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Fourth Industrial Revolution for the Earth Series

Harnessing the Fourth Industrial Revolution for Water

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About "The Fourth Industrial Revolution for the Earth" series

The "Fourth Industrial Revolution for the Earth" is a publication series highlighting opportunities to solve the world's most pressing environmental challenges by harnessing technological innovations supported by new and effective approaches to governance, financing and multistakeholder collaboration.

About the World Economic Forum

The World Economic Forum, committed to improving the state of the world, is the International Organization for Public-Private Cooperation. The Forum engages the foremost business, political and other leaders of society to shape global, regional and industry agendas.

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The majority of the world's current environmental problems can be traced back to industrialization. Issues such as climate change, unsafe levels of air pollution, depletion of fishing stocks, toxins in rivers and soils, overflowing levels of waste on land and in oceans, and loss of biodiversity and deforestation are negative consequences of industrialization.

As the Fourth Industrial Revolution gathers pace, innovations are becoming faster, more efficient and more widely accessible than before. Technology is becoming increasingly connected, and we are now seeing a convergence of the digital, physical and biological realms. Emerging technologies, including the Internet of Things (IoT), virtual reality (VR) and artificial intelligence (AI) are enabling societal shifts by seismically impacting economies, values, identities and possibilities for future generations.

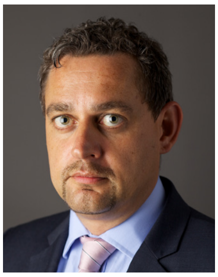
We have a unique opportunity to harness this Fourth Industrial Revolution – and the societal shifts it triggers – to help address environmental issues and transform how we manage our shared global environment. The Fourth Industrial Revolution could, however, also exacerbate existing threats to environmental security or create entirely new risks that will need to be considered and managed.

Harnessing these opportunities and proactively managing these risks will require a transformation of the "enabling environment", namely the governance frameworks and policy protocols, investment and financing models, the prevailing incentives for technology development, and the nature of societal engagement. This transformation will not happen automatically. It will require proactive collaboration among policy-makers, scientists, civil society, technology champions and investors.

If we get it right, it could create a sustainability revolution.

This "Fourth Industrial Revolution for the Earth" series is designed to illustrate the potential of Fourth Industrial Revolution innovations and their application to the world's most pressing environmental challenges. It offers insights into the emerging opportunities and risks, highlighting the roles various actors could play to ensure these technologies are harnessed and scaled effectively. It is not intended to be conclusive, but rather to stimulate a discussion among diverse stakeholders to provide a foundation for further collaborative work. This paper looks at the Fourth Industrial Revolution and water.

Foreword



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Over the course of history, scientific discoveries and technological advances have helped tackle the world's most complex and daunting challenges, and enabled innovations that have enhanced our quality of life. Vaccinations now exist for diseases that previously eradicated entire populations. The world's information and knowledge are now available to anyone with an internet connection. The invention of sanitation systems alone helped to extend our lifespan by 40 years.[1]

Just as these discoveries helped open new chapters of possibility and opportunity, today's rapidly emerging technologies such as artificial intelligence, blockchain, big data and nanotechnology – what the World Economic Forum has coined the Fourth Industrial Revolution – are enabling similar transformations across systems such as healthcare mobility and education worldwide.

A comparable opportunity exists today to open a new innovation chapter for the water sector, as the world struggles with the rapid and painful transition from believing that water was plentiful and free (or, at the very least, inexpensive) to facing the impacts of water scarcity, poor water quality and the variabilities of hydrologic events from climate change. Already, too many water crises have unfolded in cities, including: Flint, Michigan; Cape Town, South Africa; Bangalore, India; and São Paulo, Brazil.

What the world is now experiencing can no longer be framed as "normal". The past can no longer be used to predict seasonal weather events and precipitation. There is a pressing need for new public policies and business strategies as well as for innovations in technology, financing and partnerships to thrive in the 21st century. These developments will be possible only with better-quality and more accessible data, and the creation of more useful information. This is a role that technological advancements can play in supporting leaders from all sectors.

Imagine the potential of harnessing the power of remote sensing to provide vastly improved predictions of droughts and flooding, real-time monitoring of water quantity and quality within watersheds, improved water-utility asset management, off-grid and localized solutions coupled with "frictionless" water-trading platforms. Digital technologies such as connected devices (IoT), predictive analytics and artificial intelligence are emerging as powerful tools in achieving sustainable, resilient and equitable access to water.

Admittedly, Fourth Industrial Revolution technologies alone will not solve water-security challenges. They can support and help inform decision-makers from governments and other sectors only if these solutions are designed together with the engagement and commitment of diverse stakeholder groups – incumbents, start-ups and entrants from other sectors.

Through the World Economic Forum's Global Water Initiative and its Water Security Rewired platform, these stakeholder groups are converging to explore the applications of Fourth Industrial Revolution solutions for the water sector, with aims of accelerating adoption, rapid expansion of competitive choices, new investment into innovation and potential leapfrogging to solve 21st-century water challenges.

As a community, we have a tremendous opportunity, as well as a responsibility, to embrace the potential technology and innovation at our fingertips, and to create the right infrastructure, financing and policy mechanisms to not only prepare for the challenges of tomorrow, but to make the most of what is possible for our agenda today.

We hope this Fourth Industrial Revolution insight paper on water will be another milestone on this continued journey.

The Fourth Industrial Revolution and the agenda for change

Water challenges are complex and interrelated, which is why water is often framed as a "wicked problem". In general, this refers to "a complex problem for which there is no simple method or solution, there is no single answer and every attempt can matter, because it affects the things people depend upon. Wicked problems are often socially complex, and they have to deal with changing behaviours and outcomes that are unforeseen."[2]

For seven consecutive years, water issues have ranked among the top five global risk factors in the World Economic Forum's annual Global Risks Report.[3] In 2018, of those global risks perceived to have both the highest likelihood to manifest and the highest impact on the world in the next decade, all but one can be linked to water. Over this period of time, while other risks have emerged and disappeared – including the financial crisis and chronic diseases – water has remained. While the challenges are well known, and progress has been made, it is sobering to see that finally solving the water challenge continues to elude us.

"Business-as-usual" approaches will not be able to address the risks presented by water insecurity, nor will these approaches be enough to sustain the world's water needs for much longer. However, technical advancements and new capabilities emerging from the Fourth Industrial Revolution could fundamentally disrupt the status quo and spark new ways of tackling the global water challenge. This section outlines five of the most pressing water-related challenges where new solutions are needed.

Obtaining a complete, current and accessible picture of water supply and demand

At the heart of water resource management are decisions about how best to allocate a finite resource across multiple competing users with increasing demand. With a projected 40% gap by 2030 between global water supply and demand under business-as-usual practices (e.g. public policy and technology), competition for already scarce water resources will intensify, leading to difficult and painful allocation choices affecting the public sector, businesses, civil society and ecosystems.[4] Balancing these trade-offs requires an understanding of the quality of the water, how much water can be sustainably used, and an accurate picture of current and projected water demand from human as well as economic use (water used for agriculture, energy generation and industrial use). Unfortunately, issues of data access and quality prevent leaders at every level of society from comparing priorities for water, evaluating potential solutions and making informed decisions that balance economic, social and environmental interests. A related challenge is that where data does exist, it is often scattered across multiple government departments and stakeholders, and is also not readily compatible (or interoperable) with other data sources. From rural communities to multinational corporations to city planners and national governments, decision-makers struggle with the confines of isolated and fragmented information.

The potential impact of technology

The Fourth Industrial Revolution technologies have the potential to assemble more complete, current and accessible information on water supply and demand. Satellite imagery and other earth observation tools are delivering profound new insights on water supply in parts of the world where conventional ground-based methods to measure water supply are not feasible or practical. As an example, in 2021 the Surface Water Ocean Topography mission (SWOT) – a joint satellite mission between NASA and France – will use radar technology to provide the first global survey of Earth's water and measure how bodies of water change over time. According to NASA, the satellite will survey at least 90% of the Earth, studying lakes, rivers, reservoirs and oceans roughly twice every 21 days.[5] Another effort, Digital Earth Africa, is working to employ emerging technologies such as cloud computing, advanced satellite imagery and advanced machine learning to deliver

a unique continental-scale platform to democratize capacity to process and analyse satellite data.

Advanced satellite monitoring technologies, such as Interferometric Synthetic Aperture Radar (InSAR), are also helping to fill in data gaps relating to groundwater management. InSAR is a mapping technique that identifies earth surface deformations using radar imagery from orbiting satellites.[6] In contrast to conventional satellite imagery, which uses visible or infrared light to ascertain images during the day under a cloudless sky, InSAR radar technology can be applied regardless of weather conditions or time of day while providing insight within a centimetre's precision of the elevation changes of the earth's surface.[7] In cases where groundwater is being over-extracted or recharged, InSAR can observe the development, and potentially use artificial algorithms to fill in data gaps, thereby enabling water managers to understand the status of an aquifer better.[8] This degree of hydrological insight can provide an unprecedented understanding of groundwater usage, helping to address issues of neglect, over-extraction and assumptions about capacity.

Virtual sensors are also being deployed to help improve our understanding of water usage, bringing improved efficiency and lower costs than traditional physical sensors. These virtual sensors employ artificial intelligence (AI) software that uses deductive reasoning to process information from various machines to determine what a physical sensor output would be. The results are transcribed in a real-time configuration that is understandable and accessible for water managers and stakeholders alike. Virtual sensors are particularly useful when physical sensors cannot withstand harsh environments, are too expensive, or if abnormalities persist in physical sensor readings.

Providing access to and ensuring the quality of water, sanitation and hygiene (WASH) services

Currently, the statistics regarding access to WASH services are grim, with approximately 4 billion people living in water-scarce regions, and more than 2 billion people still living without access to safe drinking water and basic sanitation services.[9,10] Water-borne diseases that result from this lack of access kill more than half a million people, most them under the age of five, each year.[11]

Determining how best to improve and scale WASH service delivery is fundamental to human and environmental security, particularly in today's context, where factors such as population growth, increased migration, urbanization, rising economic activity and climate change threaten the capacity of existing WASH systems and infrastructure.

With an estimated 3 million people moving to cities every week, meeting urban water and sanitation needs will be particularly challenging.[12] In many cities, this growth places stress on already outdated and ageing pipes, exacerbating leakages and disruptions in access. In South Africa, for example, a fifth of households with municipal piped water reported interruptions that lasted for more than two days in 2014.[13] This was three times higher in regions elsewhere in the country.[14]

In addition to increasing the vulnerability of centralized infrastructure systems, another challenge associated with urbanization is that a quarter of all city inhabitants are projected to live in informal settlements by 2030 – accompanying the rapid expansion of megacities in emerging economies.[15] While centralized water and sanitation systems may have worked for some cities in the past, such approaches are often not feasible in today's sprawling metropolises and informal settlements.

Even where water and sanitation connections exist, the quality of services provided are often a challenge. Particularly in rural and peri-urban areas, water distribution services often struggle to deliver a constant supply of potable water due to underground water leaks and poor water-quality monitoring. Furthermore, pollutants from agricultural and pharmaceutical run-off, ageing infrastructure or insufficient water treatment systems threaten the health of communities and ecosystems throughout the world.

The potential impact of technology

Advanced technologies can transform business models needed for WASH service delivery and maintenance and, in doing so, unlock a variety of new economic opportunities.

Remote sensors and IoT-enabled monitoring systems can improve the accuracy and speed with which centralized utility systems can detect and repair leaks and ensure water quality. Similarly, artificial intelligence and machine learning can provide context to historical data, making it easier to predict infrastructure risks and inform replacement plans in real time, optimizing capital, revenue, operating costs and services. Blockchain offers potential opportunities for municipalities to record water-quality information in a transparent and openly accessible manner that is protected from third-party tampering. The addition of blockchain-based smart contracts could automatically trigger repairs by (and payments to) pre-approved suppliers, overcoming the long processing times and bureaucracy that can hinder repairs in some jurisdictions.

Autonomous vehicles, drones and AI can also be used to optimize transport routes as well as monitor service delivery and maintenance, saving financial resources and work hours with real-time feedback. This is particularly useful in harder-to-reach peri-urban or rural areas where there is less financial incentive for service providers to deliver. Machine learning offers further opportunities to help enhance service provision by collecting data from physical or virtual sensors to develop more nuanced predictions.

There are also Fourth Industrial Revolution applications to address access to sanitation and hygiene. For example, current work by the Toilet Board Coalition is exploring how advanced sensors fitted to toilets, combined with mobile technology, IoT and AI may be able to provide cheap, effective and regular health checks and infection flags to sanitation users, potentially generating additional revenue streams with significant health-system benefits. Communal toilets equipped with Fourth Industrial Revolution-enabled monitoring systems can also be used to gather digital health information to help curb disease outbreaks.

Managing growing demand

Among the important drivers of the projected 40% supply-demand gap are the interrelated trends associated with economic growth and the demand for water, energy and food.[16] The global population is currently increasing by approximately 83 million people each year.[17] By 2050, it is projected to reach 9.8 billion people, more than two-thirds of whom will live in cities.[18,19] One result of urbanization will be higher levels of industrialization and water use, especially for the energy sector and among industries such as agriculture, food- and beverage-processing, manufacturing and mining, which tend to be among the thirstiest. Particularly in emerging economies, the transition from low- to middle-income cities currently entails a shift towards more protein-intensive diets that place greater pressure on agricultural, freshwater and coastal aquaculture resources. With agriculture already accounting for an estimated 70% of freshwater use globally,[20] feeding a 9.8 billion-person planet will require new approaches to inspire the smartest and most efficient use of water resources. Perhaps unsurprisingly, the International Union for Conservation of Nature (IUCN) estimates that, by 2050, demands for water, energy and food will increase by 55%, 80% and 60%, respectively.[21]

The potential impact of technology

Fourth Industrial Revolution capabilities can play a powerful role in mitigating demand across water-intensive industries. In the agriculture sector, for example, companies such as Microsoft are demonstrating how precision irrigation techniques can employ smart sensors implemented in crop fields to divulge information about soil conditions, as well as use drones to take images of fields, and AI to interpret data and model a heat map of the crop area.[22] The machine learning between various Fourth Industrial Revolution technologies enables managers to decide where and how to use their water resources most efficiently and effectively, thereby saving resources, time and money. Together, such Fourth Industrial Revolution technologies can generate and convey insights to a myriad of stakeholders in a digestible, straightforward message on their mobile devices in real time or in a daily report.

While remote sensors, AI and IoT are already being deployed by utilities to better understand demand and enable smart-water metering, blockchain offers opportunities to further influence the behaviour of end users.[23] By enabling peer-to-peer trading of water allocations among users in an open and transparent manner, blockchain-backed smart contract systems can help optimize water use and encourage better stewardship.

Fourth Industrial Revolution technologies such as remote sensing (satellite imagery and drones), IoT and AI can collectively help monitor the health of water systems in different geographies. Better insight into the quality and quantity of available water can in turn lead to more accurate and responsive pricing mechanisms for water that scale conservation, reuse and recycling.

Ensuring water quality

While public attention often focuses on water availability, the world also faces a water-quality crisis. Today, only 20% of wastewater globally is properly treated before being discharged into receiving water bodies, where it degrades natural ecosystems, causes water-borne illness or infiltrates aquifers and further jeopardizes the quality and availability of freshwater supplies.[24] With 21 of the world's 37 largest aquifers in decline, and 13 of these aquifers in critical stress, the world cannot afford to degrade any more freshwater resources.[25] An important challenge in improving water security is therefore to maintain the integrity of existing water-supply sources.

Wastewater treatments are vulnerable to disruption and are not designed to filter out harmful pollutants such as phosphorus, faecal matter, lead, oil and detergents from commercial, industrial and agriculture industries. Microplastics are also a major source of concern. Used in a variety of product, including garments, microplastics can release more than 700,000 plastic fibres per machine wash, the majority of which find their way into water systems and soil.[26] Furthermore, 80–90% of microplastics are embedded in sludge from wastewater treatment plants, which is often used in the agriculture sector as fertilizer.[27]

Agricultural production also contributes to terrestrial and aquatic ecosystem degradation by depleting freshwater resources and causing eutrophication, or dead zones, from run-off along many coastlines around the world. As food production increases to meet the demands associated with population growth, urbanization and industrialization, more and more contaminants are pumped into water sources, often illegally. As noted in the 2010 UNEP/UN-Habitat publication, Sick Water? The Central Role of Wastewater Management in Sustainable Development, "it is clear that future demands for water cannot be met unless wastewater management is revolutionized".[28]

The potential impact of technology

Fourth Industrial Revolution technologies can offer a range of solutions to address poor water quality and its impacts on society and the environment.

Around the world, sensors are being deployed into water bodies to collect data pertaining to water flow, water quality and quantity. That information is communicated through IoT devices, an ever-growing network of physical objects with internet capabilities that can transmit data on accessible user-friendly platforms such as a mobile device or tablet. IoT-enabling sensors allow decision-makers to detect issues such as how and where waterways become contaminated from wastewater treatment plants or eutrophication from agricultural run-off, and prioritize remediation strategies accordingly.

Xylem Inc. is a water-technology company that has increasingly focused on Fourth Industrial Revolution digital water-technology solutions. One example is its partnership with the National Great Rivers Research and Education Center (NGRREC) to monitor water quality along the entire length of the Mississippi River.[29] This partnership is part of a broader initiative to establish a global network of real-time water-quality monitoring platforms on great rivers around the world. A series of monitoring buoys creates a system for the real-time monitoring of water quality, phytoplankton data and nitrate loading, and a data-logging and transmitting platform to support fisheries, emergency response, research and source water data.[30]

Where pollution sources are pinpointed, new innovations in treatment technologies can then be deployed as part of the water-reclamation process. For example, a new polymer membrane, combined with AI software, can now continuously analyse data from flow and pressure sensors to determine the best treatment.[31]

The application of such breakthrough technologies can be scaled and enable water-quality trading. For example, blockchain potentially offers new opportunities to support transactions made via such a market and provide a new class of incentives to suppliers and potential users.

Building resilience to climate change

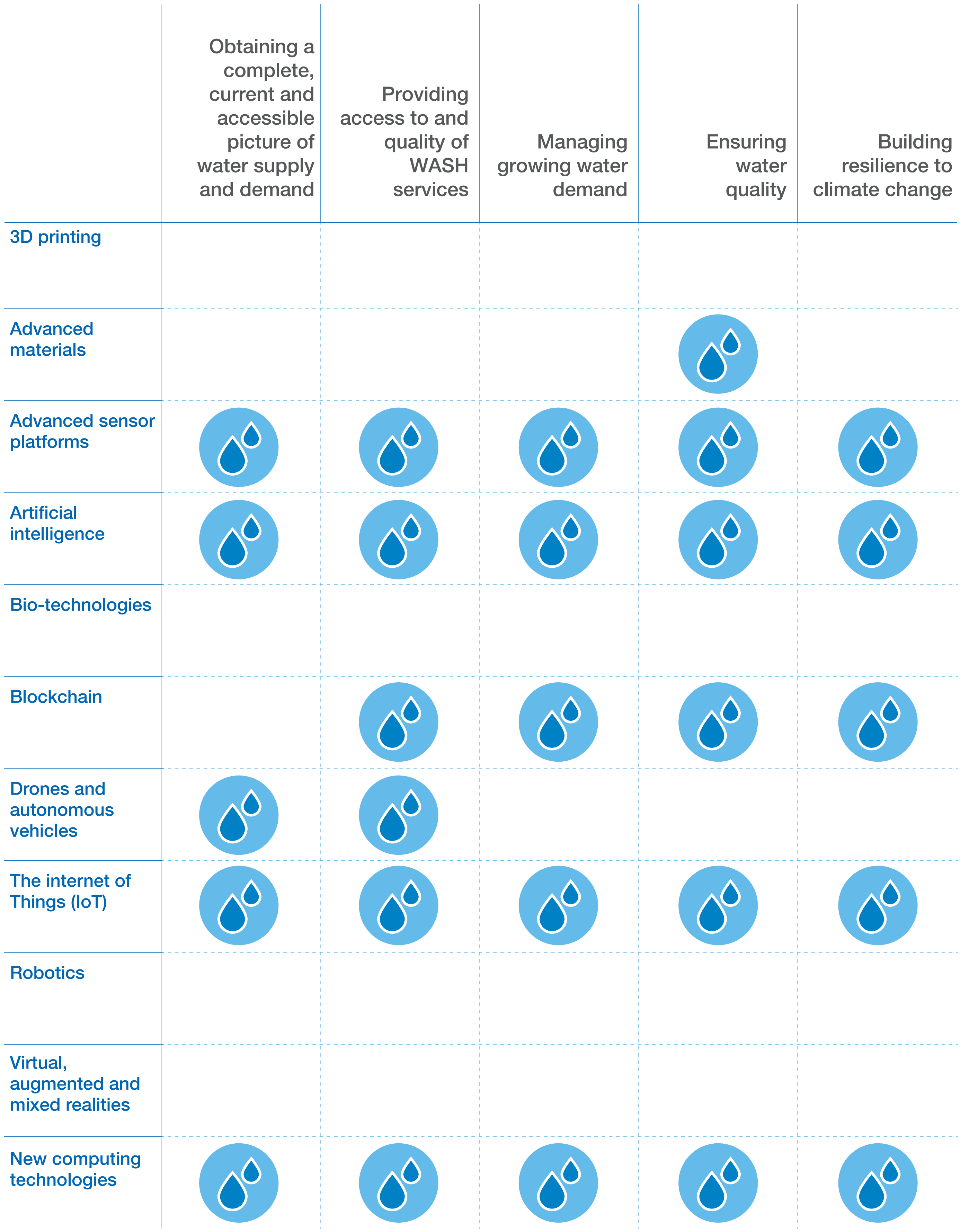
According to the World Bank's Unchartered Waters report, 60% of the world's population lives in areas of near-permanent water stress.[32] This includes nearly all of South Asia, the Middle East and North Africa. Climate change impacts, manifested through more intense and frequent extreme weather events such as floods and droughts, threaten to make water supply more erratic and unpredictable, disrupting continuity across global economic value chains and upending social stability. Such scenarios could cost regions such as the Middle East and Africa up to 6% of their GDP by 2050 due to water-related impacts on agriculture, health and incomes, while also having the potential to exacerbate other threats such as migration, food insecurity and the risk of conflict.[33]

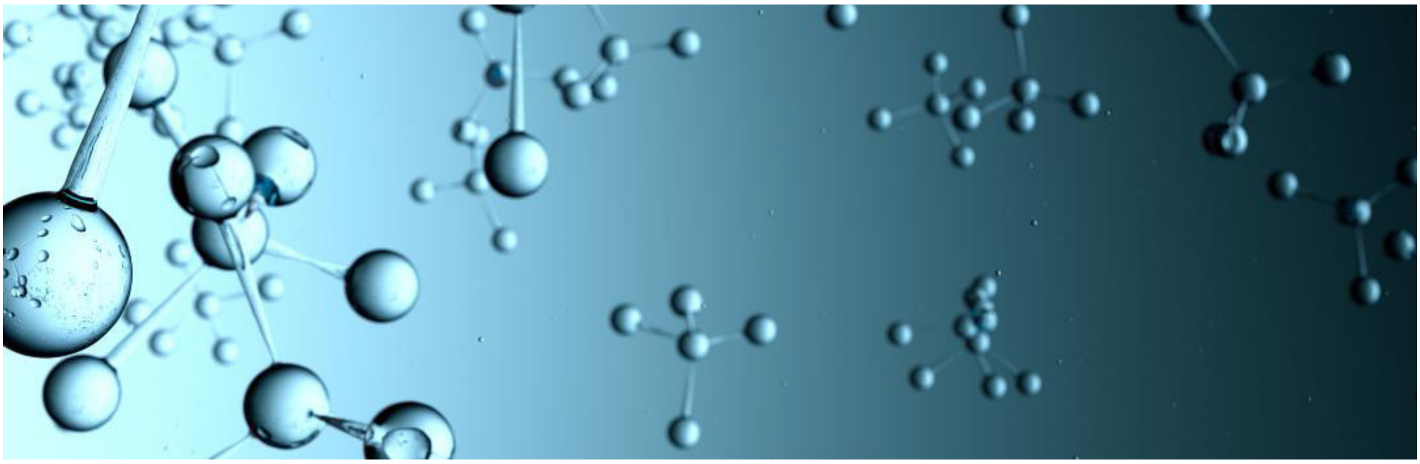
Additionally, more than 2.5 million people have died from natural disasters over the past 30 years, which have cost almost $4 trillion.[34] In 2017 alone, extreme natural events, such as floods, hurricanes and droughts, cost the global economy about $330 billion, making last year the costliest ever in terms of weather-related disasters.[35]

These statistics illustrate the critical need to build and enhance resilience across economies and to "future-proof" global value chains. Building resilience to droughts, storms, floods and other extreme weather events associated with climate change is an increasingly important factor for emerging economies to attract private-sector investment. According to the International Food Policy Research Institute (IFPRI), "current 'business-as-usual' water management practices and levels of water productivity will put approximately $63 trillion, or 45% of the projected 2050 global GDP at risk".[37]

An increased focus on resilience can give supply chains a competitive advantage, thereby attracting new jobs

Figure 1: Development level of Fourth Industrial Revolution technology applications that address water and sanitation challenges





A closer look: The impact of water insecurity on local communities and global supply chains

The Chennai flood in India in December 2015 was the worst flooding caused by rainstorms in the past 100 years. The area has a population of 7.6 million, over 250 of whom were killed and more than 3 million were left without safe drinking water. There were also severe disruptions to business operations.[36] Chennai is not alone as many global cities are facing risks to their water supplies from the variability of hydrologic events (e.g. droughts and flooding). The human cost of the 2012 floods in Thailand was devastating, with over 800 deaths and 13.6 million people affected. In addition to the severe infrastructure damage along its coastal regions, 65 of Thailand's 76 provinces were declared flood disaster zones, and over 20,000km2 of farmland was damaged. While Thailand's GDP shrunk by 9% as a result of the floods, the ripple effect paralysed the global value chain for manufacturing vehicle parts and computer hard drives. Economic losses were estimated by the World Bank at 1.4 trillion Thai baht ($45.7 billion), which makes the floods one of the top five costliest natural disaster events in modern history.

and talent. It can also better inform the planning of major infrastructure assets such as energy systems, agriculture corridors or even cities themselves. According to the World Resources Institute (WRI), almost half of the world's thermal power-plant capacity – mostly coal, natural gas and nuclear – and 11% of hydroelectric capacity are located in highly water-stressed areas.[38] Placing infrastructure investment appraisals for these major assets within the wider hydrological (and weather-related) dynamic of the watershed, coastline or river basin within which they will be built will be imperative to ensure the development of resilient integrated infrastructure systems.

The potential impact of technology

Blockchain can play an important role in de-risking financial investments for more resilient water infrastructure. In China, for example, Newater Technology is partnering with NW Blockchain Limited (NWBL) to raise $4.77 million for a 20-year build-operate-transfer contract for a wastewater treatment plant by selling asset-backed tokens.[39] Similar to selling private equity, the asset-backed tokens will fund the resources for the wastewater treatment plant, and Newater Technology will run and operate the facility. Additionally, blockchain's smart currencies and smart contracts enable the automatic transfer of digital currencies when contractual agreements have been met, thereby overcoming currency fluctuations and exchange-rate risks of the countries involved. The transparency and efficiency of blockchain notably protects infrastructure finance and potentially enables smaller wastewater treatment plants to acquire capital to expand their production. This would be difficult within traditional investment capital markets due to slow verification processes and a preference for larger-scale projects that yield economies of scale and fit within institutional investors' typical risk profiles.[40] Blockchain could also enable smaller retail investors to invest capital in large-scale infrastructure projects, as the smart contract capability makes it possible for such projects to be funded by hundreds of backers rather than just a handful.

Technologies such as satellite imagery, IoT, big data and AI can also be exploited for better scenario planning and forecasting to improve resilience at all levels of society (regional, national and subnational). In an urban context, for example, remote sensing technologies for flood prediction (e.g. Cloud to Street) and comprehensive design tools for hydraulic modelling (e.g. Autodesk Storm and Sanitary Analysis) are among the various services emerging to inform infrastructure investment decisions about urban planning and preparedness. The Fourth Industrial Revolution-enabled advancements in the collection and integration of disparate water-data sources will be crucial to informing resilience strategies and developing solutions at scale.

Transforming ‘business as usual’ in water

Solutions enabled by Fourth Industrial Revolution technologies have the potential to transform and spark a new innovation agenda for the water sector. While these technologies will not provide a single or complete solution to the world’s water challenges, they will profoundly improve the toolkit available for leaders from government, business and everyday communities to understand, manage and use water resources. The following game changers represent five of the most profound ways in which the Fourth Industrial Revolution will transform approaches to water management.

21st-century water infrastructure systems and management

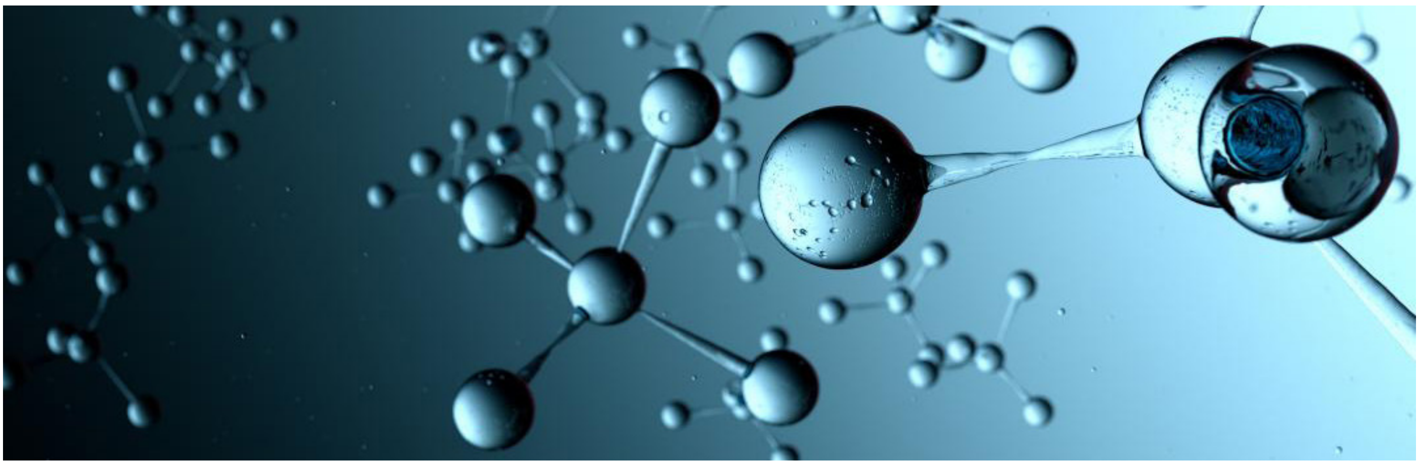
Fourth Industrial Revolution technology, particularly in the digital realm, is transforming the face of water and wastewater systems as we know them today. Not only are utilities able to operate and manage centralized systems more efficiently and effectively, technology solutions are also opening up opportunities for more off-grid, decentralized systems to meet the needs of individual corporations and rapidly expanding urban populations. In both of these settings, technological advancements are also redefining the way consumers view and interact with water data, helping to ensure the integrity and quality of water and wastewater services.

Enhancing operational excellence

In centralized systems, a wave of new digital solutions have emerged as powerful tools to manage utilities in a more cost-effective manner. For example, the need to repair and replace infrastructure with limited funding is driving the adoption of technologies to proactively identify leaks through remote sensing and robotics.[41] Other solutions, ranging from predictive analytics (e.g. TaKaDu) to asset management (e.g. RedEye) and improved customer engagement (e.g. Dropcountr), will further revolutionize water management in centralized systems. Intelligent water platforms can help integrate these solutions to monitor real-time performance and improve cost-effectiveness.

The maintenance of assets can also be enhanced and improved through the potential of virtual-reality and augmented-reality solutions to facilitate staff training.[42] The Coca-Cola Company is already using this technology in bottling plants to connect technicians to remote experts who can help service equipment, thereby eliminating the costly expense of sending technicians around the globe. The same can be conceived for maintaining water and wastewater systems.

As centralized wastewater treatment centres shift to embrace economic opportunities offered by the circular economy, digital tools can also help monitor real-time performance and ensure the safety of energy, nutrients and other materials/products generated by treatment processes. As for the current use of Fourth Industrial Revolution technology in wastewater treatment plants, artificial intelligence is making its debut in municipal wastewater treatment plants by improving ultrafiltration membranes. Specifically, an AI algorithm is embedded into the operating system that automatically initiates the correct cleaning protocol of filtration systems depending on the system’s overall performance. Given that traditional cleaning mechanisms either over- or under-clean water, the AI algorithm intelligently chooses the perfect cleaning intensity, thereby drastically reducing the total energy and resources used while also improving the ultrafiltration membrane life and the overall reclaimed wastewater quality.[43]



The shift towards decentralized or off-grid systems

Fourth Industrial Revolution water-technology solutions will also facilitate the adoption of more off-grid and localized solutions for water and wastewater treatment along with strategies to build hybrid decentralized-centralized systems. Such innovation will be imperative as existing centralized systems struggle to meet the needs of a growing population and face increasing difficulties in obtaining financing, as well as dealing with political factors and climate change externalities. This shift towards decentralized water systems will play an important role in fulfilling future needs and improving overall urban planning and preparedness.

For example, microgrid strategies used in the power sector are being adapted for urban water systems to help buffer against vulnerabilities associated extreme weather events.[44] Elsewhere, real-time and remote monitoring of water-system performance as well as quantity and quality will facilitate the broader adoption of off-grid water generation (e.g. Zero Mass Water) and localized treatment technologies (e.g. Organica). Digital solutions will also change the relationship of water provider to consumer, which historically has been a one-way relationship through emerging real-time water-quantity-monitoring technologies (e.g. Waterlyzer and Lishtot).

The shift to decentralized infrastructure solutions is not new. Other sectors, such as the energy and telecommunications

Deploying decentralized water-reuse solutions in megacities

Scott Bryan, Imagine H20

By 2050, nearly 70% of the world's population will reside in cities.[46] More than 90% of the projected growth in urbanization will be driven by emerging markets, particularly in Asia and sub-Saharan Africa (UN).[47] As a result, urban water resources will experience heightened stress and existing infrastructure will struggle to meet the basic needs of expanding populations.

Decentralized water solutions, enabled by Fourth Industrial Revolution technologies, will become a powerful tool in building resilient infrastructure. Specifically, establishing a syndicate to facilitate broader investment and deployment of water-reuse systems in industrial parks could help emerging cities that are struggling to manage unreliable water supplies.

The limits of traditional solutions to the challenges posed by urbanization have grown increasingly apparent. The development of large-scale water infrastructure is no longer viable in many settings due to political factors, climate risk, public acceptance and limited financing options. For many emerging economies on the front lines of climate change, new approaches are urgently needed to augment existing water systems and improve affordable access to underserved populations.

Decentralized water solutions, driven by both technological advancements and business model innovation, will become more prevalent. In energy, models such as rooftop solar and district heating demonstrate important paradigms for future water infrastructure. Water reuse, driven partly by the falling cost and improved efficiency of membrane bioreactor (MBR) technology over the past ten years, can become common practice in a city's built environment and industrial zones. As witnessed in the renewables sector, proven technology paired with innovative financing models as well as incentives can lead to rapid market adoption and impact.

In particular, deploying water reuse in industrial zones within megacities and secondary cities represents an important way to ensure economic resilience. At the same time, it alleviates stress on municipal water systems as well as surface and groundwater supplies. A focus on industrial parks could create efficiencies in sourcing and potentially the trading of water resources among companies. Additionally, larger corporations seeking to manage reputational risk could be encouraged to play a proactive role. In some situations, coupling water-reuse systems with solar installations could reduce the energy required to treat water while creating attractive projects for investment. In turn, using private capital to make industry more resilient can have promising outcomes for municipalities struggling to address resiliency and affordability.

Water reuse is a proven technology quickly gaining scale in California and other regions with stressed water supplies. Deploying this technology on a smaller, distributed scale will rely on the integration of Fourth Industrial Revolution technologies, including IoT, to actuate and control processes, as well as AI to efficiently manage systems and resources.

Decentralized water-reuse systems must be deployed on a larger scale to create the required resource efficiencies. As a result, creating the financial mechanisms to effect mass adoption opportunities will be critical to water-reuse systems, just as financial innovation has enabled the proliferation of solar and wind in the energy sector.

Creating a syndicate to enable the large-scale financing of distributed water-reuse systems would be essential to accelerating the deployment of solutions in urban areas. Syndication enables larger investment in what would otherwise be a series of individual investments that would not make sense on their own. A syndicate also attracts larger financial institutions into the market, which benefits from existing expertise and the sheer scale of capital available. The right syndicate model could adhere to transparent reporting guidelines for both financial and natural resources. Such a model could secure funds from institutional investors, international finance institutions, influence investors and, potentially, corporations pursuing alternative corporate social responsibility models.

A coordinated approach to financing, deploying and managing water-reuse systems in industrial zones located within megacities, is an important step towards water resiliency.
The combination of proven reuse technology with syndicate financing could become a model for investment in other distributed water solutions.

The push for more open and transparent water data: A spotlight on California

The California Open and Transparent Water Data Act offers a prime example of a public policy response to stakeholder interest coupled with vastly improved data-management practices to inform public policy decisions. In September 2016, the State of California approved AB 1755, the Open and Transparent Water Data Act, which requires the Department of Water Resources (DWR) to create, operate and maintain an open-access, state-wide integrated water data platform. Support for the bill cited the platform as a unique opportunity to utilize information technology as a tool to help water managers explore ecological and water data so that they operate California's water system more effectively.[48]

DWR, in consultation with other state and private groups, must release an operational integrated water data platform with available water and ecological/fisheries state agency datasets by September 2019, and include data held by federal agencies by August 2020.[49] Development of the data platform involves input from UC Berkeley's California Council on Science Technology, and an Aspen Institute Dialog Series report called "Internet of Water: Sharing and Integrating Water Data for Sustainability".[50]

As a result, increased access to data will support better-informed decisions and cost-effective investments, foster entrepreneurship, innovation and scientific discovery, and provide unique opportunities, such as the development of data-search and packaging products and services.[51] Municipal wastewater treatment facilities currently report discharge volume and water-quality data to the regional water board, but there are no clear protocols for promoting compatibility among datasets that would allow for sharing, aggregation and analysis by multiple groups.[52]

While the Sustainable Groundwater Management Act (SGMA), passed in 2014, the uncoordinated and inconsistent data collection among California's more than 2,000 local and state agencies involved in groundwater management is one of the factors contributing to poor groundwater management in the state.[53] Environmental Defense Fund identifies AB 1755 as a critical policy action in the development of a California Water Market that would facilitate a more resilient water system for the state's farmers, municipalities, industries and residents.[54]

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industries, have made this transition quite successfully. There are opportunities for the water sector to build on this progress to help deliver services to millions of "off-grid" customers. For example, the M4D Utilities programme at the GSMA highlights that, while 2.4 billion people lack access to an improved source of sanitation, 95% of this population is covered by mobile networks, with unique subscribers at 63%.[45] The programme is working with Loowatt and others to test mobile payments for sanitation services.

The benefits of decentralized approaches to service provision include the reduced need for costly and maintenance-heavy grids, the ability to reach disparate communities, and the speed of deployment. India and Africa are clear cases where mobile telecommunications have allowed far more people to become connected more quickly.

Real-time, interoperable water data

Emerging Fourth Industrial Revolution technologies – machine learning, artificial intelligence, advanced sensors, satellite imagery, robotics and more – are providing breakthrough solutions to common water-management challenges by unlocking a wealth of previously unobtainable data about the health of water systems at the global, regional, watershed and local scale.

By revolutionizing data acquisition and analytics, these technologies are bridging data gaps and performing assessments, monitoring system resilience, predicting breakdowns and enabling better source-water protection. With continued innovation enabling more precise understandings, analysis and insight, it is now possible to better inform local, near-real-time decision-making at a lower cost and with less effort.

Combined with new forms of public-private collaboration, these technologies can support decision-makers across industry, government and civil society to balance trade-offs, identify common priorities and help make smarter investment choices. For example, new collaborations could unlock and release more sources of data into the public domain. This would be a significant advance in creating a holistic view of water challenges in a given geographical area, selecting an optimal set of solutions, and getting such solutions approved, financed and implemented. The push for more open-source water platforms can further encourage the interoperability of such water-data sources, while technologies such as machine learning can be used to fill in the gaps to offer even more complete, reliable insights.

Empowered communities and consumers

Technology-enabled solutions for getting more, and better, water data into the public domain can fundamentally alter political, economic and social dynamics in a given locality. For example, "citizen scientists" can increasingly collect real-time water data with low-cost sensors (e.g. US Environmental Protection Agency and State of Georgia), open-source data platforms (e.g. California Open and Transparent Water Data Platform) or smart residential irrigation and water-management systems (e.g. Rachio), thereby ensuring that they have access to the latest water quality and quantity information.

Similarly, blockchain applications can enable everyone from households, industry consumers, water managers and policy-makers to access the same data on water quality and quantity and make more informed decisions. Such transparency can help inform consumer decisions about when to conserve or use water. It can in turn help prevent corrupt behaviour in situations where there may be an incentive for local authorities to tamper with or withhold water-quality data.

Blockchain technology could also support peer-to-peer trading of water rights in a given basin, allowing water users who have enough or are willing to share their excess water resources with others in the area to do so 24/7 without relying on a centralized authority.[55] Imagine a scenario where farmers in the same water basin could make the decision to trade their allocations based on the latest weather data, crop prices, market trends and longer-term climate trends – much of which is already accessible via their mobile devices.

Redesigning supply chains

Advanced technologies are enabling companies to innovate and disrupt traditionally water-intensive supply chains. From operational efficiencies to entirely new business models, companies and their investors are better understanding and quantifying their water-related risks, and are devising new strategies to address these issues.

The agricultural sector represents a prime example of how companies are using Fourth Industrial Revolution-derived insights to optimize water use and increase productivity. As highlighted in a recent PwC report, Clarity from Above, drones equipped with hyperspectral, multispectral or thermal sensors can help farmers to detect more accurately and quickly where fields are dry.[56] Additionally, once the crop is growing, drones allow the calculation of the vegetation index, which describes the relative density and health of the crop, as well as the heat signature, which depicts the amount of energy or heat the crop emits.[57] Precision agriculture enabled by drip irrigation technologies (e.g. Netafim), and on-site sensors (e.g. Arable) can then be deployed for improved efficiency and increased productivity.

Technologies are also unlocking new business models that minimize dependency on water. AeroFarms, for example, builds and operates vertical-farming warehouses on major distribution routes and near population centres. By employing technology and data for precision agriculture techniques, AeroFarms uses 95% less water than field-farmed food and has yields 390 times higher per square foot annually.[58] As such, AeroFarms defies traditional growing seasons and impacts due to climate change. It is also able to manage its products from seed to package, raising the standard for traceability and the ability to respond to an increased demand in responsible sourcing from stakeholders.

Advancements in traceability and transparency of products, enabled by technologies such as blockchain, will place further pressure on supply chains to manage water resources more efficiently. For example, a new brand of sparkling water in Europe – FACT Water – includes a scannable code on each can that provides consumers with greater transparency about the water's source.[59]

Diversified sources of supply

In a world where only 0.3% of the earth's water is readily accessible for human consumption, creating new sources of supply can fundamentally alter the trajectory of global development.

Nanotechnology holds the potential to unleash new water sources at scale, and in doing so, it can bring benefits across multiple industries, including water decontamination, infrastructure development and monitoring systems. The global economy has already recognized the potential impacts of this technology, with expected investments in the nanotechnology market – which is expected to exceed $125 billion by 2024.[60] Given that nanotechnology can manipulate and manufacture new materials, devices and systems at an atomic level with a fundamentally new molecular organization and function,[61] the potential uses in the water industry are far-reaching and encouraging.

For example, nanomaterial graphene-based membranes could disrupt the desalination market by halving the cost it takes to turn non-traditional sources into potable water and doubling the capacity in the next three to five years.[62] Nanomaterials are also being applied in the water-distribution space to improve efficiency by coating pipes in a self-healing material that can reduce corrosion and friction, thereby reducing total energy resources.[63]

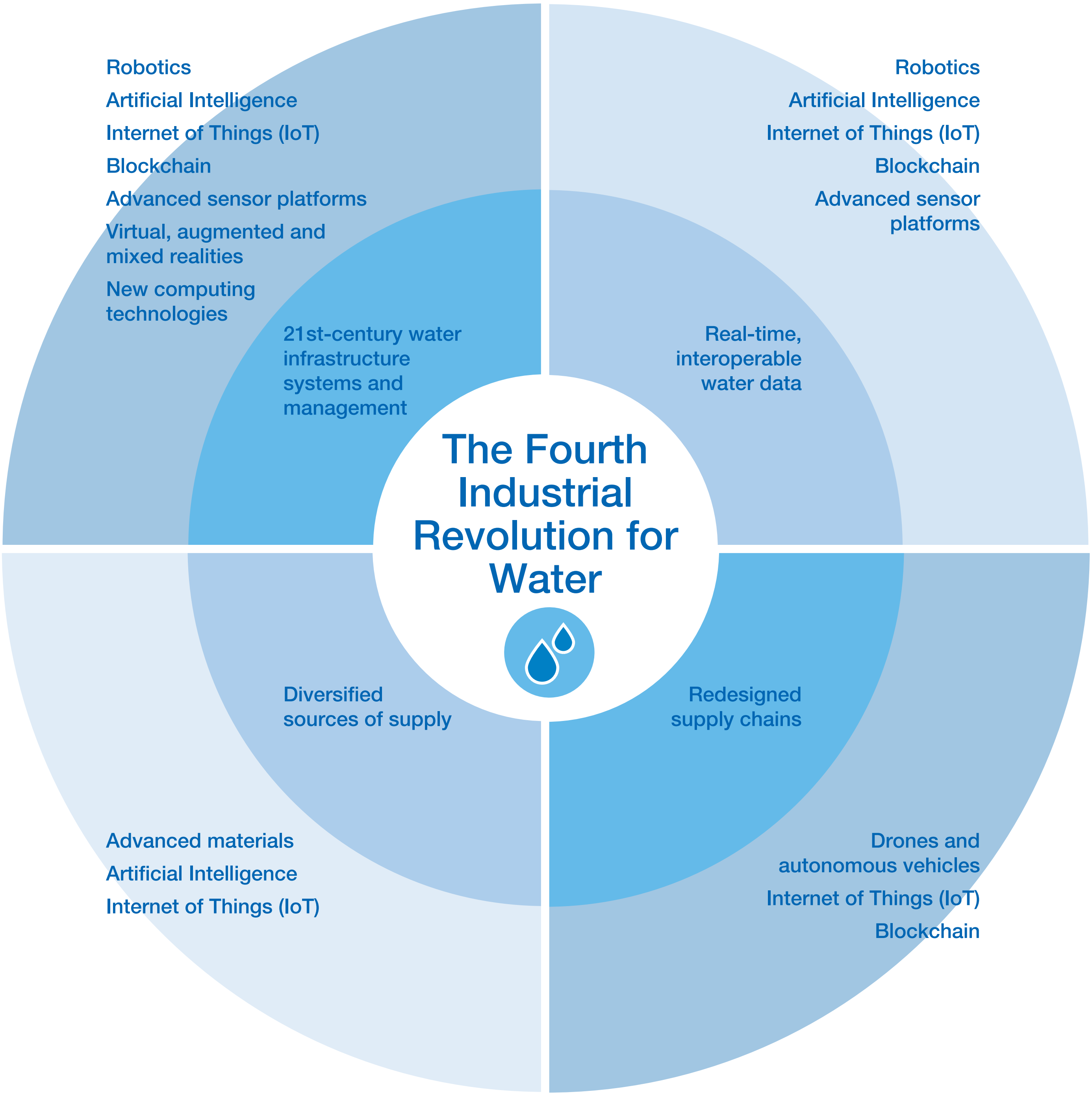
A related breakthrough is in nano-absorption, which couples nano-sized materials with various metals and/or fungi to absorb contaminants in wastewater plants. In some cases, nanomaterials containing iron minerals have been shown to absorb 90% of the organic contaminates passing through them in 30 minutes.[66] Given their low cost and efficiency, nano-absorption materials may help dramatically scale the rate of water treatment and reuse worldwide.

Revolutionizing desalination

In the past 30 years alone, drastic improvements have been made in the desalination process, with new technology and enhanced operating systems. According to the Water Desalination Report, current operating plants require only a quarter of the energy compared to systems in the 1980s, due primarily to efficient pumps, membranes and energy-recovering devices.[64] Sun-rich countries, such as Abu Dhabi, are also starting to integrate renewable sources of energy into desalination plants, thereby reducing energy costs and potentially offsetting the energy demand during peak hours.[65] The future of desalination is not only bright in terms of technological advancement reducing cost, but the ability to use natural resources to produce potable water in water-scarce regions is also promising.

In addition to unlocking new sources of water via reuse, other material advancements are enabling scientists to harvest water from the air more easily in arid, water-scarce regions.[67,68] For example, Zero Mass Water is using solar panels to extract the humidity out of the air and condensate it into a liquid form to create a new source of water.[69] This process requires zero infrastructure or electricity as their solar panels can generate 4–10 litres a day per two-panel array, depending on the sunlight and humidity.[70] Another pioneer in this space, Watergen, uses electricity from a grid to dehumidify water molecules in the air, producing 25–30 litres of water each day per device.[71] Advanced technologies such as IoT could offer promising opportunities to help scale such diversified water-supply sources. For example, connecting IoT-enabling sensors with nanotechnology advancements can provide operational efficiency insight to water suppliers or inform water users on their mobile devices of water availability produced from dehumidification processes, leading to an offset of traditional water consumption.

Figure 2: The Fourth Industrial Revolution innovation game-changers for water and sanitation



Risks or challenges to manage

While digital water technologies are being adopted and there is great promise in their ability to transform the sector, there are challenges and risks in scaling adoption.

An overview of the challenges is provided below.

Funding

One of the most pressing challenges is finding a source of funding for innovative technologies, including digital solutions. The sectors that most need digital technology solutions are the agricultural and utility sectors, which are also currently the most challenged in terms of access to capital. The agricultural sector alone faces unique challenges, with an estimated 500 million family farms worldwide, most of which are less than 2 hectares.[72] The question is: how do these family farms afford digital technologies? If not the smallholder farmer, will it be global food and beverage companies, public institutions or NGOs that embrace digital technology solutions? With regards to utilities, many of them face inadequate funding due to ratepayer expectations and a lack of public-sector investment. In the USA alone, it is estimated that $1 trillion is necessary to maintain and expand services to meet the demand for drinking water over the next 25 years according to a 2017 American Water Works Association report.[73]

Utility sector digital technology innovation adoption

In general, the water and wastewater utility sectors are slow to adopt new technologies for a variety of reasons. These include: a lack of incentives; risks (real or perceived); isolated groups of data owners/departments and lack of workforce training in digital solutions. Water utilities are entrusted with delivering safe drinking water to the public and, as a result, proven technologies are strongly favoured over unproven or emerging technologies. However, there are now strategies to "de-risk" new technologies coming from water-technology hubs and accelerators working closely with utilities (e.g. Imagine H2O, WaterStart and Current).

A 2017 article from Water World, titled "Adoption of Smart Water Technologies Remains a Utility Management Challenge", lays out the challenges facing the water-utility sector. The article highlights survey results from the Smart Water Networks Forum (SWAN) annual conference, where attendees were asked whether they thought adoption of data-driven technologies was a technology challenge or a management challenge for utilities.[74] Some 81% of people who voted agreed it was a management challenge, suggesting that, "while the technology has been developed to enable smarter water networks, there remains a challenge to convince water utilities."[75]

Another significant challenge is tied to the need for workforce training. In general, water-utility workforces are not trained in digital technology solutions and workforce transformation will be necessary to scale the adoption of digital technologies.[76]

Cybersecurity

Cybersecurity is critical in a digitally connected world. There is no shortage of examples of breaches in digital security, and the resultant business disruption and theft of data and information. The water-utility sector is not alone in having to keep pace with the ever-increasing assault on public- and private-sector enterprises. In 2015, the US Department of Homeland Security (DHS) responded to 25 cybersecurity incidents in the water sector (8.5% of the total incidents reported) and 46 incidents in the energy sector.[77] Comparatively, between 2014 and 2015, the reported number of water-sector incidents increased by 78.6%, from 14 to 25.[78] While there are numerous benefits associated with water infrastructure becoming more connected through the IoT, this connectivity comes with increased exposure to cyber-related threats that must be managed in the future through improved data-security measures.

Open-access data and information

While technological advancements will unlock powerful new sources of data and insights, ensuring equitable access to that information is another matter. Asymmetries in access to information on water availability and quality can easily exacerbate inequalities and tensions between stakeholder groups. It is important to acknowledge that unless there are financial incentives and a strong regulatory environment in place, these newly derived insights can easily remain proprietary assets that are available only to those willing and able to pay for them.

Fortunately, "open-data" platforms have prompted interest in the quest to ensure public-sector decision-making is transparent. The California Open and Transparent Water Data Act is a public-policy response to stakeholder interest coupled with vastly improved data-management practices to inform public policy decisions. There is also a push by stakeholders for companies to increase the transparency of their data.[79] What this really means, and the consequences of such increased transparency, have yet to be defined. However, it is clear that a move to transparency in the public and private sectors is driven by a need to build trust with stakeholder groups. Blockchain platforms to improve traceability and transparency, along with open-data platforms, are emerging as technologies able to address this need.

Accelerating innovation and impact: Opportunities and recommendations

The myriad challenges that comprise the global water crisis are among the world's most pervasive and "wicked" problems; as such, they are prime targets for innovators in the pursuit of new markets. And that innovation will come. As highlighted in previous sections of this paper, a range of promising new solutions have already emerged in the past few years. But if the experiences of other sectors serve as any indicator, the bulk of the transformation is yet to come.

The sweeping impact of the Fourth Industrial Revolution will undoubtedly transform the water agenda, as has already happened in other sectors such as health, mobility and energy. These examples serve as powerful case studies of the speed and scale with which this disruption occurs, and the potential implications it will have for both innovators and incumbents in the water sector.

How this disruption affects the scientists, academics, practitioners and policy-makers who comprise the global water community will depend entirely on their ability to prepare for, adapt to, and be part of forthcoming changes. More can and should be done to ensure that innovations continue to be developed in the public interest, and that institutions and governments are equipped to actively shape these advancements rather than absorb them as passive bystanders.

New platforms and approaches to collaboration will be vital in navigating this transition, as history has already shown us that the efforts of individual actors and institutions are insufficient in solving the world's water challenges. The following recommendations could offer the beginnings of a roadmap for stakeholders to work together to harness the opportunities and mitigate the risks that the Fourth Industrial Revolution creates for improved management of the world's water resources.

Priority 1: Promoting the rise of an innovation ecosystem

Building a strong and diverse culture of innovation is critical for the water community's ability to fully harness the Fourth Industrial Revolution. Without this, technology-enabled solutions will still be developed, but likely by a select few and not necessarily in a way that gets to the root of water challenges. However, by identifying and targeting vital levers of influence, an entire new innovation ecosystem, can arise that incubates ideas from the ground up and encourages the next generation of technology-savvy water leaders.

Various accelerators and challenge programmes have emerged in recent years to encourage water-related innovations. The Water Innovation Engine, for example, established by the High Level Panel on Water (HLPW) and the Australian government in 2017, has issued several investment challenges. Other innovative initiatives include AB InBev's ZX Ventures and the partnership between Techstars and The Nature Conservancy.

A broader range of entrepreneurs and subject-matter experts are also entering the quest for innovative water solutions. The water sector desperately needs such "outsiders" to inject new thinking into its operations. This might include experts in material science (e.g. Zero Mass Water) and companies in the information technology sector (Microsoft AI for Earth). Interest is also being created in the form of prize-awarding competitions (Imagine H2O and XPRIZE Water Abundance) and programmes (101010) that intentionally engage outsiders and promote innovation.[80]

Building on the progress of such initiatives, the game changers identified in the previous section of this paper could serve as potential thematic tracks of focus for a broader global accelerator platform to emerge. Perhaps drawing on the expertise and resources of a handful of leading accelerators, such a platform could pool funding and channel interest among top entrepreneurs to uncover solutions to some of the sector's biggest challenges. In addition to gathering ideas, a more coordinated and global accelerator approach would also send an important signal from the international community about the desire and commitment to scale investment to the water space.

Along similar lines, imagine the potential of directing even 1% of the $12 billion that was disbursed by the Organisation for Economic Cooperation and Development's (OECD) Development Assistance Committee (DAC) members in 2015 to the water sector to help scale and de-risk emerging water technologies.[81] This would translate to $120 million that could be deployed in support of new and existing research and development platforms or accelerators. The Swiss Agency for Development and Cooperation is one example of a bilateral development agency that has identified technology and innovation as a priority across its portfolio of water investments. What might happen with a concerted effort across all OECD DAC members?

Sustaining this culture of innovation will also depend on how we invest in and shape the next generation of water leaders and entrepreneurs. Engaging leading water-sector organizations, in partnership with leading technology universities around the world (e.g. MIT, Stanford, Korea Advanced Institute of Science and Technology, Tsinghua University, Indian Institute of Technology), course curriculum modules could be developed that would engage students in applying technology concepts to real-world water-sector problems. This would help stimulate creativity in technology solutions for the water sector, while inspiring and building a pipeline of the next generation of water leaders in government, industry and research institutions. Such investments could prove instrumental in resurrecting and re-energizing a workforce that is – especially in the case of many water utilities – both ageing and dwindling.

Priority 2: Shifting towards agile multistakeholder governance models

Mainstreaming new technologies and approaches cannot be left to accelerators and investors alone. Governments, as the ultimate custodians of water resources, must remain at the centre of the innovation agenda. Allowing government officials to make the most of the Fourth Industrial Revolution will require new solutions that can help them better navigate the complexities of resource-management decisions. How, for example, might technological advancements help local officials better understand and synthesize disparate sources of water-related information in real time? Could the creation of new platforms lower these transaction costs for governments and facilitate more confident and agile decision-making across ministries?

Despite clearly having potential benefits for decision-makers, the Fourth Industrial Revolution also raises important questions about the future of water governance. As governments are ultimately responsible for ensuring that technologies are developed and scaled responsibly, they will need to develop new policy frameworks and protocols for how emerging technologies are tested and refined.

Existing institutions will need to adapt their structures and approaches to help governments navigate this transformation – from think tanks to NGOs to research institutes to existing public-private partnerships. New work streams and research pillars are desperately needed across these entities to explore the implications of emerging technologies in areas ranging from ecosystem management to sanitation to water-risk disclosure. Those institutions that manage to embrace and get ahead of this transformation will be best suited to drive and shape it.

The World Bank offers an encouraging example of what this can look like in practice. As part of its commitment to harnessing and deploying disruptive technology for development, it recently launched a new Disruptive Technologies for Development Fund in partnership with Credit Suisse, which aims to "harness public- and private-sector technology, data and expertise to help its clients manage the opportunities and risks of rapid technological change".[82] The Global Water Practice is among the leading branches within the bank exploring how best to capitalize on the opportunities associated with advanced technologies. Through research, capacity-building and cross-sector collaboration to identify and pilot the use of technologies, it has the potential to spur greater demand for innovations that can accelerate sustainable growth.

Could other existing institutions evolve their operating models in a similar fashion to advance a strong technology agenda and contribute to the nimble governance structures needed to responsibly scale innovation? For example, how might entities such as Global Water Partnership or the Water Supply and Sanitation Collaborative Council reconfigure themselves to help governments navigate technological transformation in areas such as integrated water resources management (IWRM) and WASH? Could the country-based multistakeholder platforms established by the 2030 Water Resources Group perhaps serve as "test beds" to trial new advanced-technology solutions?

Conclusion

The Fourth Industrial Revolution holds the promise of ensuring universal access to safe drinking water along with water for industry, energy, agriculture and ecosystems. The pace and scale with which this transformation happens depends entirely on the urgency and creativity displayed by our institutions. Technology innovators are starting to identify the opportunities for disruption in the water sector for Fourth Industrial Revolution-enabled solutions, and this paper has highlighted numerous examples of successful technology-enabled water solutions in the public and private sectors.

By coupling these breakthrough technologies with innovations in financing, partnerships and governance models, existing institutions can help ensure they are both useful and accessible to decision-makers on the front lines of addressing the water challenge and that they continue to benefit the poor. In some cases, entirely new platforms will be required to enable water experts, policy-makers, practitioners, technology providers and investors to co-develop, test and ultimately scale up such innovative solutions. New dialogues and convenings that bring incumbents together with entrepreneurs and innovators from other sectors will be essential in promoting a new wave of multistakeholder collaboration, charting a path forward for a 21st-century global action agenda on water.

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About the Fourth Industrial Revolution for the Earth Initiative

The World Economic Forum is collaborating with PwC as official project adviser and the Stanford Woods Institute for the Environment on a major global initiative on the Fourth Industrial Revolution for the Earth. Working closely with leading issue experts and industry innovators convened through the World Economic Forum's Global Future Council on the Environment and Natural Resource Security, and with support from the MAVA Foundation, this initiative combines the platforms, networks and convening power of the World Economic Forum and its new Centre for the Fourth Industrial Revolution in San Francisco. It also brings Stanford University's Woods Institute for the Environment's researchers and their networks in the technology community together with the global insight and strategic analysis on business, investment and public-sector issues that PwC offers. Together with other interested stakeholders, this partnership is exploring how Fourth Industrial Revolution innovations could help drive a systems transformation across the environment and natural-resource security agenda.

Annex I
List and description of Fourth Industrial Revolution technology clusters most relevant for environmental applications

Fourth Industrial Revolution technology clusters

The following descriptions are provided as background and are not intended to be exhaustive.[83]

- **3D Printing.** Additive manufacturing techniques used to create three-dimensional objects based on "printing" successive layers of materials.
- **Advanced Materials** (including nanomaterials). A set of nanotechnologies and other material science technologies, which can produce materials with significantly improved or completely new functionality, including lighter weight, stronger, more conductive materials, higher electrical storage (e.g. nanomaterials, biological materials or hybrids).
- **Artificial Intelligence.** Computer science learning algorithms capable of performing tasks that normally require human intelligence and beyond (e.g. visual perception, speech recognition and decision-making).
- **Robotics.** Electro-mechanical, biological and hybrid machines enabled by AI that automate, augment or assist human activities, autonomously or according to set instructions.
- **Drones & autonomous vehicles.** Enabled by robots, autonomous vehicles can operate and navigate with little or no human control. Drones fly or move in water without a pilot and can operate autonomously or be controlled remotely.
- **Biotechnologies.** Encompassing bioengineering, biomedical engineering, genomics, gene editing, and proteomics, biomimicry, and synthetic biology this technology set has applications in areas like energy, material, chemical, pharmaceutical, agricultural and medical industries.
- **Energy capture, storage, and transmission.** New energy technologies range from advanced battery technologies through to intelligent virtual grids, organic solar cells, spray-on solar, liquid biofuels for electricity generation and transport, and nuclear fusion.
- **Blockchain (and distributed ledger).** Distributed electronic ledger that uses cryptographic software algorithms to record and confirm immutable transactions and/or assets with reliability and anonymity. It has no central authority and allows for automated contracts that relate to those assets and transactions (smart contracts).
- **Geo-engineering.** Large-scale, deliberate interventions in the Earth's natural systems to, for example, shift rainfall patterns, create artificial sunshine or alter biospheres.
- **Internet of things**. A network of advanced sensors and actuators in land, air, oceans and space embedded with software, network connectivity and computer capability, which can collect and exchange data over the internet and enable automated solutions to multiple problem sets.
- **Neurotechnologies.** Technologies that enable humans to influence consciousness and thought through decoding what they are thinking in fine levels of detail through new chemicals that influence brains for enhanced functionality and enable interaction with the world in new ways.
- **New computing technologies**. This includes technologies such as quantum computing, DNA-based solid state hard drives and the combining of Third Industrial Revolution technologies (e.g. big data, cloud) with the other technologies (e.g. IoT, advanced sensor platforms). Quantum computers make direct use of quantum-mechanical phenomena such as entanglement to perform large-scale computation of a particular class of currently impossible tasks by traditional computing approaches.
- **Advanced sensor platforms** (including satellites). Advanced fixed and mobile physical, chemical and biological sensors for direct and indirect (remote sensing) of myriad environmental, natural resource and biological asset variables from fixed locations or in autonomous or semi-autonomous vehicles in land, machines, air, oceans and space.
- **Virtual, augmented and mixed reality.** Computer-generated simulation of a three-dimensional space overlaid to the physical world (AR) or a complete environment (VR).

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83. Descriptions are provided in the context of the Fourth Industrial Revolution for the Earth initiative and were compiled by project partners from commonly available sources.

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