Water resource prospects for the next 50 years on the water planet: personal perspectives on a shared history from Earth Day, the Fourth Industrial Revolution and One Health to the futures of alternative energy, bioconvergence and quantum computing

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ABSTRACT

The history and the future of water resource management as well as the endeavours that it influences are inextricably woven into the fabric of the past, current and future states of all life on our watery planet. From the first Earth Day in 1970 and the founding of the International Water Resources Association (IWRA) in 1971 to the development of modern biotechnology applications and alternative energy sources across subsequent decades, this paper reflects on these and other historical underpinnings of how we manage the use of our essential water resources now and might hope to in the future.

Introduction

Water resource management is a logistical challenge that has been integral to human survival from the beginning of civilization. The availability of potable surface water was the primary determinant of where human settlements could develop, with the effective effluence of wastewater being the essential counterpoint. Our shared history of water resource management began in prehistoric civilizations with diversion of surface water, digging of wells and fabrication of vessels in which to transport water. Over thousands of years, an ever-increasing rate of technological development has continually increased our ability to relocate water across greater distances and in greater volumes, such as via Roman aqueducts (Figure 1), allowing human settlements to continually grow in size and geographical distribution.

Processes have subsequently been developed and evolved to purify water for potability and to treat wastewater upon diversion. These have been a hallmark of successful development in civilizations around the world, but the world community now finds itself faced with dire water supply challenges for which the traditionally evolved, centralized infrastructure proves insufficient, with sustainability issues looming ever larger.

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At the time of the founding of the International Water Resources Association (IWRA) in 1971, I was in my formative years as well, and found my first summer job at the swimming pool in the apartment complex where my family lived. My eagerness to help and the lifeguards’ loathing of the more menial tasks soon found me under private contract with each of them to clean strainer baskets, hose down the deck and rearrange the lounge chairs. I soon found myself doing routine water testing, adjusting chlorine levels, backwashing the filters and maintaining the appropriate water level. As a result of the latter, I was the first to notice when the water level began requiring more frequent replenishment.

Coincidentally, as an avid naturalist and budding nature photographer attuned to the causes of the first Earth Day, I was also quite familiar with the ecology of the creek that flowed through the woods behind the pool. I noticed that there was a new trickle of water entering the creek from the direction of the pool and that frogs, salamanders and crayfish had become less prevalent downstream of this than they were upstream. I printed some of my photographs to illustrate this to the pool manager and the pool was closed to be drained and repaired. Within weeks of it being refilled, amphibians had moved back downstream, but only upon reflection on this now do I realize that this was my first foray into water resource management issues.

A quarter of a century later, basic water requirements for human activities were still being elucidated. Gleick (1996) defined and quantified them ‘in terms of quantity and quality for four basic human needs: drinking water for survival, water for human hygiene, water for sanitation services, and modest household needs for preparing food’ (p. 83). Considering the unmet basic needs for water around the world, the decadence of a
swimming pool even as a shared resource for working-class apartment dwellers becomes a questionable indulgence as we find ourselves at a crossroads in which we are considering water resource management issues at the global level.

Soon, these considerations may extend beyond our own planet to the Moon, Mars and eventually human beings may visit the celestial bodies of other solar systems, with water resources as a pivotal concern (Gayen et al., 2020; Witze et al., 2020). We can only imagine what may be within the realm of possibility within the next 50 years and beyond. Does humanity have a history to record that might extend as far into the future as our recorded history extends into the past? As our understanding of prehistory expands, such as through the work of van der Valk et al. involving million-year-old DNA, so too does our ever-increasing technological advancement hold the potential for a greater future for our planet and the water resources we must share sustainably with all other living things (van der Valk et al., 2021). Alternatively, some believe we may have already defined the limits beyond which there is no return, but rather an ever-accelerating decline.

Chaos will reign if allowed to do so, yet there is hope exemplified by the evidence that the Montreal Protocol is resulting in ozone layer recovery and the prospect that satellites could soon map not only every tree on Earth but also capture images of river colour changes that could give rise to a new ‘continental-scale understanding of rivers’ (Banerjee et al., 2020; Brandt et al., 2020; Gardner et al., 2020, p. 1). If such things are waypoints in a course forward, how do we chart that course collaboratively and navigate it collectively to reach a future state of sustainable water resource management?

Earth Day

A worldwide enlightenment to many aspects of this predicament has come to the fore across the past half-century. Earth Day, now symbolized by The Blue Marble (Figure 2), was first celebrated in the United States in 1970, and now includes globally coordinated events in which over 190 countries and 1 billion people are engaged (Earthday.org, n.d.). It was born of a newly awakened awareness of our deteriorating environment’s negative impact on human health, as had been brought to light during the previous decade through Rachel Carson’s Silent Spring, which had followed her bestseller The Sea Around Us from the decade before (Carson, 1951; Carson et al., 1962).

Earth Day has come to be known in the United States for having given rise to its Environmental Protection Agency (EPA) and environmental laws such as its Clean Water Act (Nelson, 1980). In 1990, the Earth Day movement officially became an international affair which bolstered recycling efforts around the world and ushered in the 1992 United Nations Earth Summit in Rio de Janeiro, ‘which drew 178 nations and around 100 heads of state’ (Tollefson & Gilbert, 2012, p. 20). The IWRA was also founded a half a century ago, in 1971, and by its 7th World Water Forum was hosting visitors from 168 countries, including 121 official national government delegations, while taking on such issues as food security (Steduto et al., 2018; World Water Council, n.d.).

As with Earth Day, the IWRA also was conceived over the preceding two decades as awareness of the need to supplement and unify global efforts surrounding water resource development and management became clear. Proposing the World Water Council in 1994, the IWRA has also come to be known for globally coordinated events such as its World Water Congresses, which continue to foster innovation and development in the
field of water resource management around the world. Consolidated efforts such as these led to the United Nations General Assembly and the Human Rights Council recognizing the need for accessible drinking water and sanitation as a basic human right several years later (Gleick, 1998; Langford, 2005). With the IWRA’s XVI World Water Congress in 2017 came the Cancun Declaration, intended to fuel ongoing, urgent mobilization of knowledge generation and of governments around the world, as well as donors, professionals and the rest of society to join in united efforts to achieve United Nations sustainability goals and a broader agenda by 2030 (IWRA, n.d.; United Nations, 2015).

The breadth of the challenges before us is reflected in the 45th volume of Water International, which covers water issues from across the globe, some of which include the intersections of the Blue, Green, and Red Agendas in dealing with the Navajo Nation’s water scarcity, Ghana’s free-water initiative, mercury pollution in Columbia from gold mining, Greece’s water-short southern Aegean Islands, ownership of water resources in Iran, the Fukushima Daiichi Nuclear Power Plant’s influence on bottled water consumption, the Ganges and the concept of the legal personality of a river, fuzzy logic and geographical information system (GIS) in East Africa transboundary water management, and community-led solutions in Haiti, as well as the diversity of institutional structures offering wastewater services in Australia and historical consideration of large dam projects around the world (Stephan & Nickum, 2020).

We are also coming to better understand the lasting damage caused by such human activities as the erosion of the sea floor through the common fishing practice of bottom trawling, which changes sediment composition in such a way as to reduce its ability to store carbon as well (Paradis et al., 2021). Other recent examples show that the world is witnessing the negative impacts human activity has on global biodiversity of freshwater fish and the population of Pacific leatherback turtles off the West Coast of the United

Figure 2. NASA/Apollo 17 crew, *The Blue Marble*, 1972. Photograph. NASA Image Gallery, NASA.gov.
States, an area that is additionally found to be impacted by increasing concentrations of toxic algae attributed to rising temperatures (Benson et al., 2020; Su et al., 2021; Trainer et al., 2020). The harmful effects of microplastics on human health and of nitrates in drinking water have also recently come to be better understood, while a chemical from tire rubber has been found to be toxic to coho salmon (Tian et al., 2021; Vethaak & Legler, 2021; Ward et al., 2018). These and other anthropogenic effects on the health of marine and freshwater ecosystems have prompted more than 100 independent aquatic-science organizations from around the world to issue a joint statement pleading for immediate, worldwide action to alleviate our negative impacts on our water resources before it is too late (American Fisheries Society, n.d.).

Hope remains, however, that positive impacts may be there to be found and cultivated soon. For example, a novel experiment is underway in Mexico to determine the viability of insuring a coral reef against hurricane damage, such that claims against damage would fund the urgently needed repairs (Einhorn & Flavelle, 2020). The status, challenges and future of approaches to bioremediation are currently being actively considered as well, with potentially promising new technologies involving such things as high surface area, nanomotor micromachines with a ‘fish-scale-like intercalated (FSI) surface structure’ and other nanomaterials having been developed and ‘demonstrated to be indispensable tools for water remediation applications’ (Vishwakarma et al., 2020; Liu et al., 2019, pp. 16, 164). Perhaps through broader applications of developments in such fields as biotechnology we can stave off and maybe even reverse extinction events, such as that of the northern white rhino (Anderson, 2021).

**Fourth Industrial Revolution**

At the time the IWRA was proposing the World Water Council in 1994, I was giving a series of lectures at national gatherings of science educators in the United States, introducing the prospect of advances in biotechnology constituting a Fourth Industrial Revolution (Jones et al., 1994). This fundamental topic would later broaden significantly and become one of historical interest, with implications for world health and the world economy, recently circling back to a focus on biotechnology yet again. Nossal (1998) heralded the phenomenon as ‘The Biotechnology Revolution’ and contemplated its potential for closing the gap in education and health between rich and poor (p. 122). Schwab (2016) characterized the Fourth Industrial Revolution as a technological revolution whereby ‘in its scale, scope, and complexity, the transformation will be unlike anything humankind has experienced before’ (p. 1). de Lorenzo (2018) suggested that the precedent had been set for us to re-establish the proper ‘cycling of elements that operates our planet’ and that ‘we may also explore ways of mitigating our impact by developing large-scale bio-based interventions aimed at restoring former environmental balances and creating new ones’ (p. 1). Water resource implications once again figure prominently, as exemplified in Figure 3, which depicts one aspect of the roles microbial biotechnology and a circular economy can play in wastewater treatment (Billund BioRefinery, n.d.; Nielsen, 2017).

Biotechnology, with its history rooted in the modification of living things to suit our purposes, has been believed to have its origins in the cultivation of plants beginning over 10,000 years ago (Bocquet-Appel, 2011). The domestication of other animals, particularly
the dog, also figures prominently in this history of biotechnology and has recently been suggested to have had its origins in Siberia over 16,000 years ago, rather than more recently in North America as previously believed (Perri et al., 2021). A subsequent area of major impact for many years has been the field of aquaculture, which may have begun over 6500 years ago with the Aboriginal Australians of Budj Bim (Machemer, 2020).

In modern history, aquaculture has become an increasingly important protein source for an ever-growing human population and since 2009 has accounted for half of all fish humans consume, with water resource management issues at its core (Naylor et al., 2009). As capture fisheries for human consumption have begun to be more sustainably managed, aquaculture for human consumption has experienced substantial increases in productivity that continue to this day (Food and Agriculture Organization of the United Nations, n.d.). However, with acknowledgement that the ‘growing demand for seafood will have to be delivered through improved and innovative culture systems and practices’ comes the realization that this has been happening at the cost of negative environmental impacts to aquatic ecosystems (Joseph & Augustine, 2020, p. 271). This includes a loss of biodiversity that needs to be more broadly understood, as do numerous other concerns including the commensurate economic impacts for those dependent upon sustainable water resource management within those ecosystems (Engle 2009; Frederick et al., 2000; Naylor et al., 2021; Stover, 2017).

With the advent and industrialization of modern molecular biotechnology, the outgrowth of even more controversial technological advances such as genetic modification has given rise to more drought and pest resistant crops as well as genetically modified salmon and prospective new strains of other fish species for commercial production as human food (McLeod et al., 2006; Stokstad, 2020). Such advances, while controversial, hold great promise as do other biotechnology applications such as bioremediation, which
has had an increasingly prominent role in water resource and other environmental restoration efforts (Md Anawar & Chowdhury, 2020; Coelho et al., 2015; Ewell et al., 2001; Jones, 1997, 2002; Straube et al., 1999).

Agriculture continues to make by far the largest demands on the Earth’s water resources, with food from animals requiring far more of it than ‘a wisely chosen crop product with equivalent nutritional value’ (Bhagwat, 2019, p. 219). For this and other reasons there is currently a great deal of interest in other new applications of biotechnology to food production, including the use of plant-derived enzymes, with microorganisms currently serving as the predominant source of such commercial products (Meshram et al., 2019). There is also increasing interest in alternative sources of food and feed for sustainability of a much-needed protein supply and with the potential benefit of reduced water resource demands, including more widespread use of insects as well as meat replacements derived from plants (van Huis & Oonincx, 2017; Vasconcelos et al., 2019).

In addition, there are now rapidly emerging prospects for improvements in the rate of expansion of the food supply chain in the form of clustered regularly interspaced short palindromic repeats (CRISPRs) and CRISPR-associated (Cas) proteins, together providing a genome-editing platform that is outpacing all previous technologies such that, as Brandt and Barrangou (2019, p. 145) have stated, ‘we are living in a CRISPR world and the future is now’ (Yu et al., 2021). Foods derived from cellular agriculture may also hold promise for the reduction of water requirements for food production (Faria-Bellani et al., 2020; Rubio et al., 2020). De novo synthesis of food with greatly minimized water requirements may not be too far in the future either, as related dual-use technologies are being developed for the purpose of space exploration (Douglas et al., 2020).

Meanwhile, global bioremediation prospects are making large-scale reinstallations of ecosystems possible and machine learning is facilitating the analysis of microbial communities in the environment at the single-cell level (de Lorenzo et al., 2016; Shi et al., 2020). The implications and potential applications to water resource management are certain to extend much more broadly and in some unforeseeable ways, especially if a holistic approach to the overall global environmental situation is pursued.

**One Health**

One example extends back two decades, from 2001 to 2003, when it had been my privilege to serve as a representative to one of the American Veterinary Medical Association’s advisory committees, where I helped to advocate against the overuse of antibiotics and also met with encouragement and support for the concept of ‘One Healthy World’. In 2004, the Wildlife Conservation Society held a conference at Rockefeller University in New York during which the current movement was officially born, coming to be known as ‘One World, One Health’ (One World, One Health, 2004). Global disease outbreaks through the middle of that decade, including the zoonotic avian influenza, served to highlight the exigency of this broader perspective on sanitation and world health, culminating by the end of that decade in the joint development by several United Nations agencies, the World Organization for Animal Health, and the World Bank of a framework for reducing infectious disease risks through an ecosystem-wide approach to global health (Gibbs, 2014).
This now involves routine, worldwide disease prioritization efforts with the promise of broader opportunities to improve human, animal and environmental health through better allocation of water and other essential resources, but 'despite the obvious benefits, the barriers to achieving a comprehensive One Health approach are formidable' (Atlas & Maloy, 2014, p. 2). Many bureaucratic barriers must be overcome in order to realize this potential, and the future will need to hold a more balanced emphasis on sustainable allocation of water resources and other environmental considerations as more foundational components of One Health from an ‘Integrative Health Risk Management Perspective’, as depicted in Figure 4 where water sanitation and hygiene figure prominently (Barrett & Bouley, 2015; GRF Davos, n.d., p. 1).

The connections between animal and human diseases as well as their interconnection to the ecosystems in which they live have long been recognized, with pathologist Rudolph Virchow having been a staunch believer in epizootic control as far back as the late 1800s (Saunders, 2000). With the advent of Earth Day half a century ago, world attention began to be focused on our deteriorating environment’s negative impact on human health as well. The tenets of the One Health concept were propelled forward when it became evident at the end of the previous century that a failure to have made the connection between human health diagnoses and those for other animals impeded the ability to recognize the mosquito-borne West Nile virus outbreak when it started in New York City in 1999. This allowed it to subsequently spread throughout the United States and around the world, teaching us many lessons in the process (McNamara et al., 2013).

However, as McNamara et al. had asked, ‘are we any better prepared to recognize and respond to a wildlife-related emerging infectious disease than we were 14 years ago?’ (McNamara et al., 2013, p. 237). During its first decade, the concept of One Health as earlier envisioned most fervently within the veterinary community came to actively support a more balanced inclusion of environmental sustainability issues as well. Yet, as climate change further alters worldwide environmental conditions, Shomaker et al.

![Figure 4. One Health: an integrative health risk management perspective. Source: GRF Davos (n.d., p. 1).](image-url)
point out that 'how humanity addresses the resulting challenges to human and animal health as well as to the world’s water and food supplies will have a major impact on how, or even if, the global community survives' (Shomaker et al., 2013, p. 49).

The devastation of the Covid-19 pandemic serves to illustrate the current need for broader action regarding zoonoses, while water resource-related and other environmental issues continue to abound. For example, it has recently been shown through isotope measurements that predominantly anthropogenic mercury which enters the ocean at the surface is bioaccumulated then deposited in deep-sea trenches where it enters food webs and is further concentrated in trench biota (Blum et al., 2020). Previously existing contamination concerns spawned the development of a luminescent bacterial biosensor for pollution monitoring in the deep-sea over two decades earlier (Jiang et al., 1998).

In the meantime, beaches and islands are being decimated by a worldwide and water resource-intensive 'sand-fuelled construction boom' and ever-increasing demands on groundwater threaten to further decrease surface water availability as well (Tweedie, 2018, p. 1; Jasechko et al., 2021). Another worldwide concern, that of invasive species, also serves to illustrate the economic impact environmental problems can bring, with recent research estimating that cost to have greatly exceeded US$1 trillion (Diagne et al., 2021). With the actual cost and concomitant negative impact on biodiversity likely underestimated, it is critically important and timely to better understand the differences between catastrophic declines across multiple populations and clustered declines among specific, rapidly declining populations in order to tailor and implement appropriate mitigation (Anderson et al., 2017; Leung et al., 2020).

Properly focused water resource management strategies may similarly take time to come to fruition, yet could have broad impact when they do. One fairly recent example traces its origins to work undertaken in the 1990s to enumerate coliforms in Washington, DC waterways, through which I was able to correlate higher levels of bacteria with storm events as well as increased water temperature, documenting the need for increased storm water retention capacity to prevent sewage overflow into the neighbouring rivers (Athena Environmental Sciences, n.d.). This demonstrated the need for subsequent studies, eventually giving rise to an award-winning project to build three large holding tunnels that began being put into service in 2018, with a dramatic, positive impact on the health and well-being of the area’s waterways, which have recently become a breeding ground for dolphins for the first time since the 1880s (Howard, 2014; United States Environmental Protection Agency, 2017; DC Water, n.d.; Daley, 2019).

Another current example of green technology being used for reclamation is that undertaken in Egypt, involving the prospect of more complete afforestation through a couple of decades of carefully orchestrated eco-restoration, with water resource management at its core (Rose, 2021; Subandi et al., 2019). Such projects may hold promise for our future but must be carefully researched, artfully undertaken and rigorously monitored. The prospects of doing so may be favourable in many cases, such as may be seen in recent use of measurements from a satellite laser altimeter to quantify global water level variability, producing a set of baseline measurement against which future human impact on the hydrologic cycle around the world can be gauged (Cooley et al., 2021). As our climate changes, satellite data can also be used to track permafrost loss, which has the potential to unleash large carbon stores as it thaws, also fuelling microbial growth that could result in additionally increased greenhouse gas production (Brouillette, 2021).
We must also be on the lookout for a wide range of other impending environmental health issues and possible solutions to scrutinize, such as popularizing the consumption of invasive species, or invasivorism, including of pythons, which may bioaccumulate mercury, and the large freshwater paiche fish or invasive carps, amidst a paucity of data on the efficacy or overall environmental impacts (Bouska et al., 2020; Elassar, 2020; Snyder, 2017). More novel emerging technologies for food production may provide for minimized environmental impacts though, such as the production of cell-cultured seafood, but prospects for conservation of fishery and water resources remain uncertain (Halpern et al., 2021). Creating ‘an equitable and sustainable blue economy’ will continue to require additional research as well as ‘evidence-based, collaborative planning’ and could potentially give rise globally to protected areas and restored biodiversity while serving as an essential storage place for anthropogenic carbon (Cisneros-Montemayor et al., 2021, p. 396; Sala et al., 2021).

In the meantime, safely and affordably meeting the energy needs to make things such as this possible while also meeting the energy demands of basic water resource management will continue to be a challenge for the future and must continue to be a focus of intense research and collaboration.

Alternative energy

Alternative and renewable energy sources will increasingly have a profound influence on the sustainability of the world’s water resource availability to meet the needs of the ever-growing human population. Our technological achievements have come at the cost of great amounts of energy, first from human effort alone with the occasional assistance of physical phenomena such as gravity and mechanical leverage, then the burning of biomass, the use of wind to move vessels over water, geothermal energy for heat, followed by the introduction of energy derived directly from animals, water and wind for windmills, with still brighter renewable energy prospects for the future (Ellabban et al., 2014). Human dependence on fossil fuels was already being called into question in the second half of the 19th century, with the first hydrogen fuel cell having been invented in 1838 and the value of solar energy being recognized shortly thereafter (Siemens, 1885; Smithsonian National Museum of American History, n.d.).

In the 1970s, the environmental movement served to promote the development of renewable energy, with alternative energy sources becoming increasingly critical to the human condition across the past 50 years. However, with increasing dependence on various methods of desalination, for example, comes an increasing dependence on affordable and sustainable energy sources, whether for distillation, through reverse osmosis or for future water treatment methods. Solar-, wind- and wave-powered alternatives are coming of age but may not be adequate for future demands. Ongoing development of battery technology is pivotal to these applications and is promising, but also may be insufficient. Alternative sources of energy may include hydrogen, fuel cells and fusion, each with its own advantages and disadvantages to be contemplated, weighed and prioritized against whatever ensuing technologies may be developed.

It was also in the 1970s that global dependence on oil fuelled an energy crisis which, coupled with geopolitics, had such a profound effect historically that it still ‘provides important insights into the nature and dynamics of the Cold War’ (Painter, 2014, p. 186).
In 1977, US President Jimmy Carter delivered a landmark speech on the nation’s energy consumption, characterizing the overall problem by saying, ‘with the exception of preventing war, this is the greatest challenge our country will face during our lifetimes’ (Carter, 1977, p. 418). In the years since, we have had stark reminders of environmental health consequences as well, including from catastrophic events such as the Exxon Valdez oil spill, the Deepwater Horizon oil spill and the Fukushima Daiichi nuclear disaster, each of which many of my colleagues and I have subsequently had some level of involvement in terms of mitigating the effects even years after each event (Beyer et al., 2016; Peterson et al., 2003; Wada et al., 2013). Yet, recent past expansions in alternative and renewable energy use have been noteworthy, particularly regarding the prospect that someday they may even ‘exponentially exceed the world’s energy demand’ (Ellabban et al., 2014, p. 748).

A current, promising example with which I have some personal experience is solar power, such as from photovoltaic arrays such as those being deployed in Figure 5. Over two decades ago, I first experimented with solar power applications for aquaculture, developing a solar powered, dissolved oxygen-actuated pond aeration system, many variations of which are now in use internationally. I later found that I could live aboard my sailboat for an extended period with a similar combination of solar and battery power to meet many of my needs, but that I remained dependent upon propane for heating and cooking. More fully renewable options may now be more available, and with much more broadscale application. However, current sustainability challenges remain to be informed by past influences and ‘how different ideological and political frameworks shaped the development of renewable technologies’ (Mittlefehldt, 2018, p. 212).

It also remains necessary to continually improve our current understanding of past innovations to further improve upon their sustainability in a circular economy, however incrementally. This can be seen in a recent assessment of hydropower reservoirs which

![Figure 5](image-url). A floating photovoltaic array on a water retention pond at a Colorado water facility in the United States. Source: Dennis Schroeder/NREL 53281.
suggests they may often absorb more solar energy than did the landscape that preceded them (Wohlfahrt et al., 2021). In this vein, another study has also recently suggested that the placement of solar panels over canals could not only prevent water loss from the canals and improve the performance of the panels compared with what would be expected over land, but could also prove to be economically viable, in that the benefits would be expected to outweigh the costs (McKuin et al., 2021). With wind- and solar-powered sailing drones equipped with acoustic equipment now surveying our oceans in the interest of sustainable fisheries, perhaps there is little time to ponder what may be next regarding the sustainability of our water resources (De Robertis et al., 2019).

Underutilized alternative forms of other existing technologies, such as the combustion of biomass, may hold prospects for providing more power in the future as well, as may be seen in the form of microalgae, which can be cultivated for the production of biofuels that ‘efficiently convert sunlight, water, and CO₂ into a variety of products suitable for renewable energy applications’ (Shuba & Kifle, 2018, p. 743). In the meantime, as wind turbines are being brought online in ever increasing numbers and larger sizes, fuel for the world’s largest fusion reactor is also being prepared for testing, and Kenya is further expanding its geothermal capabilities (Gibney, 2021; Kushner, 2021; Winters & Saunders, 2018).

With the ongoing quest to ‘decarbonize electricity production’ comes the accompanying challenge of developing the necessary energy storage capacity, with both often reliant upon financial incentives and policy imperatives, as is the case for hydrogen production (Headley & Ewan, 2020, p. 992). Fast charging, high-capacity batteries with a long cycle life will undoubtedly play a leading role and are rapidly evolving (Jin et al., 2020). Recent advances in battery technology have also given rise to the possibility that the nanostructure of commonplace kiln-fired bricks would allow them to be turned into batteries, raising the possibility of structural walls of ‘supercapacitor brick modules’ (Wang et al., 2020, p. 1). With the identification of novel electrocatalysts at the core of the development of such future technologies, great strides are also being reported through the use of ‘density functional theory calculations in combination with active machine learning’ such that the combination of supercomputing power, artificial intelligence (AI) and an immense chemical compound database makes possible the discovery of exceptionally efficient catalysts and bright prospects for better batteries as well as other alternatives to complement hydropower (Zhong et al., 2020, p. 178).

**Bioconvergence**

In a similar manner, but for a few billion years, the world around us has been engaged in an iterative process of empirical research involving extraordinarily expansive and long-term experimentation with the evolution of living things. The process has held great fascination throughout human history, for ancient Greek and Roman to Chinese and Islamic scientists, long before more modern theories and the concept of extinction gave rise to a theory of evolution as originally espoused by Lamarck then alternatively by Wallace and Darwin (Gould, 2006). As Mendelian genetics gave way to population genetics and Huxley brought them together in a modern synthesis, we approached the age of molecular biology, the concept of a molecular clock, the emergence of the field of
sociobiology, and then almost half a century ago we were grappling with Wilson’s new synthesis in which complex human behaviours were being attributed to genetic factors as well (Wilson, 1975).

Since then, we have come to better understand such things as the critical roles microorganisms and other life forms can play in water resource management and other aspects of life on Earth. Interrelated, nature-inspired technological developments in these overlapping areas have come to be appreciated more broadly as bioconvergence, which has broad application in areas such as biomanufacturing as well as bioremediation, particularly once a ‘microbe named *Acinetobacter* put on a great show following the 1989 Exxon Valdez oil spill’ (Sonkaria & Khare, 2020; Delude & Mirvis, 1998, p. 7). This convergence of biological, physical and computational technology was conceptualized graphically as bioconvergence more than four decades ago (Figure 6) and then envisioned textually more than two decades later by Ostman, who believed that it might ‘reshape the economies of the world and perhaps even the very definition of life itself’ (Ostman, 2001, p. 1).

Now, another two decades later, the past and present have come together to take advantage of a wealth of contemporary capabilities, including the computational capacity required to reinterpret existing data, as exemplified by the information that is now able to be gathered using the declassified CORONA satellite espionage programme photographs from the Cold War (Cloud, 2001). This collection of images of the Earth’s surface collected between 1958 and 1972 for the purpose of either engaging in or preventing nuclear war not only heralded the beginning of remote sensing with global satellites but now also provides for time-lapse imagery of changes in surface water resources and a great many other ecological phenomena (Klimetzek et al., 2021; Renault, 2021).

![Figure 6. W. R. Jones, Bioconvergence, 1978. Tempera on board. Old Granary Collection, Baltimore.](image)
Zooming in at the other end of the spectrum and with a view towards changes over time going forward, Google-owned DeepMind Technologies has developed an AI program known as AlphaFold which has recently outstripped numerous others in an annual competition to accurately predict the three dimensional shapes of proteins (Callaway, 2020). This convergence of technologies to make such tremendous strides in the prediction of three-dimensional structures with broad biological implications may be the closest AI has come to human intelligence thus far. Related advances, such as in the evaluation of aquatic ecosystem health through ‘culture-independent interconnected meta-omic approaches’ and other ‘high-throughput molecular technologies’, are anticipated to have far-reaching applications in wastewater treatment, bioremediation and numerous other areas of endeavour essential to sustainable development (Michán et al., 2021, p. 870).

At the global level, still other recent developments may contribute to aspects of such monitoring as well, including the interpretation of fin whale song data collected by seismometers at the bottom of the ocean not only for study of the whales themselves but also for imaging the Earth’s crust below the sea floor (Kuna & Nábělek, 2021). Still other adventitious data have also been collected from transoceanic communication cables, which have successfully been used to detect earthquakes and ocean swells, with the potential to sense tsunamis (Zhan et al., 2021). Zooming back in again, nanoscience is coming of age, giving rise, among other things, to ‘chemical or mechanical sensing devices that contain nanoscale elements and are engineered to respond to the presence of certain analytes or environmental conditions’ with huge potential applications for water resource management and more, although some of these are ‘currently being held back by technical, regulatory, political, legal, economic, environmental health and safety, and ethical challenges’ (Yang & Duncan, 2021, p. 251).

Amid the flood of data these and other biocvergent technologies bring with them are implications in the near future for an even more dramatic leap forward than the one we have all just witnessed with the production of Covid-19 vaccines during the first full year of the pandemic. This stellar achievement may soon seem to have only slightly eclipsed the accomplishment during the 1960s, while I was a child, of developing a mumps vaccine in just four years (Buynak & Hilleman, 1966). While the current onslaught of data may foretell a broader understanding and ability to positively and more rapidly impact the world we live in, the number of miniscule effects that must be measured is immense. While satellites are using ‘interferometric synthetic aperture radar (InSAR) to detect tiny movements of [the] Earth’s surface from space’, aspects of ecosystems are being mapped as well with the prospect of being able to monitor all of the trees on Earth, perhaps even while building a Great Green Wall of grasses, shrubs and trees all the way across Saharan Africa (Rosen, 2021, p. 876; Brandt et al., 2020; Cernansky, 2021). With the advent of molecular biology technology such as CRISPR, physical nanotechnologies and computational technologies that are expected to far exceed current capabilities, the next 50 years may hold the promise of human progress at an astounding rate, with unparalleled opportunities for more sustainable management of our water resources.
Quantum computing

With bioconvergence comes the need for computational analysis of unimaginably complex systems and the multivariable and multivariate analysis of the results that come from monitoring, responding to, altering and attempting to manage them in the interest of sustainability. This will require what is now referred to as quantum computing, which was identified theoretically in the early 1980s (Benioff, 1980; Feynman, 1982).

From counting on our fingers to tallying other things with sticks and stones, we developed the abacus and subsequent aids to calculate sums of money as well as astronomical and navigational positions, constituting early technologies that influenced and were influenced by aspects of water resource management, among other things. From the ensuing development of the first analogue computers, including the recently modelled ancient Greek Antikythera Mechanism and the astrolabe from over two millennia ago, to the slide rule in the early 1600s and Thomson’s tide-predicting machine of 1872, the technological development of more sophisticated mechanical analogue computers such as the differential analyser had come to fruition in the early 1900s (Cajori, 1908; Freeth et al., 2021; Hartree, 1940; North, 1974; Thomson, 1881). With the Second World War came the development of electromechanical analogue computers followed in short order by the first digital computers; transistors and integrated circuits followed with the mid-century postulation that machines might someday demonstrate intelligence, and by the early 1970s it became possible for 10,000 transistors to be integrated on a single computer chip (Turing, 1950; Hittinger, 1973).

At the time of the founding of the IWRA, our current computer age was in its infancy as well, but by the time the IWRA was proposing the World Water Council in 1994, I was serving as webmaster for an environmental biotechnology company I had founded, and Tim Berners-Lee was founding the World Wide Web Consortium. By 2000, I was involved in providing content for the White House’s website in conjunction with President Bill Clinton’s proclamation of Global Science and Technology Week, which was all quite novel at the time, yet in short order the web became a primary source of information around the world (Clinton, 2000).

Now, with an Internet of Things and advances in our abilities to engage in remote interactions expanded by the exigencies of the Covid-19 pandemic, these newer but now commonplace alternatives will play an important role in having defined our future, yet may themselves be outdated by the time this paper reaches the press, an outdated phrase in and of itself. Over the past 50 years, as computers have grown increasingly smaller yet faster as well as more portable and ubiquitous, they have become integral to a wide variety of aspects of our daily lives, with our expectations increasingly gauged against their capabilities, which are constantly limiting and continually in need of enhancement.

However, quantum computing, with a recently proven ability to simulate things that current computers cannot, may soon be within reach even though useful demonstrations of quantum supremacy currently remain elusive. Implications for multivariable and multivariate analyses on a grand scale, the predictive capabilities therein, and the routine ability to make instantaneous adjustments and adaptations to increasingly complex biotechnological systems hold the prospect of defying current imagination regarding the more distant future. Before the end of 2020, a team of researchers in China had laid claim to definitively demonstrating ‘quantum computational advantage’ for the first time,
creating a ‘photonic quantum computer’ with ‘a sampling rate that is faster than using the state-of-the-art simulation strategy and supercomputers by a factor of \(10^{14}\)’ (Zhong et al., 2020, p. 1460). The implications for quantum computing, machine learning and furthering our understanding of the complexity of life on our watery planet can now be pondered in extraordinary detail.

In a more recent publication just four months later, an international team of researchers elaborated some of the remaining challenges surrounding the development of the hardware (Figure 7) necessary to realize the potential of this quantum computing capability, which will require the convergence of a broad range of scientific endeavour to overcome the problem that ‘we must achieve error rates much lower than have been demonstrated thus far in a scalable platform, or devise a new platform entirely’ (de Leon et al., 2021, p. 2823).

In spite of remaining challenges such as this, one can anticipate extensive applications stemming from the collection and analysis of data grounded in water resource management and branching into the environmental health concerns that influence the health of humans and all other living things, as embodied in the One Health paradigm. Examples of future applications for quantum computing capabilities include the ever-increasing plethora of toxicological risk assessments that our future demands of us in the process of developing and implementing the necessary new approach methodologies that are in vitro, in silico as well as purely computational in nature, with profound implications for such fields as predictive toxicology with its increasingly prominent role in water resource risk assessment (Parish et al., 2020; Rivetti et al., 2020).

As AI develops, we are learning that machine learning is not unlike biological learning in some ways, in that it often involves putting new information in context based on reference points that are already known (Ecoffet et al., 2021). Going forward, in anticipation of progression at a doubly exponential rate previously unseen in the natural world, such reference points may be hard for the human brain to anticipate (Hartnett, 2019). One recent example of this involved the AI on an unmanned balloon steering it in

![Many different types of quantum computers are being developed. The left image shows superconducting quantum computer hardware. The right image shows trapped ion quantum computer hardware. Source: ©Intel Corporation (left photo); Chris Seck, Oak Ridge National Laboratory (right photo). | GAO-22-104422](image-url)
unpredicted ways only to arrive at its destination in record time, having unexpectedly figured out for itself how to tack through the wind in a zig-zag pattern developed thousands of years earlier by sailors (Baraniuk, 2021).

Other aspects of this capacity of quantum computing have already been brought to bear on water resource management issues such as described for solving subsurface flow problems in a way that may ‘indicate that the era of quantum-computational hydrology may not be too far in the future’ (O’Malley, 2018, p. 1). Even more recently, a team of researchers in the Netherlands has assembled and tested a three-node quantum network that provides glimmers of hope for a highly secure internet of quantum computers based on what the authors describe as ‘a key platform for exploring, testing, and developing multinode quantum network protocols and a quantum network control stack’ (Pompili et al., 2021, p. 259). A glimpse of what such capacity may be able to deliver can be found in the application of machine learning through a neural network that is being used to identify eclipsing binary stars using data from 80 million records and involving a multitude of stars, including the discovery of ‘a sextuply-eclipsing sextuple star system’ (Powell et al., 2021, p. 1). Perhaps the prospect of finding water in another solar system is not as far away as we once thought.

However, the debate about the dangers of AI continues, with one international research team recently demonstrating with theoretical calculations that ‘strict containment’ of superintelligence is ‘something theoretically (and practically) impossible’ (Alfonseca et al., 2021, p. 65). Nonetheless, in the next 50 years the prospects for much more widespread and far-flung spaceflight towards other stars, whether from here on Earth or from the Moon or Mars or beyond, will be dramatically impacted by water and energy resource challenges. Our future will rely on machine learning involving quantum computer networks grounded in up-and-coming developments that we can reasonably expect to take place at an ever-increasing rate, perhaps becoming exponentially exponential and certainly ushering in a veritable Fifth Industrial Revolution.

**Discussion**

In the 1970s as Earth Day and the IWRA were being formed my future was as well as I initiated my own grassroots efforts involving petition-signing campaigns that, with the motto ‘think globally, act locally’, helped make tuna fishing safer for dolphins and hunting less devastating for harp seals, inspired by the dedicated endeavours of such luminaries as Rachel Carson, John McConnell and Jacques Cousteau. Efforts such as theirs are only successful when solutions can be implemented through an effective translation from the ideal to the real. Through the focused and concerted efforts organizations such as the IWRA foster, goals can be set and progress can be made, often in unexpected ways.

In the 1980s, as quantum computing was first being conceived, I was conducting graduate research on ribonucleic acid (RNA) modification and stability, at a time when entire doctoral degrees in my field were earned through the cloning and sequencing of single genes and current capabilities for whole genome sequencing and technologies such as CRISPR were unimagined (Jones et al., 1990). As I was pondering the tertiary structure of RNA molecules through the alignment of palindromic secondary structures in what I referred to as a ‘palattarap’ and was serving as a reviewer of the Hubble Space...
Telestephec technical manuals, the role of RNA stabilization in the production of viable RNA-based Covid-19 vaccines was not anticipated, nor was a sextuply-eclipsing sextuple star system.

In the 1990s, as Earth Day became an international concern and the World Water Council was coming into being, I was engaged in the time-consuming effort of developing some of the first adenovirus-vectored vaccine candidates and could not possibly have imagined the speed with which the numerous and now widely available adenovirus-vectored Covid-19 vaccines could be so successfully produced. Now there may also be renewed hope for the success of a long-sought malaria vaccine, for which I had held out little hope in the 1990s after having subjected myself to a trial and challenge study of an unsuccessful vaccine candidate, contracting malaria as a result.

Recent advances of our current century have been unprecedented and astounding. Some of my colleagues and I lectured decades ago on future prospects in the field of biotechnology, envisioning credit card-sized devices capable of instantaneous DNA sequencing, which has now become a real prospect, as are much more difficult and complex ethical questions embodied in the overwhelming ability we now have to manipulate genomes. On a much grander scale, water resource tragedies have also propelled us forward in an unfortunately reactive rather than proactive way, with the 1990s and the beginning of this century bringing with them a protracted response to the Exxon Valdez as well as other oil spills, such as Deepwater Horizon, and the Fukushima Daiichi nuclear disaster along with a long list of other destabilizing environmental catastrophes.

Throughout the decade following the Exxon Valdez oil spill, as I conducted applied research on hydrocarbon dispersal using biodegradable surfactants coupled with bioaugmentation and biostimulation to effect bioremediation, I never would have imagined that in the wake of Deepwater Horizon the Gulf of Mexico ecosystem would so resiliently test this approach to the dispersal and degradation of the oil such that ‘worst-case impact scenarios did not materialize’ (Jones, 2002; Straube et al., 1999; Beyer et al., 2016, p. 28). As we now move towards alternative and renewable energy sources while aspiring to minimize future environmental disaster, a great deal of effort is being focused on nuclear fusion with high hopes across the next two decades, despite such high hopes not having materialized in the past. The abundant and affordable energy it would potentially yield could have a dramatic impact on the ability to meet agricultural and potable water needs worldwide, possibly influencing prospects for much more far-reaching space exploration as well.

However, if we outstrip the Earth’s capacity for balanced and sustainable ecosystems before this or other technologies might mature, such future developments may be to no avail as the necessary resiliency may have been lost. Could predictive computing capacity allow us to more rapidly harness and finely tune our use of the seemingly inexhaustible energy from nuclear fusion? How might this affect our use of the age-old technology of distillation as well as reverse osmosis and whatever newer products of bioconvergence may emerge? What might become the next primary rate-limiting resource after that? Could the seemingly inexhaustible supply of salt water in our oceans begin disappearing as is the sand around it?
Under the best of circumstances, sustainability will remain at risk. As we develop increasingly refined abilities to manage risk through technological developments, will these abilities increasingly be necessitated by our inability to mitigate our never-ending quest for economic growth? While some predict we will leave the planet, others maintain it will never be practical to do so, but for now and the foreseeable future, sustainability remains our only option. With current capacity-building efforts including things such as alternative energy sources and other ideally unifying but potentially divisive concepts encompassing bioethics, One Health, quantum computing, extraterrestrial water sources and so much more, new perspectives can and must be quite broadly envisioned.

Water resources and their management have been and will continue to be at the core of issues essential to life on Earth. We are confronted with near boundless opportunity juxtaposed against impending limitations, creating a dire imperative. The terms of our survival dictate that every day must be Earth Day on the water planet. Scientists and policymakers the world over must come together under a One Health paradigm and collaborate closely to help each other develop the convergent technologies that will be essential to a desirable future.

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- descending to the bottom of the hidden cistern carved from solid rock beneath the walls of Mycenae;
- marveling at the fountains in the Alhambra, the baths in Bath and the Roman aqueduct in Segovia;
- piloting a boat through the Fonserannes locks and over the River Orb on the Canal du Midi;
- seeing cormorants fish on the Li River, rafting the Ayung River, walking over the River Farset and watching a nest of leatherback turtles hatch and make their way to the sea in Puerto Rico;
- observing the water scarcity in the High Atlas Mountains and a São Paulo drought, as well as the sustainability of Canberra, the inner workings of the Hoover Dam and the abundance of the Tsukiji fish market;
- biking the length of the C&O Canal, swimming the width of the Chesapeake Bay Bridge and glissading down one of the last true glaciers in the Sawtooth Wilderness;
- visiting the Moscow Canal, Norwegian fjords north of the Arctic Circle and the Grand Canal south of Beijing, as well as Fort bij Vechten of the Dutch Water Line;
- working at the Stennis Space Center, where ancient history met the future when canals were built for barges to float Apollo V rocket parts into place for assembly;
- drafting the original design for the stormwater capture, treatment and filtration system of bioswales and rain gardens in Baltimore’s Pierce’s Park;
living for a decade on a houseboat on the Washington Channel, then later a short distance through the woods from the Thomas Viaduct;

harvesting thermophiles from remote hot springs in Yellowstone National Park in the depth of winter and descending the Grand Canyon in the peak of summer;

spelunking to previously unmapped subterranean water features beneath the Shenandoah Mountains;

floating in the Great Salt Lake, boating into grottos on the Bonifacien coastline and kayaking through wilderness for days at a time;

experiencing dead calm seas as well as over thirty-foot waves while sailing between the Caribbean Sea and the Atlantic Ocean;

contemplating my own mortality during a false missile alert in Honolulu and seeking inner peace while meandering the length of Kyoto’s Philosopher’s Walk; as well as discussing marine ecology with John Glenn, environmental activism with Jimmy Carter and the value of marine science education with Sylvia Earle.

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Disclaimer

This manuscript was prepared by William R. Jones in his personal capacity. The opinions expressed in this manuscript are the author’s own and do not reflect the views of the Food and Drug Administration (FDA), the Department of Health and Human Services, or the United States Government.

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