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The frontiers of water and sanitation

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The way in which human society uses water is continuously evolving. The present challenges related to clean water availability require the development of sustainable technologies and infrastructure. Furthermore, a stronger and wider appreciation of water inequalities and injustice demand an adequate transformation of water governance at local and global scale. We have asked nine experts in various sectors of water-related research to share their views on how water and sanitation science, technology and governance must evolve to meet the requirements of a healthier relationship between water and society.

Anna M. Michalak: Safeguarding the planet's water quality in the face of climate change

'Water, water, every where, nor any drop to drink.' This line from Samuel Taylor Coleridge's *The Rime of the Ancient Mariner* is spoken by a sailor adrift at sea. But it could equally well be a person whose water supply is contaminated and basement is flooded following a hurricane supercharged by climate change.

Human welfare and ecosystem health are inextricably linked to water. Water sustainability, in turn, is predicated on the availability of the right amount of water (not too much, not too little!) of the right quality. The 'right' quantity and quality depend on whether you are a fish, a tree, a basement, or a human being. But, regardless of who you are, both the quantity and quality of water are changing and will continue to do so.

A rich and growing literature has quantified how the amount of water available is changing in response to global change[1]. More nascent literature is working to do the same for water quality[2,3] for the world's lakes, reservoirs, estuaries, rivers, aquifers and coastal zones. Understanding the impacts of global change on water quality across a broad set of systems is challenging because water quality outcomes are the result of a complex interplay between human action at scales ranging from the local (for example, land management, water treatment) to the global (that is, climate change)[4]. This means that both impacts and solutions may occur across a cascade of scales.

In addition, long-term in situ water quality monitoring has been limited and heterogeneous. Some systems have been studied extensively, but water quality in most water bodies around the world is not regularly monitored. Also, whereas satellite observations are effective at augmenting in situ observations for parameters such as precipitation, the same is less true for metrics of water quality beyond basic characteristics based on colour[5].

Quantifying impacts across systems globally will necessarily come at the expense of the level of detail and site specificity; however, perhaps counterintuitively this should be embraced rather than avoided. For example, while understanding phytoplankton population dynamics may be possible for systems that have benefited from long-term monitoring and research, deriving general principles across entire regions or continents will necessarily require a focus on large-scale emergent properties.

Climate affects water quality both because it impacts the water bodies themselves (for example, water temperature, and stratification) and because it impacts upstream land (for example, precipitation and temperature impacts on nutrient runoff). The relative roles of these two primary pathways are poorly understood. For example, the National Lakes Assessment[6] monitored nutrient concentrations in thousands of lakes in the United States; these concentrations result from a multitude of climate-sensitive processes within and upstream of each lake.

More broadly, we know very little about how global change is impacting the co-variability of water quantity and quality outcomes. For example, in some systems drought can reduce the intensity of harmful algal blooms, while in others it can exacerbate them, amplifying the challenge to sustainability. Documenting historical co-variability between trends and extremes in quantity and quality is a necessary first step, followed by their attribution to key drivers.

Designing effective strategies for water quality management in the face of global change will also require us to move beyond pitting the environment against economic activity. For example, much of the increases in nutrient pollution in the United States over the past 30 years are due primarily to climate variability rather than land use intensification, but the leverage we have to tackle this problem may nevertheless be predicated on rethinking land management.

Lastly, just as both quantity and quality must be considered to understand water sustainability, potential trade-offs between water security, food security, energy security, and climate change mitigation must also be recognized[7]. The idea of taking a systems approach to environmental impacts is not new, but the scope and scale of the systems that we need to consider are growing. In doing so, we need to remember that win-win solutions are often possible and we should not shy away from the challenge.

Jun Xia: Toward water systems science and technology

Water security is one of the major challenges in our society. Water stress and its effect on water supply, extreme climate events like floods and droughts, poor water quality due to increasing pollution and loss of biodiversity are all interconnected problems that require sustainable solutions[8,9]. To find such solutions, water scientists and practitioners must operate along two fronts. First, it is essential to understand the complex behaviour of water systems at all scales, from global to regional and even urban and how these systems are affected by natural and social processes. Second, it is necessary to develop new ways, through science and technology, to manage water resources.

To understand how water resources are affected by natural and social phenomena in a changing environment, hydrological science must evolve from traditional physical hydrology centred on natural water cycles to a new water systems science and technology that blends natural hydrology, social hydrology and systems science[10]. Studies on the mechanisms of coupled human–water systems evolution will facilitate better planning, water exploitation, and managing water for climate, environment, economy, and society. The application of systems science to water systems entails understanding the interactions and feedback between hydrology and society, building advanced multi-source monitoring and information systems, developing integrated modelling systems, and facilitating systematic decision-making for integrated water planning and management. For example, based on water systems science and applied technology, China is developing the Yangtze River Simulator, which aims to achieve smart management of the Yangtze River through an integrated system that provides multi-dimensional strategies for water utilization, biodiversity and eco-environment protection, climate change adaptation and sustainable development[11].

A systematic multi-source and multi-scale monitoring network is essential to better understand the spatiotemporal dynamics of water systems and to further assist decision-making. Current monitoring approaches primarily include manual sampling, laboratory time-decoupled analysis and sensor-based monitoring. New monitoring techniques have emerged with the development of satellite systems and advanced artificial intelligence technology. The latest monitoring systems cover air-based, space-based, and ground-based networks, with the ability to sense water systems at multiple spatiotemporal scales. High-resolution remote sensing, drone technology and ground sensors (for example, radar, thermal infrared and video) allow for real-time acquisition of spatiotemporal data, extending the scope and accuracy of monitoring. Going forward we can also expect that mobile communication, the Internet of Things, multi-source heterogeneous data fusion and artificial intelligence will enable automatic processing as well as real-time transmission and visualization of data.

Integrated modelling of water systems should decipher and represent both the natural and societal hydrological processes, focusing on the dynamic links and feedback between hydrology and society at the watershed scale. Since the last century, researchers have developed many models, from simple structure-based lumped models to component-based spatially-distributed models. However, hydrological modelling of the interactions between connected systems has mainly been conducted by considering each system separately. As a result, the complex water systems' behaviours have not been well captured. The next-generation water systems models are expected to provide a platform for simulating natural–societal water cycling processes based on data from the systematic monitoring network. Such models would then help to better understand the co-evolving characteristics of interconnected natural–societal processes and to project the changes in hydrology and society under future climate scenarios.

To support regional sustainable development, watershed planning and management will rely heavily on intelligent technologies capable of processing massive information from monitoring, simulations and optimization phases. Previous studies show that the correlations between sustainable development levels and environmental footprints (for example, water, carbon and ecological footprints) satisfy the Environmental Kuznets Curve[12], which explores the potential inflection points of resources consumption along with the structural transformation of economies. For sustainable watershed planning and management, these relationships should be integrated into the water–environment–economy systems. This will increase our ability to build a smart framework, that is, instrumented, interconnected, intelligent and capable of tackling all the complexities of different nature discussed above. Digital twins, intelligent water affairs and other innovative technologies may also be integrated into a general social–hydrology scheme for holistic monitoring, processing massive information, analyzing the current situation, predicting future changes, enabling quick responses and optimizing troubleshooting solutions.

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Damir Brdjanovic: The rise of non-sewered sanitation

For more than a century, urban sanitation research has been dominated by sewer-based approaches, carried out by research groups from high-income industrialized countries, embracing chemistry, microbiology, physical and bioprocess engineering, mathematics and modelling[13]. Such a situation has led to remarkable technological advances in activated sludge sewage treatment which, in turn, has facilitated environmental protection, closing cycles and the recovery and reuse of energy, water and chemicals[14,15]. However, the launch of the United Nation's Millennium (and later Sustainable) Development Goals drew attention to the fact that more than half of the people on Earth do not have access to safely managed sanitation, with the vast majority of these living in low- and middle-income countries (LMICs) where sewer-based sanitation is unfeasible, impractical, or simply too expensive[16].

Partly due to this, since the turn of this century, we have seen a change in attitude towards non-sewered sanitation research, which has become highly relevant, and necessary and has started to be published in scientific journals. The decision by the Bill & Melinda Gates Foundation to invest in non-conventional approaches to sanitation (for example, The Reinvent the Toilet Challenge) has also been instrumental in increasing the visibility of non-sewer-based sanitation research; it has triggered the curiosity of many research groups and mobilized the scientific community to

BOX 1

The contributors

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engage more actively. Non-sewered sanitation has become the topic of specialized faecal sludge management conferences and dedicated scientific journals, and innovations for onsite sanitation have started appearing, as well as global network alliances and education and research programs and scholarships. The recently introduced Citywide Inclusive Sanitation (CWIS) approach[17], which embraces both sewered and non-sewered sanitation, and focuses on public services in an equitable, well-planned, properly managed, safe, sustainable, responsible, accountable and inclusive manner, is also gaining popularity among researchers from different disciplines, realizing that technical solutions alone are in principle insufficient to address sanitation challenges, in particular in LMICs.

During the last few years, leading research groups on wastewater and sludge management have started showing interest in non-sewered sanitation and, in particular, in faecal sludge management. Besides the traditionally well-established global north–south collaboration between research groups, south–south cooperation is also steadily becoming more prominent. This in turn has facilitated the transfer of knowledge from more than a century of experience with activated sludge-based sewage treatment to a rather juvenile domain of non-sewered sanitation, and to some extent vice versa. It has also clarified that we cannot simply adopt solutions from centralized, sewer-based treatment, or assume that sewage or urban wastewater characteristics are similar to those of faecal or septic sludge[18].

One of the forthcoming research areas in non-sewered sanitation is the prediction of the characteristics and quantities of accumulated faecal sludge, understanding the correlations to source populations, and eventually building a reliable database of faecal sludge characteristics. This also includes further development and verification of methods for faecal sludge analysis, as well as standardization of the experimental procedures used in faecal sludge research. Another focal area is a better understanding of the microbial and physico–chemical processes taking place in onsite sanitation containment and treatment systems to predict the characteristics and degradation of faecal sludge. In addition, the research on pathogen inactivation and destruction, reduction of volume of faecal sludge, safe reuse of end products, and treatment in the context of the circular economy and sustainability will continue to attract the interest of researchers in the coming years.

Future research will combine smart sanitation technologies and medical research, resulting in crossover innovations, such as medical toilets, that could revolutionize the public health sector in both high-income countries (for example, preventive cancer detection) and LMICs (for example, pre-diagnosis of tropical diseases) by longitudinal monitoring of users' health and early detection of epidemics[19]. Furthermore, the recent COVID-19 pandemic revealed the potential of data mining from sewage to monitor and predict the spreading of the virus. This approach could be used to expand the public health-relevant data collection to non-sewered sanitation areas (via, for example, medical toilets) as a step towards the development of a community-wide system for early detection of epidemics. Finally, more research into emergency sanitation will be necessary to support humanitarian WASH (water, sanitation and hygiene) activities.

We should also remember that onsite sanitation services provision is closely related to the necessities of the users, arguably more than is the case for sewer-based sanitation. Advancing this field will therefore require substantial consideration of social aspects, gender-based aspects of sanitation and in particular the needs of women, behavioural change and advocacy, cultural and religious aspects as well as business and financial aspects. Undoubtedly, non-sewered sanitation allows for a wide spectrum of both inter- and trans-disciplinary research and it is expected that the most impactful results will be obtained from unconventional combinations of expertise and skills.

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Aimée-Noël Mbiyozo: Water is at the heart of climate mobility

The amount of available water — whether too little or too much — is a core driver of forced displacement and immobility, particularly among vulnerable groups in fragile communities and countries. Locally-driven water solutions to avert, minimize or address forced displacement and immobility among vulnerable groups are extremely important but often overlooked.

Water scarcity is a primary factor driving climate mobility and immobility in Africa. High water stress affects about 250 million people[20]. These numbers are projected to increase with population growth combined with rising temperatures, longer and recurrent drought periods, and diminished river flows. Flood-related disasters also cause high levels of displacement; however, water scarcity pushes five times more migration.

Like climate change, lack of water is a fragility amplifier that intersects with socioeconomic stressors and exacerbates existing vulnerabilities. Marginalized people are more vulnerable because they have less access to the financial and social assets needed to cope, such as land tenure, social and legal services, political participation, paid livelihoods, governance, and infrastructure. This includes gender inequality. For example, in Sub-Saharan Africa, women are responsible for 80% of food production, and more than 60% of all employed women work in agriculture, yet they rarely own the land[21]. Similarly, water-related challenges disproportionately affect women due to gender inequalities in roles and responsibilities[22]. Women carry a disproportionate unpaid work burden and rely more on natural resources and water-sensitive sectors for their livelihoods. Water access forms a core element of daily activities and household labour, including cooking, washing, and caring for the ill, children and elderly. Globally, women and girls spend almost 200 million hours daily collecting water[23]. In water-scarce situations, girls and women must travel further to find it. This restricts their access to education, livelihoods and safety and exposes them to increased risks of violence, including sexual violence[24]. Travelling longer distances also increases exposure to potential water contamination.

Many poor people who depend on climate-vulnerable resources such as agriculture or aquaculture are at risk of involuntary immobility. The most vulnerable people have the fewest human, financial and social capital required to migrate as an adaptation strategy. As water scarcity reduces crop yields, they face diminishing returns, their resources deplete further, and they become even less mobile.

This is a dangerous cycle. Some of the most vulnerable people will be left behind in 'the poverty trap.' In many cases, working-aged men are the first to depart and leave behind women, children, the elderly, and the disabled.

Water availability also impacts other fragile situations, such as transhumance and urban settings. Changes in seasonal rain patterns and droughts affect access to arable land and grazing, altering traditional patterns and timing and even causing conflict. Water scarcity in cities impacts sanitation, access to drinking water, and the provision of essential social services and healthcare systems[25]. Unplanned urbanization can prevent proper draining and cause floods, particularly in informal settings.

Water interventions and infrastructure play a crucial role in helping to prevent or minimize forced displacement or immobility and in preparing areas to receive climate migrants. Solutions should be context-specific, flexible, adaptable and engage local leaders and community members in their design. Projects that provide water and sanitation, livelihoods and economic development, and protective climate-resilient water infrastructure and alternatives, such as nature-based solutions, are necessary and should factor in mobility and immobility considerations.

David L. Sedlak: The next stage of the reverse osmosis revolution

Over the past three decades, reverse osmosis (RO) has become one of the most attractive ways to overcome water scarcity. Each day about 60 million cubic meters of seawater is turned into drinking water in coastal cities while thousands of smaller communities use RO technology to desalinate brackish groundwater[26]. Early adopters, like Singapore and Orange County, California use RO to turn another million cubic meters per day of municipal wastewater into drinking water. The impact of RO extends beyond wealthy, water-stressed places: small-scale systems are being used by people in low-income countries to purify tap water that otherwise would be unsafe to drink. If current trends continue, over half a billion people may be consuming RO-treated drinking water by 2030.

Despite such positive developments, numerous challenges remain. Research is needed to understand and reduce the potential risks that RO and related desalination technologies might pose to human health and the environment. Further technological advancements also are needed to lower costs and make advanced water technologies accessible to more people[27].

The main human health concern of RO is related to the fact that RO-treated water is essentially free of any ions, including some that have health benefits. In recognition of the tendency of ion-free ('aggressive') water to damage infrastructure, calcium hydroxide (that is, lime) is usually added back into RO-treated water at the end of the desalination process. Although the addition of calcium and pH adjustment helps, the near absence of other ions can lead to the mobilization of geogenic toxins like arsenic when aquifers are recharged with RO-treated water[28]. Furthermore, without careful management, the chemical composition of RO-treated water could alter minerals in water distribution systems, enhancing the release of toxic metals like lead or creating conditions that are conducive to the colonization of pipes by undesirable microbes. Finally, the near absence of beneficial ions that people would normally obtain from their water supply, such as magnesium and fluoride in RO-treated water, may contribute to health problems[29]. Beyond the assessment of the risks associated with the use of RO-treated water, there is a need for research that leads to cost-effective technologies for adding key ions back to water at the end of the treatment process.

The main risk to the environment from RO treatment is related to the waste produced when ions are removed from water. In the case of seawater and brackish water desalination, the waste is a salty brine. RO treatment of wastewater also produces a salty waste, referred to as concentrate, that contains relatively high concentrations of nutrients, metals and organic chemicals. Until recently, engineers assumed that dilution of brine and concentrate by mixing wastes into seawater would be sufficient to protect the environment. However, it is becoming clear that in regions where multiple desalination plants discharge brine into shallow coastal waters, salinity can approach levels of concern. Furthermore, the discharge of RO concentrate could contribute to hypoxia, ocean acidification and compromise the health of aquatic organisms. For these reasons, it may become necessary to treat concentrates from wastewater recycling projects prior to discharge or avoid the discharges altogether[30]. For RO plants lacking coastal access, the current generation of brine and concentrate management technologies, such as deep well injection, evaporation ponds, zero liquid discharge (ZLD) or near zero-liquid discharge (NZLD) greatly increase the overall cost of water purification. To enable further spread of RO technologies, research is needed to lower the costs of selectively removing trace constituents and dewatering brine and concentrate to decrease the volume of liquid produced.

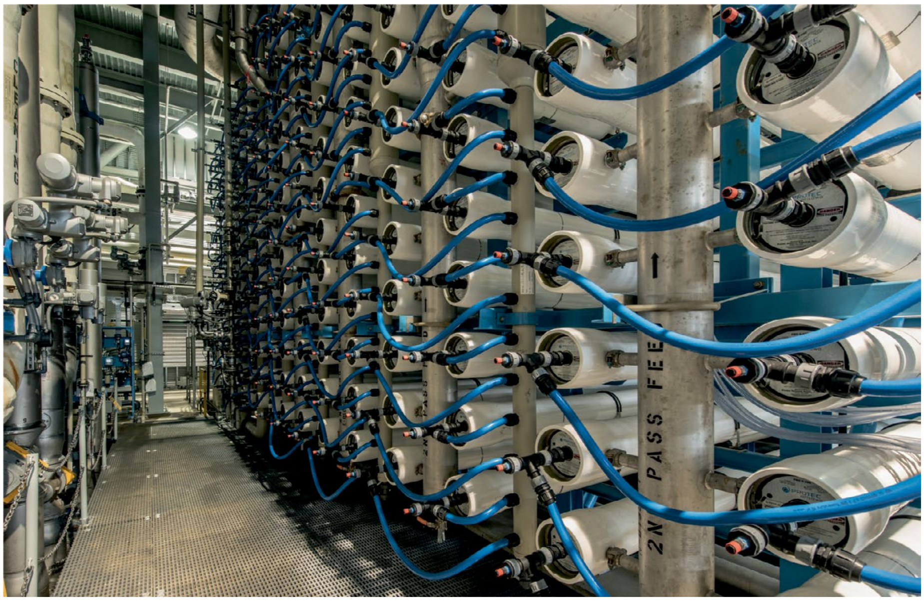
Innovations in materials science and process engineering could lower the cost and energy consumed by ZLD and NZLD systems, but the current approaches for managing residual salts (for example, landfill disposal) are not sustainable. Valorization of the solid or highly saline wastes produced in these processes could result in the production of useful products like sulfuric acid, caustic, gypsum and other commodity chemicals from desalination brines. With more selective separations, it also could be possible to develop cost-effective approaches to recover nutrients, metals and organic matter from concentrate from brines created by water reuse[27]. Thus, wastes generated from RO treatment could provide a means of supporting a more circular economy.

If researchers can resolve some of the issues identified above, desalination and water reuse – technologies that already are seeing large investments in a handful of wealthy, water-stressed locations – could play a much greater role in humanity's efforts to overcome water scarcity.

Thalappil Pradeep: Circularity in water and the role of nanotechnology

Circularity in water has emerged as a response to the unsustainable linear water model of 'harvest, use, and waste'. In a robust circular water (CW) economy, the entire cycle of water harvest and recovery can be repeated endlessly without the loss of water, and the contamination caused in the process can act as raw material or fuel for other valuable purposes. Historically, 'circular economy' was introduced in 1990 (ref. [31]), and it was later extended to multiple sectors including water and waste management, food production, and sustainable design and construction.

Incremental innovations to improve treatment efficiencies, long-distance conveyance of freshwater, and resource-intensive seawater desalination are unlikely to move towards a carbon-neutral CW ecosystem. Thus, there's a dire need to augment the existing water flow networks with disruptive water-reuse technologies to maximize circularity. It is possible to evaluate the circular and non-circular water footprints individually and focus on minimizing the non-circular portion. We may assume



that circular water consumption has negligible environmental impacts, or the extent of the impact may be considered as a deviation from circularity. Given the rapid evolution of nanoscience around clean water challenges in the past two decades, it is natural to wonder what role can nanotechnology play in the transformation from a linear to a circular water economy.

It is possible to approach CW by adopting nine strategies: rethink, avoid, reduce, replace, reuse, recycle, cascade, store and recover[32]. The loop of CW has several entry points (surface water and groundwater extraction, rainwater and humidity harvesting and desalination), and exit points (wastewater discharge, leakage, evaporation and overflows from storage tanks). Points, where water is returned to the hydrological cycle, are not covered in the strategies, as they do not retain water in the CW loop.

The sustainability of any technology is usually assessed by estimating its environmental, social, and economic performance. Sustainable nanomaterials are required to cross thresholds in the aspects of safety, stability, regeneration, reuse, and disposal. Sustainability metrics, such as mass intensity, solvent or water intensity, carbon footprint, and life cycle assessment, and tools like GUIDEnanotool, LICARA nanoSCAN, and Fuzzy-Delphi method may be applied to assess the sustainability of materials and technologies[33]. Moreover, large-scale deployment of IoT-enabled nanosensors, data analytics, machine learning, and artificial intelligence, with the support of governments and industries will contribute to the transition of the emerging technologies into a CW ecosystem at a global level. This is essential as water is also a global resource, just like air. Measurement becomes central to sustainability as global warming reminds us.

The strategies followed to achieve CW may be supported by the implementation and adoption of emerging water treatment technologies. Among such technologies, those based on nanomaterials are attractive for their potential in several ways. For example, nano-enabled filters and membrane separators, the use of nano-catalysts as a replacement for metal catalysts, the development of advanced reverse osmosis membranes for desalination and nanostructured atmospheric water harvesters can all contribute to increasing water availability. In terms of water delivery and consumption, nanofluids could replace freshwater in geothermal operations and hydraulic fracturing, self-healing nano-coatings could be used to prevent leakages in distribution networks and to realize water-efficient cooling technologies for thermoelectric power generation. Finally, the development and deployment of affordable nanosensors can ensure real-time water quality monitoring to tackle potential challenges related to water management. For instance, nanotubes and nanowires with large surface area-to-volume ratio could produce enhanced signal-to-noise ratios for ultra-trace detection.

Naturally, beyond the development of advanced water technologies, a complete transition to a CW economy will require support from the local governments, tailoring the existing norms, and availability of easy-to-implement technologies which are compliant with the existing water infrastructure as well as appropriate policy guidelines.

Upmanu Lall: The future of America's water security

America's water infrastructure — dams, levees, conveyance, and treatment systems — set the global standard in the 20th century for mitigating drought and flood risk, and providing water and wastewater services. Today, America is challenged by a deteriorating water infrastructure due to decades of deferred maintenance and under-investment. It faces climate change, fragmented governance, socio-economic inequity, and environmental impacts from failing infrastructure. Similar challenges are experienced worldwide.

Recognizing the impacts of lead in water in Flint, Michigan, and PFAS contamination elsewhere, President Biden and the US Congress approved US$15 billion for lead pipe replacement and US$5 billion to address PFAS contamination. However, whether this is the best way to address the projected US$1 to US$2 trillion needed for failing water infrastructure, recognized but not addressed by four previous administrations, remains to be seen.

Public health concerns focus on contamination and motivate responses like Biden's. However, conveyance and storage account for 70–80% of the costs of traditional designs. The USA experiences over 300,000 main pipe failures per year, up from 850 in the 1950s. Each incident is accompanied by a boil water notice, service disruption, and potential pathogen exposure. The USA has over 90,000 dams with a median age of 67 years (beyond the nominal design life)[34]. The condition of most dams owned by municipalities is unknown or poor. Decadal droughts in the Western USA have led to empty reservoirs, depleting groundwater and supply restrictions.

Investment is needed in water systems that minimize climate and pollution risks, and are affordable, efficient, reliable, and suited to local demographic, physiographic, economic, ecological, and climate conditions. The traditional approach led to large (often oversized), centralized treatment and conveyance infrastructure. As it aged, it was difficult to maintain and expensive to replace.

The lead-in-water example for Flint highlights a different problem. Water quality at the treatment plant may meet standards, but not water delivered at the tap, as it is not regularly tested. Worse, the list of contaminants is

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ever-growing, and concern over higher treatment costs has blocked efforts to add more contaminants to the regulated list. Exposure to drinking and cooking is a primary concern. This is a very small fraction of urban water use. Increasing drinking water quality violations[35] have driven an increase in bottled water sales[36].

Perhaps point-of-use treatment systems and sensors could be used to assure the quality of water for these uses, thus enabling a decentralized architecture[37] that integrates water supply, stormwater, and wastewater control and reuse. Digital architecture would provide system control even in areas with limited technical and financial capacity. The reduction in storage and conveyance costs would pay for higher treatment and digital water quantity and quality monitoring costs. Managed aquifer recharge with treated wastewater and stormwater would provide storage and address groundwater depletion. Infrastructure could be integrated with neighbourhood parks and green spaces to limit land requirements. The 'optimal' economic scale of decentralization would be determined by local factors, such as population/building density, soils, climate, roads, and condition of existing infrastructure, and offer dramatic cost reductions[38,39].

Water treatment research has focused largely on a one-contaminant-at-a-time strategy. Given the plethora of man-made and geogenic contaminants and pathogens, this is challenging. Today, membrane filtration and electrochemical technologies can complement biological treatment methods to achieve dramatic reductions in a broad spectrum of contaminants, while providing materials and energy resource recovery. The rapid growth and reduction in the cost of point-of-use filtration devices demonstrate growing consumer adoption. Point of use water quality assurance is still an open question.

The financial, technical, and social conditions are ripe for a water transformation. Climate change and ageing, failing infrastructure can be accelerants to a resilient future, especially for underserved populations that currently face the biggest challenges.

Nitya Rao: Water is a gendered human right

Water is critical for life on Earth. For humans, water security is essential for food and nutrition security[40]. The Sustainable Development Goal (SDG) 6 provides a framework for ensuring water and sanitation availability and sustainable management but it does not explicitly recognise how power and wealth imbalances mediate access and rights to water. Water scarcity is not just physical, but also experienced through socio–political processes of inclusion and exclusion[41]. It does not address issues like why it is acceptable for rural women to wait several hours or walk long distances to access water, for the urban poor to be deprived of legal connections, or for one state to deny another its share of water.

Equity and justice are central to researching water access, distribution and use, and are indicators of resource-sharing at different scales, from the household and communities to markets and states. Patterns of socio–economic inequalities shape the mechanisms through which not just overconsumption by some and under-consumption by others are justified, but also how different uses of water are prioritised. Intensification of these inequalities often leads to conflicts.

Gender relations and the intersecting identities of class, race, ethnicity, marital status and age underpin the unequal power relations that set up false dichotomies between the uses of water for production or domestic purposes, associating men with the former and women with the latter[42]. Not just does reproduction underpin the productive economy[43], but in a majority of small landholder households, water-related divisions of labour overlap due to the interlinkages between ecology (land use), embeddedness of food production and consumption systems within these ecologies, and the gendered labour use patterns therein. Women usually play central roles in farming and irrigation, alongside household reproduction. By ignoring women's work, both 'productive' and 'reproductive', costs of labour are shifted from the paid to the unpaid economy, and the inequities that reproduce male privilege are further strengthened.

In a context of persistent drought and climate variability, gendered labour relations impact health and wellbeing. In pastoralist Kenya, men are moving further away from their homes in search of pastures and water[44], and those without cattle migrate to nearby cities and towns to diversify household livelihoods. Women, though differentiated by their marital status, land ownership and the number of cattle owned, acutely feel the impact of water scarcity, most confronting trade-offs between water costs, time availability for collection and the health impacts of the same. Shortages imply either purchasing or walking long distances for safe water. As the responsibility for accessing water and ensuring water quality is privatized and placed on individual households and women within them[45], these

CREDIT: JADWIGA FIGULA/MOMENT OPEN/GETTY trade-offs get sharper, leading to declines in consumption alongside a rise in workloads. Where these cannot be managed one finds an increase in water-borne diseases, poor health and nutrition, and rising mortality. Economic advantages and disadvantages are bound to social and cultural advantages and disadvantages in relation to the value attributed to different activities[46], with women denied decision-making and control in water management institutions.

Water research needs integration of women and gender issues into mainstream agendas to ensure material wellbeing but also the transformation of these agendas to reflect strategic gender interests related to increased say in decision-making, recognition of reproductive needs as legitimate, and an equal share of benefits. Water, like land, is both a physical asset and a source of meaning, so correcting the invisibility of gendered power relations here can also contribute to the larger goal of gender equality.

Joyeeta Gupta: Water Justice is essential for life within the planetary boundaries

The current water crises related to poor water access, over-abstraction, pollution and extreme weather events — result from inequitable, unsustainable and failing governance. If justice is not central to direct and indirect water policy at all levels, it will be impossible to live within the water, climate and nutrient planetary boundaries.

There are three main issues related to water justice. First, scholars propose water boundaries to maintain water system stability, which require drastic reductions in water use, constraining water supply. Even without this constraint, many cities are reaching 'day zero' (or when there is no fresh water available for city consumption) and many basins are 'closed' (as demand exceeds supply and no more water can be extracted from the basin). Water shortage raises the price of water beyond the reach of the poor affecting and exacerbating existing problems of water, sanitation and hygiene (WASH) access, and shifts water from uses with low but necessary (for example, drinking water) to high, but not quite so necessary, returns on investment (for example, golf courses, biofuels). This requires redistributing water.

Second, declining water quality, whether because of sewage, pharmaceutical, plastic, nutrient, or pesticide pollution results from the ability of users to externalize pollution. This raises issues such as who is polluting, how, where, in relation to production for whom, or questions of liability (who is liable) and redistribution (how can pollution be reduced by restructuring production, distribution and consumption processes).

Third, extreme weather events (droughts, floods, cyclones) affect lives, livelihoods, infrastructure, and redistribute risks in society, especially in the global South. Such events are in line with climate models and will rise in the future. Sadly, the costs of such damages are not fairly distributed. To put things in context, we should consider that Hurricane Ian caused more than US$75 billion worth of damage to Florida[47], while only US$100 billion was promised annually to the entire developing world for adaptation, much of which is not being provided or provided as commercial loans[48]. Although at COP27, countries came to an agreement to finance loss and damage already caused to other countries, given the history of climate change finance, it is likely that this will be no more than a symbolic gesture. Damage caused to other countries, to the extent caused by greenhouse gas emissions should in principle be borne by those who emitted those gases[49]. However, if finance is provided through loans it may lead to a spiralling debt crisis in the developing world.

All three issues raise distributive and corrective justice points. Challenges to redistributive justice include a) past (colonial) and institutionalized inequitable water property rights and quasi-property rights in permits/concessions and contracts that cannot easily be expropriated without compensation[50]; b) the direct link between water use and GDP encouraging water use to enhance GDP and the Jevon's paradox where increased water efficiency ironically leads to higher water use; c) water overuse and 'water grabbing' by rich people and investment funds[51]; d) the externalization of local to global pollution (for example, Coca Cola sells 200,000 plastic bottles a minute, much of which ends up as plastic soup, that is, plastic pollution in the ocean[52]; e) the unwillingness to take responsibility for damage caused and pay compensation; f) the fact that some companies that use large quantities of water, directly or indirectly, avoid paying taxes (for example, Starbucks[53]) which reduces country revenues for reinvesting in public goods.

Proposed solutions often institutionalize or exacerbate existing inequities. In the market-based system, the rich (whether countries, companies or people) benefit from actual and virtual water uses while externalising damage[54], they create rules that favour them, and prevent, avoid or evade rules that regulate them or require them to pay taxes. The poor pay the final bill as their water resources are expropriated (for example, indigenous populations[55,56]) and often polluted (for example, communities near dams and mines), and cannot afford rising water prices for drinking or irrigation or the bankable loans to adapt to extreme weather events. The situation can be summarized by considering that as of 2021, 2.3 billion people live in water-stressed areas, 1.8 billion drink polluted water, and 2.8 billion people suffered from floods between 2001–2018.

The question is: Is water justice needed to live within water boundaries? I would argue that further denying the poor drinking water and sanitation services will only exacerbate health problems with spillover effects on society, and denying them adaptation services will expose them to extreme weather events that will displace millions beyond borders; all of which will have repercussions on the Earth we share. If we want to live within planetary boundaries, we have to engage in redistributive justice.

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Competing interests

The authors declare no competing interests.