydrological information is a fundamental requirement for optimizing these objectives. However, there is no economic metric for progress in achievement of sustainability and hence no way to evaluate the value of hydrological information in driving that progress. Any economic argument for additional funding must then be accompanied with a qualitative argument that describes the environmental benefits of water monitoring.

> “Decisions that determine how water resources are used (or abused) are not made by water managers alone, but driven by various socio-economic development objectives and the operational decisions to achieve them.” — UNESCO 2015

Goninen et al. (1997) compared the concept of opportunity cost to proportional cost to evaluate hydrologic data collection in Victoria, Australia. The proportional cost approach uses an allocation of cost per station proportional to the cost of running the entire network. Opportunity cost is helpful for incremental evaluation of the value of individual stations. Adding or removing a station from a network has a number of costs many of which are variable and shared with other stations in the network. Goninen et al. demonstrate that for economic evaluation of any change in network size (up or down) the opportunity cost method should be used.

Walker (2000) makes the argument that hydrological information only has value if the beneficiary takes action as a result of the information; otherwise, the benefits are potential rather than real. There are several factors at play including: data accuracy, representativeness, length of record, availability of other records, and uncertainties. Data of poor quality — or used out of context — may have a net dis-benefit. High quality data are fundamentally important for flood control and water resources management.

The National Hydrologic Warning Council provides illustrative examples of value from the USGS stream gauging network (NHWC 2006). Upgrade costs for the Folsom Dam in California could have been avoided if a long record of flows had been available to inform initial design resulting in a potential savings of US$63 million annually. In Mecklenburg County, North Carolina, increased certainty in floodplain mapping for land use regulation could have resulted in US$20 million annual savings. Accurate design of levee improvements using long flow records could save US$7 million per mile. There are more than 10,000 miles of federal project levees in the US. FEMA values data in hydrologic analysis of flood plain mapping at US$4,400 per map and 64,000 flood maps need to be updated. The value of flood forecasts and successful reservoir operations is valued at over US$1 billion annually. A value of US$30–50 million benefit is the estimated contribution of the stream gauge network to these forecasts.

Cordery and Cloke (2010) use several compelling examples of problems arising from data sparsity to support the argument that cost is not a legitimate reason for the inadequacy of hydrological information. It is far too easy to demonstrate tangible economic benefits that far exceed monitoring costs. More investment in water monitoring is needed for public safety and good stewardship of public funds.

Many different approaches have been taken to quantify the economic value of hydrological information. True, it is impossible to quantify the “total” benefit of water monitoring because the benefits are many and varied and new uses for the data are being discovered all of the time. Nonetheless, the return on investment in water monitoring has consistently been shown to be of high value, even when evaluated against use for a single specific purpose. Benefits accumulate through time. Benefits accumulate through additional applications. Benefits warrant additional funding.

Chapter 6: Closing the Gap

Too often, the empirical evidence demonstrating a highly favorable benefit/cost of water monitoring is not enough. The greater challenge is communicating the value of water monitoring in a way that enables agencies with responsibility for monitoring to have access to the resources they need to do their job. There must be widespread agreement that the sum of benefits vastly outweigh the costs.

Despite decades of studies consistently demonstrating benefits that exceed, frequently in an order of magnitude, the cost of monitoring, the gap between supply and demand for high quality hydrological information continues to grow. It is common for major infrastructure investments, policies, and planning to be founded on simplistic assumptions about the adequacy of water quantity and quality rather than factual evidence. It is useful therefore to consider heuristic excuses that are barriers to the effective allocation of public budgets for water monitoring.

The User Should Pay!

"User pay" is appropriate when data are not shared and the beneficiary who pays for the data has sole access to the data. Commercialization of water in Brazil has resulted in an increase in stream gauging (presumably because of favorable benefit/cost), but a reduction in public data accessibility.

However, when water is managed as a common-pool asset, economists would recommend a Marxist framework for pricing hydrological information: "from each according to ability, to each according to his need." In this way a consultant who makes a large profit from developing a robust design for a storage reservoir would be required to pay a large amount of money for access to the data, whereas a student, who requires data for learning the science of hydrology, would pay nothing, or next to nothing.

Apart from the problems inherent in administering variable pricing for hydrological information, such economics are highly favorable for the development of a black market, defeating cost recovery. Why pay for data when you could simply ask a student to obtain free data for you?

A fixed price model for data may be easier to administer, but it reduces the potential for the data to be used for any purpose where the realized value of use is less than the fixed cost or where the value is difficult to quantify, as in environmental stewardship. Even a fixed price model incentivizes a black market in which some of the costs of obtaining data can be recouped by the end-user by re-selling the data. If the linkage between the authoritative source of the data and metadata and the end-user is broken then any assurance that the data are truthful is lost.

These examples confirm that hydrological information is, paradoxically, more valuable when it is free than when it is not. Cost recovery constrains the use of information and every foregone opportunity for use is expensive with respect to the collective understanding and optimization of a common pool resource.

We Can't Afford It!

Budgets are tight. Decisions are difficult. Special interest lobbies are powerful. There is no public demand for more water information. We cannot ask taxpayers to pay for an activity where the full benefit is not immediate or will not fit within a political cycle of mandated priorities.

There is no lobby for water monitoring, so competition for funding is not on a level playing field relative to other spending priorities. There is no public demand for more hydrological information because the many and varied costs of water crises, conflicts, and disasters are widely perceived as inevitable consequences of living in a capricious environment.

The conversation about funding for water monitoring needs to focus on the costs of hydrological ignorance in terms of the savings gained by not monitoring. Such an approach could follow the forensic investigation method used in the airline industry where after each airplane crash there is an extensive investigation to find the root cause of the crash so that measures can be put in place to eliminate re-occurrence of preventable flight risks.

It is an obvious truth that if the right people have the right information at the right time, then better decisions can be made with respect to policies, planning, adaptive management, and engineering design. Events like floods and droughts cannot be prevented, but the likelihood of their occurrence can be reliably predicted given adequate hydrological information, in turn supporting better planning, management, and recovery.

How would well-informed policies, planning, adaptive management, and engineering decisions have differed from the decisions that were actually made? What is the difference in total costs for mitigation and compensation of undesired outcomes from these decisions relative to outcomes of well-informed decisions? What are the decisions that are being made today that use bold assumptions rather than adequate information about the true state of our water resources and how much will the resulting decision errors cost us?

Almost every level of governance in almost every region of the world devotes a substantial portion of their budgets to providing protection measures from water and providing for reliable water supply. Those that do not inevitably incur penalties either in direct costs or in lost opportunities. Ironically, almost every government in the world also chooses to save money by not investing in an adequate water monitoring infrastructure.

Forensic hydrological analysis of the sunk costs for water issues is required to determine why these costs are so high and why, in spite of such high levels of funding, so many water resource projects under-perform. In many cases a low return on investment is a direct result of invalid assumptions made about the water supply or water quality. It is only with adequate water monitoring that the truth can be revealed.

It Isn’t Our Mandate!

Water monitoring is everybody’s business and it is nobody’s business. There is no one branch or level of government that has a clear and unambiguous mandate to provide hydrological information for all stakeholders. For example, at the federal level in the United States the USGS water monitoring program falls under the Department of the Interior, whereas the equivalent agency in Canada falls under the Department of Environment. Previously, the Water Survey of Canada had been under the Department of Energy, Mines, and Natural Resources. Almost any government agency could justify the cost of running their own water monitoring program but very few do.

Any agency that undertakes the responsibility for water monitoring incurs the costs, whereas the benefits are dispersed amongst all parties that have access to the hydrological information and analyses. Formal cost-sharing arrangements are required to extend monitoring budgets to be more inclusive of the mandate for a variety of partner agencies. Many beneficiaries are content to be passive partners, keeping quiet about their need for more data so that they will not be asked to cover costs for benefits they already get for free.

Water monitoring is everybody's business. Absence of a statutory requirement for monitoring is not equivalent to an absence of responsibility for funding monitoring. Good governance is not possible when unjustified assumptions are used in place of trustworthy hydrological information.

Funding Is Politically Motivated!

New funding for monitoring does not yield immediate tangible benefits, hence there is no feedback for the value proposition. Funding for monitoring must therefore be based on faith that the eventual benefits are worth the immediate cost. Taxpayers have little faith that their taxes are wisely spent and are highly critical of any spending for which the benefits are unclear.

There are many ways of framing the argument that public investment in water monitoring is wise and cost effective. In fact, there are too many ways. Hydrological information is an extremely versatile asset. Public administrators have incentive to direct funding to activities that are specific, measurable, achievable, relevant, and time-bound in order to explain, and ultimately defend, their decisions. The many ways in which total value, now and into the future, can be found in hydrological information are collectively non-specific, immeasurable, and though achievable and highly relevant, never time-bound.

Funding for a new bridge that demonstrably reduces commute time will get funding. Stream gauging that will ensure that bridges built in the future will not be either under-designed (i.e. not survive a flood) or over-designed (i.e. designed, at great cost, to survive a flood that will never occur) is unlikely to get funded. No politician has ever been elected on a platform of increased funding for water monitoring.

Beneficiaries of water monitoring are generally unaware of the existence of the hydrological information upon which our water wisdom is dependent. It is also true that they are unaware that they are currently paying excessive costs resulting from un-wise decisions about our water resources. The public cannot make the connection between the unnecessary costs they are paying today and the strategic investments in evidence-based decision making that will ensure a secure water future.

We do not lack for evidence of the positive correlation between availability of hydrological information and water security. What is lacking is visibility of this evidence. The public need to be asked: do you want a secure water future? If the answer is yes, then the steps needed to secure that future need to be coherently explained. The first step is, always, to obtain the needed hydrological information.

We Didn't Know!

The body of evidence showing a compelling benefit/cost ratio for water monitoring is not readily available in mainstream literature; it is often in the form of obscure reports and conference proceedings. A primary motivation for writing this eBook is to assemble this evidence in an easily accessible format (e.g. Table 2) and provide links to the sources wherever possible. PDF copies of any of the papers cited — that are not copyright protected — can be obtained by contacting Aquatic Informatics directly.

> "Never again should it be possible to say we didn't know."
> — UNU-IWEH 2014

Ignorance of the value of water monitoring in support of evidence-based policies, planning, adaptive management, and engineering design decisions has been, but should not be, an excuse for inadequate investments in water monitoring.

The evidence in support of expanding public investment in water monitoring is compelling. Our success in translating this evidence into persuasive arguments that are locally meaningful in terms of the politics and priorities of time and place will determine the future of funding for water monitoring. This is something that we all have some responsibility for and it is something that we can all influence, one conversation at a time.

Chapter 7: Case Study on the Varied Uses and Value of Hydrological Information for a Small District in New Zealand

This case study provides one example of the extensive variety of ways hydrological information can used to optimize value. The cumulative return on investment cannot be quantified but the net benefit can be qualitatively explained.

Tasman District is located at the top of the South Island of New Zealand. It covers 9,600 km^2 and is home to 47,000 people, with the largest township containing 13,000 people. The district is relatively abundant in water, with annual rainfall ranging from 1 to 6 meters. Geology is varied and the hydrological characteristics of the watersheds vary greatly. The upper catchments of many of the local rivers are located in National Parks and are relatively unaffected by man, and are held in high regard for recreation. In the lower catchments, summer droughts can cause water shortages for townships and the wide variety of economic enterprises that rely on river flow and aquifers to supply water. Rivers drain to estuaries and coastal areas that support significant fisheries, including shellfish.

Up until the early 1990's in New Zealand, a significant amount of hydrological data were collected by the National Institute of Water and Atmospheric Research Ltd (NIWA), and its predecessor agencies. Since then, the emphasis on national-funded hydrological science has turned from "practical" science to research. As a result, central government funding is not readily available for data collection unless that collection links into a specific research project. Since that time NIWA has closed down many regionally significant stations collecting river flow and rainfall information, and local government agencies have taken up the slack for more general data collection that is required for engineering, water resource assessment, and the day to day needs of the public. Monitoring funded by Tasman District Council has increased steadily for the past 30 years.

Globally, water data collection is inadequate and deteriorating (Grabs 2009, Mishra and Coulibaly 2009, Lins 2008). However, in New Zealand, apart from one small decrease in the 1980s, the overall number of water level recording sites has increased since 1900. Keane (2011) records the drivers for expansion of hydrological monitoring through the years in New Zealand, commencing with demand for hydro and irrigation schemes up to the 1930s, erosion problems in the 1940s, the establishment of national hydrometric survey teams in 1951, and the International Hydrological Decade through 1964–75. In the 1980s central government agencies were commercialized and many sites were closed. A 20% cut in central government funding for hydrometric monitoring occurred in 1992. By this time, however, local government agencies were increasing monitoring efforts, and by 2010 were operating 63% of water level recorders in New Zealand, and central government, 24%. In particular, the total number of water level sites steadily increased from 1,132 in 1990 to 1,766 in 2010.

The devolution of responsibility to local government for hydrological monitoring appears to have been a positive aspect in the country. New Zealand legislation requires Councils to carry out good environmental stewardship, and Council boundaries are aligned along watershed boundaries, recognizing the importance of water in the environment. The closer the scale of governance is to watershed scale the greater the sense of ownership and responsibility for the resource. Local politicians are more intimately involved in local water issues, see the value that comes from good management, design, and data collection, and feel a greater responsibility to support these programs.

The monitoring team at Tasman is administered by the Environment and Planning Department. It would be easy to perceive that hydrological data are collected only for the purposes of allocating water, carrying out compliance checks, and managing droughts. The truth is, the uses for the data are many and varied, and the primary reason for collecting the data at any one site is often widely supplemented by others.

In particular, within Council, hydrological data are widely used for engineering purposes. The consequences of poor engineering design can be severe — a local example includes a bridge washed away not long after construction. This was an excellent illustration of the value of actual data — none were available at that time on that river, and the theoretical design proved incorrect.

The statistics used for engineering design ideally rely on long-term, continuous monitoring of flow or rainfall records. The design of bridges and dams benefits from this work. Less obvious are the culverts that carry small streams under roads — made too small, they overflow and damage the road, but if they are oversized then extra capital expense is incurred. Tasman owns bridges worth NZ$150 million and about 55,000 linear metres of culverts and channels worth some NZ$52 million, as well as river protection structures such as rock banks and levees valued at NZ$45 million.

Tasman is currently considering the construction of a water supply dam estimated to cost some NZ$80 million. The supply of both irrigation and potable water requires careful design of storage and pipe size to match the demand for water and the availability of that water. Water that is used then has to be disposed of with careful consideration of dilution and other effects on discharge locations to ensure the protection of receiving waters from excessive nutrients, agri-chemicals, and other pollutants.

In 2013, Tasman's main township suffered a significant storm when over 100 mm fell in one hour. Many houses and businesses were inundated., causing NZ$33 million in damages. This followed a storm in a nearby location in 2011, which caused NZ$34 million of damage. Evidence-based cost benefit analysis is required using accurate rainfall data to carry out modelling of stormwater pipe size and secondary flow paths.

Water supply, stormwater, and wastewater together account for 44% of all capital expenditure for the Tasman District Council, and 23% of Council's total operating and maintenance budget.

Most hydrological data collected in Tasman are published on the web in near real-time. These pages are among the most widely used on Council's website. The data are considered a valuable asset to the many people working in areas exposed to the environment. Construction contracts have substantial penalty clauses built around rainfall triggers, which may delay work or cause sediment issues. Rafters, kayakers, hikers, and fishermen use the data extensively. They are also referred to by farmers and horticulturalists to manage their business on a day-to-day basis, or longer term for crop selection or purchase of properties.

During a flood the public makes considerable use of web-based hydrological information and the Council supplies information directly to police, civil defense, schools, landowners, and the media. In times of drought the web provides information to water users regarding rationing and saltwater intrusion into aquifers.

In New Zealand the purchaser of a property can request information from local Councils about any hazards that exist for that property, including flood risk, or evidence of past floods. In recent years flood modelling has been used to assess risk in four townships. Without statistics and input data derived from accurate, long-term records, the results of this modelling would be so inaccurate as to be pointless. It is rare to have the opportunity to collect information from extreme floods, and long-term records from more moderate floods are crucial to calibrate flood models for "real-time" prediction and to gain an insight into the historical consequences of flooding.

The regional expression of the effects of global climate change can only be evaluated with long-term records of rainfall and other parameters. Many of the records in Tasman began in the 1960s, with only several stations having operated continuously back to the early 1900s. These long-term gauges are becoming increasingly important as a baseline for risk evaluation in a changing world. Information is collected on sea level to allow analysis of climate on sea level rise, as well as storm surge and data for navigation purposes.

River flow is a foundation for many water quality analyses. Many water parameters are measured as a concentration of a substance, and water flow is then needed to calculate quantities of material carried, such as nutrients or sediment. The need for greater recognition of in-stream needs is reflected in court rulings, policies, and public opinion. All freshwater research on fowl, trout, and the native fish species relies on flow and water level information. The marine farming industry closely monitors river flows to assess whether harvesting of shellfish can occur without risk from pathogens borne by rivers draining to the coast.

Rainfall is the greatest cause of soil erosion in Tasman. Significant environmental effects can result from excessive sediment in waterways and the coastal environment. Analysis of storm intensities and prior wetness are inputs to erosion studies, from which management controls are developed for soils prone to slippage.

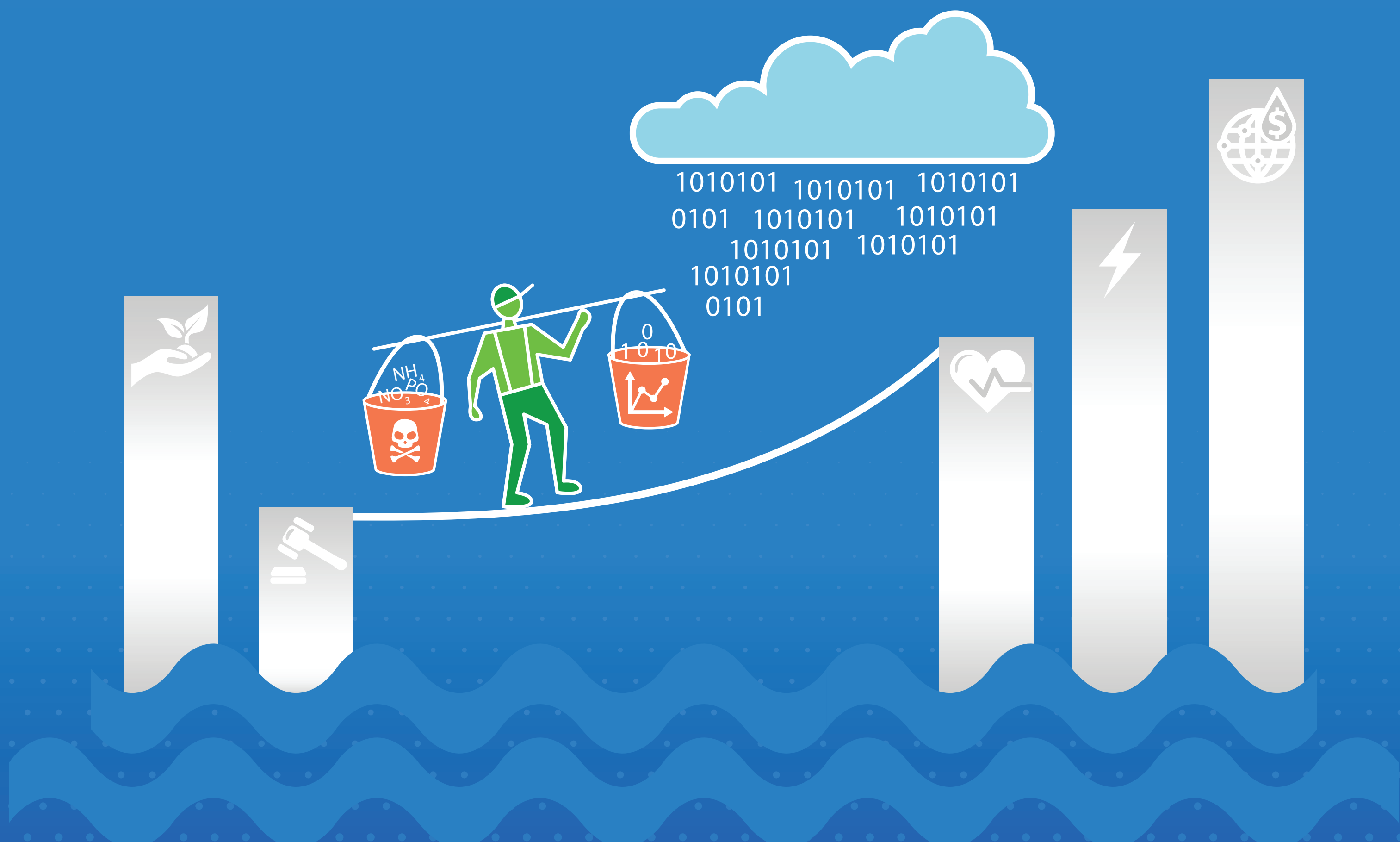
Hydrological information is often used in the legal arena, firstly to set the local plans that govern the use of water, and then to ensure that individual conditions regarding water takes and discharges are met. Hydrological data are used in death inquests and other court cases such as car accidents. The Council is tasked to collect records in an un-biased and consistent manner, which is important in settling disputes, and this is yet another consideration for having hydrological information collected by local or national government free from commercial interests.

Chapter 7 Author

Martin Doyle, Hydrologist, has 35 years of experience as a field and analytical hydrologist in New Zealand, Antarctica and the South Pacific. He currently leads a hydrology team at Tasman District Council and has been closely involved in developing national standards and a national training programme for hydrology staff in New Zealand.

Conclusion

The many and various stakeholders representing different sectors of the economy, public health, public safety, the environment, and social justice operate as distinct silos, all rising out of a common dependency on shared water. Hydrological information is the one shared link of communication that can enable the coordinated use of the common-pool resource. Water monitoring provides a common understanding of how the variability in water quality and quantity is both an opportunity for health and prosperity and a constraint on our freedom to act with disregard, or disrespect, for other uses of the common-pool.



Global expansion of competing demands for water has not been matched by commensurate growth in water monitoring. Wise and sustainable use of water is not possible unless policies, planning, adaptive management, and engineering decisions are informed by high-quality hydrological information. Increased funding for water monitoring will substantially improve the outlook for a secure water future at all levels: local, regional, national, and international.

However, there is inadequate support for public funding of water monitoring. This may be due to public willingness to accept water conflicts, environmental degradation, and water related disasters as inevitable consequences of bad luck rather than attributing root cause to the consequence of uninformed decisions. With water resources we create our own "luck" by using hydrological information instead of guesswork.

Without water monitoring, how can we:

- Reconcile our water demand with the water supply?
- Meet the needs of downstream users and vital ecosystem functions?
- Engineer structures in, and near, the water to be resilient to high likelihood events?
- Detect impactful trends and/or events?
- Provide warnings of imminent danger?

Failure to protect the environment, failure of infrastructure, failure to respect the rights of downstream users, and failure of timely warnings is not a matter of just being unlucky. Water can be collectively managed to eliminate over-use, misuse, and abuse if, and only if, trusted hydrological information is available as the foundation for building trust and consensus amongst all stakeholders.

Benefit/cost ratios have been systematically investigated and investments in water monitoring are found to produce a benefit often far exceeding, by an order of magnitude, cost when information is fit for specified purposes. However, water data are not inherently valuable. Value is created by establishing and communicating "fitness for purpose" by implementing a rigorous quality management framework. Modern data management principles and practices ensure that hydrological information is accessible, secure, and trustworthy. Shared data complete with discoverable provenance have unbounded value.

Market forces will not ensure that supply of information will respond to demand because the costs of supplying the information are disconnected from beneficiaries, many of whom are yet to be born. The need for information is a function of variability in time and space. A high spatial density of stream gauges is needed where the climate, geography, and/or land-use practices are complex. There are many highly interactive socio-economic and environmental impacts that are highly sensitive to this variability in time and space. Gauges with long time periods are especially important when driving (e.g. climate) and interactive (e.g. land-use, water demand) forces are in a state of flux. Supply of information is a function of public funding — the result of a political process that is disconnected from the physical realities driving the need for information.

In New Zealand, political divisions are structured along watershed delineations creating a socio-political connection to the water as much as to the land. The District of Tasman case study illustrates that when accountability for the consequences of decisions is closely aligned with responsibility for funding, water monitoring becomes an integral component of watershed stewardship.

Water managers around the world understand the actions needed to resolve the most important water issues in their region. They need more gauges, they need longer periods of record at existing gauges, they need to increase the number of parameters monitored at each gauge, and they need to upgrade their systems for creating and curating value from their water data. They need funding to complete the development of a water monitoring infrastructure that is adequate to inform policies, planning, resource management, and engineering decisions in response to the most impactful threats to people, the economy, and the environment.

Embracing, or ignoring, the need for increased investment in water monitoring is a choice that we all have. The benefits from investment in water monitoring are substantial. Many regions of the world are paying dearly for the money they "saved" by insufficient investment in water monitoring. The longer these regions operate without adequate information, the worse their water problems become. The choices we make leave a legacy. We get to choose the water future we want.

Inadequate funding is a shared problem. Shared data complete with relevant and meaningful context is the most efficient and effective path to the resolution of any shared problem. The results from many studies investigating the value of water monitoring have been presented and discussed in a global geopolitical context. Down-scaled, locally-compelling, evidence-based arguments can be re-constructed from this shared information to persuade local-scale agencies of the need for sustainable funding that is inextricably linked to our water future. Let's create and share the hydrological information that will ensure a secure water future.

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Meet the Author

Stu Hamilton is dedicated to improving the science and practice of water monitoring. He has 17 years of field experience in northern Canada, and nearly as many years in research and development and operational management with the Water Survey of Canada, where he oversaw the operations of over 500 stations. Stu is, or has been: Associate Expert in Hydrology with the World Meteorological Organization (WMO); Canadian Liaison with the Hydrometry Committee (TC 113) of the International Standards Organization (ISO); President of North American Stream Hydrographers (NASH); and Member of the Open Geospatial Consortium (OGC) Hydrological Domain Working Group. As Senior Hydrologist at Aquatic Informatics, Stu has written the following whitepapers (available for download):

- The 5 Essential Elements of a Hydrological Monitoring Program
- Report: Global Hydrological Monitoring Industry Trends
- Best Water Data Possible! 5 Key Requirements for Modern Systems
- 5 Best Practices for Building Better Stage Discharge Rating Curves
- Communicating Hydrometric Data Quality: What, How, & Why

Please share your insight, concerns and experience about water monitoring by joining in a conversation: please visit Stu's blog or contact him directly at stuart.hamilton@aquaticinformatics.com.

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Data consumers want real-time data they can trust. AQUARIUS Server has a unique portfolio of features for real-time sanity checking, error detection, data cleaning, data flagging, automatic bias corrections, and rating shift management. Automated procedures eliminate the majority of tedious manual data workup processes. Timely alerts inform stakeholders of any unusual events or station health issues.

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AQUARIUS Time-Series automatically builds a data processing, correction, and editing log, providing the transparency you need to defend your data. The audit log tracks all corrections, metadata, notes, and remarks for time series data. You can review a log to quickly find who performed what, when, and why. Data corrections can be undone at any time, allowing you to see the values affected. Data flags, data grades, and workflow controls enable you to track and manage data quality.

Build Better, Reliable Rating Models

A single rating model contains the ratings, shifts, blends, and periods of applicability that describe a channel as it changes over time. The AQUARIUS rating development tool is engineered to support the latest global standards set by the USGS, ISO, WMO, and OGC. It is used by national agencies like the USGS to efficiently develop accurate and legally defensible ratings and to ensure the highest confidence in their calculations of flow. You can build better, more reliable rating curves in less time.

Apply Complex Calculations & Powerful Visualizations

A powerful set of processing tools automate workflows and streamline data production. AQUARIUS Time-Series can mix data input sources, build sophisticated multi-input models, run rating curves, and calculate daily aggregates. It can also automate email notifications and publish data in real-time.

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AQUARIUS Forecast is modern software for advanced environmental modelling, delivering higher accuracy, speed, and a decisive edge. Simpler workflows make it easier to build sophisticated models of complex water resource systems. AQUARIUS Forecast is your vital decision support tool for water resource modelling, water accounting, hydropower simulations, or flood forecasting.

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A modern architecture makes AQUARIUS Server scalable from a single user to a national team managing thousands of stations. Simply add users and integrate new data sources as your monitoring program grows. User access privileges and server failover systems keep your data secure and safe. Water monitoring records can be over 100 years long – AQUARIUS Server protects your data legacy.

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