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WATER, WATER, EVERYWHERE: ADVANCING WATER SECURITY THROUGH IMPROVING WATER QUALITY

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Summary

A wide range of technologies focused on improving water quality help Indo-Pacific individuals and communities cope with some of the water-related regional stressors - climate disruption, population growth, pollution, etc. The majority of the region's population relies on contaminated water for domestic, agricultural, and industrial uses. Approaches involving filtration, heat, chemical treatment, and/or evaporation and re-condensation are available (individually or in combination) to remove particulate, chemical, or microbial pollutants. The choice of which approach to use when and where depends on the particular contaminant(s) to be removed, the use for the cleaned water, and factors such as energy and monetary needs and resources, efficiencies, and waste products. Newly evolving methods in each of the four approaches, along with innovations such as extracting water from air, offer greater efficiency, versatility, or cost-effectiveness. These innovations provide additional tools for adapting and building resilience to climate change and other water security threats.

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> "Water, water, everywhere,
> But not a drop to quench despair."
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> From Samuel Taylor Coleridge, 1834, *The Rime of the Ancient Mariner*

Abstract

In the face of climate change, population growth, pollution, and other threats, the majority of the Indo-Pacific population relies on contaminated water for domestic, agricultural, and industrial uses. A wide range of quality-focused technologies advance water security through approaches involving filtration, heat, chemical treatment, and/or evaporation and re-condensation, individually or in combination, to remove various pollutants, be they particulate matter, chemicals, or microbes. These approaches come with costs and benefits; the choice of which to use when and where depends on the particular contaminant or contaminants to be removed, the use for the cleaned water, and factors such as energy and monetary needs and resources, efficiencies, and waste products. Newly evolving methods in each of the four approaches offer greater efficiency, versatility, or cost-effectiveness; innovations such as extracting water from air complement traditional technologies. Together, these provide additional tools for adapting and building resilience to climate change and other water security threats.

1. Rationale

Throughout the Indo-Pacific region, water security has direct impacts on security of all types and at all scales; access to clean water is vital for individual human survival; for our agricultural systems; for communities' health, resilience, and well-being; for industrial processes of virtually every sort; and for nations to survive and thrive.

Both the quantity and quality of water are core issues for water security. But aside from very brief mentions of the former in the next two sub-sections, this paper focuses solely on the latter; analyzing the geopolitical machinations and influences around controlling large-scale Indo-Pacific river and groundwater flow is beyond the scope of this article. Likewise, the breadth of water conservation technologies that inherently embody quantitative aspects makes consideration of these approaches infeasible in this brief overview of water quality issues.

1.a. Context and history

Water is a key component of both the environment and the climate. Water covers about 70% of the surface of the planet and is essential to every living cell on earth. It is the major driver of climate around the planet; the importance of water's role as the 'heat engine of the earth,' with the tropical oceans absorbing heat from the sun and releasing it gradually from surface currents flowing poleward, cannot be overstated.

At the same time, the distribution of water around the planet is a major outcome of the climate. Atmospheric circulation patterns, in combination with earth surface features such as mountains, determine how, where, and when rain falls, ultimately shaping the landscapes. The long-term dynamics of these processes radically alter biomes; around 6,000 years ago the plentiful rainfall patterns that had supported lush tropical grasslands of northern Africa decreased and, perhaps in synergy with increased human occupation, the area became today's Sahara Desert.[1] Droughts, especially when prolonged or recurring, have brought down or contributed strongly to the fallings of the Akkadian, Mayan, and Khmer empires; the Tang, Yuan, and Ming dynasties in China; and likely many other regimes.[2; 3]

Thus, our planet's water resources are key components of both climate and environmental security writ large.

1.b. Regional challenges and tensions

The distribution of water resources across the Indo-Pacific ranges from deserts to jungles to glaciers, and leads to a wide range of geopolitical tensions, both internal to single countries and international. In a prominent example of the latter, China, through its jurisdiction of the Tibetan plateau, contains and controls the headwaters of 10 of the 11 major rivers across south, southeastern, and eastern Asia. Through damming many of these (via 87,000 dams built in the past 70 years[4]) the PRC exerts major control of the water resources of many of its neighbors with relatively few transboundary water resource agreements. Paradoxically, China has a smaller share of the world's water resources than it does of the world's people, and has created its 'economic miracle' of raising hundreds of millions of people out of poverty at the cost of horrendously polluting its own rivers and aquifers.[5]

Excessive aquifer pumping in rural Indo-Pacific areas, largely for irrigation purposes, has caused saline intrusion into coastal waters around the region; in Bangladesh, it is estimated that at current rates of sea level rise, about 40% of the country's productive land will be inundated.[6] In urban centers, extreme extraction underlies ground subsidence and flooding as well; due in large part to these impacts, Indonesia is relocating its capital city.

Climate change exacerbates and intensifies virtually all of these water-related challenges and tensions. Rising sea levels, more prolonged and extreme droughts, more torrential rainfall, and more frequent, hotter, and extended heat waves negatively impact individuals', communities', and nations' water use patterns by impairing agriculture, productivity, and health among other facets.
The scale of water insecurity is huge and the impact of its impurity is immense. Studies suggest that cross the region about 2.5 billion people, or roughly two-thirds of the population, do not have safely managed drinking water services, primarily due to contamination by fecal coliform bacteria.[7]

1.c. Sources, characteristics, and types of degradation

About 97% of our planet's waters lie in its salty oceans; only 3% of the water on earth is freshwater suitable for most human needs. Of that 3%, about 2/3 (68%) is locked up in ice caps and glaciers; another 30% lies deep underground; and only about 2% is readily accessible: 1.5% in non-polar, non-glacier ice, 0.35% in lakes and rivers, and 0.15% in soil.

All of this water has been on the planet for most of its existence, with the same molecules cycling continually among abiotic solid, liquid, and gaseous reservoirs and moving into and out of life forms. While we may wish to believe that the water we drink is fresh, pure, and untouched, the reality is that this constant reuse, recycling, and renewal - through the water cycle of evaporation, condensation, and precipitation - is the essential nature of water. The change in state from liquid water to gaseous water vapor is the means through which water is re-purified in nature.

Water is often called the 'universal solvent' for its ability to dissolve a wide range of other materials. This extraordinary capacity, however, means that water is easily contaminated or polluted. The ease and frequency with which such degradation happens, in conjunction with our growing, urbanizing, and 'westernizing' population's ever-increasing needs for clean water, cry out for humanity to conserve and protect its limited water resources. The United Nation's Environment Program estimated in 2021 that over 40% of more than 75,000 bodies of water surveyed across 89 countries were severely polluted.[8]

Around the world, water is polluted by many different substances and in many different ways, with much of this stemming from human activities. While agricultural runoff - including fertilizers, pesticides, and farm waste products – is the leading cause of pollution globally, many other sources contribute.[9] Sewage, oil, and radioactive substances all degrade water supplies, threaten human health, and render water unsuitable for many uses.

Other water pollutants are naturally occurring, such as arsenic that exposes 94-220 million people in around 70 countries—including Bangladesh, China, India, and the United States—to contaminated groundwater at levels above the 'safe' limit of ten micrograms per liter.[10] Acceptable 'safe' levels of water-borne exposure have been determined for many pollutants, such as heavy metals; but the range of chemicals - literally tens of thousands of different types with new ones being introduced every day - entering water supplies precludes any sort of universal assessment of their safety or toxicity.

Pollutants may arise from a single origin, such as a factory, called point-source pollution, or from widely dispersed contaminants such as dust or, increasingly, ash from wildfires. Pollutants can impact both surface and groundwater sources.

Whether natural or human-based, point or broadly sourced, and on the surface or in underground aquifers, pollution exacerbates quantity-based water scarcity. The combined impacts have massive impacts, for example, in China, where over half of the population in affected.[11]

The scale and severity of water pollution speak to the need for decontamination technologies. While various methods to clean up water have been used since ancient times, humanity's industrialization has introduced novel chemicals, some in conjunction with production of plastics, whose microscopic and nanoscale particles themselves are now ubiquitous in our water (and air and food) and are increasingly found in virtually all human tissues examined.[12]

2. Types of purification technologies

Broadly, four types of processes have been used to purify water: filtration, heat, chemical treatment, and evaporation-re-condensation. Each of these has a number of sub-types and different processes, or in many cases, combinations of processes, are used, depending on the particular contaminant or contaminants to be removed, the use desired/planned for the cleaned water, and factors such as costs, energy needs, efficiencies, waste products, etc.

Filtration is likely one of the oldest methods used to clean water, and involves passing water through some sort of barrier that physically blocks particles above a certain size. Barriers classically have been made of paper, cloth, or a sand/gravel layered mixture. Today, water managers use sophisticated technologies to produce filters, such as for reverse osmosis (RO), that are specially-designed sheets of materials incorporating pores of specified sizes and/or chemical properties to restrict the passage of specific contaminants. In a closely related filtration variation, electrodialysis, the water flows along membranes, on both sides of which are positive and negative electrodes, forming an electric field that draws salt ions through the membranes and out of the water.[13] In other designs, multiple layers of nanofibers, stacked in order of decreasing diameters, sequentially/iteratively reduce the size of particles passing through the filter.

Heating, if prolonged or at high enough temperatures, also has long been used to kill off microbes in water. Many microbes can tolerate only a few minutes in boiling water. Less widely appreciated is that simply leaving a sealed clear container of water in the sun for several hours will kill the vast majority of harmful microorganisms; the combination of heat and ultraviolet radiation from the sun has lethal effects on the bugs.

Chemical treatment of water can: (1) kill off microbes via elemental agents as halogens (usually chlorine, bromine, or iodine), silver, or copper or through more complex antimicrobial compounds; or (2) bind to and precipitate out contaminants. In this latter capacity, managers add compounds such as aluminum sulfate (alum), ferric chloride, or calcium hydroxide (lime) to the water; these react with contaminants like heavy metals, phosphates, or calcium and magnesium ions, forming insoluble solids that are removed through sedimentation and/or filtration.

Building on nature's water cycle described above, the processes of evaporation and re-condensation have been used to clean water. Many of the common pollutants - including salts, metals, and microbes – are non-volatile and thus do not evaporate from the water they contaminate. So the process of distillation, whether driven by the sun or from some alternate heat source, converts dirty water into clean water vapor that then condenses on a surface, runs off, and is collected. As long as the condensing surface is clean, the source of the water – whether the ocean, a muddy drainage ditch, or even a cesspool – does not matter; the re-condensed water will be clean and pure.

2.a. Constraints and uses

While each of these four methods is used in certain circumstances, each has limitations and drawbacks.

In the act of trapping particles, filters get clogged; depending on the nature of the filter, they must then be cleaned or discarded and replaced. Depending on the type and size of filtering being done, this can be expensive and/or technically challenging. Despite embodying both of these drawbacks, large-scale RO is being increasingly employed to provide clean water as readily available sources of usable fresh water become scarce; Israel, San Diego, and many other coastal locales whose populations have exploded in recent decades have found RO of seawater to be a partial, practical solution to growing needs for fresh water.

Due to water's high heat capacity, a great deal of energy must be put into heat-based decontamination, making this approach less than optimal in many situations. While the benefits of boiling bacteria-infested water prior to drinking it are inarguable, in many cases, especially in economically-stressed communities, the time, energy, or financial cost of obtaining the fuel needed to do so force users to make trade-offs among basic needs. In an efficient, insulated, closed system, it may be feasible to employ boiling as one component of treatment (see more on distillation below).

Chemical treatments such as chlorination must be properly calibrated to ensure the concentration is sufficient to kill microbes but not so high as to leave a distasteful remainder. Precipitation leaves insoluble residues that must be then removed by filtering or sedimentation. These approaches thus demand a certain level of technical sophistication as well as the expense of the chemicals involved. Around much of the world, large-scale municipal or state-owned water systems regularly use chemical decontamination methods, sometimes in conjunction with RO; the spreading of such systems and treatments is widely credited with massive reductions in waterborne disease and mortality rates globally.

Distillation is, in most cases, a woefully inefficient process. While simple, passive solar stills can be set up to produce several liters of fresh water per day depending on weather conditions, scaling up the processes to reliably serve large populations has proven infeasible. Considerable energy is required to run a large-scale distillation process continually, and the issue of how to deal with the left-over, highly concentrated contaminants is problematic also. At small to moderate scale, and in closed systems, distillation is often a useful option.

The preceding overview only scratches the surface of the many sub-types of these technologies. For example, removing certain types of contaminants may require very sophisticated, multi-stage processes such as cryogel filtration, or adsorption-based, electric-based, or photocatalytic-based treatments.[14]

3. Looking ahead

The technologies for water purification are dynamic, with improvements being introduced constantly. The use of graphene as the base for thinner RO membranes, for example, enables lower pressures and thus less energy to be used, resulting in cost savings. Because the membranes are also smoother than earlier versions, they accumulate contaminants more slowly and thus need to be changed out less frequently.[15] Other types of nanotechnology-based filtration are advancing rapidly, with commercial production of multiple types of filter products.[16;17;18]

Likewise, chemical treatments continue to evolve, with an example being MadiDrops.[19] This is a point-of-use microbial treatment based on silver that is simple and non-technical to use (drop the tablet in a water dispenser once per year), highly effective, leaves no odor or taste, and is extremely economical. This particular technology has also been combined with a simple filtration system, enabling ready small-scale cleansing and decontamination of particulate-laden water.[20]

Innovative solar distillation technologies have markedly improved the efficiency of the process. At least one commercial producer has developed a system wherein virtually every photon of solar radiation absorbed converts a liquid water molecule into vapor form. A single floating unit with a footprint of about one square meter can produce 10-20 liters of freshwater per day.[21]

Beyond the four basic approaches to decontamination of water outlined above, a set of small- to medium-scale technologies with a particular promise to play an increasing role as traditional water resources are stressed involves extracting water from air. Even in dry climates, air contains significant amounts of water in a vapor state. Various rapidly-evolving approaches are being used to capture this often-unconsidered reservoir; the yield of water extracted through many of these methods is highly dependent on weather patterns and sun exposure:

- Atmospheric water generators (AWGs) use electricity to draw in air and pass it over cooled plates to condense water vapor into liquid water. AWGs are particularly useful in places where solar power is plentiful and potable water is hard to find.
- Hydro harvesters use silica gel to absorb water from the air at night, and then use solar thermal energy or waste heat to produce a hot, humid air stream during the day. The air is then cooled to produce water.
- Ultraporous compounds can extract water molecules from dry air, store them as "icicles", and then release them as drinking water.
- Fog harvesting works only when relative humidity is 100%, and is currently used in a few coastal deserts.
- Dew harvesting requires refrigeration to provide cold surfaces for moisture to condense on, and still requires at least 50% humidity.

Molecular structures called metal-organic frameworks are poised to revolutionize several of these methods, with more efficient vapor capture and more readily controlled release of liquid water.[22]

Still very much under development is a sub-set of these extraction technologies called slippery rough surfaces. These involve building materials with nanoscale surface features that passively capture and condense water vapor into tiny droplets and move and coalesce them; prototypes have collected over 120 liters of water per square meter of the surface per day.[23]

4. Conclusion

A wide range of technologies to advance water security help individuals and communities cope with the stressors of climate disruption, population growth, pollution, and restriction via dams. The majority of the region's population relies on contaminated water for domestic, agricultural, and industrial uses. Approaches involving filtration, heat, chemical treatment, and/or evaporation and re-condensation are available (individually or in combination) to remove various pollutants, be they particulate matter, chemicals, or microbes. These approaches come with costs and benefits; the choice of which to use when and where depends on the particular contaminant or contaminants to be removed, the use for the cleaned water, and factors such as energy and monetary needs and resources, efficiencies, and waste products. As regional water-related challenges grow, newly evolving methods in each of the four approaches offer greater efficiency, versatility, or cost-effectiveness. Additionally, innovations such as extracting water from air are coming online. Together, these innovative technologies are providing additional tools for adapting and building resilience to climate change and other water security threats.

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