# SOLUTIONS FOR THE GLOBAL WATER CRISIS

## The End of 'Free and Cheap' Water

**Citi GPS: Global Perspectives & Solutions**

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# SOLUTIONS FOR A GLOBAL WATER CRISIS

## The End of 'Free and Cheap' Water

Over the years there have been many academic studies, government policies, non-governmental organizations (NGO) reports, industrial plans, and others all focusing on ways to improve the management of water and reduce inefficient water use over time - and yet we are still faced with the problem of a looming global water crisis. So why haven't we solved this problem? The main reason is that we are terrible at managing this resource.

In the last decade there have been improvements to the use of water resources; however, there are still an estimated 800 million people who do not have access to clean water and some 4 billion people who live under water scarcity at least one month per year. Several regions are also depleting their freshwater resources at a very fast pace — many major river basins in both developed and developing countries, are facing extremely high levels of water stress.

Water is badly managed in many of these places. It is underpriced, subsidized and in some cases given away for free. In many regions the unsustainable water use is usually acknowledged when a crisis occurs such as a flood or drought. A typical example of this is in California, the over-abstraction of groundwater has been largely ignored, until a drought hits the region, costing the state approximately $2.7 billion per year. Unmanaged water-related risks such as floods and droughts can cost an economy billions of dollars, not to mention the tragic loss of life.

Water is vital not only for the production of food, but also for energy production, for the extraction of materials, to maintain aquatic ecosystem services, for the livelihoods of people, and not least for the economy. Despite only accounting for just under 4% of global gross domestic product (GDP) in 2014, the agriculture sector consumes the majority of the world's freshwater resources (estimated at 70%), against 23% for industry and 8% for municipal use.

Business as usual cannot continue — the global demand for water is expected to nearly double over the next 15 years. With dwindling supplies in many regions this could turn into a global water crisis affecting communities, industries, food production and the environment. There are, however, a number of solutions available which, in the words of Professor Keith Richards, should be 'sustainable, collaborative and adaptive'.

Investment in well-needed infrastructure is one part of the solution. On a global level, a total of $7.5 to $9.7 trillion is needed in investment for water and sanitation and related equipment. In developed countries investment is needed to upgrade and maintain aging infrastructure, while in developing countries investment is needed to build new infrastructure. Other solutions include pricing water efficiently, developing tradable permits to encourage efficient allocation of water and adequate regulation. Technology also has an important role to play — for example, smart meters encourage users to understand their consumption practices and precision agriculture is enabling farmers to collect real time data on weather, soil, and crop maturity.

There isn't a shortage of available solutions. Finding the right solution is a matter of good governance, and choosing a mix of solutions that works for your local community. It is, however, imperative that we do get it right this time as otherwise we will be sleepwalking into a global water crisis.

# Reaching the Boiling Point with Water

## Stresses from population, agriculture, and energy require investment and innovation

### THERE IS A MISMATCH BETWEEN THE LOCATIONS OF AVAILABLE FRESHWATER AND WHERE MOST OF THE GLOBAL POPULATION LIVES

Freshwater Availability in Different Regions

Source: Curmi et al, Hejazi et al (2014), UN Population Statistics, Citi Research

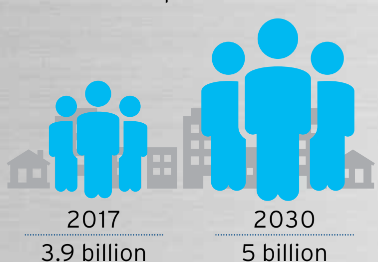

| | % global population | % freshwater available |
|---|---|---|
| Africa | 16% | 10% |
| Asia | 60% | 33% |
| North America | 5% | 29% |
| Latin America | 9% | 16% |
| Oceania | 1% | 3% |
| Europe | 10% | 8% |

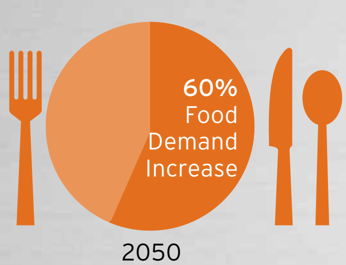
### GLOBAL DEMAND FOR WATER IS RISING DUE TO INCREASING POPULATION, THE RISE OF MEGACITIES AND INCREASED FOOD DEMAND WITH SHIFTING DIETS

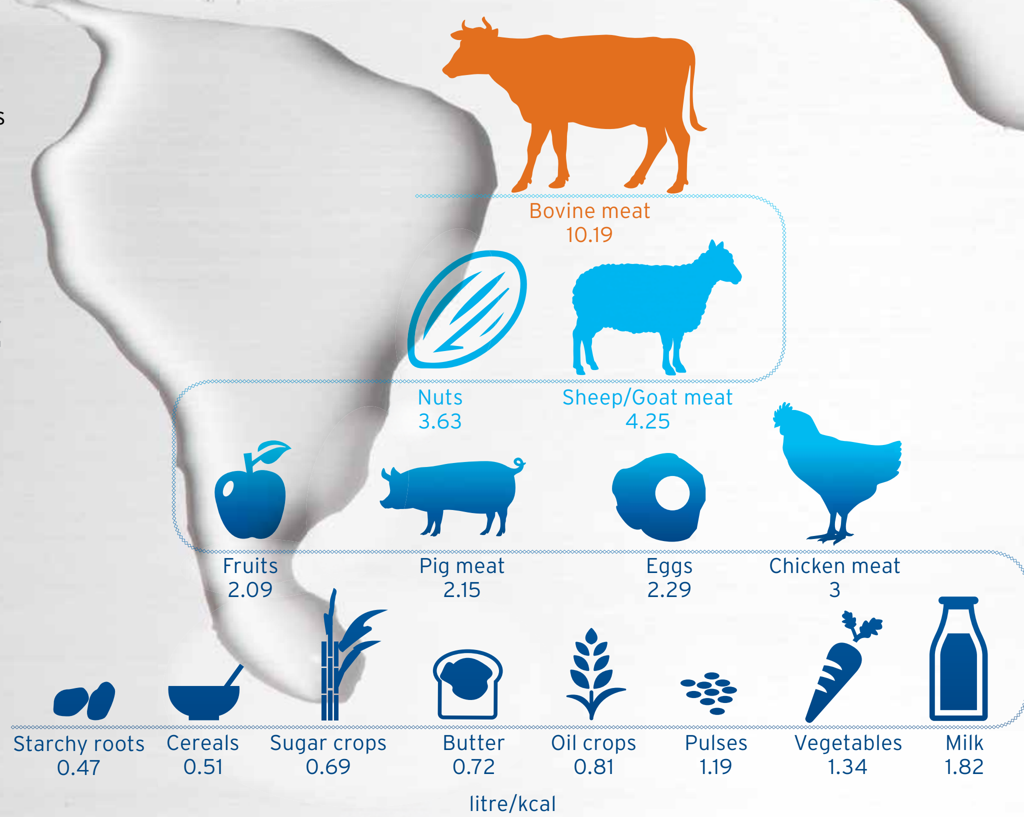
Water intensity of each calorie consumed increases as diets shift towards greater meat consumption

Source: Water Footprint Network, Citi Research

The number people living in towns and cities is expected to increase:



WATER ISSUES CREATE REAL ECONOMIC ISSUES

Cumulative water investment required in different regions

Source: Citi Research


SOLUTIONS TO AVOID A GLOBAL WATER CRISIS

Three ways to help alleviate the global water crisis:

Source: Citi Research


**Water infrastructure**
Investments of $7.5 to $9.7 trillion needed globally to upgrade, maintain, and build new water infrastructure

**Regulation and market-based instruments**
i.e. pricing mechanisms and setting up tradable water markets

**Technology solutions**
including smart water tools (metering, big data), desalination, precision agriculture and beneficial re-use of produced water

# Contents

# What is Water?

It is no secret that the world confronts multiple critical challenges in the management of water. Nor is there any hiding from the fact that these challenges arise across the chain, from source to end use, with huge issues associated with distribution. There are also multiple conflicting challenges of access and ownership in each of these three areas and they are exacerbated by the many challenges the world faces in providing adequate potable water. Most of the challenges to designing policies to improve the supply and distribution of water and to adjudicate conflicts over end-use stem from conflicting answers to the question, "What is water?"

To an economist there is a temptation to define water as a commodity and suggest it should be priced according to market principles of supply and demand. Like other commodities, it is consumed and therefore should be priced in terms of its scarcity. Abundant freshwater and ease of water access in primitive societies enabled water to be treated as a free good.

Abundant freshwater and ease of water access in primitive societies enabled water to be treated as a free good

Scarcity should provide a pricing mechanism or a distributive regulatory mechanism for sharing. In society today, one of the principle issues for market pricing relates to tapping into seawater to provide freshwater where scarce. The world has an enormous abundance of seawater, which can substitute for freshwater in some of its uses (for example, in hydrocarbon exploitation, when water injection is desirable to improve production and productivity). More importantly, seawater can be a source of freshwater via desalination and the most effective way for that to work would be to assure that market pricing is at work to encourage private sector involvement.

One problem is that while water is in some respects a commodity, in other respects it is a very special kind of commodity — similar to food and fuel (especially electricity) — where access is deemed a basic individual right, raising conflicting paths for how it should be dealt with. Governments are often tempted to assure "equity" or fairness to access certain commodities, which are deemed to be fundamental, both to the concept of equity and of well-being. More often than not issues of accessibility are deemed to require straightforward distributive mechanisms, including utility model pricing. At times re-distributive mechanisms may be deemed to be appropriate, through subsidies or differential treatment that would conflict with pricing principles associated with traditional commodity markets or even utility markets.

Access to water is also often seen as an issue related to public goods and even a specific category of special goods, a "commons"

Access to water is also often seen as an issue related to public goods and even a specific category of special goods, a "commons". Regulation of commons, whether water, the atmosphere, the Arctic, or the oceans, is an area that invites dramatic and conflicting differences of views that come down to a few key questions: How should the commons be shared? Who pays for use of the commons? How can damage to the commons be regulated? Pricing and payments principles also can be sources of conflict. Does the polluter or the polluted pay for clean-up, for example, and in what measure? The misuse of water is a classic case of the tragedy of the commons, an economic theory in which every individual tries to reap the greatest benefit from a given resource. Demand eventually overwhelms supply, and soon every individual who consumes the resource harms others who cannot readily access it. The traditional way of resolving this is to have governments or some regulatory bodies provide this public good. Where regulation is not in place or not effectively enforced, it could go the way of over-fishing, where the fishing stock has collapsed in some cases in the Atlantic and elsewhere.

Two sources of inevitable conflict need to be dealt with and adjudicated, through a combination of agreement and regulation. One source is related to water use and is exacerbated by drought conditions, as has recently been the case in California. What are the rights of the agricultural sector versus the energy sector, the two largest water users in the United States? In general, biodiversity and the environment, along with recreational use, have in many cases come ahead of these two sectors in public perception. Against those rights, how do claims for potable water in cities become adjudicated? Another source of friction relates particularly to access to river water and claims to access the water when different jurisdictions are involved, sometimes within the same country (e.g. the Colorado River) and sometimes across countries (e.g. historically the Danube, but increasingly in water scarce emerging markets). The U.S. and Canada have signed treaties to make this work, but countries that have less friendly relationships with each other have more difficulties coming to terms and the result can be a military conflict over water.

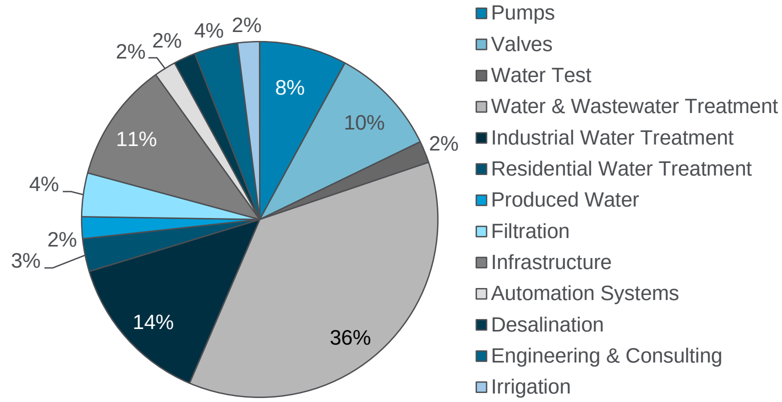
Given that water, like electricity, is more a local than a regional or global phenomenon, regulation can become extremely complex

As scarcity of water supply and adequacy of distribution have emerged as critical global problems, so too have issues come to the fore related to adequacy and integrity of water reservoirs, regulations on water use, water disposal, and water recycling. Wastewater is a similarly critical subject because its disposal and recycling involve the pricing of externalities and ultimately circles back to the issue of water use. Since "what is water" is a mixture of all of the concepts described above, regulation and pricing have become critical and urgent matters for efficient solutions. Given that water, like electricity, is a more local than a regional or global phenomenon, regulation can become extremely complex. Few governments have done what Israel has accomplished (see page 120) and declare that the government has the property rights to all water above or below the ground including rain water. That facilitates pricing and usage considerably. Elsewhere it remains a struggle to find a way to adjudicate conflicting claims while at the same time rationing existing fresh water supply, conserving it, and finding ways to grow it.

## Global Market for Water

The global water market was estimated at approximately $600 billion in 2014. The composition of the water market is complex and includes several sub-sectors and industries. Sixty-five percent of the market is primarily suppliers of water technology – firms that provide services to develop water resources as well as to distribute and treat water (see Figure 1 below).

Figure 1. Global Water Market




Source: Citi Research

In order for investment in the water sector to grow, it is important that we understand the issues related to global water management

There are a number of trends which are shaping this market including demographics, an increase in urbanization, soaring demand for food, over-exploitation of resources, old infrastructure, climate change, and other. It is estimated that the market opportunities related to the water sector could reach $1 trillion by 2025.[1] The private sector is expected to play a significant role in an integrated approach to water management and investment in a number of areas including utilities, capital goods and chemicals, construction and materials, and quality and analytics. Based on economic growth and the need to catch up with basic infrastructure, water sector investments are expected to grow faster in developing countries when compared to advanced countries, as discussed later in this report in a chapter on solutions. However, in order for investment in the water sector to grow, it is important that we understand the issues related to global water management and the opportunities and solutions needed to avoid a global water crisis. These are discussed in the next chapters of this report.

[1] RobecoSAM. (2015). *Water: the market of the future*.

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# Framing the Challenges

# The Scale of the Problem

From the droughts in California which cost the economy $2.74 billion and 10,100 jobs in 2015[2], to the floods in the U.K. in late 2015 which are expected to cost the insurance industry between £1 to £1.5 billion, it is not at all surprising that in 2016, water was listed by the World Economic Forum as a global risk of highest concern. Water is important for most economic activities and is essential to sustain livelihoods and important ecosystems.

Challenges around water management in many countries are immense. It is estimated that over 800 million people in the world do not have access to clean water and some 4 billion people live under severe water scarcity at least one month per year.[3] Of these 4 billion, almost 1 billion live in India and 0.9 billion live in China. According to the World Health Organization at least 3.4 million people die from water-borne diseases each year.

18 river basins with a cumulative $27 trillion in GDP are water-stressed

Rapid population growth, coupled with an increase in wealth and dietary changes, is increasing the demand for water. To meet this growing demand, some rivers are being diverted for use and at times are becoming so depleted that they fail to reach their ocean destinations. Eighteen river basins that flow through countries with a collective $27 trillion in GDP face 'extremely' high levels of baseline water stress.[4] According to the World Resources Institute, this means that more than 80% of water which is naturally available to different sectors (agriculture, domestic, and industrial users) is withdrawn annually, leaving different users vulnerable to scarcity. It is also estimated that one-third of the large groundwater basins are being rapidly depleted by human consumption.[5] Groundwater is increasingly relied upon in times of drought as a resilient water supply source and is currently a source of freshwater for approximately two billion people.[6] Flooding is also affecting many areas, with approximately 21 million people worldwide affected by river floods each year on average and an estimated $96 billion of global GDP exposed to river floods each year.

Water is badly managed leading to excessive use in many areas

Climate change is also expected to have an impact on the availability of water in many regions. According to the Intergovernmental Panel on Climate Change (IPPC) Fifth Assessment Report, climate change over the twenty-first century is projected to reduce renewable water resources significantly in many dry subtropical regions. A projected increase in temperature in many regions could change precipitation patterns, affect the timing of snow pack and snow melt, while at the same time alter the hydrological system.

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[2] Kat Kerlin. (2015). *Drought costs California agriculture $1.84B and 10,100 jobs in 2015.*

[3] Mekonnen M.M, A. Y. Hoekstra. (2016). *Four billion people facing severe water scarcity*, Science Advances Vol 2, No. 2, e1500323.

[4] Andrew Maddocks and Paul Rieg. (2014). *World's 18 Most Water-Stressed Rivers*, March 20, 2014.

[5] NASA Jet Propulsion Laboratory, California Institute of Technology, *Study: Third of Big Groundwater Basins in Distress*, June 16, 2015.

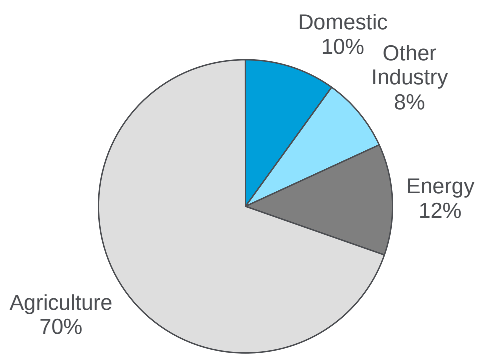
[6] Richley A.S, Thomas B.F, Lo M, Reager J.T, Famiglietti J.S., Voss K, Swenson S, Rodell M. (2015). *Quantifying renewables groundwater stress with GRACE*, Water Resources Research, 51, pp5217-5238.

## The Imbalance Between the Demand for and Supply of Water

Globally water withdrawals are estimated at approximately 3,800 km$^3$, with the majority of the water withdrawn by the agriculture sector

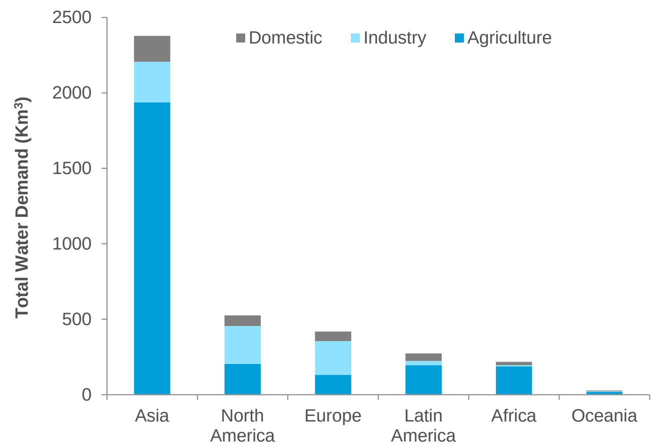
Globally, the current demand for water is estimated at approximately 3,800 km$^3$ per year. The agriculture sector is responsible for withdrawing the majority of this water (2,700 km$^3$). This only refers to the amount of surface and groundwater withdrawals — precipitation is also extremely important for this sector; in fact, approximately 60-70% of the world's food production is produced on rain-fed land. The energy sector is estimated to withdraw approximately 470 km$^3$ of water per year. Most of this water is used for power generation, however, the majority of it returns back into the system albeit at a higher temperature.[7] With regards to human consumption, the major source of demand comes from urban communities that require water for drinking, cleaning and sanitation.

Figure 2. Total Global Water Demand




Source: Curmi et al.(2013), Citi Research

Figure 3. Total Water Demand in Different Regions




Source: Curmi et al (2013), Citi Research

The possibility of using water resources for these various sectors (agriculture, industry, energy, and domestic) is determined not only by their year-to-year variability, but also by their seasonal and monthly variability, which makes the sustainable management of water resources extremely difficult.[7] Two terms are used when discussing water use — water consumption and water withdrawals — and it is important to highlight their differences as sometimes they are used interchangeably in the literature, despite the fact that they refer to different things (see feature box below).

**Water Withdrawals vs Water Consumption**

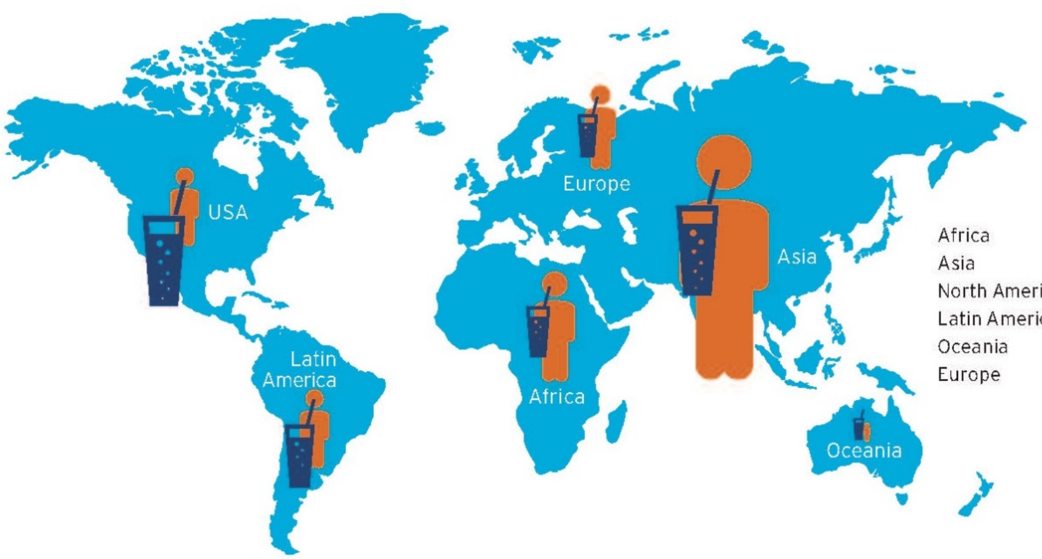
Water withdrawals are defined as water that is diverted or withdrawn from surface or groundwater, where some of this water can return back to the water system as return flows. Water consumption is defined as water that is permanently withdrawn from its source — it is water that is no longer available because it has been evaporated, transpired by plants, incorporated into products or crops, consumed by people or by livestock, or otherwise removed from the immediate water environment. For example, the majority of the water used for food production is lost or 'consumed' through the process of evapotranspiration, the process of transferring moisture from the earth to the atmosphere by the evaporation of water and transpiration from plants.

[7] Curmi E, Richards K, Fenner R, Allwood J.M, Kopec G.M. Bajzelj B. (2013). *An integrated representation of the services provided by global water resources*, Journal of Environmental Management, 129, pp 456-462.

## The Availability of Freshwater Resources

The availability of freshwater resources differs between different regions, with some areas having too much water and others having too little water. For example, China has 3% of available global freshwater resources but over 19% of the global population live there, whereas other areas such as Latin/South America have over 16% of available freshwater resources but only 9% of global population (see Figure 4). However, there are significant spatial variations that occur within each region. For example, per capita renewable freshwater resources in Africa are estimated at 3,650 $m^3$ per year; however, North Africa has only approximately 325$m^3$ per capita per year. India has over 2,500$m^3$ per capita availability of water per year; however most of this water occurs during the monsoon season. Over the years storage facilities in the form of large reservoir systems have been built to capture the water at different times to enable its availability throughout the year. Large transfer systems have also been developed to move water from where it is available to where it is limited (such as the water transfer system from the north of China to the south of the country). Even with these systems in place, river systems and groundwater resources in many areas are being depleted at a very fast pace.

Figure 4. Freshwater Availability in Different Regions




| | % global population | % freshwater available |
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Source: Curmi et al, Hejazi et al (2014), UN Population Statistics, Citi Research

### The Unsustainable Use of Water in Different Regions

The World Resources Institute through their Aqueduct Water Risk Atlas has mapped the current baseline water stress levels across the globe[8]. This assessment takes into account the total annual available flow in different countries with the total annual withdrawals expressed as a percent of total annual available flow. Experts at the Institute grouped together 12 indicators (such as time-series estimators, hydrological data, existing publications and others) into a framework identifying

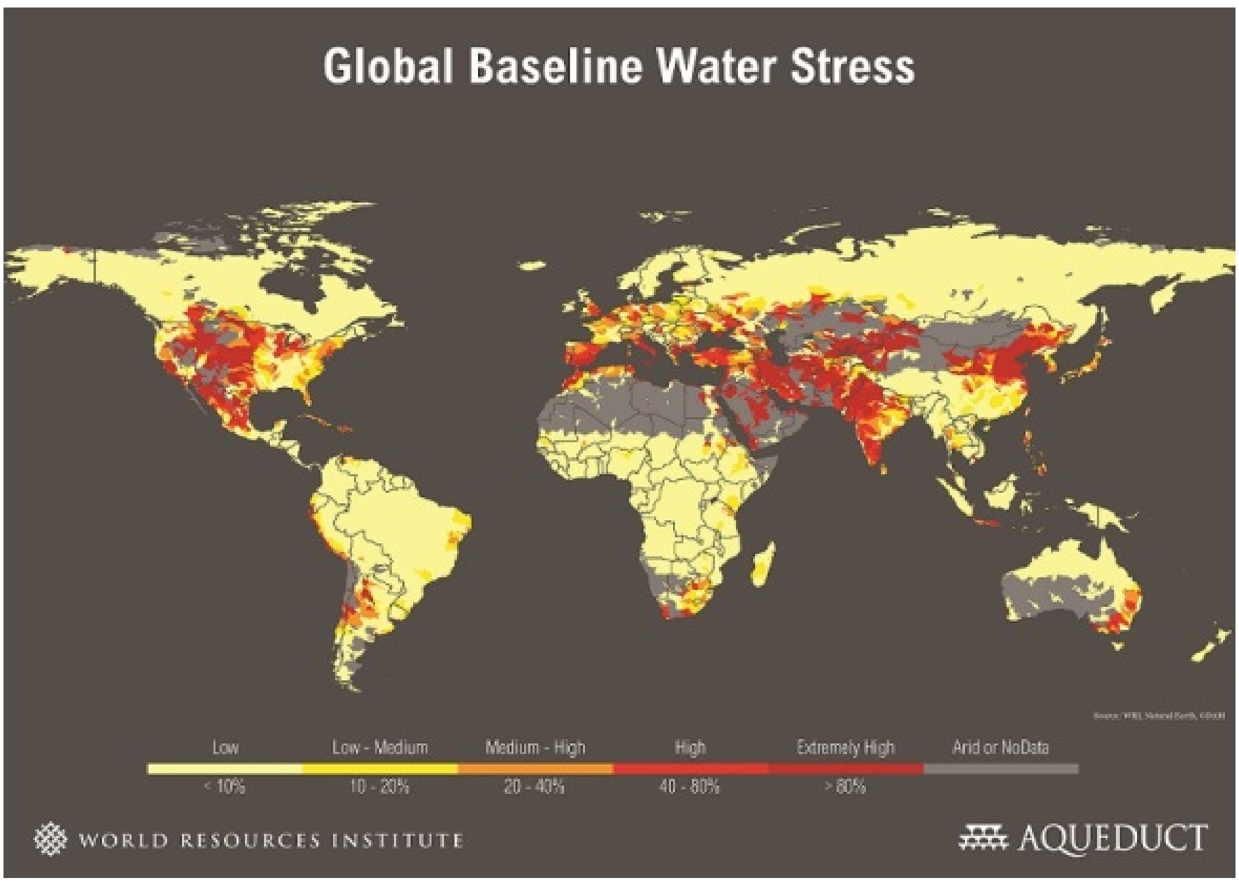
[8] There are two terms which are used to determine whether a country is using its water resources sustainably- (1) water scarcity which is defined as the volumetric abundance or lack of sufficient available resources to meet water needs within a region and (2) water stress which is defined as the ability or lack of to meet human and ecological demand for water any times.

spatial variations in water risks. The map (refer to Figure 5) shows that many regions — in particular western United States, parts of Europe, Middle East and Asia — are already suffering from baseline water stress with higher values indicating increased more competition among users[9]. Many regions have an inherent imbalance between the demand for water and the availability of clean freshwater, over time leading to the excessive depletion of river systems and groundwater resources.

**Aqueduct Water Risk Atlas- World Resources Institute**

In response to growing concerns from the private sector around water availability, water quality, climate change, and the increase in demand for water, the World Resources Institute developed the Aqueduct Water Risk Atlas. Experts at the Institute grouped together 12 indicators (such as time-series estimators, hydrological data, existing publications and others) into a framework identifying spatial variations in water risks. The result is a publicly available global database and interactive tool that maps indicators of water related risks. Future projections take into account indicators of change in water supply, water demand, water stress, and seasonal variability projected over the coming decades under scenarios of climate change and economic growth.[10]

Figure 5. Global Baseline Water Stress




Note: Arid areas with low water use are shown in gray, but scored as high stress when calculating aggregated scores
Source: World Water Resources, Citi Research

[9] Gassert F, M Luck, M. Landis, P. Reig and T. Shiao. (2014). *Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risks Indicators*. Working Paper. Washington D.C.: World Resources Institute.
[10] For more information on the methodology used refer http://www.wri.org/sites/default/files/Aqueduct_Global_Maps_2.1.pdf.

## The Depletion of River Basins and Groundwater Resources

Gassert et al (2013)[11] list the ten major river systems that are facing extremely high levels of baseline water stress. These include the Yongding He in China, which supports the municipality of Beijing, and the Colorado River system, which supports almost 40 million people across the southwestern U.S. and is inherently important for business, industry and the agriculture sector. Some of the rivers mentioned below are transboundary waters and therefore upstream water users can ultimately affect the availability and quality of water for downstream users, potentially creating tension between cities, regions, and even countries. They define water stress as the ratio of total annual water withdrawals to total available annual renewable supply. A score of 4-5 means that the basin is extremely high stress (>80%) (see Figure 6).

Figure 6. The Ten Largest River Basins that are Considered to be the Most Water-stressed

| Rank | Name | Description | All sectors | Agriculture | Domestic | Industrial |
|---|---|---|---|---|---|---|
| 1 | Yongding He, China | Main tributaries in the Hai River and is best known for the largest river flow through Beijing Municipality | 4.99 | 4.99 | 4.98 | 4.99 |
| 2 | Harirud, Central Asia | A transboundary river basin which starts in Afghanistan and flows towards Iran and Turkmenistan | 4.91 | 4.92 | 4.79 | 4.95 |
| 3 | Helmand, Afghanistan | The Helmand is one of Afghanistan's most important rivers and has been extensively developed over the years. There has been a long-standing dispute between Afghanistan and Iran which has centered on Iran's claim to a portion of the Helmand's water | 4.83 | 4.83 | 4.87 | 4.81 |
| 4 | Balkhash, Kazakhstan | One of the largest lakes in central Asia. Its drainage basin is situated in south eastern Kazakhstan (85%) and northwestern China (15%) | 4.82 | 4.84 | 4.80 | 4.64 |
| 5 | Sirdaryo | A transboundary river that flows through Kyrgyzstan, Uzbekistan, Tajikistan, and Kazakhstan | 4.78 | 4.76 | 4.96 | 4.76 |
| 6 | Indus | A major south flowing river in South Asia, it flows through Pakistan, the Indian state of Jammu and Kashmir and Western Tibet | 4.30 | 4.31 | 4.08 | 4.14 |
| 7 | Colorado River (Pacific Ocean) | One of the principal rivers of southwestern U.S. and northern Mexico. The river and its tributaries are controlled by an extensive system of dams, reservoirs and aqueducts which divert 90% of its water to the U.S. to support almost 40 million people | 4.18 | 3.97 | 4.24 | 4.48 |
| 8 | Lake Mar Chiquita | The largest lake in Argentina. The main problem for Mar Chiquita is the water withdrawal from the Dulce River for irrigation purposes | 4.13 | 4.08 | 4.18 | 4.24 |
| 9 | Bravo | The second longest river in the U.S., its basin is more than 30% arid and drains an area the size of California. It flows from Colorado, south through New Mexico and forms the border between Texas and Mexico | 4.12 | 4.08 | 4.18 | 4.24 |
| 10 | Liao He, China | Principal river in southern northeast China and one of the seven most important river systems in mainland China | 4.00 | 4.14 | 3.86 | 3.50 |

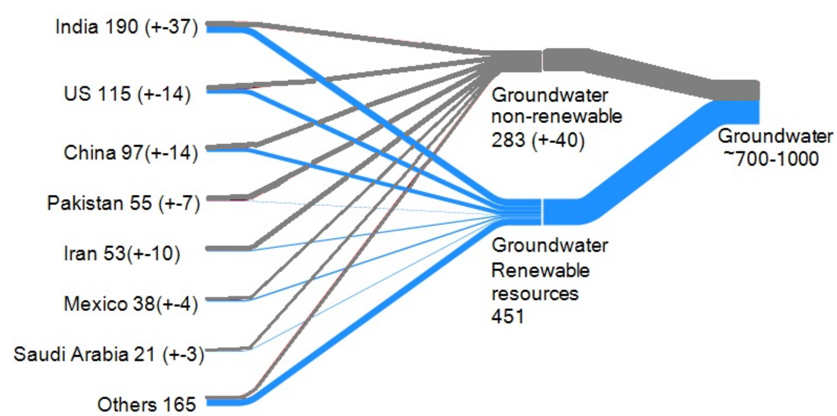
Note: Water stress is defined as the ratio of total annual water withdrawals to total available annual renewable supply. A score of 4-5 means that the basin is extremely high stress (>80%).
Source: Gassert et al (2013)[12], Citi Research

[11] Gassert F., P. Reig, T. Luo and A. Maddocks. (2013). *Aqueduct country and river basin rankings: a weighted aggregation of spatially distinct hydrological indicators, working paper*. Washington D.C.: World Resources Institute, November 2013.
[12] Gassert F., P. Reig, T. Luo and A. Maddocks. (2013). *Aqueduct country and river basin rankings: a weighted aggregation of spatially distinct hydrological indicators, working paper*. Washington D.C.: World Resources Institute, November 2013.

Approximately 700-1000 $km^3$ of groundwater is withdrawn per year, resulting in excessive use in many countries

Unlike surface water, which has been intensively used in many parts of the world, groundwater had remained, until less than a century ago, a rather underdeveloped resource. However, due to population growth and the associated increase in demand for water, food, and energy, intensive groundwater extraction began in the first half of the twentieth century. Groundwater is a key strategic source of water in times of drought. Approximately 700-1000 $km^3$ of groundwater is withdrawn per year for irrigation (67%), domestic (22%) and industrial uses (11%).[13] Despite this resource being of such critical importance, we find that overall it is badly managed in some countries. Groundwater is being pumped at far greater rates than it is naturally being replenished, so many of the largest aquifers in many countries are being mined unsustainable. The global figure of groundwater overdraft is estimated at over 280 $km^3$ (Figure 7). Studies have shown that aquifers in North China Plain, and the High Plains and Central Valley in the U.S., the aquifers beneath north-western India and others are all being used unsustainably.[14] Nearly all these aquifers underlie some of the largest agriculture production in the world and their continued excessive use could be detrimental to not only future agriculture production in the area but to the millions of people that depend on these aquifers for their supply.

Figure 7. Unsustainable Global Groundwater Use




Source: Curmi E, Citi Research

## The Current Management of Water

The main reason why we are using water so unsustainably in many regions is that we are currently managing water very poorly, leading to excessive and unsustainable usage as described above. Water in many countries is governed by public policy because competitive markets fail to account for the common pool and public good characteristics of water[15]– this leads to inefficiencies. In many places water is unregulated, ineffectively priced, or subsidized and in some cases the right to use it is given away for free. For example the Punjab region in India faces serious water shortages and a groundwater table that is falling at a very fast pace – total annual groundwater extraction is approximately 72% higher than the

[13] WWAP (World Water Assessment Programme). (2012). *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*, Paris, UNESCO.
[14] Famiglietti J.S. (2014). *The global groundwater crisis*, Nature Climate Change, Vol 4, November 2014.
[15] Kahil et al. (2016). *Improving the performance of water policies: Evidence from drought in Spain*, Water, Vol. 8, pp 34.

sustainable limit of 20 billion cubic metres. [16]The majority of water is used for irrigation purposes, with most farms having access to a tube-well. The problem of unsustainable water use in this region started in the 1970s when government subsidies, mechanization and technology were introduced in the region to encourage people to move into farming. Rice, one of the most water-intensive crops, is also the crop of choice in the area. The government has done nothing to regulate groundwater use – farmers and their families make up 60% of the population in the area, therefore any changes to the current management of water are seen as being too political. Without political will, proper pricing systems and other incentives to reduce inefficient water use, it is difficult to see how the situation would change in the Punjab region until a crisis occurs.

## Future Water Demand

John Beddington, the ex-chief scientist of the U.K. government, stated that "by 2030 the world will need to produce around 50 per cent more food and energy, together with 30 per cent more fresh water, whilst mitigating and adapting to climate change. This threatens to create a "'perfect storm' of global events…There's not going to be a complete collapse, but things will start getting really worrying if we don't tackle these problems".[17] Numerous studies have been undertaken to estimate the future demand for water and other resources over time based on a number of different population scenarios and demand and supply assumptions (refer to Figure 8).

Figure 8. Future Global Water Demand

| Global Water Withdrawals | Curmi et al (2014) | Water Resources Group | OECD | Hejazi et al. (2014)-POP/6 MDG- | Hejazi et al. (2014) POP9 MDG + |
|---|---|---|---|---|---|
| | Current | 2030 | 2050 | 2050 | 2050 |
| Municipal | 382 | 900 | 790 | 666 | 859 |
| Electricity | 470 | | 1386 | 390 | 485 |
| Primary Energy | | | | 15.2 | 22.2 |
| Manufacturing | 314 | 1500 (incl energy) | 1195 | 288 | 439 |
| Agriculture + Livestock | 2672 | 4500 | 2094 | 4837 | 6555 |
| Total | 3838 | 6900 | 5465 | 6196 | 8360 |

Source: Curmi et al, Water Resources Group, OECD, Hajazi et al, Citi Research

[16] Srivastava S.K et al. (2015). *Unsustainable Groundwater Use in Punjab Agriculture: Insights from cost of cultivation survey*, Indian Journal of Agriculture Economy, Vol 70, No. 3, July-Sept. 2015.

[17] Beddington, John. (2009). *Food, Energy, Water and the Climate: A Perfect Storm of Global Events?*

Figure 9. Future Global Water Demand

| GLOBAL WATER WITHDRAWALS | Curmi et al (2014) | Water Resources Group | OECD | Hejazi et al. (2014) Pop6/ MDG- | Hejazi et al. (2014) Pop9/ MDG+ |
|---|---|---|---|---|---|
| | Current | 2030 | 2050 | 2050 | 2050 |
| Municipal | 382 | 900 | 790 | 666 | 859 |
| Electricity | 470 | | 1386 | 390 | 485 |
| Primary Energy | | | | 15.2 | 22.2 |
| Manufacturing | 314 | 1500 (including energy) | 1195 | 288 | 439 |
| Agriculture + Livestock | 2672 | 4500 | 2094 | 4837 | 6555 |
| TOTAL | 3838 | 6900 | 5465 | 6196 | 8360 |

Note: Pop6/ MDG- scenario assumes population peaks and then declines to 5.5 billion by 2050 (i.e. not linear). Pop9/ MDG+ assumes the global population stabilizes at 9.1 billion. Curmi et al assumes population of 7 million.
Source: Curmi et al, Water Resources Group, OECD, Hajazi et al, Citi Research

Even though the results differ slightly between different studies, the fact remains that the demand for water is expected to increase. Given that we have already depleted many of our aquifers and river systems it is hard to imagine how business as usual can continue without affecting the production of food, energy and ultimately the lives of people in many areas. The International Food Policy Research Institute (IFPRI) estimates that that nearly $63 trillion of global GDP could be at risk in 2050 if current water management practices and levels of water productivity are maintained (IFPRI). There are many solutions to this problem which we discuss towards the end of this report; however, first we look at the connections between water security and economic growth.

# Water and Economic Growth

Benjamin Franklin in 1746 stated "When a well is dry, we know the worth of water". This statement brilliantly reflects the way we currently manage water. Many governments, businesses and others practically ignore water-related risks until a crisis actually occurs.

Water security and economic growth are intertwined

Water is vital for food and energy production, the livelihoods of people, and economic growth. Diminishing water supplies can result in a lower growth rate and worsen the economic prospects of many countries and regions. Water security and economic growth are intertwined, however the 'ubiquitous nature' of water means that its economic role can be difficult to isolate (see feature box below). In a globalized world, the unmanaged risks of water such as floods and droughts can not only cause chaos and economic losses in a particular region, but also affect businesses and the livelihoods of people in other places far away from the event itself. Investment in water security and improvement in efficient water use are not only a matter of protecting society from water-related risks but is also an investment that supports economic growth and social well-being even when the risks do not materialize.

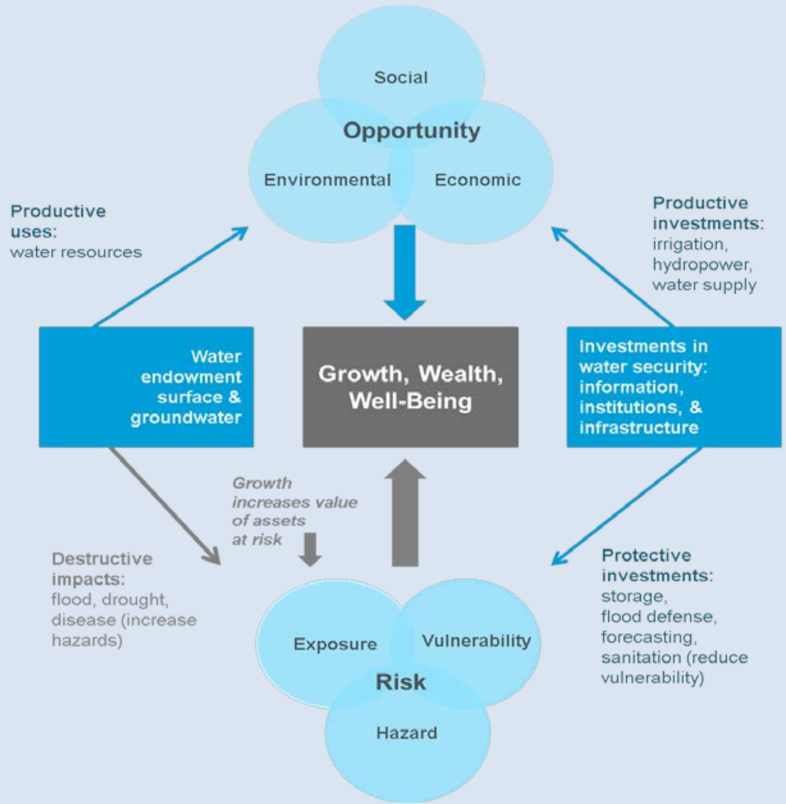
## Water Security and Economic Growth

*By Professor Jim Hall, Environmental Change Institute, University of Oxford*

Infrastructure for water supply, sanitation, irrigation, flood protection and so on is recognized as being essential for all civilized economies. Indeed the emergence of human civilizations is, in part, associated with the development of water infrastructure to enable urban agglomerations and enhance agricultural production. Today water is an essential factor in practically all economic activities. In particular agriculture, power production (from hydropower and thermoelectric plants), waterway navigation and extractive industries, and many process industries rely on large quantities of water. Yet the ubiquitous nature of water means that its economic role can be very difficult to isolate. The causal relationship between economic growth and investment in water infrastructure runs in both directions, i.e. efficiently managed water infrastructure contributes to increased productivity and growth, and economic growth yields resources that can be invested in water infrastructure.

In advanced economies, water is most noticeable when something harmful happens: droughts that restrict agricultural production and perhaps also power plant output; floods that damage infrastructure and disrupt production; or pollution incidents that result in massive clean-up costs and claims for liability. In these situations we are concerned about water-related *risks*. But water is not only a source of risk – where resources are available it represents a potential economic opportunity to increase agricultural production, generate hydropower, and open up inland waterways for navigation. In advanced economies most of these opportunities have been exploited, and sometimes over-exploited, meaning that the environment's capacity to deliver these ecosystem services has been compromised. In developing countries, there often exist opportunities to enable economic growth and enhance well-being through wise investment in water infrastructure.

Figure 10. Conceptual Framework of the Dynamic of Water Security




Source: Sadoff et al. (2015)

Our reasoning about the risks and opportunities of water security has led to the simple conceptual model, which was first published in the report *Securing Water, Sustaining Growth*[18] in 2015. We find that the 'water endowment' is a significant factor in many countries' wealth and well-being. The water endowment encompasses availability of surface water, soil water, and groundwater, and also the variability in the availability of the water resources. That endowment can be supplemented, for example through wastewater reuse and/or desalination, which would, if energy costs are low enough, add most (salty) sea water to the endowment of (potential) water. The water endowment can result in water-related risks (the lower part of the diagram) and can yield water-related opportunities (the upper part of the diagram). The scale of risks is determined by the severity of the water-related hazards (floods, droughts, inadequate water supply and sanitation, harmful water quality) and also by the exposure and vulnerability people and economic assets. When water-related risks materialize they can act as a drag on economic growth. On the other hand, if it is possible to access water-related opportunities, then these can contribute to growth. Growth yields capital to invest in water security – in water infrastructure, information to understand complex water resource systems and institutions to efficiently and equitably manage water resources. Those investments can help to access water-related opportunities, leading to a self-reinforcing growth cycle; and can help to mitigate water-related risks, reducing the potential drag on growth. A further important feedback exists because growth generally tends to increase the exposure of assets to water-related hazards, for example flood hazards. That is why the impacts from water-related risks are greatest in middle income countries, where exposure has rapidly increased but investment in risk reduction has not caught up.

[18] Sadoff, C.W., Hall, J.W., Grey, D., Aerts, J.C.J.H., Ait-Kadi, M., Brown, C., Cox, A., Dadson, S., Garrick, D., Kelman, J., McCornick, P., Ringler, C., Rosegrant, M., Whittington, D. and Wiberg, D. (2015). *Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth*, University of Oxford, April 2015, 180pp.

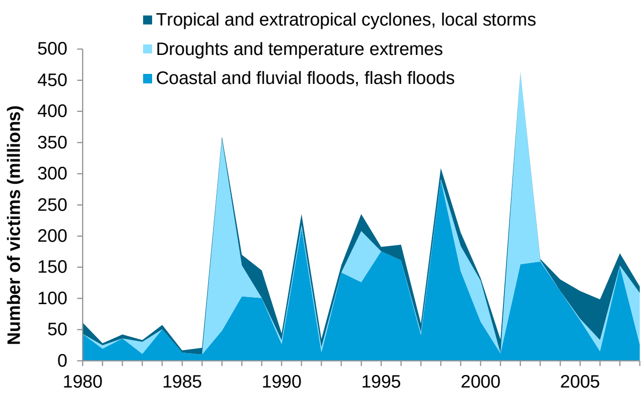
In *Securing Water, Sustaining Growth* we went on to quantify the effect of water insecurity on economic growth. That's not easy because of the difficulty of isolating the effects of water on the economy, but the impacts of unmitigated hydrological variability (droughts, floods, unpredictable rains) can be studied with econometric analysis because these climatic factors are independent variables. Our analysis robustly demonstrated that water insecurity is a drag on growth – unsurprisingly the effect is most noticeable in states that have scarce available water, have agriculture-dependent economies and are poor. Countries with more diversified economies have for the most part been able to decouple their economies from hydrological variability… until something really major happens, like the Brazilian drought, which helped to throw the country into recession, or the 2011 Thai floods, which rocked investor confidence in a growing manufacturing sector. When events like that happen we recognize economic vulnerability to water-related risks and the importance of investment to manage those risks.

## Unmanaged Risks Could Affect Local, Regional, and Global Economies

Climate change could also increase the occurrence of extreme droughts, floods, and more

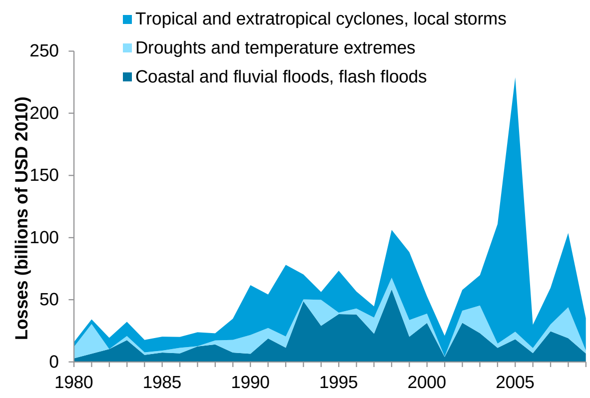
Floods, droughts, and inadequate supply of water cause damage to an economy through the destruction of physical property and important infrastructure, the loss of human capital and lives and the disruption to other economic activities. It is estimated that the cost of fluvial floods losses (rivers and streams) at a global level has increased from $7 billion per year during the 1980s, to $24 billion per year during 2001-2011.[18] Sadoff et al. (2015) believe that the economic risks of floods are increasing and spreading across different countries. This will not only cause huge economic losses in developing countries but will also affect advanced economies — the U.S., India, and China are each expected to have annual damages from floods in excess of $10 billion.[18] The World Health Organization estimates the total global economic losses from inadequate water supply and sanitation to be in the range of $260 billion annually. In some countries such as Niger, the Democratic Republic of Congo, and Somalia, the economic losses of inadequate water supply and sanitation is equal to 10% of GDP.[18] Climate change could also increase the occurrence of extreme droughts, floods, and more. The World Bank ranks water supply and flood protection as one of the top three adaptation costs to climate change, estimated between $14.4 and $19.7 billion per year.[19] These figures are considered conservative — studies done at national level show higher adaptation costs. For example it is estimated that the annual costs for future flood protection/risk management in the Netherlands alone is $1.25 billion per year.[20]

Figure 11. Number of People Affected by Global Weather Disasters




Source: Visser et al[21], OECD (2012)[22], Citi Research

Figure 12. Cost of Global Weather-Related Disasters, 1980-2009




Source: Visser et al., OECD (2012), Citi Research

[19] The International Bank for Reconstruction and Development / The World Bank. (2010). *Economics of adaptation to climate change, synthesis report*.
[20] UNEP. (2014). *The Adaptation Gap, A preliminary assessment report*.
[21] Visser H., Cleij, P., Bakker, M., Bouwman, A, and Ligtvoet, W. (forthcoming), *Trends in weather-related disaster burden: a global and regional study*, PBL Netherlands.
[22] OECD. (2012). *Environmental Outlook to 2050*.

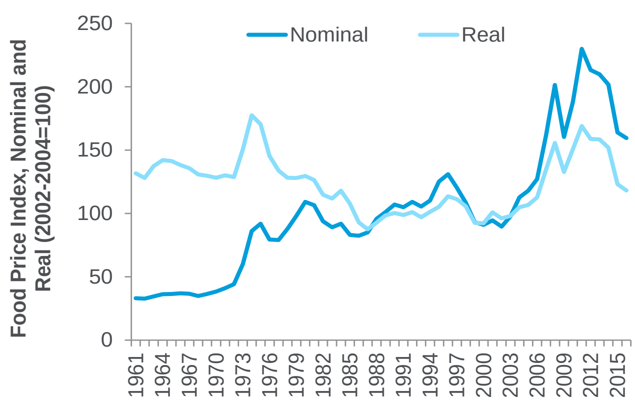
Economic losses due to floods, droughts, or inadequate water supply are not only confined to the affected region but also affect other regions far away from the event

There are plenty of examples of economic losses occurring due to floods, droughts, or inadequate water supply. These losses are nowadays not only confined to the affected region but also affect other regions far away from the event. The 2011 floods in Thailand resulted in over $45 billion of direct and indirect economic losses, 880 deaths and damage to over 7,500 industrial plants. Global supply chains in several industries were affected — the price of computers increased owing to the shortage of computer hard drives, while motor vehicle production was also hit with companies like Toyota decreasing its production by 260,000 vehicles.[23]

Water-related risks can also lead to conflicts and tensions within countries. Take Syria: the social unrest there, culminating in an already almost 5-year-long civil war, was the proximate result of a multitude of direct factors. It also followed one of the worst long periods of drought in Syria's history which lasted more than five years from 2006 to 2011. This resulted in 60% of Syria's productive land experiencing severe drought, destroying 75% of crops and 85% of livestock.[24] It is estimated that 800,000 people lost their livelihoods as a result of this drought as farmers were pushed to sell their lands and move to urban regions, which gave rise to tensions throughout the country.

In 2010, wildfires and a drought in Russia, which at that time supplied over 10% of the world's wheat exports, led to the government banning wheat exports in that time period. This coincided with floods in Australia, dry weather in Argentina and in the United States and led to a reduction in grain production and an increase in global food prices. As a result, food import-dependent countries in the Middle East and North Africa such as Egypt and Tunisia experienced above-normal food price inflation.[25] Low wages and high youth unemployment in many of these countries left the population vulnerable to increases in food prices leading to tensions. It might not be a coincidence that a food seller was at the center of the uprisings in Tunisia that started the 'Arab Spring' and that images of bread were central to Tahrir Square demonstrations.

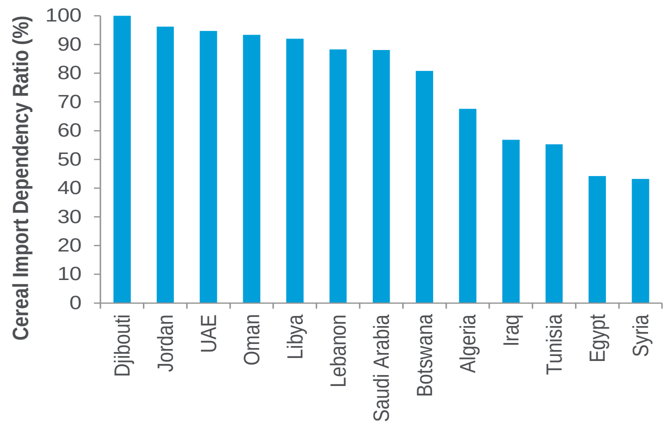
Figure 13. Food Price Index (1961-2015)




Source: FAO, Citi Research

Food price index consists of the average commodity prices of meat, dairy, vegetable oils, cereals and sugar

Figure 14. Cereal Dependency Ratio in North Africa and Middle East Countries




Source: Citi Research

[23] Grey D, Garrick D, Blackmore D, Kelman J, Muller M, and Sadoff C. (2016). *Water security in one blue planet: twenty-first century policy challenges for science* , Philosophical Transactions of the Royal Society.

[24] http://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/Erian_Katlan_&_Babah_2010.pdf

[25] USAID. (2011). *Executive Brief: Food Price Trends in the Middle East and North Africa.*

## The Complex Economics of Water

Limiting the destructive impacts of having too much or too little water is extremely important even in the most advanced economies. Improving the efficient use of water and reducing wastage through better pricing mechanisms and/or other rationing mechanisms and investing in good infrastructure can help countries prepare for such events. In many countries, however, the barriers to efficient water use and allocation are socially and politically constructed. Unlike energy, water prices are typically not determined in the markets and do not reflect resource scarcity. Prices for water are determined by policymakers who themselves are driven by effective lobbying from big water users and appeals to deep emotions, stemming from the widespread sense that charging for water is unfair or even immoral – especially when it comes to household and agricultural users of water.[26] Therefore water prices often do not reflect the realities of changing short-term and long-term scarcity, costs, needs or demand.

This politicization of water allocation and pricing is both widespread and hard to understand and rationalize. For an economist, water is a commodity. Outside the dismal profession, water, unlike other non-renewable resources, is often viewed as a public good or a human right. Fortunately, at least the human rights aspect of water use can be handled using conventional welfare economics. The public good aspect is really only appropriate for the environmental use of water (sailing on an uncrowded lake) and even there, congestion is likely to rear its head if the public good is popular, turning it into a rival good with associated negative externalities.

Like other renewable resources, water can be overused and turn into an exhaustible and exhausted resource

From a technical economic perspective, water is close to a *pure private good*: it is a renewable resource - most water that is used is eventually recycled and, at a cost and the lapse of some time, available to be used again. Like other renewable resources (think fish) water can be overused and turn into an exhaustible and exhausted resource. The economic analysis of renewable resources such as water is different from the economic analysis of non-renewable resources such as oil and gas. With oil and gas, the question of sustainability does not arise. With a finite amount of consumption in any given period, the finite stock will be exhausted in finite time. The analysis of renewable resources has to allow for the possibility that the resource, although finite at any given point in time, can last forever. Such sustainable use of the resource over time requires aligning the rate of usage with the resource's natural capacity and its timeframe for re-generation[18]. It is in principle possible that the optimal use of a renewable resource would involve 'excessive', unsustainable use that results in its exhaustion in finite time. Given how essential water is to the business of life and living, this possibility can in practice be ruled out. Sustainable use and consumption has to be the objective.

Water is rival in use or consumption and its use or consumption by third parties is generally excludable at a reasonable cost.

A good is rival if the use or consumption of a given quantity of the good means that same quantity is no longer available for use or consumption by others. Non-rival goods can be seen as goods whose supply can be expanded at zero long-run social marginal cost. This includes capital costs, (or fixed costs, including infrastructure maintenance) variable costs, (costs associated with the actual use of water) and the cost of ensuring that this potentially renewable resource is indeed renewed (the cost of ensuring sustainable use). It also allows for positive or negative externalities. Scientific or technological knowledge is non-rival. Water clearly is rival.

[26] Olmstead S.M. (2010). *The Economics of Managing Scare Water Resources*, Review of Environmental Economics and Policy, Vol 4, Issue 2, pp 179-198.

A good is non-excludable if it is impossible (or prohibitively costly) to restrict access to the use or consumption of the good. Property rights are not enforceable without excludability at a reasonable cost. Without enforceable property rights markets cannot function – and neither can most other rationing mechanisms. Secrecy and effectively enforced intellectual property rights make scientific or technological knowledge excludable.

Water can be characterized as a near-textbook pure private good: completely rival in use and often excludable at low cost

It is clear that, depending on the specific use for water that we are considering and a host of other considerations (location for instance), access to water, although certainly not excludable at zero marginal cost, is often excludable at reasonably low cost. It is possible to steal water, and the detection probability may be low and the punishment conditional on detection insufficient to constitute an effective deterrent. Households sometimes tap illegally into public water supply systems and ignore hosepipe bans during droughts. Farmers can divert water intended for irrigating other farmers' fields, etc. Often, however, the possibility exists of exclusion at a reasonable cost, which is a necessary condition for charging for use or consumption and therefore for market delivery of the good. Water can be characterized as a near-textbook pure private good: completely rival in use and often excludable at low cost.

When a good is non-rival and excludable, it can be provided efficiently by the market. If economies of scale are limited and there are no externalities in the production, use or consumption of the good, it can be allocated efficiently by private-profit-motivated suppliers in competitive markets. If economies of scale are pervasive, if there is a tendency for suppliers to collude, if there are positive or negative externalities and if the supplier and the user/consumer of water don't have the same (preferably complete) information about all relevant characteristics of the good, a regulated market – possibly a regulated monopoly – would be the best mechanism for allocating such a scarce resource.

There clearly are economies of scale in the supply (extraction, purification, storage, transportation and delivery) of fresh, drinkable water, of water fit for use as an agricultural or industrial input and in the treatment of waste water. There are externalities associated with certain uses of water - water use by farmers, industrialists and households can result in polluted or poisoned waste water. As long as the by-products of water use, be they positive or negative, can be identified, measured, attributed and priced, they don't change the nature of water as a private good. Joint production (of which water consumption that gives rise to future waste water is one example) does not rule out efficient, market-based production and supply. If property rights are defined incompletely, for whatever reason, joint production can and does give rise to externalities, positive or negative. Finally, certain consumers of water will not have the skill, the time or other resources necessary to verify water quality. Water should therefore be a regulated industry.

Certain consumers of water will not have the skill, the time or other resources necessary to verify water quality. Water should therefore be a regulated industry

But do any of the foregoing arguments about water and its uses mean that its use should be subsidized – sold at a price below the long-run social marginal cost of providing it to the user/ consumer ? The only 'classical' reason for subsidization would be positive externalities in the use or consumption of water. It is rather difficult to think of many convincing examples – an aesthetically pleasing fountain comes to mind.

Does the fact that water is essential for life, and sufficient water a necessary condition for a decent quality of life, constitute an argument for subsidizing it? Solid food too is essential for life, but although some food is subsidized (or provided free of charge, like school meals), a lot of food is sold at prices at least equal to long-run marginal cost. Health care is essential for life, but in many countries part of, most of or even all of health care is provided at a price that covers at least long-run marginal (private) cost. In cold climates, electric power is often essential for survival. Should electricity be made available free of charge to households in such climatic zones?

## Is Water a *Merit Good*?

A merit good (a concept introduced by Richard Musgrave in 1957[27] and 1959[28] is a commodity of which a particular society believes that it should be provided to individuals or households on the basis of need, rather than ability and willingness to pay. Provision should therefore not be based on consumer choice (alone).

The concept of merit goods may well lie behind many economic interventions by governments that are not motivated by conventional income - or consumption-supporting considerations (tax rebates, transfer payments or, more generally, the provision of additional cash resources to the poor). Examples include the provision of food stamps, the delivery of health services at a price below marginal cost, housing subsidies and free or subsidized pre-school, primary, secondary and tertiary education.

In many cases, merit goods provide services that anyone in a particular community is deemed to be entitled to. This brings the concept of merit goods close to the concept of primary goods, or "things that every rational man is presumed to want" (Rawls (1971)) found in the work of John Rawls or encountered in discussions about social inclusion.[29] Both merit goods and primary goods have about them a whiff of benevolent paternalism and of the philosopher-king's technocratic right to 'nudge' the indigent and/or ignorant into directions and towards actions deemed to be in their best interest, if only they knew or were able to commit appropriately. Politicians, of course, were instinctively aware of 'nudge theory' long before it made its mark on behavioral science, political theory and economics.[30]

No matter how meritorious a merit good may be, if it is scarce, it will have to be rationed

No matter how meritorious a merit good may be, if it is scarce, it will have to be rationed. Standard distributional or fairness arguments also don't imply that the opportunity cost of water use not be brought home to the user, poor or deserving as that user may be. So how should water be priced?

[27] Musgrave, Richard A. (1957). *A Multiple Theory of Budget Determination*, Finanzarchiv, New Series, 25(1), pp. 33-43.
[28] Musgrave, Richard A. (1959). *The Theory of Public Finance: A Study in Public Economy*, McGraw-Hill, New York.
[29] Primary goods are introduced in *A Theory of Justice* by John Rawls (1971). He defines primary goods as the "things that every rational man is presumed to want". These primary goods are the common base for the unanimous selection of the justice principle in the 'Original position'. Primary goods are subdivided in two categories: (1) Natural primary goods: this category includes intelligence, imagination, health, etc., and (2) Social primary goods: including rights (civil rights, political rights, etc.), liberties, income and wealth, the social bases of self-respect, etc.
[30] From Wikipedia: "Nudge theory (or Nudge) is a concept in behavioural science, political theory and economics which argues that positive reinforcement and indirect suggestions to try to achieve non-forced compliance can influence the motives, incentives and decision making of groups and individuals, at least as effectively – if not more effectively – than direct instruction, legislation, or enforcement. https://en.wikipedia.org/wiki/Nudge_theory. See Thaler and Sunstein (2008), *Nudge: Improving decisions about health, wealth, and happiness* and Kahneman (2011), *Thinking, Fast and Slow*.

## Water Pricing for Households

### Lump-Sum Cash Transfers from the State

For households that are too poor to achieve a (socially defined) subsistence level of consumption out of their own resources, the conventional but robust Milton Friedman logic suggests that, provided the authorities (1) know who the poor are and (2) can get money to them at low cost, a lump-sum cash transfer is the efficient way to deal with this distributional problem. India's biometric ID program and the associated program to link the Aadhaar numbers to bank accounts go a long way towards meeting both conditions.[31] This could make it unnecessary to subsidize household water consumption/use.

### A Life-Line or Multi-Tier Tariff

Often, and especially in emerging markets, frontier economies or submerging markets, the government either does not know the identities of the poor or has no means of making cash payments to them. In that case, subsidization of essential goods, merit goods or primary goods can solve the economic vulnerability problem. This only works, of course, if the government or its agents can monitor the consumption or use of water. That requires water metering or something equivalent to monitor and record household water use.

Household water metering is rare, even in advanced economies

It is surprising how rare household water metering is, even in advanced economies. Raising revenue from household water charges was a condition imposed on the Republic of Ireland by the EU-IMF-ECB Troika as part the country's bailout in 2010. Protests against the introduction of residential water meters (this was a first in the Republic of Ireland) were widespread, and continued till late 2016.[32] In London, U.K., the first introduction of individual residential water meters did not start until 2015, despite the fact that in 2006, Ken Livingstone, the socialist mayor of London at the time, argued that water meters should be installed in all London homes.[33]

In emerging markets, protests against rising water prices have become violent at times. For instance, the Cochabamba Water War of 1999-2000 was a series of protests against the privatization of the municipal water supply of Cochabamba, Bolivia and the associated sharp rise in water prices. One civilian was killed and the privatization was reversed.[34]

Metering permits a non-linear or tiered price schedule for water. For instance, some limited quantity of water can be consumed during a given period free of charge or at a nominal charge. This could cover the amount of water required for survival – a socially determined subsistence level of consumption. Water consumption above this limit could be at a price equal to its long-run social marginal cost or higher. Such a life-line tariff or two-tier tariff can be further refined by having more than two tariff bands (a multi-tier tariff), or by setting different tariffs for different times of the day or week, allowing for forms of peak-load pricing.

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[31] More than one billion Indian citizens have a unique biometric identity number of Aadhaar number. 400 million of them own smartphones. More than 310 people have linked their Aadhaar numbers to their bank accounts. See e.g. http://www.biometricupdate.com/201611/vendors-for-iris-recognition-aadhaar-devices-to-be-enrolled-soon and https://www.uidai.gov.in/beta/ .
[32] See https://www.rt.com/news/242973-ireland-water-protest-austerity/ and http://www.rte.ie/news/2016/0917/817201-water-charges-protest/
[33] http://www.edie.net/news/3/Londoners-told-to-conserve-water-as-drought-deepens/10181/.
[34] https://en.wikipedia.org/wiki/Cochabamba_Water_War

Metering permits a non-linear or tiered price schedule for water, but progress is slow

But progress in slow, even in U.S. states with repeated and persistent droughts like California. In 2004, the then-Governor of California Arnold Schwarzenegger signed a law mandating water meters for households and businesses by 2015. Many of the state's water utilities use tiered pricing. The (tiered) tariffs differ widely in different parts of the state.[35] This is justified if the water supply system is not physically integrated, and, even if it is an integrated state-wide system, if there remain significant differences in the cost of delivering water to the final user depending on location. Often, however, the segmented and disjointed local or regional water supply networks are obvious candidates for greater integration and connectedness. The failure to push infrastructure investment to the point where the marginal social long-run return no longer exceeds the marginal social long-run cost represents an enduring costly policy error, in California and elsewhere in the U.S.

## Differential Pricing According to Correlated Observable Characteristics

If the authorities are unable to monitor individual water consumption, it may be possible to approximate the cash transfer or life-line tariff solutions through observable characteristics

If the authorities don't know who the poor are and are unable to monitor/meter individual water consumption, it may be possible to approximate the cash transfer or life-line tariff solutions by either making cash transfers to or subsidizing the consumption of households that have one or more characteristics that can be observed by the authorities and that are correlated with the unobservable poverty characteristic.

Sometimes age is such an observable characteristic. Free school meals are an example. The winter fuel payment that the U.K. pays to the over-60s may be an example of such a third-best intervention. If even this is not feasible, or if age bears no significant relationship with poverty, the final recourse would be to subsidize all household use or consumption of water. Of course the losses of the water supplier would have to be covered by higher taxes and/or cuts in other public spending, or by charging a price for industrial and agricultural uses of water that exceeds long-run marginal social cost.

## Water Pricing for Agricultural, Industrial and Other Commercial Users

The only valid economic reason for subsidizing firms, farms and other business entities or the activities they engage in is the correction of inefficiencies: positive externalities, the mitigation of moral hazard and adverse selection. Distributional concerns apply only to natural persons or perhaps households. It is hard to think of positive externalities associated with the agricultural, industrial or other commercial uses of water. Neither are there any obvious informational asymmetries between the business users of water and the suppliers of water that would warrant a subsidy.

From an economic perspective, therefore, there is no case for charging agricultural, industrial and other commercial users of water anything less than long-run marginal social cost. Yet this is not what happens. For reasons that probably lie deep in our past as hunter-gatherers and farmers, the political influence and lobbying power of those who earn a living in agriculture, forestry, fishing and hunting is way in excess of their weight in the economically and/or politically active populations or of the share of these activities in GDP. According to World Bank data, the global share of agriculture in GDP fell from 8.1% in 1995 to 3.9% in 2014.[36] In China over the same period, agriculture's share in GDP fell from 19.7% to 9.2% and in India from 26.3 to 17, 4%. The numbers for the main country groupings by level of per capita income are shown in Figure 15 below.

[35] https://www.calwater.com/rates/rates-and-tariffs
[36] See http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS.

Figure 15. Share of Agricultural Value Added in GDP, %

| | 1995 | 2015 |
|---|---|---|
| Low income | 41.7 | 30.5 |
| Lower middle income | 24.5 | 16.3* |
| Middle income | 15.7 | 8.4 |
| Upper middle income | 13.2 | 7.1 |
| High income | NA | 1.5* |

*2014

Source: World Bank

In the U.S., the 2014 share of agricultural value added in GDP was 1.3% and in the United Kingdom 0.7%. Even lower numbers are found in Singapore (0.0%), Qatar (0.1%), Hong Kong (0.1%), Luxembourg (0.3%), Bahrain (0.3%), Trinidad and Tobago (0.4%), and Kuwait (0.4%). The largest agricultural sectors in 2014 were found in Sierra Leone (54.1%), Chad (52.6%) and the Central African Republic (47.8%),

Despite accounting for just under 4% of global GDP (in 2014), agriculture consumes about 70% of the world's accessible freshwater

Despite accounting for just under 4% of global GDP (in 2014), agriculture consumes about 70% of the world's accessible freshwater, as against 23% for industry and 8% for municipal use.[37] Municipal includes both households and non-industrial, non-agricultural private and public entities. Environmental water use is not included in these figures, because data for this category of use remain few and far between. For the U.S., the Department of Agriculture reports that "Agriculture is a major user of ground and surface water in the United States, accounting for approximately 80 percent of the Nation's consumptive water use".[38] In addition, agriculture is a major source of water pollution, especially in OECD countries.[39]. In many OECD countries, water charges for irrigating farmers don't even cover the cost of water delivery. In most countries farmers pay a price for water that is nowhere near the full (long-run marginal social) cost of water, which would include the costs of operations and maintenance (including delivery), and environmental externalities, let alone a price that includes a 'scarcity rent' – the opportunity cost of water withdrawals. In South Korea, for instance, farmers don't pay for irrigation water at all, despite the country being among the most water-stressed OECD countries.[40]

[37] See OECD, *Water use in agriculture*, http://www.oecd.org/agriculture/wateruseinagriculture.htm, and the references and links contained in it.

[38] The USDA provides the following clarifications of the different water use concepts: "Definitions: Withdrawal, Applied, and Consumptive Water-Use Estimates.
U.S. Geological Survey water use estimates generally refer to *withdrawals*, or the quantity of water withdrawn from a water source—e.g., a river, lake, or aquifer. USDA Farm & Ranch Irrigation Survey (FRIS) reports on farm *applied* water use, referring to producer estimates of the quantity of water applied to the field (for a particular crop) via an on-farm irrigation application system—e.g., a gravity-flow system or a low-pressure center-pivot sprinkler system. Annual crop consumptive-use estimates refer to the quantity of water actually *consumed* (taken up) by the crop plant over its various crop-growth stages for crop retention and evapotranspiration. Withdrawal estimates generally reflect diversion system conveyance losses, while estimates of field water applied do not. Consumptive-use estimates may or may not account for associated system efficiency losses (e.g., evaporation, deep percolation, and runoff) and salt-leaching requirements for a given crop, location, and irrigation system. Which estimate to use and how to use it are important in clarifying discussions of water use and policy."
https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use.aspx.

[39] Gruére, Guillaume (2016). *Agriculture and water: a major conundrum*, Constructif, March, http://www.constructif.fr.bibliotheque/2016-3/agriculture-et-eau-un-vrai-casses-tete.htlm?item_id=3518&vo=1.

[40] See World Resources Institute, Aqueduct, http://www.wri.org/applications/maps/aqueduct-country-river-basin-rankings/#x=-136.05&y=10.67&l=2&v=home&d=bws&f=0&o=139

Effective water management is highly unlikely without a proper pricing of all water resources used in agriculture. The same principles should also guide the pricing of water or water rights to industry. For this to be possible, two technical and institutional conditions have to be satisfied. First, the water authorities need reliable information on the impact of agricultural (industrial) activities on the quantity and quality of surface and groundwater resources. This is not easy, especially since the measurement of the availability of water and in some cases the amount of water that is currently being used in certain regions is not available. Second, clear property rights have to be attached to these surface and groundwater resources, to enable appropriate pricing of water withdrawals, water discharges and the provision of a sustainable ecosystem. Tradable property rights in groundwater and surface water, and/or in the right to withdraw or discharge given quantities of fresh water or waste water would help promote an efficient use of resources.

The question of who actually owns water resources or water rights has been at forefront of many discussions

The question of who actually owns water resources or water rights has been at forefront of many discussions - is it owned by the state, by a non-profit private entity, by a for-profit company, by an individual, or by a group of people? This discussion is surprisingly unsettled. Some jurisdictions (sometimes an international or central government jurisdiction, sometimes a state or province) recognize some form of private water property rights; however each jurisdiction determines the extent to which these private water rights are considered 'protected ownership interests'.[41] In the U.S. there are two regimes for property rights- riparian rights which are based on rights on land adjacent to water rather than water itself and prior appropriation doctrine which gives rights to individuals who have a right to the water regardless of land ownership. Selling and buying water rights is not an easy process which needs to be regulated (by institutions, by a well-regulated market etc.) to ensure fairness (and indeed respect for fundamental human rights) in times of scarcity. Private ownership of water is also rather different from private ownership of land given that water is constantly morphing from surface to groundwater and vice versa and the quantity of water that you potentially 'own' may be changing from day to day.

Finally, the political will has to be there to enforce these property rights by appropriate pricing (at long-run social marginal cost, including a scarcity rent) of water withdrawals and discharges. Where this results in unacceptable financial hardship for farmers and other affected parties, social policies, including budgetary/fiscal transfers are required. This of course requires that the authorities have enough information to identify the losing farmers, as well as the means of making payments to them without too much 'leakage' in the payment process. Pricing water appropriately is difficult politically and is technically a non-trivial market design problem, but it is not impossible. Israel and, more recently, Australia demonstrate that it can be done.

Setting the right price for water will encourage people to waste less, pollute less and invest more in infrastructure

Setting the right price for water will encourage people to waste less, pollute less and invest more in infrastructure. Tariffs for water and wastewater services for households vary significantly in different countries reflecting contrasted efforts to recover the costs of providing the service through prices – for example the price of water in Denmark is estimated at $.6.70 per m$^3$, while in Mexico it costs $0.49 per m$^3$. As noted, the price of water should reflect the cost of the supplying that resource plus any environmental or other externalities that occur from the use of that resource - such as pollution, reduction in water use for aquatic systems etc. In a sustainable water use universe, the cost of 'recycling' the used water and ensuring that at some point in the future it is available again for use must be taken into account. However, the discounted value of the recycled water that will be available again in the future should be deducted from its current price. A joint-

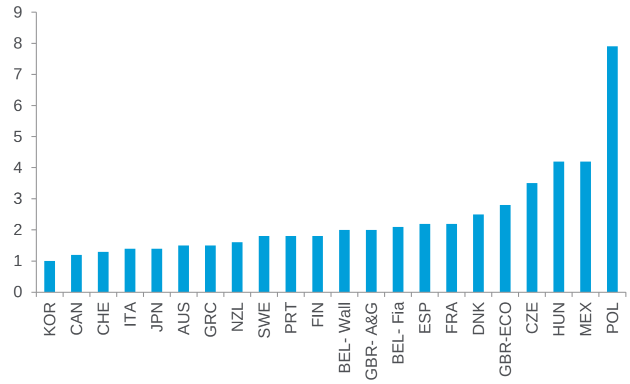
[41] Shelley Ross Saxer, *The Fluid Nature of property rights in water*.

production approach (current use of water by households produces not only immediate 'consumption utility' but also waste water that can be processed and recycled (at a cost) to be used at some future date) is the natural way to approach sustainable water use.

Figure 16. Unit Price of Water Supply and Sanitation Service to Households (USD$/m3)


Source: OECD, Citi Research

Figure 17. Water Supply and Sanitation Bills as a Share of Disposable Income: Average Income of the Lowest Decile of the Population (%)




Source: OECD, Citi Research

The marginal value of water for different uses also varies greatly because the prices paid by industry, agriculture and residential users are often unrelated. For example, in Arizona water prices vary from $27 per acre-foot for agriculture to $3,200 per acre-foot for urban users. Some of this pricing gap can be attributed to the difference in the nature and quality of water delivered to urban users versus farmers, however most of it is a function of institutions that do not allocate water on the basis of transparent economic criteria.[42]

The development of well-established markets for water can result in more efficient allocation of water

The development of well-established markets for water can in theory result in more efficient allocation of water between different users and effectively price water to encourage less wastage and move the use of water to the highest valued uses.[43] An example of such a scheme is the tradable permit system in the Murray-Basin in Australia described in more detail in the solutions section of the report. Even though such schemes have been successful in many regions they have been slow to develop. This is due to high transaction costs such as the physical infrastructure necessary for transporting water from buyers to sellers in the region, search and legal costs of enforcing contracts, and so on.[44]

There are many available solutions to the effective management of water – one just has to look at the two case studies at the end of the report as proof of how water can be effectively managed in water-scarce countries. What is definitely clear is that demand for water is expected to increase over the years, increasing the competition for this resource amongst food and energy producers, domestic use and the environment. If we continue with business as usual, global economic waste and losses will increase, leading to mounting tensions in many countries and between countries, and a reduction in the living standards of many people.

[42] World Bank Group. (2016). *High and Dry, Climate Change, Water and the Economy*.
[43] Rosegrant, Mark and Hans P. Binswanger (1994). *Markets in Tradable Water Rights: Potential for Efficiency Gains in Developing County Water Resource Allocation,* World Development, Vol. 22, No. 11, pp1613-1625.
[44] Shelley Ross Saxer, *The Fluid Nature of property rights in water*.

## Water as an Asset Class

Water is scarce, valuable and durable. It is therefore an asset. Why don't we observe more markets for water instruments, trading a variety of water rights, including water for future delivery, puts and calls on these instruments and other derivatives?

One reason for the scarcity of water rights markets is the fragmentation of water markets. Water delivery systems are regional, often local; the local and regional networks are often not physically connected. So there are no integrated national water markets let alone global water markets.

Water delivery systems are fragmented; therefore, there are no integrated national water markets

That will change. The spot market for natural gas used to be Balkanized, because of a lack of pipelines and limited liquefied natural gas (LNG) handling and shipping capacity. Increasingly, the national and regional gas markets are now physically connected, using pipelines and LNG tankers and (de)gasification and storage facilities. The gas market is beginning to look more like the oil market. While not perfectly integrated (the prices for Brent, WTI and Urals crude oil can diverge quite significantly at time), there is enough size and transaction volume to support oil futures markets and a range of oil derivatives.

We expect that, in 25 to 30 years, the physical (spot) market for fresh water will be as integrated as the oil market is today. If oil and gas were to become trapped assets, because of environmental concerns and/or major cost declines for renewable energy sources, redundant oil and gas pipelines, storage facilities and tankers could be converted to transport water instead.

Could water remain too cheap to warrant significant investment in the water sector? Only if we continue to price it below long-run marginal social cost. Properly priced, there will be massive investment in the water sector, including the production of water from currently marginal sources (desalination), purification, storage, shipping (with single-hulled water tankers) pipelines and canals. China is connecting the Yangtze River in the water-abundant south to the Yellow River in the arid, water-starved northeast using canals. Regardless of whether this Chinese mega project is the optimal way (allowing for all relevant environmental and social externalities) to bring water to people and economic activity, it points to the massive imbalances in regional water supply and demand – imbalances that will have to be addressed urgently.

Imbalances between regional water supply and demand need to be addressed urgently

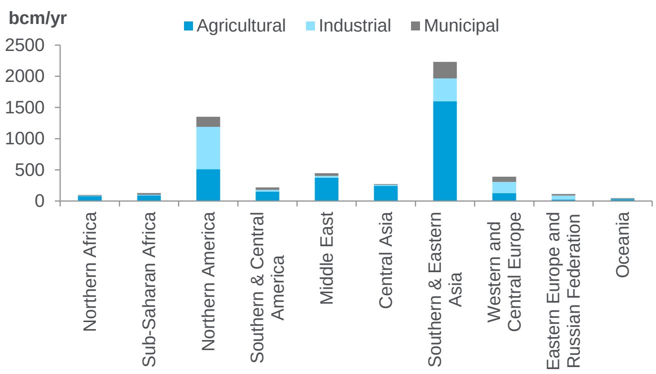
Once the spot markets are reasonably integrated (not necessarily immediately on a global level) trading in a wide range of water rights and derivative instruments will start. We expect that for supervisory and regulatory reasons, organized exchanges are more likely to be set up than over-the-counter (OTC) trading arrangements. There will be different grades and types of water just as there are light sweet and heavy sour crude oil today. Different uses for water require different a different quality or degree of purity of water. With water becoming an asset class, the words 'water bubble' are likely to take on a new meaning.

# Sector Analysis

# Agriculture - Will Feeding the Hungry Leave the World Thirsty?

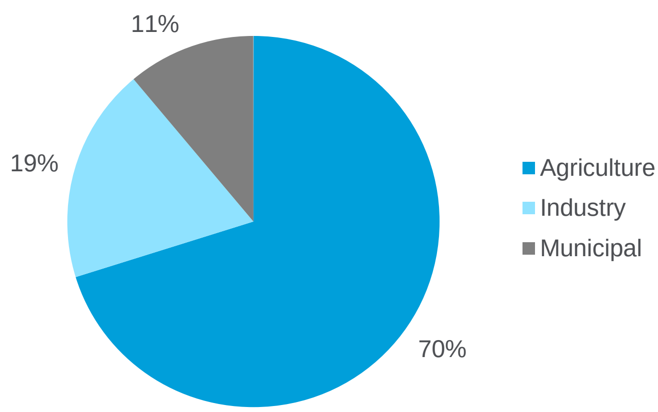
With agriculture accounting for ~70% of global freshwater withdrawals, water scarcity issues are often closely tied to agricultural activity.[45] At the same time, water scarcity is of primary concern to the agriculture industry, which will require significant growth in the coming decades to satisfy the dietary requirements of a growing global population. This problem is made more acute by shifting consumption patterns in developing countries that have accompanied unprecedented income growth — as the wealth of a nation increases, food consumption per capita increases. At the same time, diets shift away from grains and cereals and towards meat and dairy products, substantially increasing the water intensity of each calorie consumed. The growing biofuel industry, often promoted by these very governments, may further add to the demands on agricultural production in coming years, although there are some signs that the rapid growth rate the industry observed over the past 15 years is moderating.

Figure 18. Regional Water Withdrawals by End-Use Sector (2003)




Source: FAO 2011, Citi Research

Figure 19. Global Water Withdrawal by End-Use Sector (%) (2003)




Source: FAO 2011, Citi Research

Agriculture must meet the dietary demands of an ever growing global population, requiring an increasing share of the world's fixed water resources. According to the UN, the global population is expected to reach 9.7 billion by 2050, a 32% expansion versus 2015. At the same time, global demand for food is projected to increase 60% by 2050.[46] This growth in consumption will necessitate a massive expansion in agricultural production, requiring an increasing share of the world's fixed freshwater resources. Meanwhile, growing populations sharpen the competition for freshwater between agricultural, industrial and municipal uses.

Besides population growth, two important trends will drive growth in water demand from agriculture in the coming decades: (1) economic growth in developing nations and; (2) ongoing (albeit slowing) growth of the biofuel industry.

[45] FAO. (2011). *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk*. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.

[46] UNESCO. (2015). *Water for a Sustainable World.*

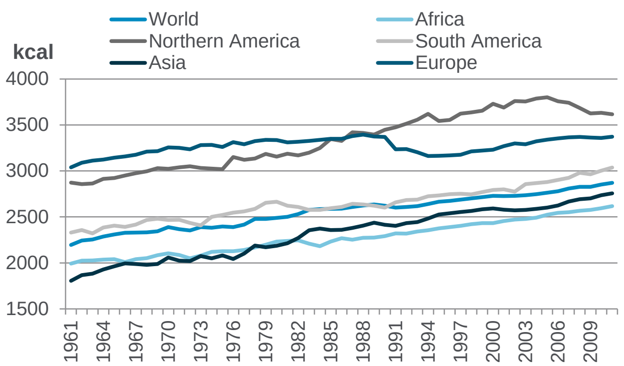
## Shifting Consumption Patterns as Developing Nations Get Richer

Not only is the global population growing, but it is also becoming richer. Economic expansion is closely associated with two major trends in food consumption: (1) an increase in calories consumed per capita; and (2) a shift in dietary preferences towards greater meat, dairy, and protein consumption. Both of these changes will increase the water requirements for agricultural production in the coming years.

The global per capita calorific consumption increased by 6% while meat consumption grew by 16% from 2000 to 2013

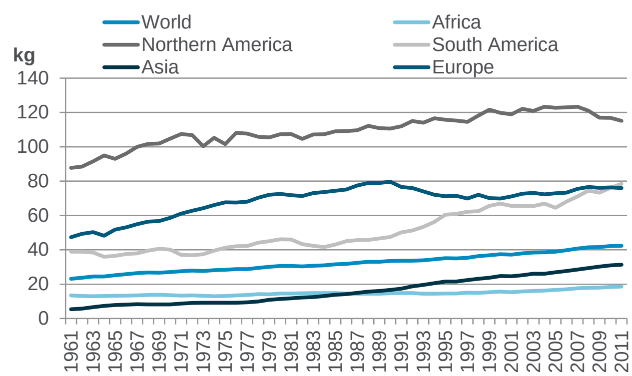
Even though both total calorific intake and meat consumption in more developed regions, like Europe and North America, have slowed or even declined in recent decades, rapid growth continues in Emerging Asia, Africa and South America, offsetting declines elsewhere. Indeed, from 2000 to 2013, the global per capita daily calorific consumption increased by 6%, while meat consumption grew by 16%, driven by high growth in the developing world.

Figure 20. Regional Daily Calorific Consumption per Capita (1961-2013)




Source: FAO Stat, Citi Research

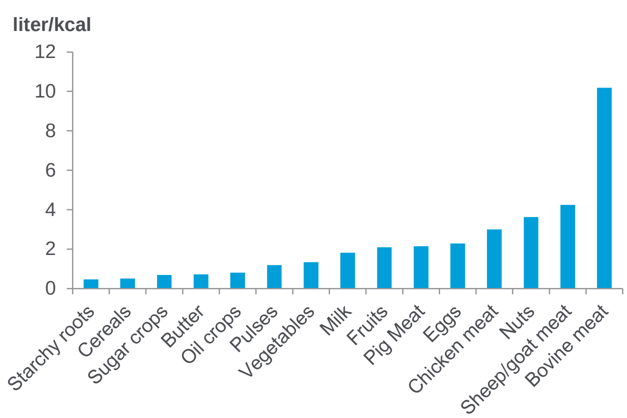
Figure 21. Regional Annual Meat Consumption per Capita (1961-2013)




Source: FAO Stat, Citi Research

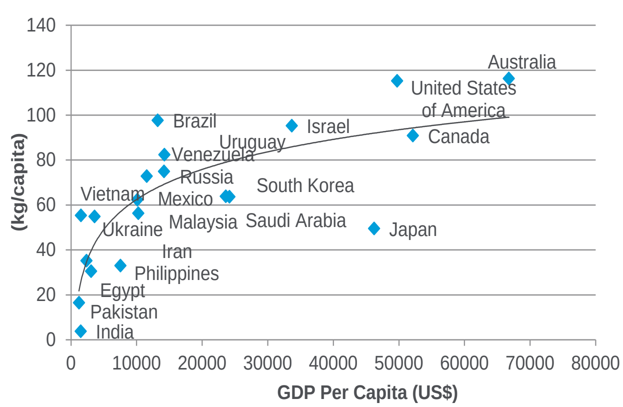
This trend will likely continue as developing economies continue to expand. The logarithmic relationship observed between GDP per capita and meat consumption per capita indicates that meat consumption increases rapidly as very poor countries become wealthier, with diminishing increases as wealth grows. But with GDP per capita in many of the poorest nations set to grow substantially, consumption growth in emerging markets should continue to offset slower growth, or even declines, elsewhere.

Figure 22. Water Intensity of Various Food Stuffs




Source: Water Footprint Network, Citi Research

Figure 23. Meat Consumption per Capita vs GDP per Capita (2013)




Source: IMF, FAO, Citi Research

Shifting diets towards greater meat consumption increases the water intensity of each calorie consumed

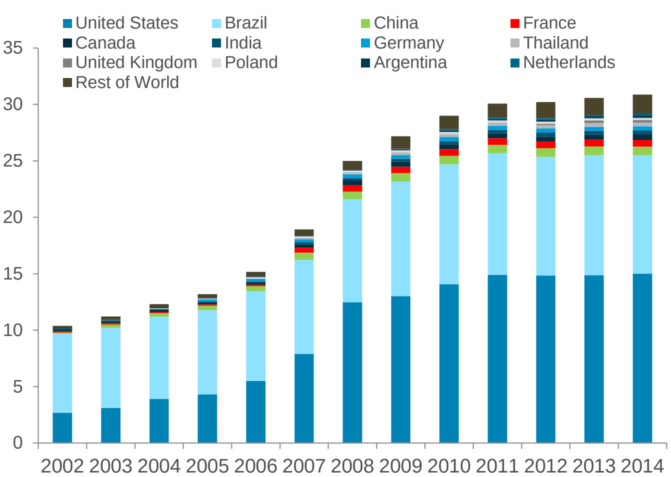
Increased food consumption per capita drives overall demand for agricultural production, which in turn drives agricultural demand for water. On the other hand, shifting diets towards greater meat consumption increases the water intensity of each calorie consumed. Raising livestock requires several multiples of freshwater vis-à-vis grains and other crops to produce the same calories because cattle and livestock require large quantities of feed, but are relatively inefficient in converting that feed to consumable calories (i.e. meat bought in the store). This significantly increases the water intensity of meat – one calorie from beef requires 20 times more water to produce than the same calorie derived from cereals.

China is perhaps the best example of the effect of rising incomes on food consumption: over the past four decades, Chinese daily consumption of calories per capita has grown 70% to over 3,100 – outpacing the growth of all its regional neighbors. While the overall pace of food demand growth there is starting to slow, Chinese meat consumption still lags its OECD counterparts (i.e. U.S., U.K.) and suggests ongoing medium-term growth of feed grain and meat demand. Meanwhile, as other developing countries progress along the same path as China, agricultural production will remain under pressure to scale higher.

## The Rise of Biofuels

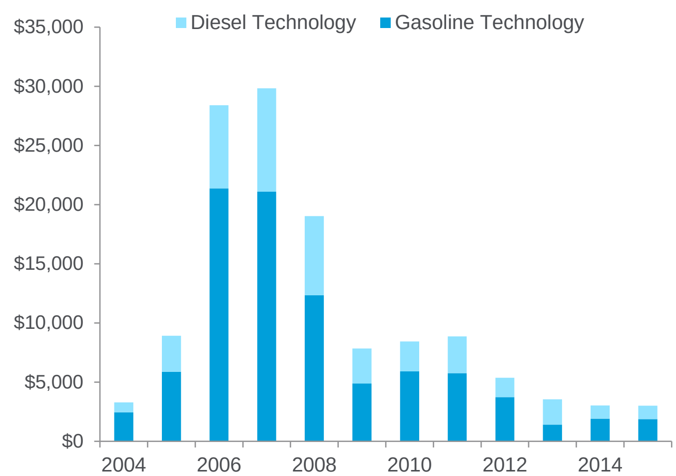
Production of ethanol, biodiesel, and other renewable fuels is a major source of water-intensive agriculture. On the low end, conventional biofuels require at least 2.5-3.5 gallons of water per gallon of processed ethanol. By comparison, refining conventional gasoline takes 1.0-1.5 gallons of water per gallon of fuel.[47] More than 95% of world biofuel output utilizes corn, sugar and soybean feedstock. More water-efficient biofuel feedstock, such as rapeseed and sorghum, are limited in availability to serve as a replacement for the main cash crops as they are less diverse and dynamic crops and do not have alternative applications as foodstuffs, animal feed or for industrial and confectionary processing.

Figure 24. Global Conventional Ethanol Production Capacity (bn-gal per annum)




Source: BNEF, EIA, RFA, Citi Research

Figure 25. Global Investment in Biofuels by Fuel Type (millions USD)




Source: BNEF, Citi Research

47 National Research Council. (2008). *Water Implications of Biofuels Production in the United States*. The National Academies Press, Washington D.C.

There are signs that the impact of biofuels on water resources will begin to stabilize as government policies shift towards cellulosic ethanol feedstock

While biofuels are a mainstay of the world transportation fuel system, there are signs that its impact on water use could begin to stabilize as conventional capacity build-out slows, and government policies shift towards non-foodstuff (cellulosic) ethanol feedstock. The growth of renewable fuels and ethanol production has largely been a 21st century phenomenon; global nameplate capacity more than tripled since the early 2000s to around 31 billion gallons per year. The majority of working capacity is located in the U.S. and Brazil which use corn and sugar as feedstock, respectively. The U.S., Europe, and Argentina also produce biodiesel using soybeans or rapeseed. But capacity build-out has held flat since 2011 as global investment in renewable gasoline and diesel technology has plunged from a pre-Great Financial Crisis peak of $30 billion to less than $10 billion in 2011 to below $5 billion each year since 2013. In the United States, the world's leading producer of biofuels, the industry is maturing as domestic production capacity which grew 400% since pre-2005 to over 15 billion gallons per year in 2015, is expected to grow by 5-7% on aggregate through 2020.

Biofuel use is underpinned by government mandates and requires ongoing policy support to expand use to next generation fuels. On net, the growth rate of conventional biofuel use is slowing on a global scale, particularly across the OECD (U.S., Europe), although Brazil and Southeast Asia remain strong consumers with potential for growth. On the policy front, the U.S. already blends over 14 billion gallons of ethanol each year into its gasoline pool but is likely to cap out at 15 billion gallons with a shift to cellulosic. In Europe, Brussels finally reformed its Renewable Energy Directive to cap crop-based biofuels at 7% with its 10% blending target for 2020. Brazil has more recently raised its blending standards (but more as a function of the fiscal regime) and Indian and Chinese policies look promising for biofuels but not to the same scale as the growth seen in the U.S. in the past 10-15 years. Growth in Asian biofuels may also shift towards non-foodstuff feedstock as well, given limited arable land and lack of freshwater there vis-à-vis the U.S. and Brazil, which have large but still generally limited exportable surpluses. Bottom line, with biofuel processing getting more efficient and policy mandates becoming less aggressive about using crop-based transportation fuel, the water-intensity of the industry could begin to ease.

Cellulosic feedstock such as wood pellets or algae require less freshwater to develop when compared to conventional biofuels

Cellulosic ethanol — or non-crop-based feedstock — seems to be the broader goal of policy makers both in the OECD and Emerging Markets, with normal crop-based conventional biofuel production mostly built-out and integrated into transportation fuel systems. Newer cellulosic ethanol plants are less water-intensive than traditional plants (using 2-6 gallons of water per gallon of fuel vs. 9.5 gallons previously) and cellulosic feedstock (i.e. wood pellets, algae) often require less water to grow or in the case of algae do not require freshwater to develop.[48]

Biofuels are very water-intensive but the rapid growth rate of the past decade might be moderating. The industry still places a burden on water supply, but should adoption of next-gen biofuels increase, amid a flattening of crop-based processing, this water-intensive industry might have seen its most inefficient days behind it.

[48] MIT. *The Water-Sustainable Management of Biofuels*. http://12.000.scripts.mit.edu/mission2017/biofuels-overview/

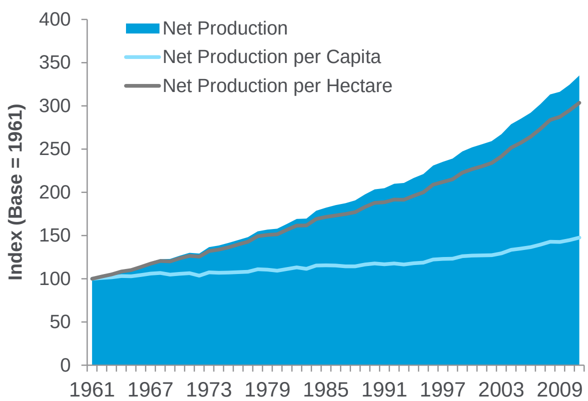
## Agriculture Use (and Abuse) of Water Resources

Achieving agriculture growth of the scale that is needed to feed the world will necessitate a drastic change in the management of water resources

Compounding water scarcity issues, there are increasingly limited resources that can be called on to achieve the size of output growth required of the agriculture industry. Untapped fertile land is limited in many parts of the world, meaning that farmers will need to increase yields significantly on already-cultivated land in order to grow production. Though yields have scope to increase in some parts of the world, without proper management and implementation of environmentally sustainable practices, increased farm productivity may continue to come at the cost of environmental and water resource degradation. To be certain, increased fertilizer/pesticide use, more extensive irrigation and other water-intensive practices were main drivers of the rapid productivity gains achieved in the agricultural industry post-WWII. But as water resource constraints become increasingly binding, meeting growing demands will require a drastic rethinking of water management in agriculture to ensure sustainable growth.

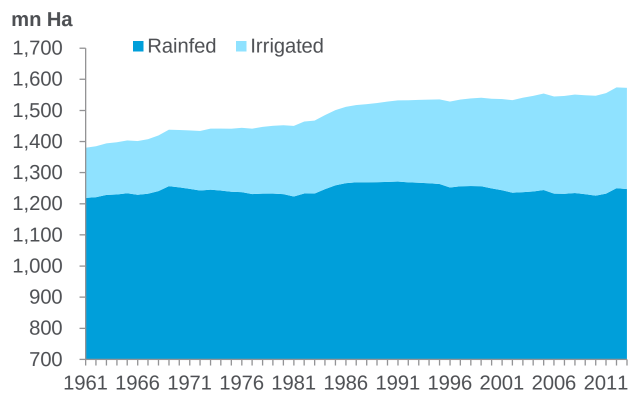
Food production has grown more than three-fold since the early 1960s, growth that was primarily achieved through crop intensification and yield improvements. During the same period, net cultivated land expanded by only 12%, while intensity and productivity grew dramatically. The growth of irrigated agriculture was an important driver of these gains – growth in land equipped for irrigation more than doubled since the mid-1900s, accounting for the entire net increase in cultivated area. The growth of irrigation not only allowed for greater water control and intensified production in arid and semi-arid regions, but also made possible the practice of double cropping and supported the rise of high-yielding fertilizer-responsive crop varieties. Indeed, irrigated systems typically have yields roughly twice those of non-irrigated systems under similar conditions.[45]

Figure 26. FAO Global Agricultural Production Index (1961 = 100)




Source: FAO Stat, Citi Research

Figure 27. Land Under Irrigated and Rainfed Cropping (Historical)




Source: FAO Stat, Citi Research

Rainfed agriculture accounts for approximately 60% of global agriculture production

Though irrigated agriculture has expanded rapidly, rainfed agriculture is still the predominant production system worldwide. Rainfed agricultural accounts for ~80% of cultivated land, though it is responsible for only ~60% of global agricultural production due to the higher productivity of irrigated crops.[45] Rainfed agricultural is particularly important in less developed parts of the world, accounting for as much as ~97% of cultivated land in sub-Saharan Africa.[45]

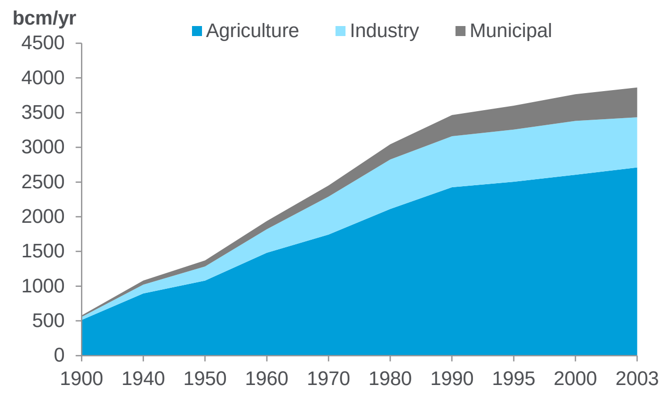
## Depletion of Freshwater Resources through Irrigation

Abstraction of freshwater from surface and groundwater, including streams, lakes, rivers, aquifers, and reservoirs for irrigation can put significant stress on a regions' water supply if withdrawals exceed replenishment rates. In some parts of the world, freshwater resources are being abstracted at rates that far exceed natural replenishment rates, leading to falling aquifer levels and a drying up of lakes and rivers. River basins and aquifers supplying large areas of irrigated cropland are often the most heavily depleted.

Total groundwater and surface water withdrawals for irrigation have nearly doubled since the mid-1950s

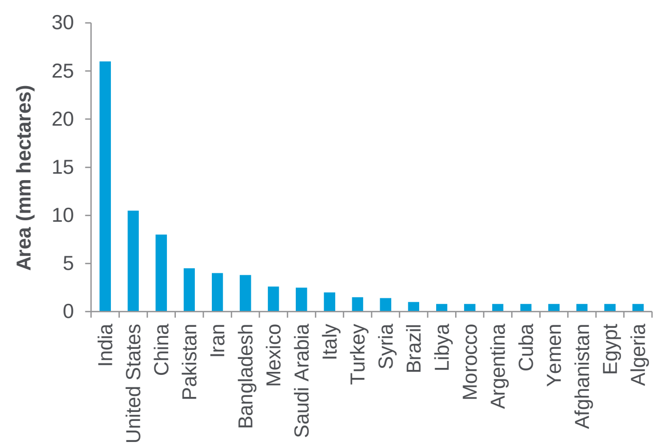
Indeed, freshwater withdrawals have risen rapidly alongside the expansion of irrigated agriculture. Total ground and surface water withdrawals for irrigation have nearly doubled since the mid-1950s, with agriculture accounting for ~70% of freshwater withdrawals today. Roughly 38% of agriculture withdrawals originate from groundwater, with the remaining 62% originating from surface water. And, unlike water withdrawals for other uses, much of the water withdrawn for agriculture is consumptive – the water withdrawn is not returned to its source but rather considered to be lost via evapotranspiration, the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

Figure 28. Freshwater Water Withdrawals by End-Use Sector




Source: FAO 2011, Shiklomanov 2000, Citi Research

Figure 29. Top 20 Groundwater Irrigating Countries




Source: Shah 2006

The quantity of groundwater withdrawn has grown nearly ten-fold since the 1950s

The expansion of groundwater irrigation has been particularly aggressive, with the quantity of groundwater withdrawn annually growing nearly ten-fold since the 1950s, largely due to increased agricultural use.[49] The rise of groundwater irrigation has been driven by rapid growth in Asia, the United States and the Middle East – together, India, the United States, China, Pakistan, Iran and Bangladesh account for well over 80% of global groundwater abstraction.[49] Groundwater is typically abstracted at the highest rates in areas with limited rainfall, and hence slower recharge. Indeed, some areas, like the Arab peninsula, are dependent on non-renewable or fossil groundwater resources, which have negligible recharge rates on a human time-scale.

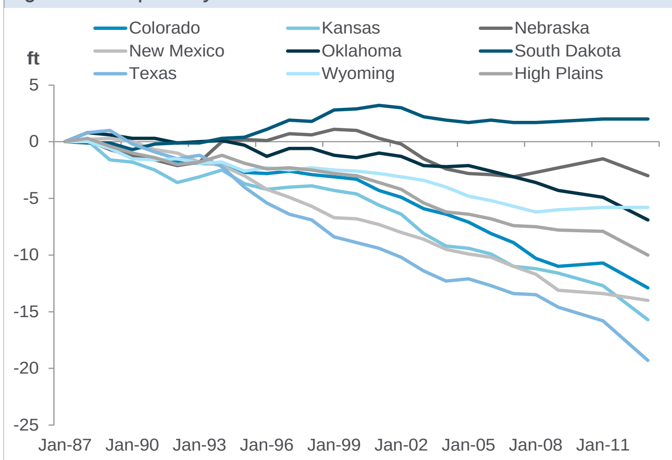
[49] Shah et al. (2006). *Groundwater: A global assessment of scale and significance*. FAO.

**Dwindling Resources - The Ogallala and Central Valley Aquifers**

The Ogallala Aquifer (located in the High Plains region of the U.S. spanning parts of Kansas, Colorado, New Mexico, Texas, and Oklahoma) and the Central Valley Aquifer (in California) together supply groundwater resources for ~42% of irrigated land in the United States.[50] [51] Agricultural production in these regions has grown exponentially since the 1950s when the practice of groundwater irrigation became widespread and permitted unprecedented crop growth in semi-arid regions previously limited by insufficient or unreliable rainfall. Sometimes termed the "grain basket" and "vegetable basket" of the United States, respectively, production in the High Plains and Central Valley region together accounted for ~20% of the market value of agricultural production in the U.S. in 2007.[52]

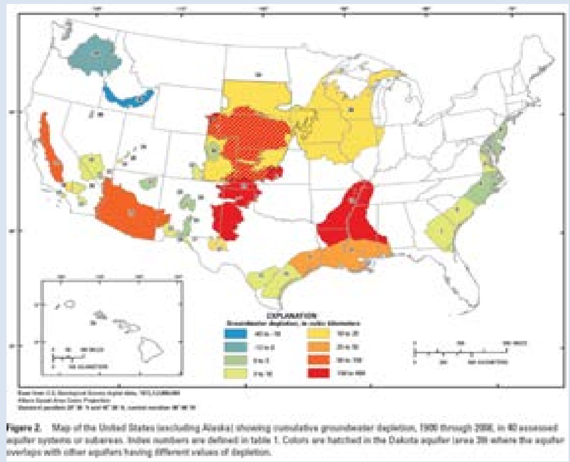
But the rapid growth in irrigated farming in these regions has led to the overexploitation of these aquifers and significant depletion of their water levels. Together, these two aquifers account for ~50% of all groundwater storage declines in the U.S. since 1900.[52] Indeed, according to some estimates, extrapolating the current depletion rate in the Ogallala Aquifer suggests that 35% of the southern High Plains will be unable to support irrigated agriculture within the next thirty years.[52] Meanwhile, though the Central Valley Aquifer is estimated to see ~7 times higher recharge than the Ogallala,[52] a recent satellite study found the Central Valley Aquifer to be "highly stressed" due to high depletion rates[53].

Figure 30. Cumulative Area-Weighted Average Water-Level Change in High Plains Aquifer by State Since 1987




Source: USGS, Citi Research

Figure 31. Map of the United States Showing Cumulative Groundwater Depletion, 1900 Through 2008 in Assessed Aquifer Systems/Subareas



Source: USGS

Globally, aquifer depletion is increasingly becoming a critical issue, particularly in North Africa, the Middle East, and Asia but also in parts of the U.S., especially the Ogallala and Central Valley aquifers. From 2003 to 2013, a study used satellite imaging to look at groundwater depletion at 37 of the world's largest aquifers. Eight of the studied aquifers were considered overstressed, with negligible natural replenishment to offset withdrawals, while five aquifers were considered highly or severely stressed with high withdrawal rates relative to natural replenishment.[52] In another study, estimates of global groundwater sustainability suggest that the size of the world's groundwater footprint is already ~3.5 times the actual area of active groundwater resources, with ~20% of the world's aquifers being heavily overexploited.[54]

[50] Faunt, C.C., ed., (2009). *Groundwater Availability of the Central Valley Aquifer*, California: U.S. Geological Survey Professional Paper 1766, p. 225.

[51] Gollehon, Noel and Winston, Bernadette. (2013). *Groundwater Irrigation and Water Withdrawals: The Ogallala Aquifer Initiative.* USDA Natural Resources Conservation Service.

[52] Scanlon, et al. (2012). *Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley*. USGS Staff -- Published Research. Paper 497.

[53] Richey et al. (2015). *Quantifying renewable groundwater stress with GRACE*. Water Resources Research.

[54] Gleeson, et al. (2012). *Water balance of global aquifers revealed by groundwater footprint*. Nature 488: 197-200.

~24% of the world's river basins are under severe water stress

Surface water resources are also severely at risk, both due to excessive withdrawals and the depletion of groundwater resources which can reduce surface water flows. Some estimates suggest that ~24% of the world's river basin area is under severe water stress.[55] In Mexico, Lake Chapala lost 80% of its volume between 1979 and 2001 due to agricultural withdrawals while in China and India some rivers in highly populated areas have been severely depleted due to heavy irrigation and municipal/industrial use.[45] Some rivers no longer discharge to the sea year-round due to excessive withdrawals for irrigation (see box below).

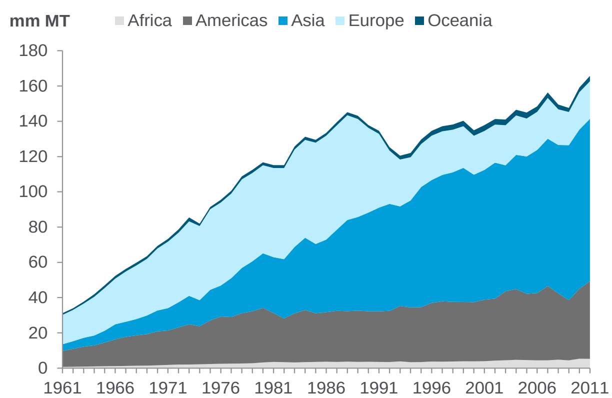
**Dwindling Resources – The Yellow River**

The Yellow River in China is the second largest river in the country by length and basin area, flowing through nine provinces and emptying into the Bohai Sea. Since the 1950s, irrigation of the land around the river has risen dramatically, with an estimated ~91% of all surface water abstracted from the Yellow River used for irrigation purposes.[56] Since the rise of irrigated agriculture in China, the river has experienced a significant decline in downstream flows, leading to severe depletion of the water level in the lower river such that it no longer discharges to the sea year round. Irrigation has also caused a degradation of the water quality in the river, with major ions and salinity increasing in concentration. Despite the implementation of water allocation quotas, overexploitation continues by the provinces in upper basins as regulators possess insufficient resources for monitoring water use and imposing restrictions.[57]

## Agricultural Run-Off Degrades Freshwater Supplies

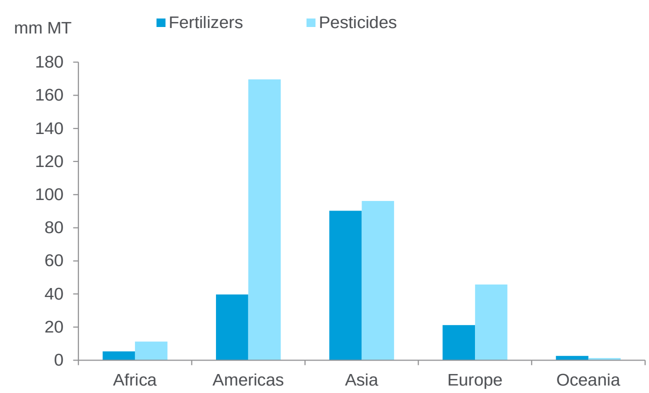
Modern agricultural practices, including fertilizer and pesticide use, can contaminate freshwater sources, a problem that affects both rainfed and irrigated crops. Yet fertilizers/chemicals are also essential for increasing crop yields – somewhat of a catch-22 for water-resource management. To be sure, the use of pesticides and fertilizers in agriculture has grown immensely since WWII, when nitrogen-based fertilizers first rose in prevalence. The use of fertilizers was a critical development that supported the growth of agricultural production during this period. Today, nearly all the farmland in the Northern Hemisphere, including in China, uses fertilizers, with the largest shortfall in the Southern Hemisphere.

Figure 32. Historical Fertilizer Use by Region




Source: FAO Stat, Citi Research

Figure 33. Fertilizer and Pesticide Use by Region (2010)




Source: FAO Stat, Citi Research

[55] Alcamo et al. (2003). *Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions*. Hydrological Science, 48: 339-348.
[56] IBID
[57] Chen, J.,D. He, and S. Cui. (2003). *The response of river water quality and quantity to the development of irrigated agriculture in the last 4 decades in the Yellow River Basin, China*, Water Resources. Res.,39, 1047.

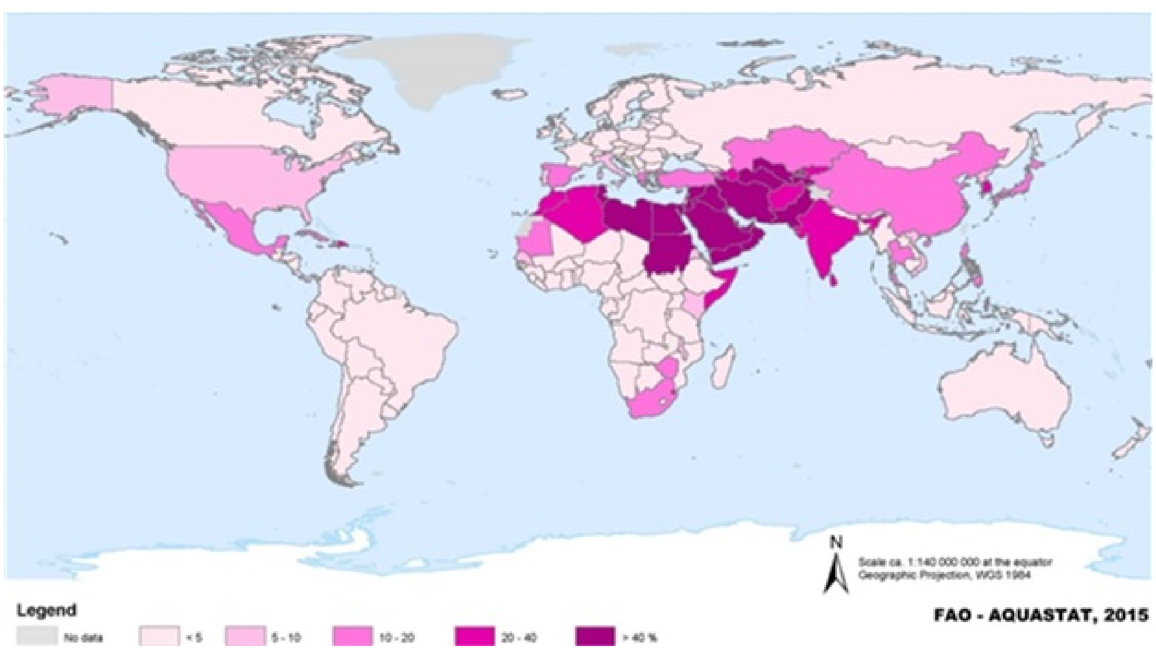
Nearly 30% of streams and over 80% of shallow groundwater near farmland in the U.S. had samples that exceeded nitrates levels for drinking water

Besides the ecological damage caused by the accumulation of nitrates and pesticides in aquatic ecosystems, contamination of freshwater effectively reduces the quantity of water available for human consumption. For example, according to the U.S. Geological Survey (USGS), nearly 30% of streams and over 80% of shallow groundwater sampled near farmland in the U.S. had one or more samples that exceeded the maximum contaminant level of nitrates for drinking water.[58] Besides the U.S., contamination through agricultural run-off is a serious concern in many parts of the world, with high levels of fertilizer use including Asia, Europe and some parts of Latin America.[45]

## Water Scarcity and Agriculture: A Local Problem with Global Repercussions

Globally, there are sufficient water resources to satisfy all human water needs in the coming decades, but these resources are unevenly distributed and divergence is growing between regions experiencing high population growth and regions possessing abundant freshwater resources. Indeed, in some low rainfall regions with growing populations, like North Africa, the Middle East and Central Asia, most available freshwater resources have already been abstracted, with irrigation withdrawals accounting for some 80-90% of this depletion.[45] Meanwhile, in other regions, water withdrawals for agriculture make up only a small fraction of the renewable water resources. But trade in agricultural goods permits the 'virtual trade' of land and water, allowing water-scarce nations to "import" water (i.e. foodstuffs) from water-abundant nations. Though global trade is a critical means of adjusting for regional disparities in water endowments, it also transmits regional scarcity issues into the world market, potentially impacting wholesale commodity prices and food inflation. As water resources become more constrained, the impacts of water scarcity are unlikely to stay localized.

Figure 34. Proportion of Renewable Water Resources Withdrawn for Agriculture Use (by Country)



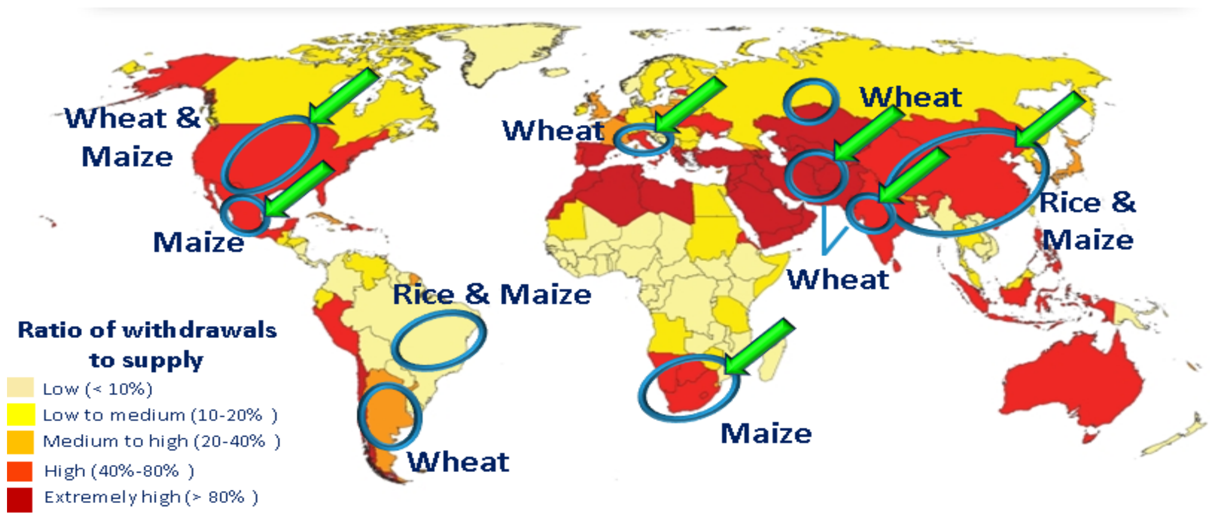

Source: FAO Aquastat

[58] Dubrovsky, N.M., and Hamilton, P.A. (2010). Nutrients in the Nation's streams and groundwater: National Findings and Implications: U.S. Geological Survey Fact Sheet 2010-3078, p. 6.

In the Middle East and Central Asia the ratio of agricultural water withdrawals to renewable resources is 47 and 57% respectively. This increases to 170% in North Africa

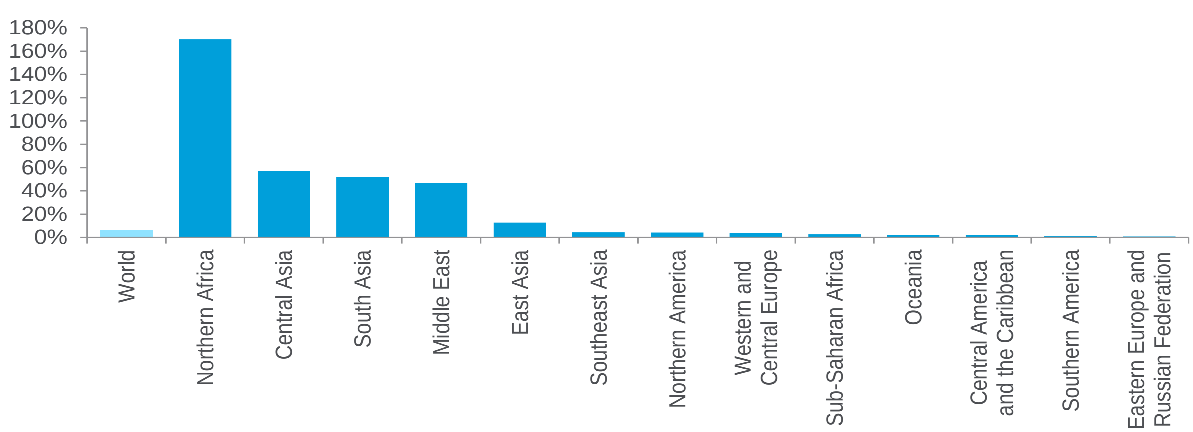
Total water withdrawals for irrigation represents less than 10% of the world's renewable water resources. But this seemingly sustainable number masks large geographical discrepancies in water scarcity – in some regions this ratio is as high as 170%. Water resources in regions such as the Middle East, Central Asia and North Africa are severely stressed due to sever overexploitation of water for agricultural use (see Figure 34). There is also considerable variation in water scarcity within countries where there is growing concern in certain localities, though at the national level, the pressure on renewable water resources from agriculture is relatively low. On the other hand, some regions use only marginal proportions of their renewable water resources for agriculture, either due to a great abundance of water resources (like in South America) or due to minimal agricultural industrialization (like in Sub-Saharan Africa).

Figure 35. Water Stress by Country and Key Crops :2040




Source: World Resources Institute, Citi Research

Figure 36. Pressure on Water Resources Due to Irrigation (Irrigation Withdrawals as % of Annual Long-Term Average Renewable Water Resources)




Source: FAO 2011, Citi Research

India and China account for ~40% of the world's area equipped for irrigation

Exacerbating these regional scarcity issues is the growing mismatch between areas possessing abundant water resources and areas experiencing rapid population expansion and industrialization. Over the last several decades irrigated agriculture has expanded rapidly in East and Southern Asia as populations exploded and economies prospered, with India and China alone accounting for ~40% of the world's area equipped for irrigation today.[45] These areas are now experiencing some of the most severe water shortages due to relatively limited renewable water resources to support this growth, which has led to overexploitation of aquifers and rivers (see Box 2). Going forward, some of the areas expected to see the strongest population growth are also those with the most constrained water resources – Northern Africa is expected to expand 58% by 2050 while Western Asia (Middle East) is expected to grow 54% as compared to the global population growth of 32% over the same period.[59]

## Yet Water Scarcity is a Global Issue…

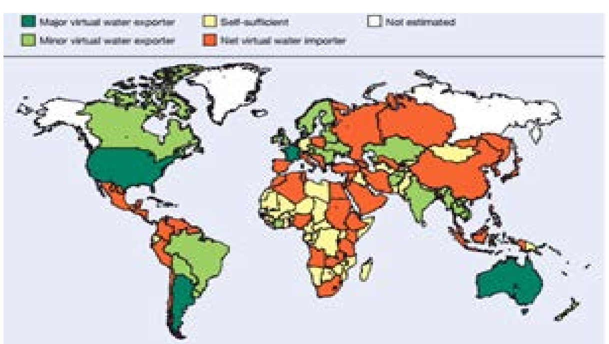
Most of the world possesses sufficient water resources to supply agricultural, municipal, and industrial use into the coming decades. But water scarcity issues in specific localities will only become more intense and local water scarcity issues will have tangible global impacts in a world deeply interconnected by trade.

Global trade of agricultural goods allows for the virtual trade of land and water resources. The virtual water trade refers to the implied water use that would have been required to produce locally those agricultural goods that are imported from other countries. For example, Egypt, a water-scarce nation, imported ~8-mn tonnes of corn and ~11.5-mn tonnes of wheat in 2014/15, which would have required ~16,300 mmcm of water to produce locally, effectively "importing" those water resources. The size of the global water trade through agricultural goods is significant – in 2014/15, total global corn and wheat exports alone were 328 mm tonnes accounting for enormous amounts of virtual water.

The virtual trade of water is an important means of meeting global future food demand

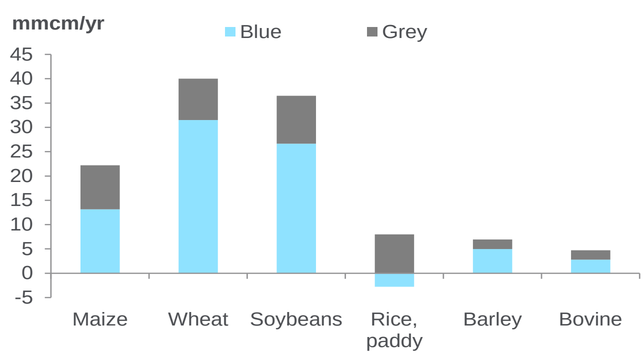
The virtual trade of water resources is a critical means of relieving the burden on water-scarce nations and will be an important means of meeting global demands for food in the future (see section below). Virtual trade in water can significantly reduce the stress imposed by agriculture on local freshwater supplies in water scarce nations. Indeed, estimates of the global savings in blue (surface and groundwater withdrawals) and grey (water pollution) water use suggest that global trade may result in ~136-mmcm of global water savings each year as efficient producers sell to inefficient importers.[60]

Figure 37. Virtual Water Trade in Agriculture Goods Trade



Source: Molden 2007

Figure 38. Global Water Savings (Blue & Grey) Related to Trade in Agriculture Products, by Product (1996-2005)




Source: Hoekstra 2012

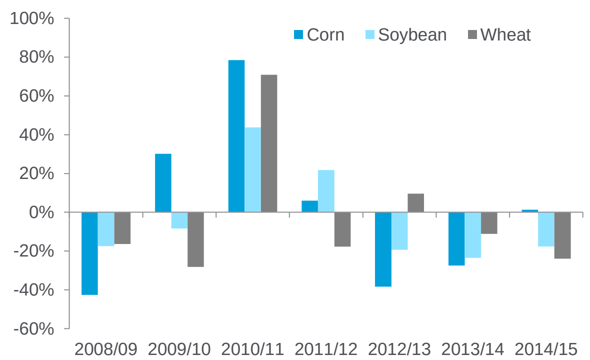
[59] United Nations. (2015). *2015 Revision of World Populations Prospects*. http://esa.un.org/unpd/wpp/.

[60] Hoekstra, A.Y. and Mekonnen, M.M. (2012). 'The water footprint of humanity', Proceedings of the National Academy of Sciences, 109(9): 3232–3237.

Estimates of supply/demand dynamics in global agriculture markets to 2050 project that most international commodity prices could rise between 20-50%

However, the virtual water trade also acts as a mechanism for transmitting regional scarcity issues into the global market. Prices of agricultural commodities traded in the global market will reflect regional water scarcity issues by decreasing supply from exporting nations and/or increasing demand from importing nations, thereby tightening the global supply/demand balance for agricultural goods. Estimates of the supply/demand dynamics in global agricultural markets to 2050 project that under a baseline scenario, which assumes the continuation of current trends and agricultural policies, most international commodity prices could rise by 20-50%, varying by crop.[61]

Figure 39. Annual* % Change in Soybean, Corn, and Wheat Prices




Source: Bloomberg, Citi Research, *US Crop Year

Figure 40. Daily Sugar No.11 Contract Prices


Source: Bloomberg, Citi Research

Local water constraints can have a massive impact on commodity prices

Examples of the impact that local water constraints can have on international commodity prices are abundant. During the 2011-12 drought that affected large swaths of the continental United States, including the "bread basket" in the Midwest, international wheat, corn, and soybean prices rose 40-80% over a short span of a few years. In 2009, a drought in India led sugar prices to spike to a 30-year high and two years of drought conditions in Asia in 2014 and 2015 on the back of the El Nino weather pattern led to sugar's recent renewed strength. Likewise, the recent drought in California significantly impacted prices of certain agricultural goods like fruits, vegetables and nuts. Irrigation is an important means of buffering the effects of variable rainfall and drought on prices, but as ground and surface water resources become more constrained, the sensitivity of global prices to weather will increase.

## Promoting Sustainable Growth in the Agriculture Sector

Given that the majority of land suitable for rainfed agriculture has already been appropriated for human use, most forecasts of future agricultural production generally assume that yield increases will be the predominant driver of production growth going forward. Achieving these yield increases in a way that protects the sustainability of the earth's freshwater resources will be critical. There are several avenues through which this can be achieved, including: (1) closing the yield gap between current and potential yields, particularly in parts of the world where yields still have significant scope for improvement; (2) implementing more water-efficient irrigation practices, including drip irrigation and deficit irrigation; (3) sourcing water for agriculture from unconventional sources including desalinated water and wastewater; (4) implementing water conservation practices in agriculture including runoff capture and soil management as well as demand-side management of food consumption; and (5) increasing trade between water-scarce and water-abundant nations.

[61] Rosegrant et Al. (2013). *The New Normal? A tighter global agricultural supply and demand relation and its implication for food security*.

## Bridging the Yield Gap

Agriculture in many parts of the world has substantial scope for realizing yield improvements. Yield improvements in both irrigated and rainfed agriculture could be important drivers of growth going forward. Globally, the achieved yield gap, or the difference between actual and potential yields, is just over 50% of potential, though yield gaps vary significantly by region.[62] In sub-Saharan Africa for example, the yield gap suggests that yields could as much as double if full potential were realized. Other regions show significant scope for yield improvements including Eastern Europe and Central Asia, though yield gaps are smaller in the developed world.

A significant challenge to achieving yield improvement is socioeconomic barriers and accessibility of technology to farmers

Many strategies are available to improve crop productivity in low-yielding regions including better soil management, increased use of fertilizers and pesticides, adoption of higher-yielding crop varieties, and greater mechanization. However, so far realizing these gains has proved to be difficult. A significant challenge to achieving potential yields is socioeconomic barriers that limit the affordability and accessibility of technologies to farmers in lower income parts of the world. But evidence of yield improvements achieved in certain regions indicates these difficulties are not insurmountable.[63]

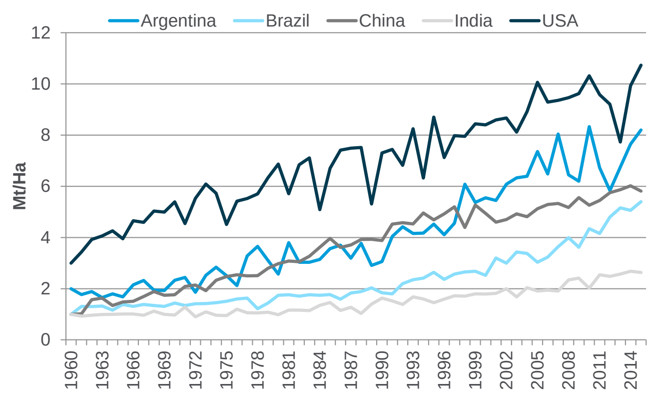
Conservation farming techniques can also help improve soil quality and reduce pests without the use of fertilizers and pesticides, thereby boosting yields and improving water efficiency while limiting harmful agricultural pollution. Such solutions may be particularly important in low-income areas where access to modern agricultural technologies may be limited. These solutions include agroforestry (incorporating trees in farming systems) and crop diversification practices like crop rotation and intercropping (growing two or more different crops on the same land) which can improve nutrient recycling and soil fertility.

Figure 41. Estimated Yield Gaps (Percentage of Potential) for Cereals, Roots, and Tubers, Pulses and Sugar Crops, Oil Crops, and Vegetables Combined (2005)

| Region | Yield Gap |
|---|---|
| Northern Africa | 60% |
| Sub-Saharan Africa | 76% |
| Northern America | 33% |
| Central America and the Caribbean | 65% |
| Southern America | 52% |
| Western Asia | 49% |
| Central Asia | 64% |
| South Asia | 55% |
| East Asia | 11% |
| Southeast Asia | 32% |
| Western and Central Europe | 36% |
| Eastern Europe and Russian Federation | 63% |
| Australia and New Zealand | 40% |
| Pacific Islands | 57% |

Source: Fischer 2010

Figure 42. Historical Corn Yields in Select Developed and Developing Countries (Argentina, Brazil, China, India, U.S.)




Source: USDA, Citi Research

[62] Fischer. (2010). *Security and abundance of land resources: competing uses and the shrinking land resource base.*
[63] Molden, D.J. (ed.). (2007). *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London and the International Water Management Institute, Colombo, Sri Lanka

## Improving Water Efficiency in Irrigation Systems

The expansion of irrigated agriculture through the conversion of rainfed crops to irrigated crops may be an avenue for increasing global agricultural production to meet growing demand. Improvements in the water efficiency of irrigation may make such an expansion in irrigated land possible, and help improve water sustainability in already over-stressed regions.

Deficit irrigation could be one strategy that can reduce water consumption

Deficit irrigation is one strategy that can reduce water consumption without significantly impacting crop yields. This strategy involves using sub-optimal levels of water in irrigation, allowing mild water stress during the growing phase when crops are less sensitive to moisture requirements (i.e. prior to pollination). Several studies conducted on the implementation of deficit irrigation on various crops have shown that the practice can significantly improve water efficiency while keeping yield losses to minimal levels.[64]

Figure 43. Drip Irrigation Field in Punjab State, India (December 2015)

Source: Citi Research

Drip irrigation is another important method of improving water-efficiency in irrigation. Drip irrigation systems can be significantly more water-efficient than traditional flow systems. In drip irrigation, small quantities of water are applied close to the root of the plant, localizing the application of water to crops, thereby reducing the excess water that is lost through evaporation and run-off. Though some of the water that is "wasted" through conventional systems will flow back into the hydrological cycle, the quality of this water may be compromised and the quantities that are lost can be sizeable – drip irrigation reduces these losses.

## Use of Unconventional Water in Irrigation

Unconventional water sources for irrigation may also provide a means of reducing withdrawal rates of freshwater. Unconventional sources of water could include desalination of both seawater and brackish water (freshwater mixed with seawater), and treated wastewater. Due to the high energy input required, desalinated water use in agriculture has so far been mostly uneconomical, outside of coastal regions producing extremely high-value crops. However, the recent collapse in energy prices alongside technological improvements may make desalinization a more widely viable source in the future, particularly as the cost of using surface and groundwater rises.

[64] WWAP (United Nations World Water Assessment Programme). (2015). *The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris*, UNESCO.

Treated wastewater can provide another unconventional source of water for the agriculture sector

Treated municipal wastewater provides another source of unconventional water for irrigation. The advantage of wastewater is that it is already typically high in nutrients; however, water contaminants in wastewater can be hazardous to human health. Nonetheless, wastewater offers a promising source of irrigation water, if appropriately treated and managed. Treated wastewater is already used extensively in some of the world's driest regions like the Middle East and North Africa, accounting for as much ~10% of total irrigation water use in countries like Malta, Kuwait, and Qatar.[45] Large projects in cities such as Los Angeles are already looking to recycle wastewater for direct human consumption with the advancement of micro-filtration technology.

## Implementing Water and Food Conservation Practices

Minimizing unproductive water evaporation through better soil moisture management and water harvesting can be important methods of improving water efficiency in agriculture. Water harvesting, which involves the collection of run-off to be stored for later use, can boost yields two to three times versus conventional rainfed agriculture.[45] Water harvesting can be practiced on rainfed crops or in conjunction with irrigation to minimize water withdrawals. Other conservation farming practices for limiting soil evaporation include the use of crop residues and mulch, maintaining ground cover and minimizing tillage.

Reducing food wastage saves not only food, but water and energy used to grow that product

Demand-side management for agricultural goods could also help improve water security by minimizing the burden on agricultural production growth. The Food & Agriculture Organization of the United Nations (FAO) estimated that ~32% (by weight) of the food produced globally in 2009 was lost or wasted.[65] Food loss/waste may occur during production, storage and handling, transportation, at the wholesale or retail level or at the consumption level when consumers purchase food but do not consume it. Much of this spoilage is concentrated in emerging markets such as India. Potential solutions to reduce food loss/waste are available at these various stages, including improving infrastructure for storage and transportation, improving harvesting, handling and storage management and encouraging increased donation of food at the wholesale/retail and consumer level.

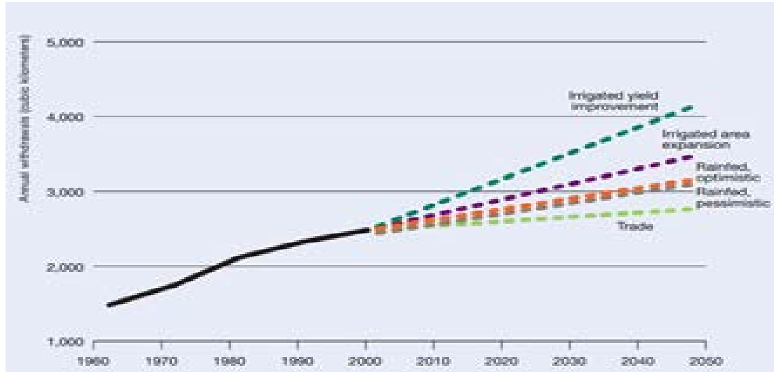
## Global Trade

Global trade between water scarce and water abundant countries can offset the impacts of agricultural production on water scarcity

Global trade is an important method of managing water scarcity, by helping to equalize global imbalances in land and water resources. In a 2005 study, researchers found, that absent political, social, and economic constraints, increases in global trade could almost completely offset the impacts of growing agricultural production on water scarcity. In this scenario, countries with abundant water resources, like North America, Latin America, Northwestern Europe and Eastern Europe increase production, while water-scarce nations maintain or reduce production or switch to high-value crops like vegetables. Assuming moderate yield improvements and expansions in rainfed land, they find that global agricultural production growth can be satisfied through 2050 without any expansion in irrigated agriculture infrastructure. Though in reality such a scenario is unlikely, due to constraints that limit trade between water-scarce and water-abundant countries, it is clear that global trade would be a critical tool in an integrated approach to water conservation.

[65] FAO. (2013). Food loss and waste: Definition and scope. Unpublished.

Figure 44. Forecasted Annual Water Withdrawals from 2000 to 2050 Under Different Water Management Scenarios




Source: Molden 2007[66]

## Policy Approaches to Promoting Sustainable Water Use in Agriculture

Widespread and effective implementation of the above practices in agriculture could help to ensure the future water security of the world. But encouraging the adoption of these practices will require appropriate incentives and initiatives at the national level, as well as international cooperation, in order to be achieved. Many policy tools are available to encourage water sustainability in agriculture, and which tools are most effective will depend not only on the water constraints and demands within a country, but also the constraints and demands of surrounding nations and trade partners, the socio-economic environment and the on-the-ground economic reality for farmers.

In some cases, the interests of the farmer are aligned with the public good – for example, water conservation practices such as runoff capture, improved irrigation and soil management, can both boost farmer profits and increase water efficiency. In these cases, policies targeted towards improving education on effective water and soil management as well as accessibility to appropriate resources can be beneficial.

Investment in R&D for improving water efficient irrigation technologies can improve available technologies and reduce the costs of adoption

When the interests of the farmer and the public good are not aligned, more direct policy support may be needed. Public investment in research and development for improving water-efficient irrigation technologies and building water-saving infrastructure can improve available technologies and help bring down the costs of adoption. Subsidies to farmers that adopt water-efficient technologies and water conservation practices can help incentivize these solutions. Removing policies that distort water-saving incentives, such as bans on imports/exports which may reduce beneficial trade between water-scarce and water-abundant nations, can be equally important.

Water pricing may be a critical method of aligning farmer incentives with water conservation goals. The concept of pricing water began to attract increasing attention from policy makers in the early 1990s as a tool for demand management and has been implemented in various forms in countries across the world. Though many technical and political limitations make the pricing of water difficult, some form of water pricing for irrigation exists in many countries globally including Australia,

[66] Molden, D.J. (ed.). (2007). *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London and the International Water Management Institute, Colombo, Sri Lanka.

Brazil, China, Canada, Chile, Colombia, France, India, Israel, Italy, Mexico, the Netherlands, New Zealand, and South Africa.[67] In many locations, however, prices remain too low for cost recovery and fail to incentivize water conservation, though there are some exceptions[67].

In Israel, for example, irrigation water prices are set to reflect the true cost and scarcity of the resource.[68] A combined quota and tiered pricing system is used to allocate water to farmers in Israel, in which the lowest tariff is charged for consumption up to 50% of the farmer's quota, a higher price for consumption of 50-80% of the quota and the highest price for consumption above 80% (Becker, 2013). Though this system of block pricing introduces inefficiencies to water allocation, water transfers are also allowed between farmers creating a secondary market for water resources. Water pricing has helped to promote the adoption of water conservation practices and technologies among Israeli farmers and to divert resources and capital towards developing new water-saving technologies in agriculture.[68] Since Israel abandoned water subsidization and implemented full-cost pricing, total water usage across all sectors has dropped by nearly twenty percent.[68] A case study on Israel's management of water resources is found at the end of the document.

[67]Dinar, A, Pochat V., Albiac J ed. (2015). *Water Pricing Experiences and Innovations.* Springer International Publishing.
[68] Siegel, Seth. (2015). *Let there be water: Israel's Solution for a Water-Starved World.* St. Martin's Press.

# The Energy Sector

## The Energy-Water Nexus: Energy is Water-intensive Just as Water is Energy-Intensive

The shale revolution in the United States and Canada has brought to the fore highly politicized issues related to fracking. Is the water supply adequate to meet the use requirements of hydraulic fracturing? Are aquifers adequately protected as drilling penetrates aquifer layers both to reach shale formations and to pump out oil and gas? How is 'produced water' — water brought or returned to the surface during the oil and gas extraction process — treated as it is produced together with oil and gas? What should the minimal level for the treatment of water used in fracking be? And not least, how should the disposal of water be regulated given the overwhelming evidence that if disposed of at bedrock levels seismic activity can be accelerated?

Water withdrawal is water that is diverted or withdrawn from the surface of a groundwater source

Water consumption is water use that permanently withdraws water from its source, i.e. through evaporation or consumption by people or livestock

And drilling is only the tip of the iceberg. There are question marks over the interdependence of water and energy in general, the adequacy of global water resources in energy production and the re-use of produced water. Not least of these is water that is withdrawn for power generation, which in some places like the U.S. rivals the total water withdrawn by the agriculture sector (overall, however, the agriculture sector still consumes the most water).

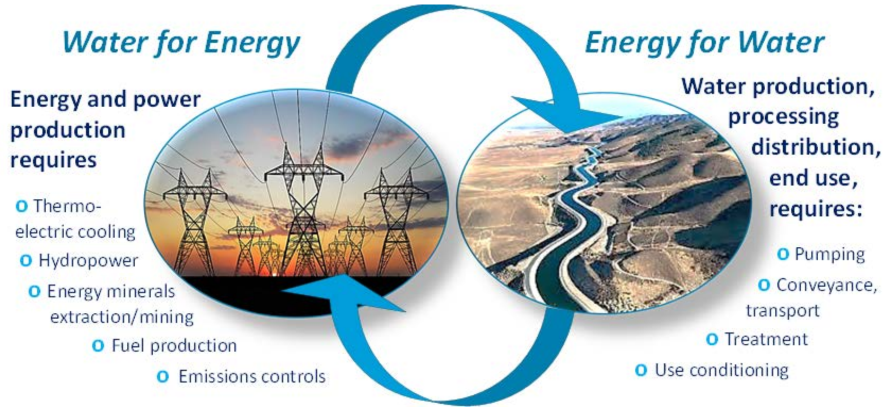
Fracking techniques alone consume a tremendous amount of water. On average, according to the *Oil and Gas Journal*,[69] deep shale wells can consume anywhere between 1.5 and 16 million gallons of water per well.[70] At the peak of the shale revolution some 35,000 wells were drilled in the U.S, of which around 25,000 used high volumes of water for either shale oil or gas. That equated to total withdrawals of over 35 trillion gallons per year with some wells using some 95-million gallons of water each day. Although this sounds like a large number, it's only about 0.2 percent of total annual water withdrawals in the U.S. On a per well basis that amounts to (1) the amount of water that is consumed in New York City in about five minutes, (2) irrigating 500 acres of corn in a full year, or (3) watering a typical golf course for 1 week. But concerns over fracking are less about the volume of water used and more an issue of preventing consequences that can be severe if water use is not properly regulated.

## Multiple Layers of Interconnectivity

Drilling alone barely touches the connections between water and energy. In the U.S., where data on water use is most readily available, oil, natural gas, and coal drilling and mining combined are estimated *to withdraw* more than one percent of the freshwater used in the United States. But the numbers are very different if we turn to water consumed as opposed to water withdrawn. The largest consumption of freshwater is for irrigation — primarily in the agricultural sector — with the remainder used for recreational and household/commercial use. But water withdrawal in thermoelectric generation is nearly as much as irrigation in terms of withdrawal and the two uses combined account for about 80 percent of total withdrawals in the United States. When it comes to electricity, much of the use of water is for cooling power plants, but environmental requirements to scrub coal to make it more environmentally friendly make water usage slightly higher than otherwise.

[69] *Special Report: Hydraulic fracturing, water use issues under congressional, public scrutiny*, Oil and Gas Journal (July 6, 2009), p. 30.
[70] USGS Hydraulic Fracturing FAQs: https://www2.usgs.gov/faq/categories/10132/3824.

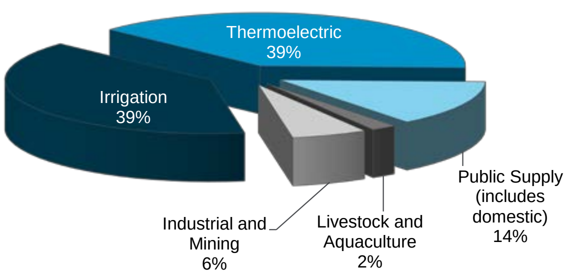
Figure 45. Nexus between Energy and Water




Source: U.S. Department of Energy, "The Energy-Water Nexus and Climate Change", December 7, 2015

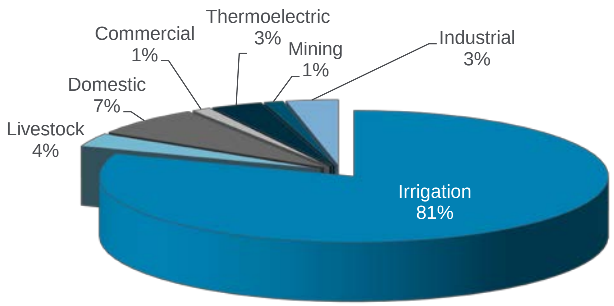
The nexus between energy and water is depicted graphically in Figure 45. Water is about as energy intensive as energy is water-intensive. Energy is required to treat and move water from its sources (rivers, lakes, groundwater) to its end users (agriculture, cities, energy producers). Energy is also required for desalination, which is extremely important in places like the Middle East, in order to provide a continuous, reliable supply of water. In places like California, some 20% of total energy use is used to treat and transport water.

Figure 46. U.S. Freshwater Withdrawals by Sector




Source: U.S. DOE

Figure 47. U.S. Freshwater Consumption by Sector




Source: U.S. DOE

At first glance, it would appear that the main issue with the interdependency between energy and water, like that between agriculture and water, is the resilience of the freshwater system, not just in the United States and Canada, but globally. Competition for the earth's water resources and drawdowns in freshwater lakes and ground water have given rise to efforts to develop best practices designed to preserve the availability of freshwater and the recapture and recycling of water once used.

Figure 48 summarizes the multiple connections between water and energy resources. The table notes that solar photovoltaic and wind, which along with hydroelectric are the main sources of renewable energy, have minimal use of water. Other alternatives to carbon-intensive uses are water-intensive, including nuclear power, whose water withdrawal requirements are even greater than those of conventional thermal power plants, as well as concentrated solar power (CSP) and carbon capture and sequestration (CCS).

Figure 48. Water: Uses and Impact on Quality

| Energy Element | Connection to Water Quantity | Connection to Water Quality |
|---|---|---|
| **Energy Extraction and Production** | | |
| Oil and Gas Exploration | Water for drilling, completion, and fracturing | Impact on shallow groundwater quality |
| Oil and Gas Production | Large volume of produced, impaired water* | Produced water can impact surface and groundwater |
| Coal and Uranium Mining | Mining operations can generate large quantities of water | Tailings and drainage can impact surface water and groundwater |
| **Electric Power Generation** | | |
| Thermoelectric (fossil, biomass, nuclear) | Surface water and groundwater for cooling** and scrubbing | Thermal and air emissions impact surface waters and ecology |
| Hydroelectric | Reservoirs lose large quantities to evaporation | Can impact water temperatures, quality, ecology |
| Solar PV and Wind | None during operation; minimal water use for panel and blade washing | |

*Impaired water may be saline or contain contaminants

| Energy Element | Connection to Water Quantity | Connection to Water Quality |
|---|---|---|
| **Refining and Processing** | | |
| Traditional Oil and Gas Refining | Water needed to refine oil and gas | End use can impact water quality |
| Biofuels and Ethanol | Water for growing and refining | Refinery waste-water treatment |
| Synfuels and Hydrogen | Water for synthesis or steam reforming | Wastewater treatment |
| **Energy Transportation and Storage** | | |
| Energy Pipelines | Water for hydrostatic testing | Wastewater requires treatment |
| Coal Slurry Pipelines | Water for slurry transport; water not returned | Final water is poor quality; requires treatment |
| Barge Transport of Energy | River flows and stages impact fuel delivery | Spills or accidents can impact water quality |
| Oil and Gas Storage Caverns | Slurry mining of cavers requires large quantities of water | Slurry disposal impacts water quality and ecology |

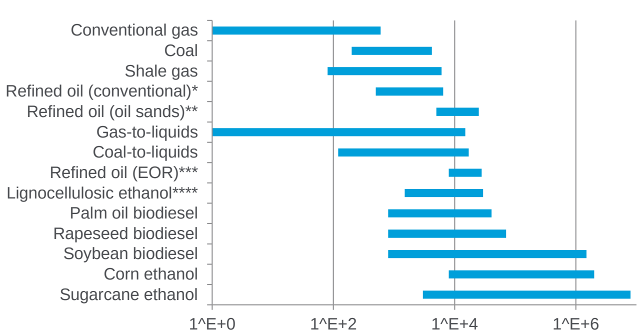
**Includes solar and geothermal steam-electric plants

Source: U.S. Department of Energy, "Report to Congress on the Interdependency of Energy and Water", (December 2006)

A significantly greater problem when it comes to the energy-water nexus is a set of four uses of water in the energy system that can be significantly noxious and environmentally contaminating. These include shale exploration, which has been the focus of considerable recent attention, plus coal (and other mining activities), biofuels, and oil sands. The issue here is less the availability of the earth's water resources than their future usability.

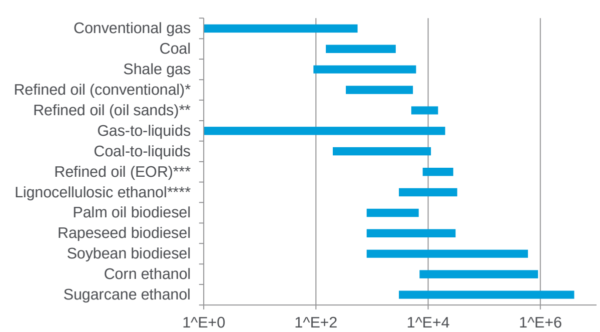
The following graphs are helpful in assessing the impacts of energy use on water use, particularly at locations where water scarcity is already or may become a problem. In primary energy production, as a resource categorized as renewable, various biofuels require more water than coal and gas because of irrigation and processing.

Figure 49. Water Withdrawal for Primary Energy Production – Highest for Biofuels (liters per toe)




Source: IEA, Citi Research

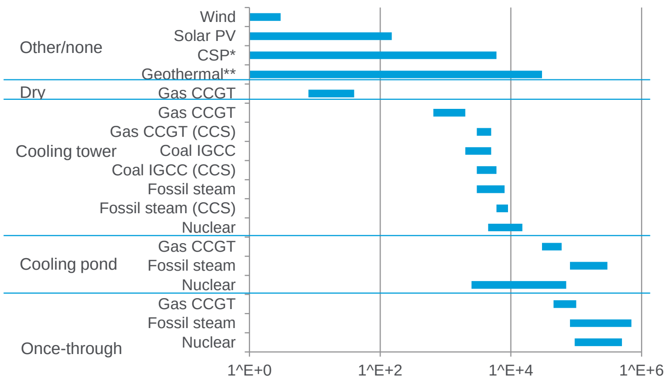
Figure 50. Water Consumption for Primary Energy production – Highest for Biofuels (liters per toe)




Source: IEA, Citi Research

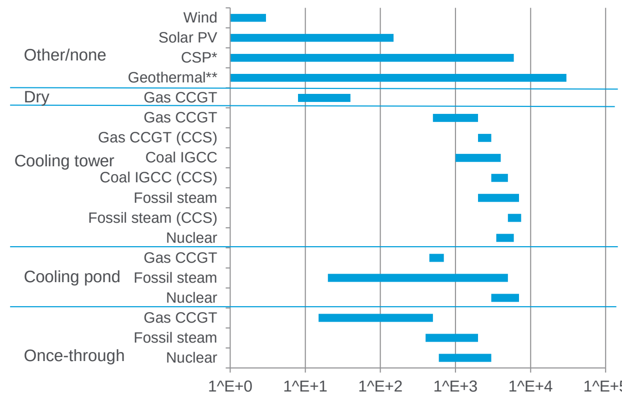
In power generation, the opposite tends to happen regarding the water use by renewable sources, as wind and solar usually use much less water, though the range is large. Cleaning or panel washing is the primary usage of water for non-thermal renewables (ex-hydro). However, traditional forms of thermal generation, including coal, gas and nuclear, tend to use more water for cooling.

Figure 51. Water Withdrawal for Power Generation – Lowest for Renewables Generally, But the Range is Large




Source: IEA, Citi Research

Figure 52. Water Consumption for Power Generation




Source: IEA, Citi Research

# Shale Exploration

A significant amount of attention is being focused on water issues related to the shale revolution in the United States and Canada. Two issues loom large: (1) the adequacy of water supplies, including underground aquifers capable of providing freshwater for hydro-fracking; and (2) the integrity of aquifers in the exploitation of shale gas and tight oil and in the disposal of waters used in the fracking processes. Although there are multiple issues in the energy-water nexus, these concerns have increasingly attracted the attention of public groups in the United States leading to movements to prevent fracking or to significantly increase regulations. For example, the environmental advocacy organization Environment America and its Research and Policy Center, argues that "fracking poses grave threats to the environment and public health" by "contaminating drinking water…consuming scarce water resources…endangering public health with air pollution…exacerbating global warming… damaging America's natural heritage…[and] imposing costs on communities."[71]

The shale revolution has excited the imaginations of many over the years due in part to the superabundance of original shale source rock for oil and gas globally, and the huge resources of commercially exploitable shale formations that have become within reach of current exploitation methods through hydraulic fracturing. Shale-based natural gas and oil formations that have been the targets of hydrofracking contain an abundance of oil and gas, but the molecules are trapped in semi-porous rocks. Water, which contains sands and chemicals that are specifically designed to break open the pores of the rock, is put under high pressure to releases trapped hydrocarbons from the rock.

[71] See Environment America Research & Policy Center, *Fracking By the Numbers: Key Impacts of Dirty Drilling at the State and National Level*. (October 2013). p.3. Critical assessments and suggestions for regulation can be found on the web sites of the Sierra Club, National Resource Defense Council and the Environmental Defense Fund. Among the Washington-based think tanks that has devoted significant research on water issues and fracking is Resources for the Future.

The availability of the water supply is a critical issue for hydrofracking given that somewhere between 1.5 and 16 million gallons of water per well is required to make the well productive. The availability of water has been a problem in big producing areas like Texas, where production of oil from tight shale formations has now exceeded 3 million barrels per day. It is also a prevalent problem throughout the U.S. Southwest, including resource-abundant Southern California and Arizona, and has also become problematic in the resource-rich grain belts of Minnesota, Nebraska, Iowa, and Illinois, as well as in the eastern seaboard region of the country, particularly Appalachia. According to Ceres, nearly half of oil and gas wells recently hydrofractured in the U.S. are in regions such as Texas and Oklahoma, with high or extremely high water stress.

## Risks and Regulations

Water use in fracking is one of the key issues of contention, and has three main aspects — adequacy of water, disposal of wastewater, and the integrity of aquifers

Citi conducted significant analysis of the risks and regulatory concerns associated with fracking in our Citi GPS report *Energy 2020: North America, the New Middle East?* (March 2012). We noted then three issues which dominate this discussion: (1) the availability of water, (2) the disposal of waste water, and (3) the integrity of aquifers. These risks have led to an ongoing moratorium of fracking in New York State as well as calls for further oversight for what many people feel is largely unregulated technology that (combined with horizontal drilling) has unlocked U.S. energy independence. One generally agreed upon issue is a best practice involving the insertion of concrete funnels that can protect aquifers when they surround the tubulars through which fracking fluids and extracted hydrocarbons flow.

### Availability of Water and Fracking

The use of water in fracking remains relatively modest compared to other uses

On the whole, the use of water in fracking remains a modest proportion of total water consumed compared to other industries such as agriculture. Nevertheless, fracking is a water-intensive process. For example, the U.S. EPA estimates approximately 9.5 billion gallons of water were used for fracking in the Barnett shale which is equal to 1.7% of the total freshwater used in the region. The agency also projected that Barnett shale groundwater use could increase from around 3% of total groundwater use in 2012 to 7-13% by 2025, though this could be offset by a fall in the number of wells completed. Emerging best practices in recycling the water used in fracking should see the process become less water-intensive over time, although the efficacy of these techniques also varies by geology of each shale play.

Figure 53. Estimated Water Needs for Fracking of Horizontal Wells at Various Shale Plays

| Shale Play | Formation Depth (ft) | Porosity (%) | Organic Content (%) | Freshwater Depth (ft) | Fracturing Water (gal/well) |
|---|---|---|---|---|---|
| Barnett | 6,500-8,500 | 4-5 | 4.5 | 1,200 | 2,300,000 |
| Fayetteville | 1,000-7,000 | 2-8 | 4.0-9.8 | 500 | 2,900,000 |
| Haynesville | 10,500-13,500 | 8-9 | 0.5-4.0 | 400 | 2,700,000 |
| Marcellus | 4,000-8,500 | 10 | 3.0-12.0 | 850 | 3,800,000 |

Source: U.S. EPA, Citi Research

Developing regulations on water in fracking comes down to three key areas — the chemical composition of fracking fluids, the treatment of water and waste water disposal

Hydraulic fracturing and water are at the center of a number of regulations. Perhaps even more concerning than the volume of water used in fracking is the chemical composition of hydraulic fracturing fluids, and the treatment of water used. A number of regulatory bodies, such as the Environmental Protection Agency (EPA), the Interior Department, and various state governments are involved in establishing regulation and it appears that, without major accidents or environmental disasters occurring, hydraulic fracturing in the U.S. should continue without a dramatic cost increase due to increased regulation.

Although other fracturing techniques, such as foam fracturing and propane are available, hydraulic fracturing is favored due to its convenience and cost. With hydraulic fracturing, some of the fracturing fluids remain in the formation but this is not unique to unconventional exploitation. In conventional hydrocarbon production, water drive or water flooding is often used to push the oil or gas out (known as enhanced oil recovery), and some of the water stays behind. Overall, rather than recycling 100% of the water pumped into a formation, recycling as much of the fluid coming back to the surface as possible is still helpful in reducing water use.

## Disposal of Wastewater

Setting regulations on the treatment of wastewater is a key part of the overall regulatory effort. In general while there are still some concerns in the U.S. on the adequacy of regulations, particularly in areas where federal regulations may be restricted and more lax state guidelines are in effect, the major concerns are related to the spread of fracking internationally — into countries where regulatory regimes are weak and where there is a greater likelihood of adverse impacts. Guidelines in the U.S. derived from the Clean Water Act set standards for the discharge of industrial wastewater based on “Best Available Technologies,” similar to emission regulations. A direct, on-site discharge of wastewater from oil and gas production into waters of the United States is prohibited. Outside of trying to implement some form of recycling or reuse of this water in the injection process, disposal for this produced water is often sought, mainly via injection wells depending on location, costs, and state regulations. The risks from produced water are not just limited to underwater reservoirs and wells. Communities have also been impacted by ‘above-ground’ contamination from residual industrial activity, transportation, and storage. Opponents point to this tangential risk a direct causality of fracturing.

The treatment and disposal of waste water is key…as well as the use of diesel and other chemicals in fracturing fluids

Currently, the Underground Injection Control (UIC) program of the Safe Drinking Water Act (SDWA) regulates the siting, construction, and operation of injection wells. Although current regulations in the U.S. require certain disclosure and regulation of fracturing fluids and chemicals used, it is possible that the new Trump administration could relax water regulation, as it has already done with coal mining.

…and the EPA could require companies to disclose the chemical composition of the fracture fluid — viewed by some in the industry as a trade secret

Further, the U.S. EPA also requires companies to disclose the chemical composition of the fracture fluid under the Toxic Substances Control Act (TSCA). However, some in the industry remain opposed to disclosing the composition and making of the frack-fluid as they still view fluid composition as a trade secret — similar in nature to how Coca-Cola is made.

Besides Federal regulations, regulators from states, such as Pennsylvania, impose restrictions on water use, recycling, and disposal and also introduce local impact fees. These fees could be redirected toward funding road repairs, environmental clean-ups, and plugging abandoned wells. With respect to water issues, some fees deal with cementing wells while others focus on per gallon fees for wastewater treatment. In addition, producers are required in some states to disclose the chemical compositions of fracturing fluids and air emissions from the wells, in addition to well spacing and distance from water sources and buildings. Ohio and Arkansas, followed by most other states, halted the approval of new injection wells after earthquakes were detected that were believed to be related to wastewater disposals into injection wells.

Environmental assessments have pushed policymakers to focus on two main risks: potential water (and air) contamination — both above and below ground — as well as seismic activity. For example, the U.S. EPA found fracking to be the "likely" cause of water contamination in the small town of Pavillion, Wyoming. This news has been frequently touted by interests against the use or expansion of fracking. However, because the EPA's multi-year study was not fully conclusive it is therefore unlikely to restrict future activity, although it has opened the door for new and updated regulations. A later study from Stanford University, however, found that water contamination did occur in Pavillion. A second regulatory report suggests a link between fracking and an earthquake in the Fayetteville shale play in Arkansas, as well as one in Ohio. Government regulations, including those proposed in California, now target these issues through environmental standards and disclosure requirements on fracking fluids, although U.S. Federal regulations could be loosened, with more lax enforcement, due to the Trump administration's stance on relaxing regulations and cutting government funding that affects enforcement.

Seismic activity has been associated with both fracking and disposal of wastewater

More critically there has been growing recognition internationally of the potential seismic consequences from the disposal of fracking wastewater close to the earth's bedrock. In the U.S., there were notable cases in Fayetteville, Arkansas (from fracking itself) and Youngstown, Ohio (where local authorities allowed disposal of waste fluids as a means of generating revenue). In the U.K., earthquakes in the Midlands, where fracking had begun before this decade, triggered a study by the Royal Society and the Royal Academy of Engineering.[72] The report noted that best practices can diffuse the risks of aquifer contamination and it placed a high priority on well-integrity. It also called for the regulation of plans for disposing of wastes before fracking begins so as to minimize seismic activity. The U.K. had banned fracking pending this study and even at present, the new policy to enable fracking is progressing very slowly. The study states that seismic activity above a magnitude of 3.0 on the Richter scale was rare — a level similar to the "vibrations" from a passing truck, a conclusion also drawn by the U.S. Geological Survey.

In the U.S., however, the growth of earthquakes in Oklahoma, perhaps the only state that both allows fracking and disposal of waste deep into tight rock formations and dense shale rock, has created public outcries against the latter practice. Earthquake activity began to grow as this decade opened. Between 2004 and 2008 there were between one and three measured earthquakes in the state. But by 2009 there were 20 recorded earthquakes in the state at magnitude 3.0 on the Richter scale or higher and there was no earthquake greater than 4.0. By 2015 there were 890 quakes, 30 of which were higher than 4.0. This is a serious concern, not only in the U.S., but elsewhere in the world, where regulations dealing not just with waste disposal but with other aspects of water use are likely to be much less reliable than in the U.S.

[72] *Shale gas extraction in the UK: A Review of Hydraulic Fracturing,* July, 2012..

# Harnessing the Fruits of Produced Water

Produced water is water brought or returned to the surface during the oil and gas extraction process

One of the most intriguing aspects of the energy-water nexus is that the energy sector (and the mining and extractive sector more generally) is actually the largest “producer” of water in the world — water brought or returned to the surface during the oil and gas extraction process. However, this “produced water” tends to have high salt content and also often contains toxic substances including various chemicals and heavy metals that can make it costly to treat and reuse.

Tapping into this potential source of water has thus become a critical subject in some energy-producing countries, particularly in the U.S., where it has become part of the broader policy debate over fracking, as well as part of the public policy debates in drought-ridden Western states where freshwater has been in short supply. The treatment of produced water is being explicitly tied to the treatment of water used in hydraulic fracturing to make it both useful for reuse in fracking, and potential to be reused for industrial, agricultural and even drinking purposes. For economic and environmental reasons, there are growing efforts to use produced water for more beneficial uses rather than pure disposal in injection wells. At stake is the protection of water quality when produced water is treated and returned to the environment, as well as the reuse of produced water for other beneficial uses after treatment (which can include desalination).

## What is Produced Water?

“Produced water” is a byproduct of oil and gas production, including conventional and shale oil and gas production, as well as coalbed methane. It is water that comes to the surface along with produced oil and gas, at a weighted average water-to-oil ratio of around 10:1 in the many mature fields U.S.[73] (meaning that for every 10 barrels of oil, one barrel of water is produced) versus a global average of close to 3:1; older wells around the world could see water-to-oil ratios of 50:1.[74]

Produced water can include:

- **Natural groundwater -** formation brine or water that is native to the geologic formation prior to development, which is then produced alongside hydrocarbons in conventional reservoirs.
- **Flowback water from conventional crude oil production** - water that has been injected into the well for artificial lift by water flooding.
- **Flowback from unconventional oil and gas production such as shale gas, coal seams, and tight rock formations** - (often considered “wastewater”), water that has been pumped into the well along with chemicals and sand for hydraulic fracturing of unconventional/shale/tight oil and gas formations, and returned to the surface over the producing life of the well; often over 90% of the water stays within the formation.

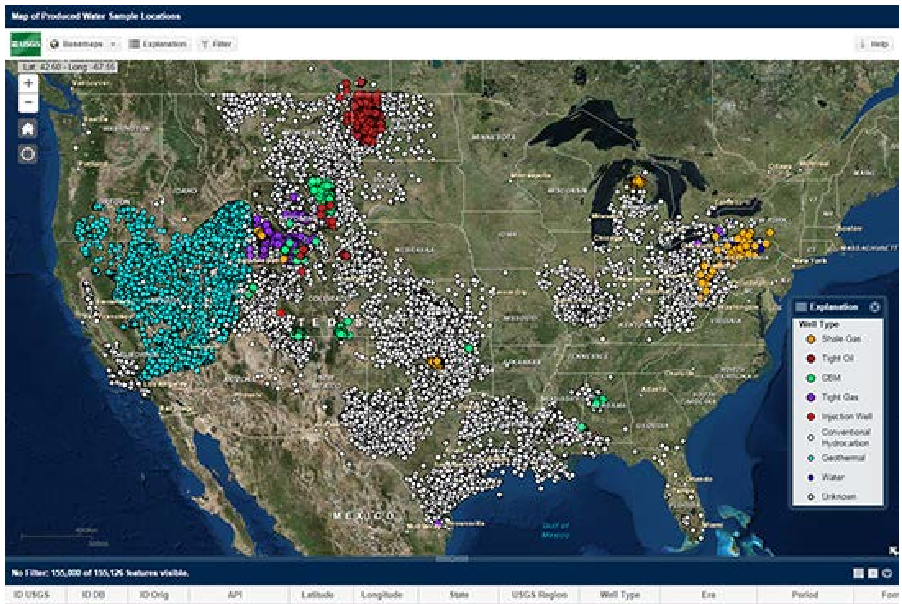
[73] Clark, C.E., and Veil, J.A. (2009). *Produced water volumes and management practices in the United States*: Argonne National Laboratory.
[74] Khatib, Z. and P. Verbeek. (2003). *Water to value - Produced water management for sustainable field development of mature and green fields*" Journal of Petroleum Technology: 26-28.

Produced water is also considered "wastewater"

Volume-wise, natural groundwater and flowback water from production via conventional reservoirs are a much larger source of produced water than flowback of wastewater from hydraulic fracturing, which peaks in the first few months before dropping to near zero after half a year, whereas groundwater and flowback from conventional oil production continue for years on end.[75]

But in terms of additional contaminants and greater controversy in political discourse, it is produced water (also considered "wastewater") from the hydraulic fracturing process for shale production that is particularly salient.

Figure 54. Produced Water from Wells Across the U.S., Mapped by the USGS Produced Water Database




Source: USGS * The United States Geological Survey (USGS) maintains a database of produced water quantity and quality across the US (http://eerscmap.usgs.gov/pwapp/).

## How Big is Produced Water by Volume?

Around 11-12 billion cubic meters ($km^3$) of water are produced globally each year by the oil and gas and extractive sectors. This is 0.3% of the world's 3,800 $km^3$ of water withdrawals, and 2.4% of the 470 $km^3$ withdrawn globally by the energy sector including power generation (Curmi et al, 2013). This includes groundwater coming up to the surface, as well as flowback from injected water. This compares to 31-32 $km^3$ per year of treated water from desalination plants globally.

Outside the U.S., an estimated 50 billion barrels are produced each year at thousands of wells worldwide, at an average weighted water-to-oil ratio of 2:1 to 3:1 (see NETL). This is around 8 $km^3$ of produced water per year, globally. Together with the ~3.3 $km^3$ produced in the U.S., this is some 11-12 $km^3$ of produced water globally.

[75] Kondash, A.J., Albright, E., and Vengosh, A. (2016). *Quantity of flowback and produced waters from unconventional oil and gas exploration*. Science of the Total Environment 574 (2017) 3014-321.

Figure 55. Top 10 US States for Produced Water in 2012

| Ranking | State | 2012 Water (bbl/yr) | % of Total Water |
|---|---|---|---|
| 1 | Texas | 7,435,659,000 | 35 |
| 2 | California | 3,074,585,000 | 15 |
| 3 | Oklahoma | 2,325,153,000 | 11 |
| 4 | Wyoming | 2,178,065,000 | 10 |
| 5 | Kansas | 1,061,019,000 | 5 |
| 6 | Louisiana | 927,635,000 | 4 |
| 7 | New Mexico | 769,153,000 | 4 |
| 8 | Alaska | 624,762,000 | 3 |
| 9 | Federal Offshore | 358,389,000 | 2 |
| 10 | Colorado | 320,191,000 | 2 |

Source: Veil Environmental

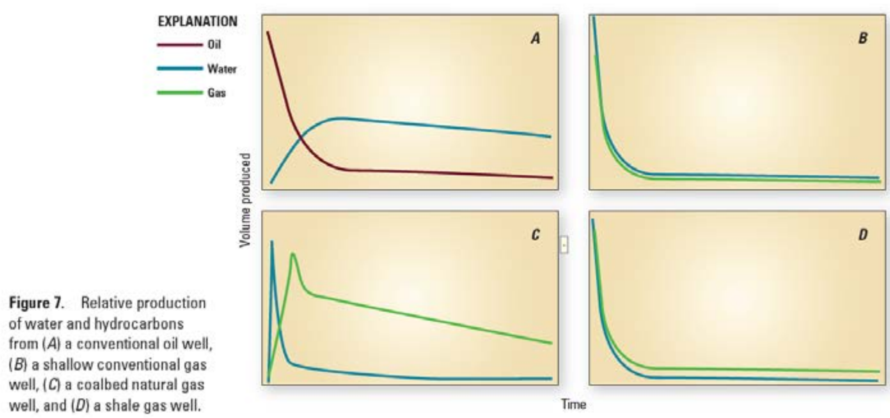
A 2009 study by Clark and Veil showed that for the U.S. in 2007, 3.3 $km^3$ of produced water was generated from 1 million wells, equal to about 9.2 million cubic meters per day. In barrel terms, this was 21 billion barrels, or 58 million barrels per day. Of the 3.3 $km^3$ of produced water, 98% of onshore produced water was injected into subsurface formations — 60% was used for enhanced oil recovery in oil and gas wells while 40% was disposed. Of the offshore produced water, over 90% was discharged into the sea or ocean.

In 2009, 98% of onshore produced water was injected into subsurface formations — 60% was used for enhanced oil recovery in oil and gas wells while 40% was disposed

Texas was the largest producer by far at over 7 billion barrels of produced water in 2012**,** with California, Oklahoma, Wyoming, and Kansas clustered closely together at 1-3 billion barrels per year (see Figure 55).

The update to the Clark and Veil study which contained data up to 2012, noted an increase in U.S. oil production of 29% and an increase in U.S. gas production of 22%, though produced water only increased by less than 1% to 21.2 billion barrels, which is still around 3.3 $km^3$ of produced water per year. The seeming discrepancy here is because the recent growth in oil and gas production has come from shale and tight formations, which experience large volumes of flowback and produced water at first, but which see a quick drop-off for a relatively low level of lifetime produced water generation per well. In contrast, conventional oil and gas reservoirs tend to start with a small volume of produced water initially, which then grows over time, leading to a high level of produced water generation per well. Broadly, the volume of produced water varies over the lifetime of the well. Just as there are "type curves" for oil or gas produced from a given well over time, there are type curves for produced water too (see Figure 56).

Figure 56. Illustrative Type Curves for Oil, Water, and Gas




Source: USGS

In conventional oil production, much of the water generated is returned to conventional reservoirs

For conventional oil production — where the world's giants include Russia, Saudi Arabia and other OPEC producers, as well as China, Mexico, Brazil, and Norway — the amount of water generated can continue to rise over time as oil fields age, certainly in relationship to the oil produced, but likely also on an absolute basis. Much of this water is returned to conventional reservoirs to enhance the recovery of hydrocarbons and to manage the declining rate of oil output. However, some of this water is in water-stressed regions like the Middle East, where water reuse in other areas may be particularly salient.

In the Middle East, the Gulf Cooperation Council (GCC) countries are major oil producers, and their produced water volumes are substantial, but produced water management outside of enhanced oil recovery is relatively undeveloped. Revenue from the produced water treatment sector in the GCC countries is almost $500 million currently, according to Frost & Sullivan. They see Qatar as having a particularly high water cut (produced water as a percentage of total production), but see lower levels in Saudi Arabia, Kuwait, and the UAE, which means these countries tend not to focus on produced water treatment outside of enhanced oil recovery, although interest appears to be growing.

In shale production, a "crossover point" is the point at which the volume of produced water is greater than the water inputs needed for hydraulic fracturing

For shale production, while current concerns are about the adequacy of water supply, future concerns could be about dealing with surplus water produced by shale wells. This is the concept of the "crossover point" — i.e. a point in the future where the volume of produced water could be greater than the water inputs needed for hydraulic fracturing — meaning a growing surplus of water that needs to be managed in the next decade or so. At first, the water used for hydraulic fracturing is far greater than the volumes of produced water as mentioned earlier, but as more wells are drilled, the cumulative produced water volume from already-drilled wells continues to rise but flowback volumes stay relatively stable (assuming the number of wells drilled per year is fairly stable). Regions with many shale wells could find themselves needing to deal with a growing local surplus of produced water, which could be a further impetus for water reuse in fracking and additional treatment for other beneficial reuse (Veil 2014).

## How is Produced Water Currently Managed?

Only a small proportion of produced water is transported and treated at off-site commercial facilities or recycled for beneficial reuse

On the whole, produced water has been considered a byproduct of oil and gas production, but economic, environmental, and regulatory considerations are driving a growing change in thinking towards the reuse of produced water. In the U.S., there are key differences in managing produced water based on whether the well is onshore or offshore. Produced water from offshore wells tends to be discharged into the sea or ocean. However produced water from onshore wells is mostly injected underground into disposal wells — either into producing formations for enhanced oil recovery (EOR) at a later date or into deep injection wells for storage. Only a small proportion of produced water is transported and treated at off-site commercial facilities or recycled for beneficial reuse. Off-site commercial facilities tend to use either disposal wells or evaporation ponds (large, shallow, artificial ponds that use the sun to evaporate water). Evaporation in surface ponds is also used directly onsite in a small number of cases in Western U.S. states.

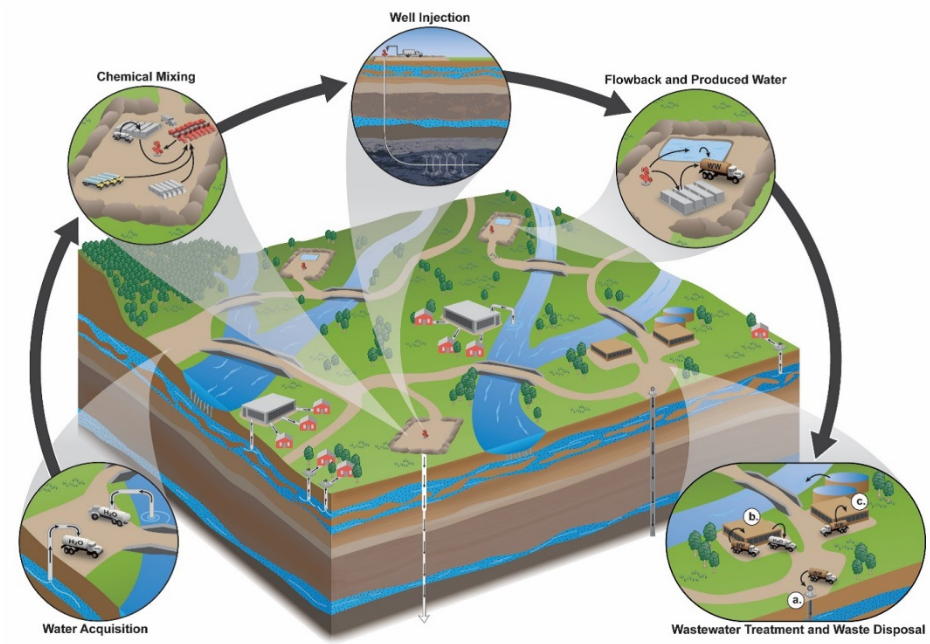
Injection wells are usually close to the oil and gas wells because water transportation is costly, but even then, finding a suitable formation to inject into may not be easy as the geography may not be suitable for deep injection wells. For shale wells particularly, which generate significant volumes of flowback wastewater in the initial stages right after hydraulic fracturing, the produced water is often first diverted to storage in surface ponds, which need to be properly lined in order to prevent the wastewater from trickling down into groundwater.

Disposal of produced water from shale formations through subsurface injection can create problems with groundwater contamination and seismic activity

Disposing of produced water from shale formations through subsurface injection can also face problems with groundwater contamination and induced seismic activity, as discussed earlier. Groundwater contamination can be avoided through maintaining best practices of inserting cement funnels and well casings, as well as lining storage ponds and minimizing truck transportation spillage. Meanwhile, seismic activity around shale drilling areas has become very frequent, particularly in the state of Oklahoma, and remains a problem to be addressed.

Municipal treatment plants are not typically prepared for treatment of water with the level of contaminants in produced water, so private treatment plants have sprung up to deal with the growing volumes of produced water from the prolific shale formations across the country, from Pennsylvania to North Dakota to Texas. Meanwhile, shale producers are also increasingly reusing water for enhanced recovery.

Figure 57. Potential Beneficial Reuse Scenarios for Onshore Produced Water




Source: Hagstrom et al (2016)

Beneficial reuse – other than re-injection for enhanced oil recovery – is difficult to quantify**,** but reported approaches include: (1) recycling of flowback water for new drilling and hydraulic fracturing fluids; (2) spreading of (salty) produced water on unpaved roads for dust control and de-icing during the winter (reportedly in Ohio); and (3) limited reuse for irrigation, but the water needs to be of low salinity or have been treated to such. Some produced water from coalbed methane in the Powder River Basin in Wyoming and Montana is processed into water with low salinity, which can then go toward livestock and irrigation use. Other industrial uses include equipment washing, steam conversion, and fire control. There could also be value in the byproducts of produced water treatment, including brines, salts, calcium, magnesium, iron, bromide, and iodide.

Figure 58. Produced Water Management Practices in the U.S. in 2012

| | Injection for Enhanced Recovery (bbl/yr) | Injection for Disposal (bbl/yr) | Suface Discharge (bbl/yr) | Evaporation (bbl/yr) | Offsite Commercial Disposal (bbl/yr) | Beneficial Reuse (bbl/yr) | Total Produced Water Managed (bbl/yr) |
|---|---|---|---|---|---|---|---|
| 2012 | | | | | | | |
| Onshore Total | 9,225,152,000 | 7,947,716,000 | 605,129,000 | 691,142,000 | 1,373,131,000 | 125,737,000 | 1.9968E+10 |
| % | 46.2 | 39.8 | 3.0 | 3.5 | 6.9 | 0.6 | 100.0 |
| Offshore Total | 62,703,000 | 62,703,000 | 515,916,000 | 0 | 0 | 0 | 641,322,00 |
| % | 9.8 | 9.8 | 80.4 | 0.0 | 0.0 | 0.0 | 100.0 |
| U.S. Total | 9,287,855,000 | 8,010,364,000 | 1,121,045,000 | 691,142,000 | 1,373,131,000 | 125,737,000 | 2.0609E+10 |
| % | 45.1 | 38.9 | 5.4 | 3.4 | 6.7 | 0.60 | 100.0 |

Source: Veil Environmental

Because water demand is a very local issue, and salt removal and transportation are both expensive, the most likely uses of produced water are for enhanced oil recovery (EOR), and for recycling for drilling and hydraulic fracturing fluids in shale oil and gas production.

Right now, it is it is rare to find produced water that is treated and then goes into agricultural, livestock or drinking uses

If the cost of water treatment falls or a market for selling produced water develops or local offtake agreements (agreements between produced water generators and water buyers on future production) are forged, other potential reuses for produced water such as irrigation, rangeland restoration, animal consumption, industrial use, and drinking water could be established. For now, it is rare to find produced water that is treated and then goes into agricultural, livestock or drinking uses, but this could grow in the future, depending on regulatory changes, the water quality of the produced water source, local treatment options, options for transportation, and local demand. Other obstacles include lack of public acceptance, legal risks if water quality is substandard, and the lack of water rights and pricing in many regions, which is crucial to be able to sell produced water. As the range of existing treatments for wastewater and seawater to supplement existing supplies begins to be more widely used and acceptable – such as recycling of municipal wastewater, or desalination of brackish water and seawater – the beneficial reuse of produced water could become more widespread in the future.

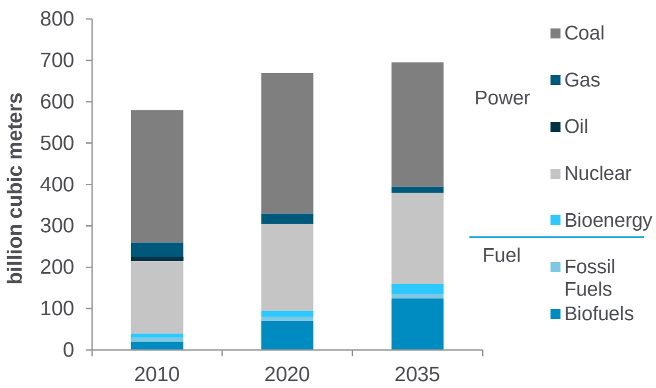
## Power Generation and Water

All thermal power technologies require water in order to cool and condense steam

By far the most prevalent use of water by the energy sector is in power generation. All thermal power technologies, whether they involve coal, natural gas, fuel oil, biomass, solar thermal, nuclear, or geothermal steam require water in order to cool and condense steam. In the past, it was traditional to build thermal power facilities close to natural water sources like rivers. Large quantities of water would be required and while these water resources were not totally used up, a vast amount was lost due to evaporation. Changes in law and regulation now require water used in power generation to be returned to its source, significantly reducing thermal power consumption in the United States as well as elsewhere in the OECD. Even so, power generation requires significantly more global oversight given the growth of power demand projected in future decades.

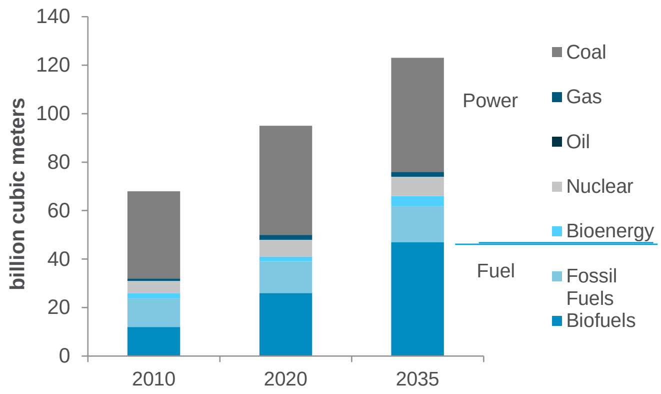
The tremendous growth in energy supply and consumption driving water use and the emerging water scarcity problem created in certain regions due to climate change, demand greater attention from the public, policymakers, businesses, and investors. About 15% of the world's total water withdrawals come from energy production, amounting to about 583 billion cubic meters (bcm) of water in 2010, of which 66 bcm was consumed.[76] The International Energy Agency (IEA), in their New Policies Scenario, expects global water use for energy production to increase by ~20% for water withdrawal and by ~85% for water consumption between 2010 and 2035, because of the continued growth in conventional power generation and, more significantly, a tripling of global biofuel supply based on government policies that mandate the use of biofuels.

Figure 59. Energy-related Water Withdrawals Could Grow by ~20% Between 2010 and 2035...




Source: IEA, Citi Research

Figure 60. ...But Energy-related Water Consumption Could Rise by 85% Between 2010 and 2035




Source: IEA, Citi Research

## Power Generation and Water: Cooling

Competition for water in times of water scarcity poses challenges to electricity generation

Water is essential in most forms of power generation. Thermoelectric power plants — the most dominant form of electricity generation — pass steam through turbines to generate electricity. The heat used to boil the water to create steam comes from burning coal or natural gas, nuclear reaction, or directly through solar or geothermal energy. After it goes through the turbines, the water needs to be cooled for it to be turned into steam again. The largest demand for water in an electricity plant comes from the cooling process for condensing steam back into a usable working fluid.

Closed-loop cooling withdraws less water than open-loop cooling, but it consumes more

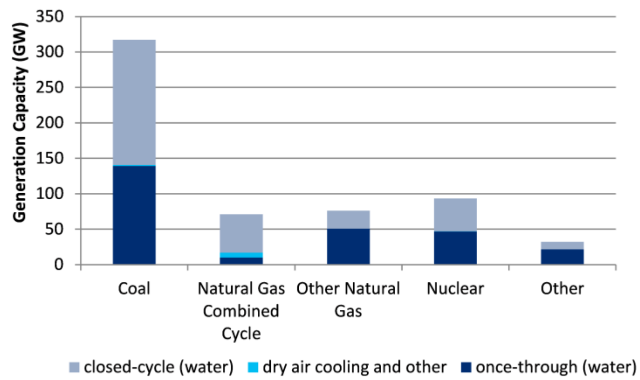
The competition for water in times of water scarcity poses challenges to electricity generation, particularly in regions where water use is tight for human consumption, agricultural irrigation, and power generation. As human consumption and irrigation are usually given priority, the capacity to generate power is usually curtailed in times of a drought, such as in California. The situation becomes more problematic during warmer summer months, when water temperatures climb and water levels in rivers decline. Coal and nuclear power plants, particularly those with open-loop (once-through) cooling, are often forced to reduce generation right when the demand for electricity is at its highest. Open-loop cooling requires withdrawing water from rivers or other water bodies before returning much of the water back to the system albeit at a higher temperature. Closed-loop cooling contains water inside water pipes in closed-loop, so that it generally does not withdraw water from the outside, but instead an outside water body is used to cool pipes. This withdraws less water when compared to open-loop cooling, but consumes more.

Dry cooling is another emerging method of cooling, which uses air passing over cooling water by one or more large fans. However, dry cooling is not effective for power plants that use a lot of steam, such as coal and nuclear power plants. Dry cooling is also not as efficient as other cooling processes as dry cooling plants incur

[76] IEA (2012) *World Energy Outlook – Water for Energy*

energy penalties, meaning power plants using them are not as efficient when compared to power plants that use once-through or wet tower cooling. Of the 1,655 cooling systems in the U.S. as of 2012, only 56 use dry cooling, of which 51 belong to gas-fired power plants.

Figure 61. Capacity of Power Plants by Cooling System Type in the U.S.




Source: EIA, Citi Research

High river water temperatures and low river water levels threaten ecosystems and waterborne transportation

The need to reduce power generation in times of drought, low river water levels, or high river water temperature derives from the need to keep water levels adequate and water temperatures moderate. As a power plant is cooled, the water used to cool it is warmed before being discharged back into the water source. Therefore the cooling of power plants necessarily warms up the water. But if the water temperature is too high, it can disrupt the river's ecosystem and potentially be fatal to species. In addition, if the water level of the river is already low, water withdrawal for cooling can lower the water level further. If the river is also used for shipping, low water levels could threaten waterborne transportation.

Cutting back generation from coal or nuclear power plants in times of low water levels or high water temperatures, which tend to occur when outside air temperatures are high, exacerbates the problem of generation shortage, leading to higher power prices in regions with competitive markets or even brownouts/blackouts. With high outside air temperatures, electricity demand usually rises, as the demand for air conditioning increases. But if the usual set of coal-fired and nuclear power plants cannot generate electricity, more expensive forms of generation are turned to if and when they are available. Although generation adequacy is a key focus of many power regions, there are circumstances when there is simply not enough power supply. When this happens, demand has to be curtailed.

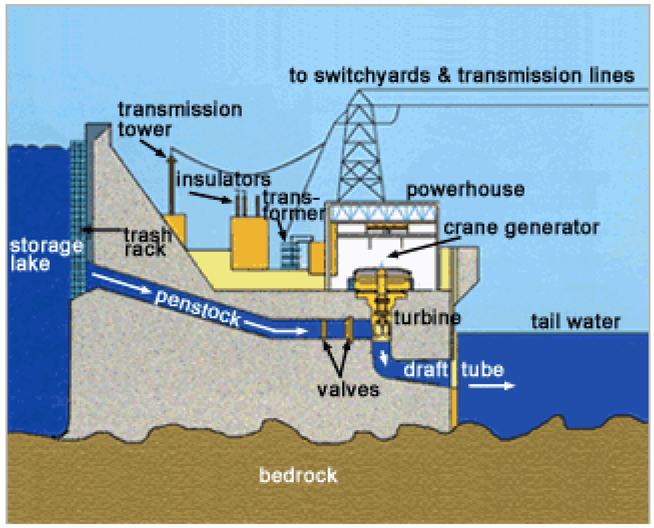
In addition, in locations where water production requires significant energy use, drought and high temperatures would not only sharply narrow the gap of surplus power between supply and demand, but also worsen the deficit of power supply to demand in more severe situations. For example, in India farmers who need to grow crops would draw more heavily on water pumps to obtain ground water during periods of high air temperatures. Higher water pump use raises electricity demand. Further, the utilization of water desalination, where available, rises in times of high air temperature or water stress elsewhere in nearby regions. Power demand also rises as a result.

Water shortage problems affecting generation is not uncommon globally. In the U.S., the Midwest, Southeast and Texas have had experiences with severe drought that limited generation. The 2006 drought in Europe also caused several utilities to shut or curtail power generation from fossil and nuclear power plants.

## Power Generation and Water: Hydroelectricity

Hydroelectricity is one of the earliest forms of generation and makes up the bulk of all renewable energy generation, but its future faces many challenges, from limited new sites and climate change, to perhaps even environmental activism.

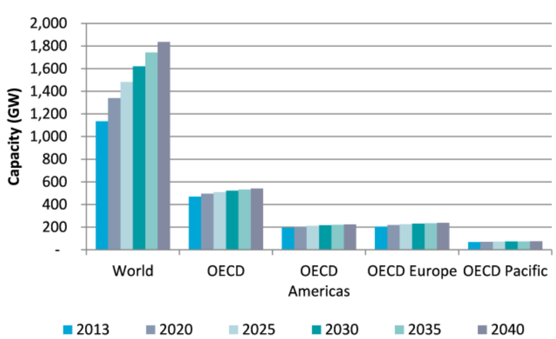
Figure 62. Hydroelectricity Generation Process




Source: U.S. Department of Interior

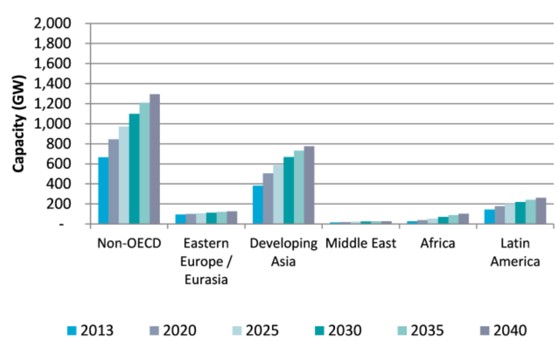
The growth of hydroelectric generation will likely slow in the advanced economies but could still grow significantly in emerging market countries. In developed countries, large-scale hydroelectric power generation already exists at many suitable sites, as the generation technology reached maturity early on. Hydro dams were also thought to be good ways to regulate water flow, serving multiple additional purposes: power generation, irrigation, recreation, and economic development. The developed world also typically has stronger environmental protection laws that consider water conditions for aquatic life, thereby placing some limits on the growth of hydro generation.

Figure 63. The IEA Projects Only Modest Growth in Hydro Generation Capacity in the OECD Under its Base Case New Policy Scenario…




Source: IEA, Citi Research

Figure 64. …As Much of the Growth in Hydro Generation Capacity Would Take Place in Non-OECD Countries, Most Notably Developing Asia




Source: IEA, Citi Research

Over time, some have become critical of hydroelectric dams for their potential harmful impacts, leading to the demolition of some dams as they can restrict the age-old migration path of fish and also trap sediment, which is critical for maintaining the physical processes and habitats of aquatic systems downstream.

A 2010 study by seismologists at the China Earthquake Administration found that the Three-Gorges Dam in China, with massive amounts of water held back behind dams, triggers more frequent seismic activities. Dams can also restrict the availability of water downstream, affecting other states in the United States or other countries, including Mexico in North America.

# Water Issues and the Mining Sector

Access to water is a major requirement of mining. Water is used for a variety of purposes, but primarily for mineral processing and dust suppression. It is estimated that the mining industry is the second largest industrial user of water after the energy sector. Miners can face a number of water-related challenges which include shortages, surpluses, and contamination and there are linkages between them. Project risks may arise if water issues are not appropriately addressed, such as regulatory constraints, shortages that impact on production, or conflicts with local communities that lead to disruptions or even closure, as discussed in more detail in this chapter.

## Water Used in the Mining Sector

Water in the mining industry is used predominately for ore processing, solvent extraction, and dust suppression.

- **Ore processing / concentrating:** Ore is ground into a slurry with water in order to extract the mineral of interest. This is typical for metals such as copper, gold, and zinc, where the mineral of interest forms only a small part of the rock (ore) that is mined. It is also the approach used for upgrading lower grade iron ore into higher grade pellets (common in Brazil, whereas higher grade iron ore such as the ore that Australia produces is mostly shipped directly without upgrading).

Ore processing is used for upgrading lower grade iron ore into higher grade pellets

- **Solvent extraction:** Some technologies involve extracting the mineral of interest via a solvent extraction process. An example of this is the copper SX/EW (solvent extraction / electro-winning) process that is common in Chile.
- **Dust suppression:** Water is sprayed on haul roads and the like to suppress dust. The Australian Pilbara iron ore operations utilize this technique.

In the case of coal mining, water is needed to wash the resource in order to upgrade it by removing waste material before transporting from the mine site.

Water consumption per unit of output depends on the mine configuration, metallurgy, climate, and approach to recycling.[77] Water use per unit of saleable product will tend to be higher for low-grade operations, since water consumption depends largely on ore production volume and mill throughput volume, rather than on the quantity of final product. Mudd (2008) calculates the use of water in various mining sectors and for different commodities, as shown in Figure 65 below.

[77] Gavin M. Mudd, *Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining*, Monash University, April 2008.

Figure 65. Summary Data for Water Consumption and Different Material Commodities

| Mineral/Metal | Total number of years of data | v. ore throughput (e.g. kL/t ore) | | v. ore grade (e.g. kL/t ore) | |
|---|---|---|---|---|---|
| | | Average | SD | Average | SD |
| Bauxite (kL/t bauxite) | 17 | 1.09 | 0.44 | - | - |
| Black coal (kL/t coal) | 18 | 0.30 | 0.26 | - | - |
| Copper (kL/t ore; kL/t Cu) | 48 | 1.27 | 1.03 | 172 | 156 |
| Copper-gold (kL/t ore; kL/t Cu) | 42 | 1.22 | 0.49 | 116 | 114 |
| Diamonds (kL/t ore; kL/carat) | 11 | 1.32 | 0.32 | 0.477 | 0.170 |
| Gold (kL/t ore; kL/kg (Au) [a] | 311 [a] | 1.96 [a] | 5.03 [a] | 716 [a] | 1,417 [a] |
| Zinc ± lead ± silver ± copper ± gold (kL/t ore; kL/t Zn ± Pb ± Cu) | 28 | 2.67 | 2.81 | 29.2 | 28.1 |
| Nickel (sulfide) (kL/t ore; kL/t Ni) | 33 | 1.01 | 0.26 | 107 | 87 |
| Platinum Group (kL/t ore; kL/kg PGM) | 30 | 0.94 | 0.66 | 260 | 162 |
| Uranium (kL/t ore; kL/t $U_3O_8$) | 24 | 1..36 | 2.47 | 505 | 387 |

[a] If one mine is removed from the data (five points), which ranges from 28 to 48 kL/t ore and 5,800 to 9,442 kL/kg Au, the average and standard deviation become 1.372 and 1.755 kL/t ore and 609 and 1,136 kL/kg Au, respectively
Source: Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining, Gavin M. Mudd, Monash University, April 2008.

## Water Issues for Mining Companies

Mining projects (especially copper and gold projects) face challenges securing access to water

Mining projects in many parts of the world face challenges in securing access to water, as discussed in a 2012 Citi report "*Water Risks & Challenges: The Growing Impact of Water Scarcity on Mining*". Copper and gold projects in South America (specifically Chile and Peru) feature highly among projects with water-related challenges. Our report called *"Copper Book – The Return of Dr Copper"* also highlights that the lack of water availability together with declining ore grades and limited capital expenditure are likely to dampen Chilean copper exports over time. Projects are also facing challenges in many parts of the U.S., Australia, and Africa. Many of these regions face increasing water scarcity due to high competition of water between different sectors and in some areas due to climate change issues. The lack of availability of water can affect production and mineral processing (e.g. Escondida in Chile), the transportation of the mineral down river (e.g. Oki Tedi in Papua New Guinea) or curtail the main energy source in copper fields as low availability of water decreased the production of hydroelectricity in regions such as Africa.

### Examples of Water-Related Disruptions to Mines

### Escondida, Chile

Water availability has been a key factor in determining production performance at Escondida in Chile, with the company regularly commenting that water restrictions have constrained production. For example, BHP reported that Escondida copper production decreased by 2% in the half year ending December 2014 to 553 kilotons (kt). Strong operating performance was offset by the impact of water restrictions during the December 2014 quarter, as BHP had anticipated, as well as industrial action and a power outage in the September quarter. In March 2016, BHP reported that production increased by 18% from the December 2015 quarter as higher concentrator throughput was achieved as a result of improved water availability. In the medium term, completion of the Escondida Water Supply project will help to enable the utilization of three concentrators. BHP reported that the $3.4 billion Escondida Water Supply project, involving a new desalination facility to ensure continued water supply to Escondida, was 99% complete in January 2017, with initial production targeted for calendar 2017.

### Copper Market – Africa and Asia

In its January 2016 copper outlook, Wood Mackenzie[78] reported that weather was a major contributor to mine production disruptions in 2015, accounting for ~320kt of shortfalls worldwide, and that producers in Africa and Asia in particular required resumption of normal rainfall if further production cuts were to be avoided. In 2015, low water levels in one of Zambia's major hydroelectric dams caused many producers to scale back due to reduced or interrupted electricity supplies.

WoodMac also reported that low river levels associated with El Nino had resulted in suspension of production at Ok Tedi in Papua New Guinea, where resumption of normal rainfall would be required for production restart. Water is required for concentrating and for barging the copper concentrate downriver to the port, and low water levels also reportedly affected the Ok Menga power station, the mines' main source of power. At Ok Tedi, force majeure was declared in August, and production restarted in March 2016[79]. On the same island, WoodMac reported that the phenomenon also led to production being scaled back at PT Freeport Indonesia (Irian Jaya).

Community opposition based on water-related concerns is often a major contributing factor to stalled water projects

Growing social and environmental awareness is also forcing water issues into a broader public forum. Lengthy delays to project approvals, production disruptions or potentially even mine closure have occurred due to conflicts with local communities over the availability of water resources in the area. In our observation, community opposition to mining projects is often grounded in fears about water, as well as concerns about impacts on the agriculture sector and concerns about the pollution of water resources. The issue may be more contentious in areas where local communities lack access to clean water supplies, while miners have access. Concerned communities can readily find information on what has happened at other operations, and a company's or the broader industry's perceived poor track record can fuel opposition to new projects. A number of large projects have been stalled, mothballed, or abandoned sometimes after considerable capital has been expended. Community opposition based on water-related concerns is often a major contributing factor. High profile examples include the Newmont Mining's Conga copper and gold mine in Peru and Barrick Gold's Pascua-Lama mine on the Chile/Argentina border, which are discussed in the box on the next page.

Too much water can also prove a challenge. Heavy rainfall or flooding can cause operational disruptions (i.e. flooded pits) and potential concerns about the pollution of water courses can hamper water disposal. When water is discharged from, or flows off or through a mine site, this can prompt concerns over pollution of water resources and impacts on agriculture.

[78] Wood Mackenzie, January 2016, *Copper: what to look for in 2016.*
[79] https://ramumine.wordpress.com/2016/02/06/ok-tedi-board-approves-png-copper-mine-restart-from-march-1/

## Projects Delayed by Water-Related Issues

Below are some diverse examples of how water-related issues have very significantly impacted the progress of specific major projects, leading to major delays or indefinite mothballing.

### Conga Copper/Gold Project, Peru (Newmont, Buenaventura, International Finance Corp)

The Conga copper and gold project is located in the Cajamarca region in Northern Peru in a region that has abundant surface and ground water. The Andean farming community has long been concerned about plans to replace four natural lakes with engineered reservoirs, citing negative experiences with the existing companies operating the nearby Yanacocha mine. Construction at the ~$4.8 billion project commenced in 2010 and fierce demonstrations resulted in Peru's president declaring a state of emergency in November 2011 and asking Newmont to suspend operations. Opposition has persisted. Work was suspended, except on water-related projects. By the end of 2015, ~$1.7 billion had been expended on the project, including on water-related facilities. In February 2016, Newmont announced that it would not proceed with the full development of Conga without social acceptance, solid project economics and potentially another partner to help defray costs and risk, and that it is currently difficult to predict when or whether such events may occur. It said that under the current social and political environment, the company does not anticipate being able to develop Conga for the foreseeable future.

### Tia Maria Copper Project, Peru (Southern Copper Corp.)

The Tia Maria copper SX/EW project is located near Arequipa in southern Peru, and has faced delays since 2011, with protests and related deaths. The company initially proposed a development using freshwater from local sources, with locals fearing that the project would drain rivers, pollute water resources, and harm agriculture. The Government rejected the project's Environmental Impact Study citing water sourcing as one of the issues. The company subsequently changed its plans, and its revised environmental plan that involves desalination was approved in 2014. However, the media reports that protests continued in 2015, resulting in numerous deaths and injuries. In February 2016, Southern Copper reported that while it has received environmental approvals, the issuance of a construction permit has been delayed by the Peruvian authorities due to pressures from anti-mining groups. The government has recommended a dialogue roundtable to resolve the differences. The company has launched a communications plan, and claims that anti-mining groups have confused the community over the project's water source and consumption. It now states that the project will only use seawater, which will be transported >25km to an elevation of 1,000 meters above sea level, constructing a desalinization plant at a cost of $95 million. The company states that it guarantees the Tambo River water resources and the water resources from the wells of the areas will be used solely for farming and human consumption, as it has been done until today.

### Pascua Lama Gold Project, Chile (Barrick Gold)

Barrick Gold's Pascua Lama gold, silver, and copper project, straddling the Chile-Argentine border at an altitude of ~5000 meters in the Andes, has faced substantial opposition and delays, and has been stalled since 2013. On the Chilean side, there is very little precipitation apart from winter snowfalls, and water from snow and glaciers provides the valleys below with the majority of their water resources. Community concerns regarding activities on glaciers and the peri-glacial environment, and the impact on water supplies, meant that Barrick had to redesign the surface mine outline from its initial plans to avoid and protect these ice features. The company must also ensure that snowmelt run-off is diverted around the mine area, and protected. The company planned that water coming into contact with the mine area would be captured for operational use, particularly due to the presence of sulphides in the rock which creates the potential for acid rock drainage. In mid-January 2013, Barrick reported a compliance failure, when erosion of a channel meant that some run-off water was diverted into the operational area, contrary to permit conditions. The project was mothballed in 2013 when a Chilean court ordered the company to halt construction over water management concerns. Only activities necessary for environmental protection were allowed until the water management system had been completed. The suspension announcement was made by Barrick on April 10, 2013. Barrick subsequently shelved the project citing cost overruns and falling bullion prices. The company's share price fell from ~$34 in early January to ~$15 in July 2013. In 2016, the company commented that it is re-evaluating plans for the project, potentially considering a smaller pit. Meanwhile, a class action suit is underway, involving German asset manager Union Investment, alleging that Barrick made false statements about Pascua-Lama relating to environmental compliance, internal controls, and accounting for capital costs and accounting statements. A U.S. judge has stated that the plaintiffs have provided ample evidence to support their claim and those investors who purchased Barrick Gold stock between May 2009 and November 2013 can join the action. In September 2016, Barrick brought back a former executive to advance a scaled-back development plan for the project that would focus on Argentina.

### El Dorado Gold, El Salvador (OceanaGold)

In El Salvador, community and government concerns about the pollution of river water contributed to the El Dorado gold project being stalled. 'Anti-mining' groups are concerned that mining will destroy surface waters — which most of El Salvador relies on for drinking water — and displace people from their land, and concerns are fueled by pollution observed from some existing older operations. The mining company, Pacific Rim, subsequently acquired by ASX-listed OceanaGold, filed an arbitration claim with the International Centre for the Settlement of Investment Disputes (ICISD) in Washington in 2009, seeking monetary compensation of ~$300 million, following the passive refusal of the El Salvador Government to issue a decision on its permit applications for the project. In March 2016, Oceana stated that the matter is with the Tribunal for determination, and that it is strongly committed to seeking a negotiated outcome to the permitting impasse.

### Los Pelambres Copper Project, Chile (Antofagasta)

At Los Pelambres, local farmers in the town of Caimanes alleged that a tailings dam built in 2008 to create a reservoir for mins waste, created a water shortage in the already dry area, and blamed the dam for drying up a local stream and contaminating underground water. The company, Antofagasta, stated that a drought began around the same year that the dam opened. In 2015, a Chilean judge ordered the company to demolish the dam, and the company continued to operate while the appeal process is underway. The company stated that operations will have to stop if the tailings dam can't operate. Residents are reportedly also concerned about the safety of the dam, following the Samarco dam collapse in Brazil. The company partially attributed a decline in copper production at Los Pelambres in 2015 to community actions. Following the community issues last year, Antofagasta has said it will use desalinated water for all future expansions at Los Pelambres, which has added $400 million to the previous capex budget of $1.2 billion for an expansion of 95ktpd ore processing capacity. In May 2016, Antofagasta signed an accord with the community to bring their protests to an end and company Chairman Jean-Paul Luksic told shareholders the deal "addressed certain requirements set down by courts in Chile and will see Los Pelambres invest in future water supply solutions, safety measures, community development projects and compensation."

Miners, particularly in water-stressed regions, cannot take access to water for granted and may increasingly have to be "self-reliant" when it comes to water sourcing**.** Miners may have to actively pursue alternatives to accessing water from local freshwater sources. Governments are implementing increasingly stronger restrictions on access to water by miners as they try to balance mine development with the needs and concerns of communities. Project delays in Chile, Peru and El Salvador, discussed in the box above, were partially due to constraints posed by governments.

Efficiency and recycling measures will be particularly important where water is scarce

There are a number of ways in which water is sourced for various projects, ranging from endeavors to acquire water rights, sourcing water from abandoned mines in the area, through to the use of recycled municipal waste water, building desalination plants, and direct use of seawater. We suspect miners in regions of water scarcity will increasingly plan for solutions like desalination or the direct use of seawater from the early stages of project development to avoid conflict and potential delays or worse. Efficiency and recycling measures will be particularly important where water is scarce, and recycling can help to contain potentially contaminated water from leaving the site. Some solutions to address scarcity are more expensive than others, and optimal solutions will vary with project configuration, and local conditions. In some regions, particularly South American copper and gold mining regions, miners increasingly have to become "self-sufficient" in sourcing water by using seawater, either directly or desalinated. Examples are BHP's desalination plant at Escondida (copper, Chile) and direct use of seawater at Antofagasta's Centinela/Esperanza project (copper, Chile).

Engineering solutions also clearly add to project costs**.** The associated cost of water solutions, when balanced against project economics and long term commodity prices, may prevent the construction of some more marginal projects. Recent tailings dam failures are only likely to exacerbate concerns about the potential impact of mining on water resources. Impacts can occur both through major dam failures and also due to seepage. The high profile November 2015 failure of BHP and Vale's Samarco iron ore tailings dam in Brazil sent tailings the length of the Rio Doce River to the ocean, and killed 19 people, resulting in a suspension of operations and a clean-up bill expected to be in excess of $2 billion for Samarco, BHP and Vale. The 2014 failure of the tailings dam at Mount Polley gold and copper mine in British Columbia had already shone a spotlight on this significant risk area. The nature of tailings dam risks will be influenced by factors such as geology, geography, and the nature and chemistry of the tailings. For example: is the dam in an earthquake-prone area, a mountainous or flat area; are there communities or ecologically sensitive environments downstream; are the tailings wet and unconsolidated or thickened or dried; finally, are there chemical issues such as acid prone materials or cyanide (the latter typically used in gold processing)?

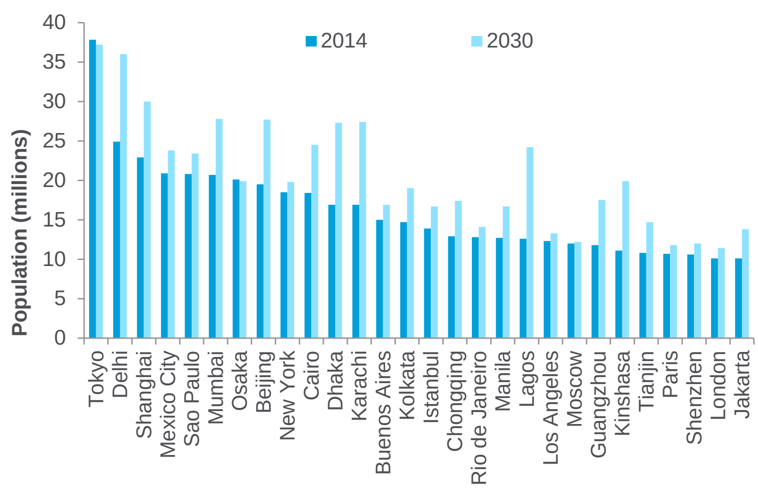
# Other Uses of Water: Urban and the Environment

Water is not only essential for the agriculture and industrial sector as described above, but is also essential to maintain the livelihoods of human beings and to sustain the environment.

## Domestic Water Demand and Urbanization

It is estimated that over 800 million people in the world do not have access to clean water. The demand for water for domestic purposes (cleaning, sanitation, and drinking) is estimated at approximately 400 $km^3$. Due to population growth, demand is estimated to increase to 660-900 $km^3$ by 2030. The majority of this demand will occur in cities — currently more than half the population (3.9 billion people) live in towns and cities; this number is expected to increase to 5 billion people by 2030. Forecasters predict that by this time there will be 27 megacities with a population in excess of 10 million people — of which 21 will be in the "Global South" (Figure 66). The increase in urban population will bring with it economic, social, and environmental problems which cities need to be prepared for.

Figure 66. Population in Cities > 10 Million in 2014 and Projections in 2030




Source: Citi Research

Interbasin transfers of water secures 180 million people from water scarcity in the largest 100 cities in the world

Some cities are already facing acute water problems. They are particularly vulnerable because they depend on resources such as water, food, and energy to be imported from outside the city boundaries. In many areas, city infrastructure has not kept pace with the massive urban growth, leaving people without adequate access to drinking water and sanitation. The concentration of millions of people into small areas increases the stress on finite water supplies available in or near city centers. To counter this, many urban centers either invest in the building desalination plants and/or water treatment plants or exploit water resources far from the city center. Figure 67 lists some of the largest urban water transfer systems in a number of cities around the world. Los Angeles, for example, uses cross-border transfers to obtain the majority of its water from hundreds of miles away — places including the Colorado River, the Delta in northern California and the snow pack of the eastern Sierra Nevada mountains.

Interbasin transfers secure water to 180 million people in the largest 100 cities in the world where water is scarce. The largest cities import 43% of their water supply from interbasin transfers, making them responsible for transferring 3.2 million cubic meters of water at a distance of 5,675 km every day, which when calculated on an annual basis is equivalent to ten times the size of the Colorado River.[80]

Figure 67. Major Urban Water Transfers

| City | Country | Population in 2014 (Million) | Cross-basin transfer (Million litres per day) |
|---|---|---|---|
| Los Angeles | U.S. | 12.3 | 8,895 |
| Boston | U.S. | 4.7* | 3,307 |
| Mumbai | India | 20.7 | 3,220 |
| Karachi | Pakistan | 16.1 | 2,529 |
| Hong Kong | China | 7.2 | 2,447 |
| Alexandria | Egypt | 4.4* | 2,300 |
| Tianjin | China | 10.8 | 2,179 |
| Tokyo | Japan | 37.8 | 2,170 |
| San Francisco | U.S. | 3.6* | 2,014 |
| San Diego | U.S. | 3.2* | 1,442 |
| Ahmadabad | India | 7.1 | 1,363 |
| New York | U.S. | 18.6 | 1,348 |
| Tel Aviv | Israel | 3.3* | 1,225 |
| Pretoria | South Africa | 1.5* | 1,217 |
| Sydney | Australia | 4.5* | 1,210 |
| Chennai | India | 9.6 | 1,130 |
| Algiers | Algeria | 2.8* | 1,070 |
| Aleppo | Syria | 3.0* | 1,062 |
| Athens | Greece | 3.3* | 1,036 |
| Cape Town | South Africa | 3.4* | 994 |

* Population in 2010 (source McDonald et al. 2014)
** cross basin transfer is defined as the surface withdrawal of water from a drainage basin that does not contain any part of urban agglomeration

Source: McDonald et al (2014), Citi Research

~381 million people in large cities have water supplies that are considered to be stressed

McDonald et al. (2014)[81] estimate that even when taking into account the current urban water supply infrastructure, around 25% of the population in these large cities[82] have water supplies that are stressed. These include cities in both developing countries (e.g. Delhi and Karachi) and developed countries (London and Los Angeles) – see Figure 68. The authors use the same definition of water stress as defined in the previous chapter (use/availability). Any value greater than 0.4 for surface water and 1 for groundwater was considered to be stressed. The water stress index was higher for groundwater, as the stock of accumulated water in aquifers could be substantial and allow cities to continue using this resource for years, until this stock was completely depleted. They estimate $4.8 trillion of economic activity that occurs in one-quarter of water-stressed cities identified in this analysis depends directly or indirectly on the availability of adequate water supplies.

[80] Postel, S. (2014). *World's largest cities move water equivalent to ten Colorado Rivers to meet their annual water needs*.
[81] McDonald R.I, K. Weber, J. Padowski, M. Florke, C. Schneider, P.A. Greene, T. Gleeson, S. Eckman, B. Lehner, D. Balk, T. Boucher, G. Grill, M. Montgomery. (2014). *Water on an urban planet: Urbanization and the reach of urban water infrastructure*, Global Environmental Change, 27, pp 96-105.
[82] The authors define large cities with population greater than 750,000 people.

Figure 68. Largest Cities Under Water Stress

| Urban agglomeration | Country | Population in 2014 (Million) | Population 2030 (Million) |
|---|---|---|---|
| Tokyo | Japan | 37.8 | 37.2 |
| Delhi | India | 24.9 | 36.0 |
| Shanghai | China | 22.9 | 30.0 |
| Mexico City | Mexico | 20.9 | 23.8 |
| Beijing | China | 19.5 | 27.7 |
| Karachi | Pakistan | 16.9 | 27.4 |
| Kolkata | India | 14.7 | 19.0 |
| Istanbul | Turkey | 13.9 | 16.7 |
| Chongqing | China | 12.9 | 17.4 |
| Rio de Janeiro | Brazil | 12.8 | 14.1 |
| Los Angeles | U.S. | 12.3 | 13.3 |
| Moscow | Russia | 12 | 12.2 |
| Tianjin | China | 10.8 | 14.7 |
| Shenzhen | China | 10.6 | 12.0 |
| London | U.K. | 10.1 | 11.4 |
| Lima | Peru | 9.7 | 12.2 |
| Bengaluru | India | 9.7 | 14.7 |
| Chennai | India | 9.6 | 13.9 |
| Hyderabad | India | 8.6 | 12.8 |
| Wuhan | China | 7.8 | 9.4 |

Source: McDonald et al. (2014)[81], UN, (2014)[83], Citi Research

## Case Study- Mexico City

Mexico City is the fourth most populated city in the world with 18% of its population concentrated in a 4,250 $km^2$ area. The Mexico City metropolitan area generates a total of 35% of Mexico's GDP.[84] As Mexico's population increased during the past century, existing infrastructure to supply water became insufficient to meet demand (urban demand currently exceeds locally-available renewable freshwater resources by 1.73 times) which has resulted in over-extraction from its aquifers and the transportation of water over large distances. Today the city receives 29% of its water from the Cutzamala River system and the Lerma Chapala basin. Water from the Cutzamala system is moved more than 125 kilometers and pumped an additional 1,100 meters in elevation.

It is estimated that four out of the 14 aquifers in the Valley of Mexico Basin are overexploited and inter-basin transfers have resulted in social conflicts with communities in the donor basin due to the lack of compensation for the perceived exploitation of their resource.[85] If Mexico City continues to grow at the present rate, extraction will exceed availability of water by a factor of 2.25 times by 2030.[86] The growth of Mexico City has been supported by a policy that is based on the over-exploitation of water resources. The city's complex and aging infrastructure suffers from numerous failings — 29 water treatment plants are supposed to assure the suitability of water for normal use, but some 40% of water is lost through leakage or to people who do not pay for it. The price for water is also considered to be cheap when compared to other metropolitan areas in Mexico. Recognizing that water could no longer be considered a public good which is free for all to exploit, the government launched an initiative to increase the pricing system based on fixed tariffs and increased private sector participation in the distribution, metering, billing, and maintenance of water networks. Water infiltration programs to recharge groundwater and rainwater harvesting have also started. It remains to be seen whether these measures will improve the water situation in the city.

[83] United Nations, Department of Economic and Social Affairs, Population Division. (2014). *World Urbanization Prospects: The 2014 Revision Highlights.*

[84] Chelleri L, Schuetze T, Salvati L. (2015). *Integrating resilience with urban sustainability in neglected neighbourhoods: Challenges and opportunities of transitioning to decentralized water management in Mexico City*, Habitat International, 48, pp 122-130.

[85] WWF. (2010). *Big Cities, Big Water, Big Challenges.*

[86] Morales J.A and L. Rodriguez Tapia, *The Growth of Water Demand in Mexico City and the over-exploitation of its aquifers, in Water Resources in Mexico*, Vol 7, Springer.

Urban water management solutions depend on cities' individual limitations

The solution to urban water scarcity varies depending on which limitation a city faces. In regions which have a geographical limitation in water availability such as cities like Los Angeles and Beijing, increased coordination among other cities/towns within the region may help alleviate some of the stress. Rich cities have the purchasing power and are able to obtain the majority of their water outside their urban agglomerate as shown in Figure 67. Watershed management in these areas is therefore of utmost importance to ensure a reliable water supply and transfer of good quality water supplies. These can include forest protection, reforestation, introducing best agriculture practices, and so on. Competition in these basins from other sectors will increase, so effective management and allocation of water between users is imperative. Other solutions include investment in infrastructure to maintain and improve the current infrastructure (for example reducing leakage in pipes and distribution networks, building desalination plants, investing in green infrastructure, and better urban water management systems such as smart metering).

## Water Needed to Sustain Aquatic Ecosystems

Water needed to maintain ecosystems is a fairly a new issue and scientific research in this field has only been underway for the last decade. This concept became relatively important in the literature once it became obvious that in many areas the use of water has become unsustainable, sometimes having a huge negative effect on aquatic ecosystems. Many managers have started to use the term 'environmental flows', which is defined as the 'quantity, quality and the timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems'.[87] Smakthin et al. estimate that approximately 20-50% of total renewable water resources are needed to maintain aquatic ecosystems in fair condition — this however differs by region. Freshwater ecosystems provide a range of goods and services to humans such as fisheries, flood protection and wildlife, and some of these services are worth trillions of U.S. dollars.[88] Therefore when calculating sustainable allocations of water for different sectors, it is important to take into consideration not only the needs of the agriculture, energy, and domestic sectors, but also the requirements of water to maintain ecosystems in good condition.

[87] Swedish Water House et al. (2009). Securing water for Ecosystems and Human well-being: The importance of Environmental Flows

[88] Smakthin V, Revenga C, Petra Doll. (2004). A pilot global assessment of environmental water requirements and scarcity, Water International Vol 29, pp 307-317

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# Framing the Solutions

# Complexity of Water Management

Integrated water resource management promotes the coordinated development and management of water

Managing water for different users is not easy (as outlined in the box below). The availability of water resources varies from day to day, from season to season, and from year to year. It is also difficult to measure water with any accuracy given that part of the available resource is found underground. There have been many studies done over the years highlighting these problems and suggesting potential solutions. Concepts such as integrated water resource management (IWRM) which is a process which promotes the coordinated development and management of water, catchment-based management which encourages collaborative working at a river catchment scale, better pricing systems, and investment in infrastructure have all been suggested as solutions to water management over the years by policymakers, academics, and industry leaders. The problem with global water resources is not with its availability but with the management of the resource itself which requires good institutions, appropriate legislation, adequate pricing systems, and good water infrastructure to provide clean water resources. The effective management of water is not rocket science. There have been many countries that have managed water effectively over time — like Singapore and Israel where the investment in technology such as desalination, adequate pricing, and good regulation has encouraged the efficient use of freshwater by different sectors (refer to case studies at the end of the report). We explore some of these solutions in more detail in the next section of the report.

## Water Management and the Complexity of the Social-Ecological System

*Professor Keith Richards, University of Cambridge*

It is almost a truism that managing water requires integration; and the principles of IWRM (Integrated Water Resource Management) were presented at the Rio World Summit in 1992, in the form of the Dublin Principles. A variant of this integration, IRBM (Integrated River Basin Management), had been in existence since the 1930s, traceable to the Tennessee Valley Authority (TVA), and exported as a concept to many other large catchments globally, even as its later failings became increasingly apparent. Today, the complexity and uncertainties of water as a resource have increased such that the notion of managing it almost seems hubristic.

Catchment-based IRBM was seen as a necessary framing for water, since river basins are spatial units that permit measurement of the water resource; and measurement is the first requirement of management (and, indeed, of monetization). Precipitation falls on the land, and its runoff drains gravitationally to a downstream point on a river where the outflow can be measured and the water balance assessed, although reliable data are needed on the rainfall, evaporation and transpiration that occur across the basin's surface. Managing water also requires understanding moisture fluxes across the land and back to the atmosphere, but influencing these processes by managing land is difficult, because the fixity of land means that its ownership can be given legal status that inhibits intervention and regulation. Given the fluidity and (apparent) continual renewal of water, owning it is more elusive, and the legal status of access to water has therefore varied more widely.

Inputs, outputs, and storage of water vary continually on all time scales, from day to day, season to season, and year to year, so the data requirements for reliable management are considerable. At the extremes, management of water involves dealing with the risks of flooding and of drought; and decisions about infrastructure to facilitate the protection or storage that these extremes require need investments with payback periods extending well into the future. The (uncertain) changes in average and extreme conditions as climate change affects a basin thus need to be estimated, but so too do the changing fluxes across the land surface associated with changes in land cover. The latter may often be as important as the effects of climate change, especially when incremental decisions, each of which seems insignificant in itself, are cumulated over time (for example, when forest clearance for agriculture led to increased surface runoff and soil erosion - just as in the Tennessee Valley in the early 20th Century, leading to the need for soil conservation - and the TVA). Water management thus also requires land management, across broad catchment scales; and therefore requires collective responsibility.

Although there are practical uncertainties about measurement, in principle the water resource can be measurable — for example as the 'renewable freshwater resource', or the 'effective precipitation' (the average runoff after actual evapotranspiration is deducted from rainfall). However, the usable water resource involves both surface and subsurface water, and the largest volume of available water is often that stored in subterranean aquifers as groundwater. Neither the volume nor the residence time of this water source are reliably known, and in many agricultural regions (from the Indo-Gangetic Plain to California), groundwater has been mined for years to supply the needs of irrigation at rates faster than it is being naturally replenished as part of the renewable resource (as described in the section on agriculture and water use). This is now a crisis for these regions, where future water security can only be improved by reducing extraction rates, although this will reduce crop yields and threaten (global) food security.

When water is withdrawn to be used, variable amounts may be returned to a river, and only the 'consumptive use' is lost to other users. However, the return flow is often polluted, and may not be re-usable without some form of treatment. The boundary between water consumed and water returned is therefore fuzzy; if the quality of return flow is badly degraded, it has effectively been consumed. Polluted water can be treated and reused, and this can happen on multiple occasions as the water drains downriver and is extracted, used, treated, and returned. The available resource is therefore not a static amount, but is dynamically dependent on how often this cycle can occur in a basin, which depends on the scale of the basin, the technical limits on the volume and rapidity of treatment, and the cost of the treatment.

Water resource management therefore involves more than an integration with land use; it also involves integration with the energy system (see section on energy and water), in that it costs an energy input to treat water in order to augment the water resource. Thus, the water-land-energy nexus is now a closer approximation to the integrated system within which water resource management occurs. And wherever water resources are under stress, regulations or incentives are needed to ensure that all water users internalize the environmental costs of the treatment needed for re-use to be feasible.

Water is implicated in almost every human activity, a ubiquity that is reflected in the assessment of the 'virtual' water content embedded in products, or required to produce them. The physically embedded water in, say, a vegetable crop, is insufficient to prevent its long-distant transport, but the total water use required to grow it may be a significant drain on the water resource of the source region. Using the virtual water concept, it is now possible to examine the global water footprint of a country, a city, or even a person, and to consider a global dimension of water management. A water-stressed region should logically develop its economy by importing goods that have large virtual water contents from regions with plentiful water; however, this rational outcome seems to be rarely achieved, and more commonly, water-stressed regions appear to export virtual water. Perhaps virtual water will indeed require global water governance.

This issue exposes one of the key problems for IRBM, which is that few aspects of human organization are necessarily structured around river basins. The spatial units within which political and fiscal decision-making occur rarely match river basins, and the distributions of population and economic activity do not match rainfall and runoff patterns. It would be unrealistic and unreasonable, to require the spatial units within which all other human activities function to be adjusted to match hydrological boundaries. Indeed, one of the criticisms of the TVA was that its catchment-scale management unit overlaid an unaccountable water bureaucracy onto pre-existing political structures. The inevitability of boundary mismatch is reflected in the necessity of water management taking place within a polycentric system of overlapping administrative units at different spatial scales and inter-related institutions, each addressing a particular sector of the complex social-ecological unity. This implies that water management will often appear to involve high transaction costs, and may appear to be inefficient when viewed from the perspective of a single part of the system. But removing part of this evolved, collaborative governance structure risks losing the very integration that water, and its many ramifications, demand.

If this already seems complex, the Dublin Principles also emphasize participatory approaches to water governance, in which all stakeholders and interested parties are engaged in helping to identify optimal water management strategies. What is less than clear is how stakeholders should be identified, or how they should be engaged; for in the case of water, everyone is a stakeholder. Access to potable water is a necessary public good for all humans, and since 2002 has been an independent human welfare right under the UN International Covenant on Economic, Social and Cultural Rights (ICESCR); it is the sixth of the UN 2015 Sustainable Development Goals that there should be "universal and equitable access to safe and affordable drinking water for all" by 2030. This is coupled with the need for adequate sanitation, since the absence of this threatens the provision of potable water. Participation somehow needs to engage not only existing stakeholders - the identifiable institutions (formal and informal, customary and official), agencies, non-governmental organizations (NGOs), businesses, and industries, but also to find ways of consulting people. Finally, a voice also needs to be heard on behalf of the ecosystems on whose multiple provisioning, regulating, supporting, and cultural services humans rely.

It therefore appears that water governance and management always intervenes in what is a complex social-ecological system, and must increasingly involve a nexus that embraces water, land, energy, institutions and people, while also integrating all of these. Indeed, IWRM is no longer sufficient; WRM needs to have new adjectives attached to it, such as Sustainable, Collaborative, and Adaptive. This includes embracing solutions from both the supply side through the investment in water infrastructure to ensure multiple use of water for different sectors (including the environment and human beings), effective policies that enable more efficient use of water (pricing systems, tradable permits) and the use of innovative technologies, as discussed in more detail in the next section.

# Demand-Side Solutions: Market-Based Instruments and Regulation

## Global Investment

Solutions regarding too much or too little water have been dominated by supply-side engineering for many years. Even though there is an urgent need to invest in water infrastructure as described in the next section, demand-side solutions that aim to reduce the inefficient use of water should also form part of the solution. In some countries the allocation of water is highly political, favoring one sector or even a particular region over another. Institutions that govern the use of water are usually reluctant to raise water prices to reflect the true cost of water.[89] Market-based instruments such as efficient pricing and tradable permits, together with good legislation and strong institutions, can help policy makers manage the allocation and demand for water by different users.

## Efficient Pricing

Water prices do not reflect the scarcity of the resource or other externalities such as pollution costs

Unlike energy, water prices are typically not determined in the market — they are usually set by institutions that govern the resource and in many cases do not reflect the scarcity of the resource and other externalities in their pricing level. Properly managed pricing mechanisms can be an excellent policy instrument for managing the demand for water and for recovering costs. The price of water should reflect its marginal cost and include other environmental externalities and opportunity costs. Another issue to take into consideration is equity pricing which is concerned with the fairness of resource and cost allocation across economically varying groups in a society.[90] Policies targeted to equity pricing can include subsidizing the cost of water use for low-income level populations or adopting various pricing mechanisms to account for varying income levels. Typically pricing mechanisms, regardless of sector, are set up as either as fixed-price, which could be based on household size or farm size, or volumetric-price based on the quantity of water (water meters are required for volumetric pricing mechanisms). Volumetric pricing could also include block pricing where users pay different amounts for different consumption levels — the water price is set per unit of water consumed and remains constant for a certain quantity of consumption (first block). As the consumption of water increases, the tariff shifts to the next block of consumption and so on, until the highest block is reached.[91] In the U.K. only 48% of households have water meters while the rest have their bills estimated based on an assessment of a property's historic rental value or have been moved to an assessed charge.[92]

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[89] Olmstead S.M. (2010). *The Economics of Managing Scare Water Resources, Review of Environmental Economics and Policy*, 4 (2) pp 179-198.
[90] Ward F.A., Pulido-Velazquez. (2009). *Incentive pricing and cost recovery at the basin scale*, Journal of Environmental Management 90, pp 293-313.
[91] SSWM (Sustainable sanitation and water management), *Water pricing –Increasing Block Tariffs.*
[92] William Andrews Tipper. (2015). *Cutting the cost of water, The case for improving water efficiency in the UK*, Green Alliance.

The use of water for agricultural purposes is rarely adequately priced (or in some cases, is given for free). In the U.S. pricing depends on a number of factors including water rights, allocations, and contractual arrangements. Some farmers with riparian leases (see definition in first chapter of the report) or agreements with the federal government pay as low as $5-10 per 1000 $m^3$, while other farmers with less favorable agreements or those who purchase water from state-level irrigation agencies pay much higher prices ranging from $20 to more than $100 per 1000 $m^3$.[93] Water prices pertaining to surface water often differ from those pertaining to groundwater, even though these two resources are interconnected. Many states regulate the use of surface water very carefully, while the use of groundwater is not regulated as much. In some cases, farmers prefer to use groundwater as the only cost they incur is related to pumping costs. Pricing the full cost of water would encourage farmers to grow high value and low-water-intensive crops and provide an incentive for farmers to invest in better irrigation methods and other innovations. Israel is an excellent example of a water-scarce country which uses price as an incentive for farmers to seek out water-efficient crops (see case study on Israel in the next chapter).

## Water Markets: Tradable Permits

Water markets allow users rather than governments to make complex decisions about the allocation of water resources

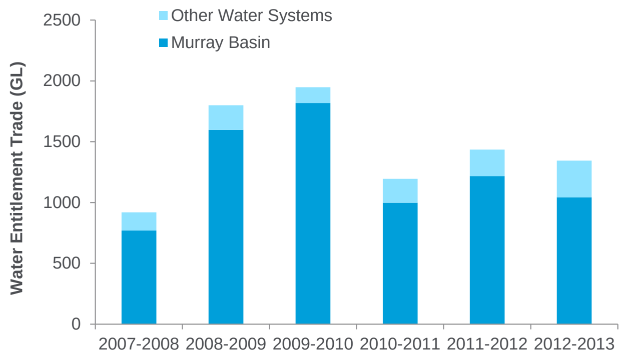
In recent years, the water market approach has been gaining ground in some parts of the world, especially with regard to the allocation of water for irrigation purposes. A water market constitutes a system of formal rules and regulations that govern the buying, selling, and leasing of water use rights (also known as water entitlements) that are ideally traded independent of land titles.[94] Water markets allow users, rather than governments, to make complex decisions about who should use water, where it will be used, and for what.

Australia has set up an effective water market for the allocation of water for irrigation purposes

Australia has been at the forefront of establishing an effective water market for the allocation of irrigation water to farmers in particular from the Murray-Darling Basin (MDB). The market covers parts of six jurisdictions – including four states (Queensland, New South Wales, Victoria, and South Australia), the Australian Capital Territory and the Australian government.[95] The water rights in the MDB consist of: (1) water access entitlements, held on the balance sheet of the owners that provide an ongoing share of the consumptive pool in a water resource plan; and (2) water allocations which refer to the volume of water that is assigned to that entitlement. Figure 69 shows the water entitlement trading in Australia from 2007 to 2013. In 2008, the Australian government also started purchasing water entitlements from farmers to increase environmental flows in the basin (Figure 70). This also had an effect on the volumes that were traded. Water for the environment is provided in two main forms: (1) a rules-based approach where water is left in the river after all holders of water rights have either taken or sold their allocations; and (2) environmental entitlement water where the Australian government holds a specified volume of water entitlement that it purchased from water users and is used for environmental purposes.

[93] OECD. (2010). *Agriculture Water Pricing: United States.*
[94] Debaere et al. (2015). *Water markets as a response to scarcity*, Water Policy, 16, pp 625-649.
[95] Grafton R.Q. and Horne J. (2014). *Water markets in the Murray-Darling Basin, Agricultural Water Management*, 145, pp 61-71.

Figure 69. Water Entitlement Trading Volume in Australia




Source: National Water Commission( 2014)[96], Citi Research

Note: GL refers to gigalitres

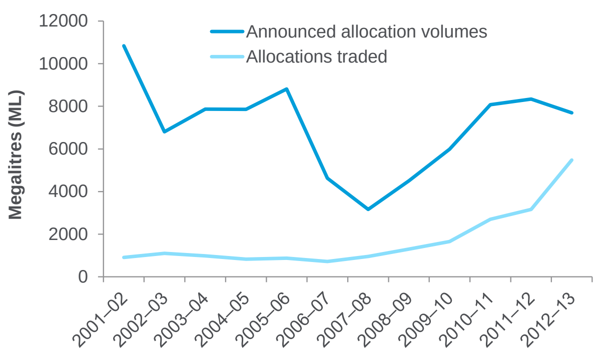
Figure 70. Australian Government's Annual and Cumulative Entitlement Purchases over Time


Source: National Water Commission (2014), Citi Research

The average price of water during the 2007 drought exceeded $800 per ML encouraging the sale of water to farmers who grew high value crops

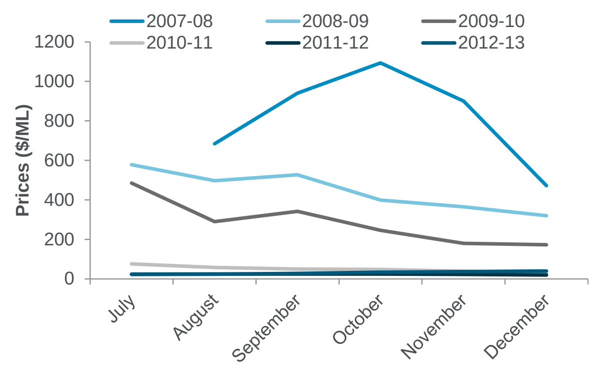
The sharp increase in water trade in seasonal allocations after 2007 was in part attributable to the severe drought (known as the Millennium Drought) that dramatically reduced water allocations (refer to Figure 71 for water allocations in the southern Murray-Darling Basin). To make up for the shortfall of allocated water, farmers — especially those who grew high valued crops — used the water allocation market to secure the water that they needed. Farmers also responded to less available water by changing their crop mixes and improving irrigation technology. The market prices for water allocations have varied in response to seasonal variations in water availability and water scarcity (Figure 72). For example the average price of water during the 2007-08 drought in the southern MDB (August to December) exceeded $800 per megaliter of water.[97] At this price, water extraction is uneconomic for many crops and effectively encouraged the sale of water to farmers who grow high value crops or permanent plantings such as orchards. In 2010-11which was effectively a wet year, the average price during the same months was $45 per megaliter of water.

Figure 71. Sharp Fall in Water Allocation Volumes in Southern Murray-Darling Basin During the 2007-08 Drought




Source: National Water Commission (2014), Citi Research

Figure 72. Average Allocation Prices in the Southern Murray-Darling Basin




Source: National Water Commission (2014), Citi Research

[96] National Water Commission. (2014). *Australian water markets: trends and drivers 2007-08 to 2012-13*, NWC, Canberra
[97] ML= megaliter, 1 ML=1e6 $m^3$

The trading of water could generate substantial economic returns for both buyers and sellers and reduce the impact that a drought could have on regional GDP

The trading of water could generate substantial economic returns for both buyers and sellers and also reduce the negative effect that a dry year could have on a particular sector/region. It is estimated that inter-regional and intra-regional trade of water reduced the effect of Millennium Drought on regional domestic product in the southern MDB from $11.3 billion to $7 billion.[98]

There have been other places where water markets have been effective. The Northern Colorado Water Conservancy District (NCWCD) is one of the most mature and longest operating water markets of the United States.[99] This market emerged from the development of the Colorado-Big Thompson Project (C-BT), a federally-funded water transfer project from the Colorado River to the eastern edge of the Rocky Mountains. The volume of water that is delivered each year depends on the availability of water and seniority of the water rights acquired for the project. Another example is the market that was developed on water allocated from the Edwards Aquifer in Texas. A cap was set up on the amount of total water extractions from the aquifer especially in drought periods. The 2016 drought in California also raised the discussion of whether the state should set up a water trading system similar to Australia. In the 1980s California did adopt laws that jump-started a water trading system. However it became apparent that this was not working to its full capacity and there were major barriers to sharing water amongst different users including: (1) the complicated water rights that are currently in place; (2) the highly decentralized system of water supply management with hundreds of urban agencies and irrigation districts involved; and (3) conveyance limits on physically moving water between potential buyers and sellers.[100]

Water markets can be an effective way of managing the allocation of water amongst different users, however there are several elements that need to come into place before such a system is effective. These include amongst others: (1) the development of a basin-wide political leadership; (2) a regulated framework that facilitates trading; (3) concise market information on trading that allows timely and accurate decision-making by market participants; (4) the establishment of a competitive market that responds to seasonal changes in supply and demand for water; (5) effective control and monitoring of extractions; (6) physical systems that allow the timely delivery of water from one user to the next; and (7) the flexibility in reconfiguring water rights in a way that promotes trade.

[98] Grafton R.Q. and Horne J. (2014). *Water markets in the Murray-Darling Basin, Agricultural Water Management*, 145, pp 61-71.
[99] Debaere et al. (2015). *Water markets as a response to scarcity*, Water Policy, 16, pp 625-649.
[100] Gray el al. (2015). *Allocating California's Water, Directions for Reform, Public Policy Institute of California.*

## The Importance of Regulation

The ability to regulate and allocate water resources whether market-based instruments or command and control systems are used depends primarily on the an effective legal system

Market-based instruments are usually put into practice to enable water users to comply with specific legislation. The authority and ability of any country, state, and/or province to regulate, allocate, and control water resources whether they use market-based or command control systems depends primarily on whether an effective legal framework for dealing with water resources is in place, and if so, what approach the framework has for the ownership and allocation of water.[101] Countries have enacted different legislation to govern the use and quality of water resources. In the U.S., water is governed by both Federal and state law. One problem, however, is that Federal law in some cases has affected the management of water in different states, for example in the allocation of riparian rights for water resources.

The European Union has established a number of directives on water resources. The Water Framework Directive enacts certain procedures to ensure 'good' quality status for water bodies and requires public participation and full cost recovery from primary water users, including externalities such as environmental costs.[102] The member states need to transpose the legislation into national law; however they can develop any mechanism to ensure compliance.

China has over the last few years been increasingly focused on the water sector as a metric for the improvement of environmental protection. The country has started to implement tougher legislation on the use and quality of its water resources and they have developed the '3 Red Lines' Policy which sets targets for total water use, water use efficiency, and water quality. These targets are subdivided at a provincial level and at a national scale. Tougher regulations for tier-1 wastewater treatment plants and higher treatment rates have also been promoted by China's Ministry of Environmental Protection (MEP) for more stringent air and land pollution control. In the third quarter of 2015, the new Chinese Environmental Protection Law became effective and a series of policies were issued to support the waste water treatment industry, including The Water Pollution Prevention & Control Plan (水污染防治行动计划), commonly known as "ten water policies" (水十條). Speaking with industry players, some clear challenges for the water sector include collection of sewage and policing of the polluters. While collection can be summed up as collaborating with local cities to ensure city zoning meets the standards and timely building of sewage pipelines, policing of the polluters is more challenging, as the source of pollution is hard to monitor. Active policing will help ensure industrial companies are meeting their expected pollutant levels at all times, so wastewater plants can treat it properly.

[101] Salman M.A Salman, Daniel D. Bradlow. (2006*). Regulatory Framework for Water Resources Management*, The World Bank.

[102] Green C and Fernandez- Bilbao. (2006). *Implementing the Water Framework Directive: How to Define a "Competent Authority*, Journal of Contemporary Water Research and Education, 135, pp 65-73.

Figure 73. Water Pollution Reduction Plan (水污染防治行动计划) Published by State Council

| Major Criteria | 2020 Target | 2030 Target |
|---|---|---|
| 7 Major River Systems | >70% above Level III Standards | >75% |
| Black Smelly Water | Below 10% in Prefecture or Larger Cities | Eliminate |
| Drinking Water Quality | >93% above Level III Standards in Prefecture or Larger Cities | 95% |
| Underground Water | Below 15% in "Extremely Bad" Level | |
| Coastal Water | 70% to reach Good Status (Level I and II) | |
| Beijing-Hebei-Tianjin | Reduce Unusable (Below Level V) Water Table by 15% | |
| Yangtze and Pearl River Delta | Reduce Unusable (Below Level V) Water Table | |

Source: State Council, Citi Research

China is also tightening up industrial wastewater treatment standards. The Ministry of Environmental Protection has produced guidelines for different industrial wastewater metrics. Outdated regulations for the textile and steel sectors were refreshed in last 2-3 years (see Figure 74 for steel standards). Heightened industry standards could trigger industry consolidation in industries ranging from waste to energy, giving medium to small companies a higher chance to exit the market versus larger companies with advanced technology and ample financial resources which could gain market shares.

Figure 74. Rising Standards for Steel Sector Wastewater Discharge

| | Wastewater Emission (m3/ ton) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Shortage Area | Sufficient Area | pH level | Suspended Particles | COD Level | Ammonia Nitrogen | Zinc | Volatile phenols | Phosphorus |
| 1992 (Grade I Standard) | 10.0 | 20.0 | 6 to 9 | 70 | 150 | 10 | 2 | 0.5 | NA |
| 1992 (Grade II Standard) | 10.0 | 20.0 | 6 to 9 | 150 | 200 | 25 | 4 | 0.5 | NA |
| 1992 (Grade III Standard) | 10.0 | 20.0 | 6 to 9 | 400 | 500 | 40 | 5 | 2.0 | NA |
| 2012 Requirement (Oct 2012-Dec 2014) | 2.0 | 2.0 | 6 to 9 | 50 | 60 | 8 | 2 | 0.5 | 1.0 |
| 2012 Requirement (Jan 2015 Onwards) | 1.8 | 1.8 | 6 to 9 | 30 | 50 | 5 | 2 | 0.5 | 0.5 |

Source: Citi Research

Regulation creates a framework for the effective management of water whilst market based instruments provide effective tools for its implementation

There are many different policies and instruments that governments are using to improve the efficient use of water. Regulation creates a framework for the management of water; while market-based instruments provide effective tools for its implementation. The trading system in Australia is a good example of how such a scheme is successful in controlling water use, especially in times of drought. Such trading schemes require good institutions, well-established water rights, physical systems that allow such trading to take place and low-transaction costs. Pricing water at the right level also provides excellent incentives to reduce the demand for water, while other policy measures such as rebates could also encourage change, even though an assessment of what is economically feasible should be undertaken before such policies are undertaken. Effective pricing could also leverage and pay off investment in infrastructure, which is needed in many countries. The Importance of Good Institutions and the Integrated Management of Resources

Water, energy and food resources are interlinked. For example, water is needed for the extraction and production of energy, while energy is required for desalination and treatment of water resources. Therefore, energy policies could actually have an effect on the demand for water resources. However, the energy, agriculture, and water sectors are usually governed by different government institutions and rarely do these institutions talk to one another – it is therefore important that these resources are managed together. For example in the U.K., the Department of Environment, Food and Rural Affairs (DEFRA) is responsible for policies to do with water and the agriculture sector, while energy policies are the responsibility of the Department of Business, Energy, and Industrial Strategy. Even though energy policies could affect water use in the U.K., and even if the two departments actually work together on a regular basis, they usually do so after the policy has been put into place. It is important to actually measure and analyze the effect that a policy or regulation in one resource could actually affect the demand of another resource (see box below).

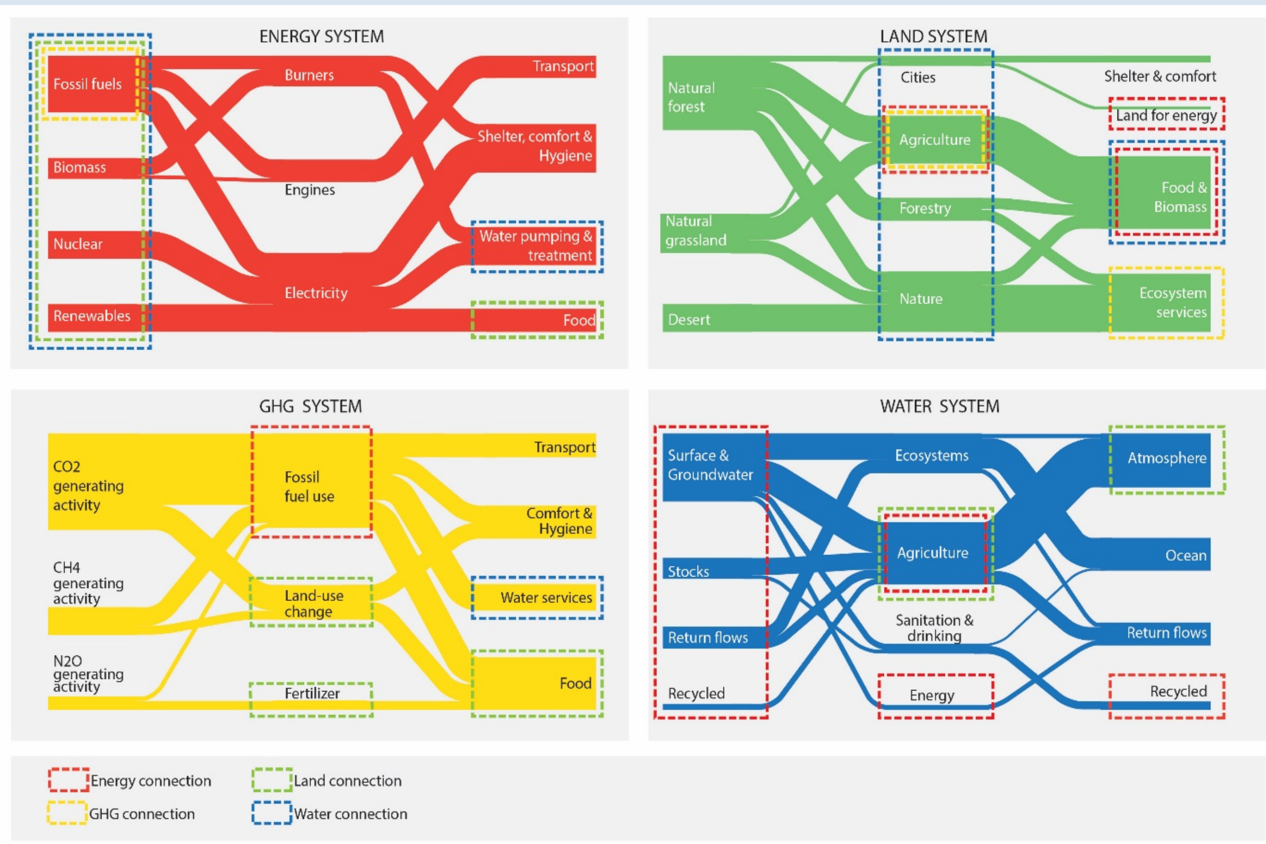
## The Importance of the Integrated Management of Water, Food and Energy Resources

*Professor Julian Allwood, Professor Keith Richards, Dr. Richard Fenner, Dr. Zenaida Subral Mourao, Dr. Dennis Konadu, Ying Qin and Dr. Grant Kopec, The Foreseer Project, University of Cambridge*

Globally, we have plenty of freshwater. However its quality and quantity varies, so local shortages occur and create competition between agricultural, domestic, energy and industrial uses. This competition will intensify as the world's population grows and the impacts of climate change strengthen. Furthermore, water, food and energy systems are intricately interdependent as illustrated by Figure 75. For example, water is required to deliver energy, for fossil fuel extraction and refining, hydropower, thermal power generation, heating, and in the irrigation of energy crops. Meanwhile, energy is required in the transport, treatment, distribution and discharge of water. Water shortages can therefore constrain energy production, for example, when a sustained heat wave in France in 2003 led to the shutdown of nuclear reactors and a 50% reduction in electricity exports.

Increasing competition and the coupling between energy, water and food demonstrates the need for integrated resource policies and the University of Cambridge's Foreseer group (www.foreseer.org) has developed an online tool to help. The Foreseer tool uses data and models that capture the links between water, food and energy systems. Users can explore future resource scenarios interactively, by altering parameters that influence climate change impacts, population growth and technology choices. The tool has been applied to assess groundwater stress in California, to examine the water and land implications of the U.K.'s carbon plan, and to examine conflicts between China's energy sector and its recent "3 Red Lines" water policies.

Figure 75. The Interconnected Natural Resource System, as Represented by Foreseer




Source: Foreseer Group, University of Cambridge

## U.K. 2050 Carbon Plan and its Implications for Water, Food and Land

The U.K. Climate Change Act (HM Government, 2008), introduced a legally binding target for greenhouse gas (GHG) emissions reduction. This requires significant decarbonization of the energy sector through deployment of renewable and other low-carbon technologies. Consequently, the U.K. Department of Energy and Climate Change (DECC) developed the 2050 Carbon Plan (HM Government 2011), which presents four potential pathways to achieving both 80% GHG emissions reduction and energy security by 2050. Each pathway consists of a different mix of primary energy sources and technologies, all of which influence other resource uses in particular with land needed for energy system infrastructure, bioenergy and agriculture, and with cooling water used in thermal power generation and the refining of liquid fuels.

Our work,[103][104] has shown that some of these pathways could have significant unintended impacts. Using biofuels to decarbonize transport requires large areas of land conversion to bioenergy cropping, while power generation will increase competition for water in some U.K. catchments, particularly those which are already over-licensed[105]. For example, the 'Higher nuclear, less energy efficiency' pathway would by 2050 require between 18% and 43% of all U.K. land for bioenergy growth, leading to competition with domestic food production. Natural hazards such as flooding and coastal storm surges, which are becoming increasingly severe, also create risks for energy infrastructure and agricultural production. Future U.K. energy policies should therefore be examined for their influence on land and water use.

## Water/Energy/Food Nexus – The California Experience

California has been under severe drought since 2012, but the allocation of water was an issue for the state even during years of higher precipitation, as demand exceeded supply. The shortfall has been met by extracting more groundwater than is replenished each year. Recently, the snowpack that sustains much of the water cycle in California has been decreasing, exacerbating the problem. Measures taken to deal with the drought have focussed mainly on urban uses, even though these account for only 10% of total water use.[106] Agriculture, on the other hand, which requires 41% of all water use while contributing just 2% of GDP, is driven mostly by market considerations, but many current crops are particularly water-intensive. Just three crops, alfalfa, hay, and livestock feed, require 30% of agricultural water use.[107] As water prices have remained low, there has been little motivation for farmers to choose crops with reduced water intensity, to manage underground water more efficiently, or to adopt more efficient irrigation practices. Similarly, with low prices, technical options to allow more efficient use of treated water, increase the use of recycled water, or to reduce urban water demand, have not been deployed fully.

[103] Konadu, D. D., Mourão, Z. S., Allwood, J. M., Richards, K. S., Kopec, G. M., McMahon, R. A., & Fenner, R. A. (2015). *Not all low-carbon energy pathways are environmentally "no-regrets" options*. Global Environmental Change, 35, 379-390.
[104] Konadu, D. D., Mourão, Z. S., Allwood, J. M., Richards, K. S., Kopec, G., McMahon, R., & Fenner, R. (2015). *Land use implications of future energy system trajectories—The case of the UK 2050 Carbon Plan*. Energy Policy, 86, 328-337.
[105] Konadu, D. D., & Fenner, R.A. (2017). *Catchment level water resource constraints on UK policies for low-carbon energy system transitions by 2030*. Global Challenges (forthcoming). DOI: 10.1002/gch2.201700006.
[106] Curmi et al. (2013). Visualising a Stochastic Model of Californian Water Resources Using Sankey Diagrams. Water Resources Management, 27, 3035.
[107] *California Agricultural Water Use: Key Background Information*, Pacific Institute. (2015). Retrieved from: http://pacinst.org/publication/california-agricultural-water-use-key-background-information/

California uses freshwater for hydroelectricity generation and for cooling in thermal power stations, with 15% of all U.S. hydro capacity in California. Water shortages reduced hydro power generation to 40% of 2011 levels by 2014.[108] The electricity system responded by increased use of natural gas, leading to higher greenhouse gas (GHG) emissions, although this has been mitigated to some extent by deployment of renewable wind and solar PV generation. If the drought continues and water demand is unchecked there is an increased risk of electricity shortage, especially during summer months, with lower water flows and storage but higher air and water temperatures.[109] This could lead to higher dependence on imported electricity from neighboring states, which are also suffering similar problems. The drought also increases the risk of wildfires which threaten the transmission grid. If groundwater levels continue to decrease, more energy will be needed to pump water from deeper aquifers and higher temperatures could lead to higher water demand for irrigation. Both effects further competition for water and exacerbate pressure towards unsustainable groundwater extraction. We used the Foreseer™ tool to examine groundwater stress in California[110] and concluded that even with current policies to curtail urban and agricultural water use, California could run out of economically viable groundwater as early as the next decade, and no later than 2050. The Foreseer™ tool can now be used by policy makers to explore the interdependencies between water, energy and land use in California.

### The '3 Red Lines' Water Policy of China and the Implications for Energy Provision

China has 22% of the world's population but only 6% of the world's freshwater,[111] with a water-stressed North and a water-abundant South. For example, water availability in the Haihe basin in the north is around 360$m^3$/cap whereas that in the Yangtze basin in the south is around 2400$m^3$/cap.[112] Economic growth increases pressure on the country's water supply and China's pursuit of water, energy, and food security is particularly challenging as most coal and gas reserves as well as cultivated land are in water-stressed regions.

To tackle growing concerns over water scarcity and pollution, the Chinese government has implemented the '3 Red Lines' water management plan. One of the associated policies aims to reduce industrial water use, of which the energy sector is part. Meanwhile, through its energy policies, China is planning to reduce its GHG emissions intensity through increased generation from renewables, nuclear and gas. We used the Foreseer™ tool to reveal that China's future energy plans could conflict with the '3 Red Lines' water policy, but the amount of water used in the energy sector is highly dependent on technology choices, especially for power plant cooling. For example, the development of inland nuclear power plants would increase freshwater use in the energy sector. If future inland nuclear plants use a mix of wet-tower and once-through cooling, this new demand would be around 11% of the energy sector's total water demand by 2035. However, if only wet-tower cooling is used, future water withdrawals would be significantly decreased.[113]

The complex connections between water, energy and food in the U.K., California, and China demonstrate the need for a holistic analysis of responses to climate change and development of agricultural, energy and industrial strategies. The Foreseer research project is developing a suite of tools and techniques to make better use of data and models on natural resources.

[108] *California's continued drought, reduced snowpack mean lower hydropower output*, April 2015, www.eia.gov/todayinenergy/detail.cfm?id=20732.

[109] 2014 Summer Loads & Resource Assessment, California ISO, retrieved from: www.caiso.com/planning/Pages/ReportsBulletins/Default.aspx

[110] Ibid, ref 20

[111] Guan, D., Hubacek, K. (2008). *A new and integrated hydro-economic accounting and analytical framework for water resources: a case study for North China*. Journal of environmental management 88 (4), 1300–13.

[112] Yang, H. (2003). W*ater, environment and food security: a case study of the Haihe River basin in China*. Ecology and the Environment 2003;60:27–36.

[113] Qin Y, Curmi E, Kopec GM, et al. (2015). *China's energy–water nexus–assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy*. Energy Policy 82,131–43.

# Supply-side Solutions: Investment in Infrastructure

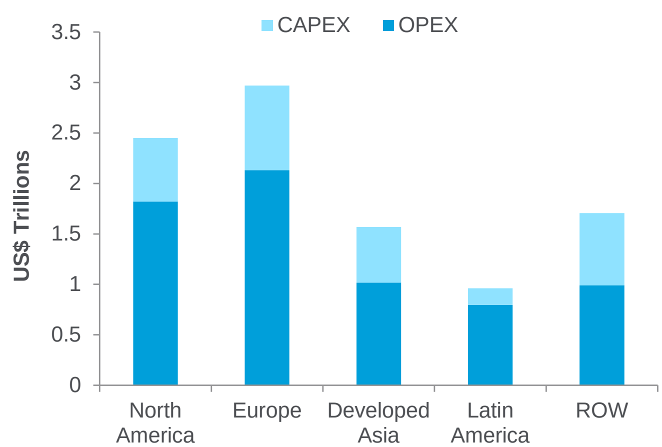
Many countries, regions, and cities have over the years invested large amounts of money in infrastructure to ensure a constant reliable supply of water. Infrastructure projects include water transfer systems (for example, the China South-to-North Water Diversion Project expected to cost $62 billion), storage facilities, desalination plants, wastewater treatment plants, and others. However, in the last decade there has been a lack of investment in water infrastructure, especially in developed countries. Following the financial crisis, many governments have been tightening their public spending budget and even though investments in water infrastructure are important, they are currently competing with other pressing matters such as housing and transport.

## Water Infrastructural Investment Needs

An estimated $9.7 trillion is needed to operate, update and maintain water and sanitation infrastructure

The investments needed to deliver sustainable water and sanitation services, to operate and maintain infrastructure and update and expand the coverage of services are enormous. Lloyd Owen[114] estimates that globally $9.7 trillion is needed from 2010 to 2029, while McKinsey puts the figure at $7.5 trillion between 2016-2030 (excludes equipment spending). In his analysis, Lloyd Owen divides the cumulative water infrastructure investment needed into different regions covering 67 countries. The author identified seven main drivers for investments in water and sanitation services including extending access to water and sanitation services, addressing challenges of population growth, providing industrial water and wastewater services in the context of global growth, meeting the World Health Organization's drinking water guidelines, securing water supplies and dealing with exceptional rainfall in the context of climate change.

Figure 76. Cumulative Investment Required in Different Regions (2010-2029)

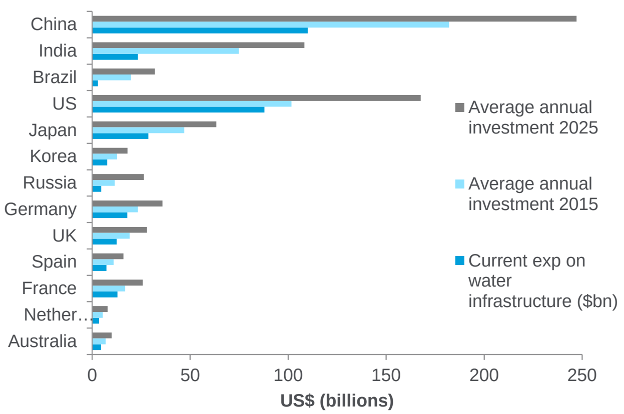



Source: Lloyd Owen, Citi Research

[114] Lloyd Owen D. (2011). *Infrastructure needs for the water sector, unpublished, commissioned by the OECD.*

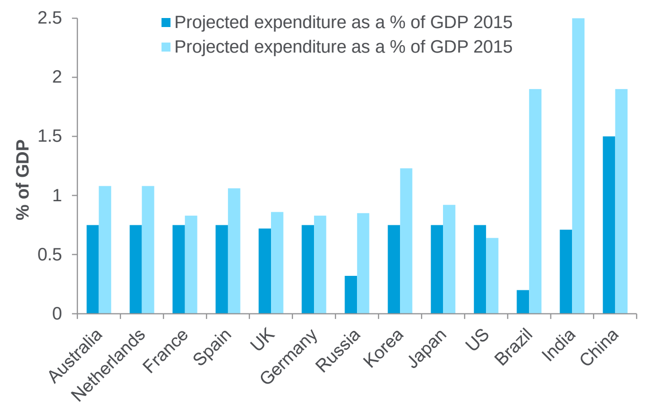
The OECD estimate that an annual investment of $0.8 trillion from 2010 to 2020 is required for water infrastructure in OECD and BRIC countries (Brazil, Russia, India, China); this increases to $1 trillion per year between 2020 and 2030, up from a current expenditure on water infrastructure of $0.6 trillion annually.[115] They estimate current expenditures based on the proportion of GDP allocated to water services for OECD and BRIC countries. Going forward, the level of expenditure on water services for high income countries should be of the order of 0.75% of GDP (ranging between 0.35% and 1.2%) and could go up to 2.5% for some BRIC countries and 6% for some low-income countries. [116]

Figure 77. Current Annual Expenditure and Future Expenditure Needs for Water Infrastructure




Source: OECD,Citi Research

Figure 78. Projected Expenditure as a % of GDP on Water Infrastructure




Source: OECD, Citi Research

Inadequate water and sanitation infrastructure is costing Africa the equivalent of 5% of GDP

In developing nations, the situation is different — a significant percentage of the population still does not have access to water and sanitation services and therefore investment is needed to build new infrastructure, rather than upgrade or undertake improvements. According to the African Development Bank inadequate water and sanitation infrastructure is costing Africa the equivalent of 5% of GDP. Africa's available resources are abundant but unevenly distributed in time and space and only 5% of its available water resources are developed. In Sub-Saharan Africa, the investment needs for water supply and sanitation are estimated at $21.9 billion per year and $3.4 billion for irrigation. A funding gap of $13.8 billion per annum is estimated.[117] According to the Asian Development Bank (ADB), its 45[118] developing bank members require a cumulative investment of $800 billion in total for water and sanitation infrastructure from 2016 to 2030. Meeting these huge financing needs is one of the largest challenges facing many developing countries in Asia.

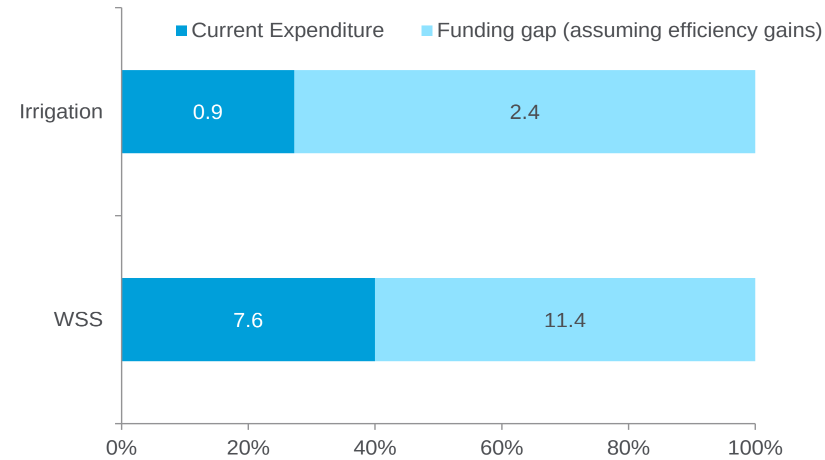
[115] OECD. (2006). *Infrastructure to 2030, Telecom, Land Transport, Water and Electricity.*

[116] OECD. (2011). *Benefits of investing in water and sanitation: An OECD perspective,* OECD publishing.

[117] This assumes that current expenditure continues (estimated at $7.6 billion and $0.9 billion p.a. for water supply and sanitation and irrigation respectively[117]) and there are some efficiency gains

[118] Asian Development Bank. (2017). Meeting Asia's Infrastructure Needs.

Figure 79. Annual Investment in Water Infrastructure in Sub-Saharan Africa (Current Expenditure and Funding Gap, US$ Billions

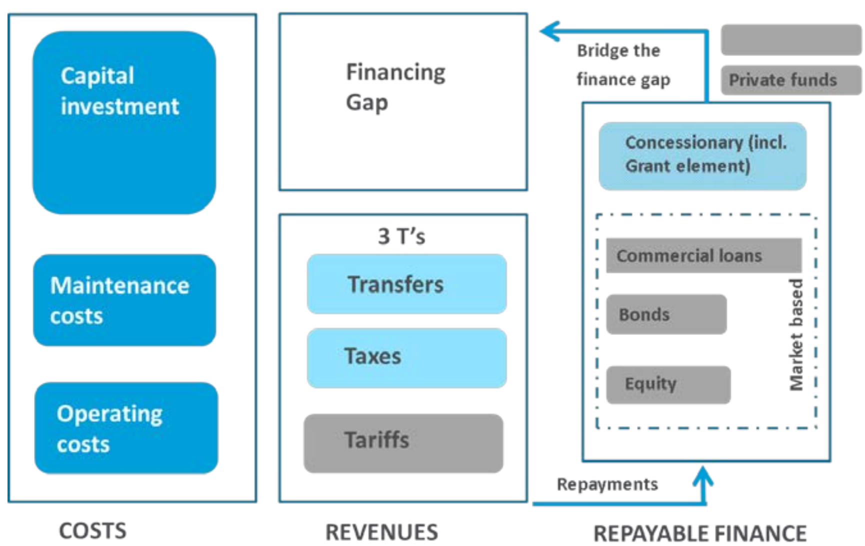



Source: Foster V, Briceno-Garmendia (2010), Citi Research

## Investing in Infrastructure: Making It Happen

At present the majority of water infrastructure is financed through tariffs, public taxes, and transfers from international communities. However, even though these mechanisms are important, they also have their limitations. Increasing water tariffs is one potential solution, but opposition to this is primarily due to limited willingness to charge for agriculture and domestic usage; affordability issues for the poor are also a major concern. In fact, agriculture water usage in many countries is either free or undercharged. However, the good news is that new financing instruments are surfacing, allowing various types of institutional investors such as pension funds, insurance companies and sovereign wealth funds who are seeking yield to invest in infrastructural projects. Water infrastructure takes many forms and needs finance at every point of the water cycle, from the collection, storage, transportation, treatment, distribution, and use. Solutions for financing are highly country-specific and are dependent on the structure and ownership of the local water companies.

Figure 80. Sources of Finance




Source: OECD (2010), Citi Research

Our Citi GPS report *'Infrastructure for Growth: The dawn of a new multi-trillion dollar asset class'* provides more details on how to unlock global infrastructure investment including the number of instruments that are available for private investors to the appropriate level of return in the different stages of infrastructure. It also provides details on water infrastructure needs in the U.S., U.K., China, India, and Brazil.

## Using Green Infrastructure to Achieve Multi-functionality in Urban Stormwater Management

*Dr Richard Fenner, Reader in Engineering Sustainability, University of Cambridge, Engineering Department*

Infrastructure assets, such as bridges, roads, railways, power plants, and residential and domestic buildings provide the basic services that allow modern communities and global society to function. They are specific to the geographic location within which they must operate, and represent capital goods that are typically long lasting (sometimes for centuries). In relation to the provision of water services, infrastructure is required to find, store, treat, and deliver water to where it is needed, and then to collect, transport, and treat wastewater so it is safely separated from people and made fit to return to the environment. Other forms of infrastructure are also needed to protect communities from natural extremes exhibited by the movement of water in the form of floods and droughts.

Delivering such infrastructure has to be achieved against a wide set of constraints, including resource scarcity, the need to be adaptable to a changing climate and maintaining performance as part of a wider system, as well as reducing the carbon footprint of water industry operations. To deliver this the following principles are increasingly being adopted: seeking multi-functionality of assets so that multiple benefits can be accrued, working with natural systems and achieving resilience by accepting redundancies in the system and moving from centralized to decentralized solutions.

One area where these principles are clearly demonstrated is in the drainage of cities and adaptive approaches to flood risk management. Green infrastructure (GI) can be considered as an interconnected network of multi-functional green spaces and the flood risk management services that such GI projects provide have been utilized over a range of urban areas in the U.S., Australia, and Europe. An important trend in stormwater management is not to pass excess surface water quickly downstream through large capacity concrete pipes, but to use natural vegetated surfaces in Sustainable Drainage Systems (SuDS) where water can be stored close to where it originates and has the opportunity to infiltrate into the ground. Thus there are opportunities for integrating SuDS/GI assets into the urban fabric and such initiatives can provide both an important engineering function whilst adding to the greening of city landscapes.[119]

These approaches can include “daylighting” streams to add amenity value and leisure opportunities in urban areas, as well as stimulating economic revival. A successful example can be found in the Augustenborg area of Malmo, Sweden, where the surface landscaping of drainage features has played a major role in transforming what was hitherto a declining area, with many social problems, into a highly attractive and desirable urban environment. The retrofitted stormwater management solutions included 6 kilometers of canals and channels and ten retention ponds. Rainfall is channelled through visible trenches, ditches, ponds, and wetlands. These landscape features are integrated into the townscape within 30 courtyard areas, which also provide recreational green spaces for residents. A 50-year rainfall event in 2007 cut most of Malmo off from the rest of Sweden, while Augustenborg was not affected.

Kazmierczak and Carter (2010)[120] have reported that the total sum invested in the physical improvements in Augustenborg and related projects was around SEK 200 million ($24M). Remaining funding mainly came from local authorities, principally the City of Malmo, as well as from the Swedish government’s Local Investments Programme for ecological Conversion and Eco Cycle Programme (SEK 24M), the Swedish Department of the Environment (SEK 4M) and EU programme LIFE (SEK 6M) and the EU URBAN programme also supported the regeneration of Augustenborg.

The benefits achieved from this joint approach to storm water management and urban regeneration included:

[119] CIRIA RP 993. (2015). Benefits Assessment of SUDS Tool (BeST) http://www.susdrain.org/resources/best.html

[120] Kazmierczak, A., Carter, J. (2010). *Adaptation to climate change using green and blue infrastructure, A database of case studies*, http://www.grabs-eu.org/membersArea/files/Database_Final_no_hyperlinks.pdf , accessed: 12 February 2016 (Interreg IVC Green and blue space adaptation for urban areas and eco towns (GRaBS) project.)

- Adaptation to more extreme rainfall events.
- Reconfiguration of public spaces between housing blocks provided residents with opportunities to grow their own food in small allotments and created places for leisure and where children can play.
- Biodiversity in the area has increased by 50%. The widespread use of green roofs, predominantly the Botanical Roof Garden, has attracted birds and insects, and the open storm water system provides a better environment for local plants and wildlife. In addition, flowering perennials, native trees and fruit trees were planted, and bat and bird boxes installed.
- The environmental impact of the area (measured as carbon emissions and waste generation) decreased by 20%.
- The participatory character of the project sparked interest in renewable energy and in sustainable transport among residents, after they heard about similar plans for other areas.
- After completion the turnover of tenancies decreased by 50%, and unemployment fell from 30% to 6% (Malmo's average).
- Participation in elections increased from 54% to 79%.

Figure 81. (Left) Stormwater drains are brought to the surface as part of urban landscaping, (Right) A dry retention pond is designed to function as an outside classroom for the adjacent primary school in terms of dry weather, while allowing stored water to infiltrate through its base in wet periods

Source: Dr. Richard Fenner, University of Cambridge

Many cities have adopted these kinds of soft engineering solutions for managing urban stormwater with well-documented examples as observed in Melbourne, Australia and in many U.S. cities including San Francisco, Chicago, Seattle, and Philadelphia. Often the move to adopt these practices is driven by a pressing problem which needs considerable investment to solve. For example, in Portland, Oregon, water quality in the River Willamette had deteriorated dramatically due to frequent spills from the overloaded sewerage network. In 2002, Portland experienced 50 overflow events, discharging around 13 million $m^3$ into local waterways. The choice faced by the city was clear: it could invest in expanding the below ground pipe network by building more grey infrastructure, or it could look upstream and attempt to take water out of the system at the source. This was the basis for the city's successful Grey to Green initiative. The city budgeted $50 million in stormwater management fees to invest in green infrastructure over 5 years, adding over 100 hectares of eco-roofs, installing 920 green street components, planting over 80,000 trees in yards and along streets and buying over a 1000 hectares of high priority natural areas . Its downspout disconnection program disconnected more than 56,000 downspouts from over 26,000 properties within the Combined Sewer Overflow area, allowing more than a million cubic meters of stormwater to infiltrate into the ground annually. The city has installed street gardens in curb extensions (see Figure 82) and flow tests have shown these can reduce peak flow from a 25 year storm event by 88% — enough to protect local basements from flooding and reduce total runoff to the combined sewer system by 85%. The city estimates that resolving flooding and other problems caused by runoff in the region using only conventional infrastructure and pipe solutions would have cost an estimated $144 million, compared with an estimated $86 million using largely green infrastructure. Such measures also provide benefits in terms of enhancing water quality, providing amenity and recreational spaces, adding to urban biodiversity and providing other functions such as carbon sequestration and pollutant trapping on leaf surfaces.[121]

Figure 82. Street Gardens and Community Green Space Accept Runoff from Disconnected Roof Downspouts in Portland, Oregon

Source: Dr. Richard Fenner, University of Cambridge

To pay for improved stormwater and wastewater control Portland's projects have been funded through operating capital; paid directly by ratepayers; debt, which is repaid through public utility fees on developed property; and system development charges, incurred when there is new development or a change in property use. Portland residents pay among the highest combined sanitary and stormwater rates in the U.S., with average monthly fees increasing from $30 in 2001 to $53 in 2011 and are expected to reach $69 soon. The Clean River Rewards program was implemented in 2006 to offer a stormwater fee discount of up to 100% of the on-site portion of the bill, or up to 35% of the total stormwater charge, for retaining stormwater on-site through green infrastructure practices. Partial credit for residential properties can also be received for tree-planting, installing eco-roofs, and having less than 100 $m^2$ of impervious surfaces. Green infrastructure installations are monitored by the city through random visits, and fees up to $250 can be imposed for failing to maintain infrastructure properly. Soon after the program opened in 2006, the Clean Rivers Rewards program had 14,000 participants, with the city hoping eventually to attract 100,000 participants.

[121] US EPA. (2010). Portland Oregon, A case study of how green infrastructure is helping manage urban stormwater challenges in Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Gree nInfratsructrue EPA-841-F-10-004 August 2010 http://www.epa.gov

The economic cost-benefit of adopting green infrastructure looks attractive, with evidence from cities such as Philadelphia confirming this view. A study by Stratus Consulting compared solutions for controlling Combined Sewer Overflow events in four watershed areas, using options ranging from traditional infrastructure based approaches (e.g. storage tunnels) to more innovative green infrastructure through incorporating tree planting, permeable pavements, green roofs and more. It was found that the green infrastructure approaches provided a wide array of important environmental and social benefits to the community, and these benefits are not generally provided by the more traditional grey alternatives. Two options have been compared, including managing 50% of impervious surface in Philadelphia through green infrastructure, with a tunnel option based on system of tunnels with an effective diameter of 10 meters. The benefits accrued over a 40-year study period from 2010-2049 were calculated in terms of present value and showed $2,846.4 million dollars of benefits for the green infrastructure solution compared with $122 million dollars of benefits for the tunnel option.

Many practitioners seek to monetise the disparate range of multiple benefits which can accrue for incorporation in conventional cost-benefit balance sheets, and tools have recently been developed that attempt this. For example, CIRIA's BeST (Benefits of SuDs Tool) methodology provides a structured approach to evaluating a wide range of benefits, often based on the drainage system performance overall. It follows a simple structure that begins with a screening and qualitative assessment to identify the benefits worthy of further evaluation. Then it provides support to help quantify and monetise each benefit. On completion of the evaluation, the tool provides a series of graphs and charts to present the benefits based on Ecosystem Services (ESS) and Triple Bottom Line (TBL) criteria.[122] Published by CIRIA, it can be downloaded from the Susdrain website at the following URL: http://www.susdrain.org/resources/best.html.

The opportunities presented by green infrastructure go beyond the single functional brief of dealing with urban stormwater; instead they can be used to enhance urban living spaces by creating blue-green amenities, which add to the social and environmental uplift of an area. Furthermore, if all the multiple benefits of such solutions are accounted for, then a city's balance sheet can show significantly cheaper solutions than traditional grey approaches. Such practices are becoming widespread and represent a big step towards the vision of creating truly water-sensitive cities.

[122] CIRIA RP 993. (2015). *Demonstrating the multiple benefits of SuDS – a business case*. Available at http://www.susdrain.org/resources/best.html (accessed 25 May 2016).

# The Role of Technology

Technology has always played an extremely important role in the management of water. Desalination has enabled water-scarce countries to provide a reliable supply of potable water, while water treatment plants have allowed water to be re-used over and over again. Improvements to technology are enabling some new and innovative ways to manage water use effectively. Smart water management tools, efficient desalination plants, drought resistant crops, and precision agriculture all seek to alleviate some of challenges in the water sector. This chapter highlights some of these new innovations that could change the water industry.

## Smart Water Management and Urban Water Supply

Smart Water Management tools include sensor networks, smart meters, modelling and analytics, SCADA systems etc.

Smart Water Management (SWM) tools fall into five main categories: (1) data acquisition and integration (e.g. sensor networks, smart pipes, and smart meters); (2) modeling and analytics; (3) data dissemination and data storage; (4) management and control (e.g. SCADA systems); and (5) visualization and decision support.[123] Technologies such as smart metering, remote monitoring (SCADA), geographic information systems (GIS), and telecommunications systems allow for the provision of real-time data. For water utilities this means that they are able to make real-time improvements, meaning water losses in water distribution networks can be reduced. An example of this is the Wireless Water Sentinel (WaterWiSe) currently being marketed by Visenti Pte Ltd which has been deployed by the Singapore Public Utilities Board (PUB). It is a cloud-based smart grid solution which has been integrated into the PUB's user interfaces to monitor online hydraulic and water quality parameters, to detect leakage remotely, and to assimilate real time data into hydraulic models.[124] According to Visenti, WaterWiSe has helped detect and localize pipe bursts and leaks, reduce response time, and raise the productivity levels of field engineers. The U.S. EPA is using an assimilation of information and communication technology (ICTs) including sensor technologies, models, software and GIS to create a comprehensive drinking water contamination system (UNESCO, 2014). The system enables timely detection and appropriate response to drinking water contamination incidents to mitigate public health impacts.

Smart meters can collect water usage every 15 minutes, giving customers' detailed information

Smart meters enable companies and customers to better track and monitor water usage. In the U.K. the process of rolling out smart meters has started; Thames Water has started to install them in some households and plans to complete installation to all its customers by 2030.The new meters that are being installed can collect water usage every 15 minutes, giving customers' detailed information on how much water they use[125]. The city of Long Beach in California is also testing smart meter systems in a number of households, with the aim of extending the scheme to all interested households.

Several new water technologies are also being used in developing and emerging countries. In India, Sarvajal, an organization founded in 2008 by the Piramal Foundation, is improving water access with the use of cloud computing and mobile technology which reduces costs. The organization is installing solar powered dispensing machines that use pay-as-you-go smart cards. The machine sends data to the company's central server which helps Sarvajal know the levels of available water and ensure a constant supply of water in the area.[126] ICT technology is also being used in the Kyuso district, located in the eastern part of the horn of Africa,

[123] UNESCO. (2014). *Partnering for solutions: ICTs in Smart Water Management.*
[124] www.visenti.com
[125] www.thameswater.co.uk
[126] www.sarvajal.com

where water-point data transmitters are incorporated into the handle of a water pump. This technology collects data on the amount of water used from the hand pumps, providing real time monitoring. It also alerts the system when the hand pump is broken, allowing for quick repair and maintenance to be carried out.[127]

## Innovations in Desalination: Urban Water Supply

Desalination – removing salts from water – is one of the most energy intensive and expensive ways to boost freshwater supply, but is seeing a renaissance as urbanization and industrialization increase water use in water-stressed areas, and as water-related crises are increasingly common. Though relatively costly, desalination is a drought-proof source of additional supply that can process abundant seawater or underground "brackish" water. Technologies are improving, boosting the efficiency of desalination and lowering costs over time.

Nevertheless, desalination remains a higher cost option in the context of expanding water supply, other approaches of which include reuse, conservation, demand side management and pricing. Desalination is usually an appropriate option only when other sources are scarce, or water transportation costs are high. But given growing scarcity of water and falling costs of desalination, it should continue to grow as one of a variety of sources of water supplies.

### What is Desalination?

Desalination is an energy intensive range of technical processes used to remove salts from water

Desalination refers to a range of technical processes that remove salts from water. It tends to be highly energy intensive, and thus the availability and cost of energy sources usually determines the type of desalination process chosen for a given location.

There are different methods of desalination. Thermal desalination is an older, more established technology, used predominantly in the Middle East. Commercial thermal desalination plants typically use a multi-stage process that falls under several key designs: multi-stage flash (MSF), multi-effect distillation (MED), and vapor compression (VC). All three are mature technologies that may have limited improvements going forward.

Membrane technologies are a newer set of processes, with reverse osmosis (RO) being the predominant desalination technology. Because no phase change is needed (as there is in VC), less energy is required. However, it still requires energy – to provide pumping pressure for reverse osmosis (used for both seawater and brackish water) and electrical energy for electrodialysis (used mainly for brackish water treatment). An emerging and promising membrane technology is forward osmosis, which uses very little energy, but is still in its early days, not yet quite commercially viable and lacking scale; for now, it also works at a slower speed than other forms of desalination.

[127] UNESCO. (2014). *Partnering for solutions: ICTs in Smart Water Management.*

Figure 83. Key Desalination Technologies

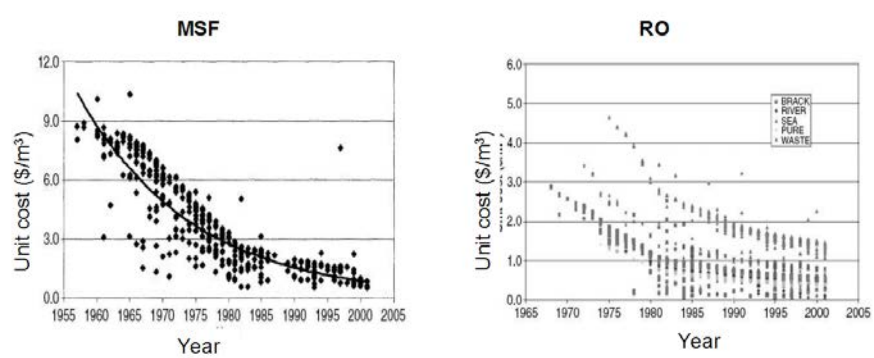
| Separation Mechanism | Energy | Process | Name |
|---|---|---|---|
| Water separation | Thermal + Electrical | Evaporation | Multi Stage Flash (MSF) |
| | | | Multi Effect Distillation (MED) |
| | | | Thermal Vapor Compression )TVC) |
| | | | Solar Desalination (SD) |
| | | Crystallization | Freezing |
| | | | Formation of hydrates |
| | | Evaporation and filtration | Membrane Distillation (MD) |
| | Electrical | Evaporation | Mechanical Vapor Compression (MVC) |
| | | Ionic filtration | Reverse Osmosis (RO) |
| | | | |
| Salt removal | Electrical | Ionic migration | Electrodialysis (ED) |
| | Chemical | Others | Ionic Exchange (IX) |
| | | | Extraction |

Source: CETaqua

Reverse osmosis systems remove salt and other impurities from water through the use of pressure and polyamide membranes

Most new desalination plants today use reverse osmosis technology, and costs have fallen steadily over time. Reverse osmosis (RO) systems force water at high pressure (some 80 bar, or 40 times the pressure within a car tire) through cartridges containing thin-film composite polyamide membranes. These membranes let water through, but hold back salt and other impurities. Membrane technologies tend to be more favorable where energy costs are high, and also can be quicker and cheaper to build, and simpler to operate versus thermal desalination processes. However, they need careful pre-treatment, high-pressure pumps and membranes can be fouled over time therefore requiring maintenance and replacement. Nevertheless, membrane technologies look to have a long runway of innovations and improvements ahead, boding well for further declines in costs over time. Reverse osmosis economics depend on location and capacity, but particularly input water quality, with RO costing $0.60 per cubic meter of brackish water or wastewater, versus up to around $1 per cubic meter for treating seawater, which has higher salinity.

Figure 84. The Unit Cost of Multi-Stage (MSF) and Reverse Osmosis (RO) Desalination Technology Over Time




Source: Citi Research

Desalination is energy intensive and can also adversely affect marine life

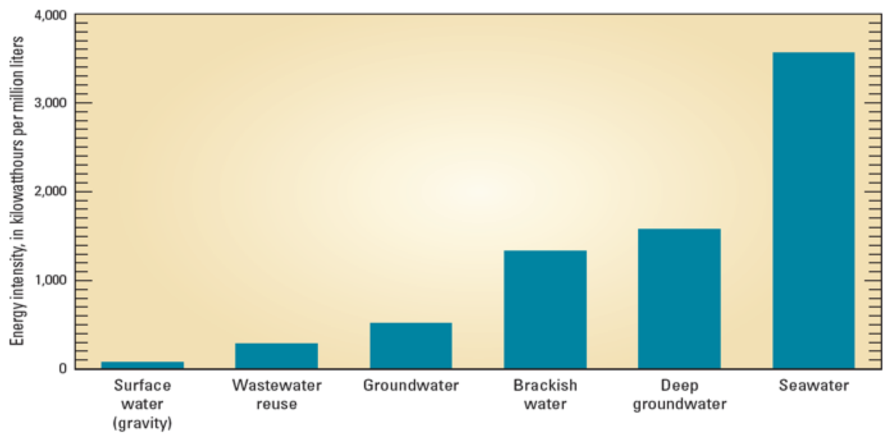
Key environmental concerns about desalination are twofold: managing the discharge of salty brine as it is reintroduced into the environment, and minimizing the carbon footprint of the energy used in the process.

- **Discharge of salty brine:** Desalination can affect the salinity of soil and water downstream. It releases waste salty brine back into the sea, which along with pump and pipe inlets and outlets, can adversely affect marine life. For instance, desalination plants in California face a zero discharge regulation that prohibits them from discharging the rejected salty brine back into the ocean.

  The salinity of the coastal waters close to desalination plants may rise over time, leading to concerns over "peak salt", where the rising salinity in turn raises the cost of desalinating this seawater source until it becomes uneconomic over time. Significant desalination capacity in the Middle East in particular has led to growing discharge of waste brine back into the small, shallow waters of the Arabian Gulf, and the damming of rivers in the region has also reduced freshwater flow to the Gulf, leading to ever-higher salinity levels.

- **Carbon footprint:** There is also some environmental opposition to desalination because it is energy intensive. If climate change is partly responsible for water scarcity issues, does it make sense to invest in additional desalination capacity if it would burn more fossil fuels, thus contributing to accelerated climate change, which could in turn mean even deeper drought in some areas of the world? Projects involving renewable energy to power desalination look more attractive from this perspective. Despite concerns, for context, energy use for heating water in households, such as for bathing or dishwashing, are some ten times more energy intensive than seawater desalination, while bottling water is also more energy intensive.

Figure 85. Typical Energy Intensity Associated with Treatment and Transportation of Water, by Source

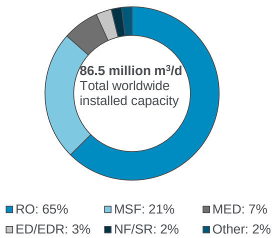



Source: USGS

Policy and regulations tend to govern water discharge, including issues to do with impacting salinity, oxygen depletion, and changes to the temperature of marine ecosystems, when desalination plants are discharging highly saline water into the sea/ocean. For example, the U.S. EPA places a 10% total dissolved solids (TDS) limit on discharge. The Florida Department of Environmental Protection has considered an increase of up to 10% of chlorides content as acceptable. Australia requests less than 1-2% of TDS at the discharge point.

## Desalination Capacity is Growing Rapidly

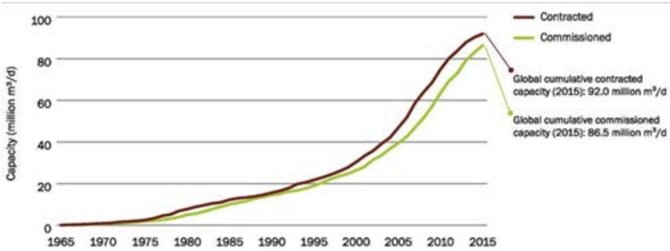
Figure 86. Global Desalination Capacity by Technology




Source: GWI DesalData / IDA

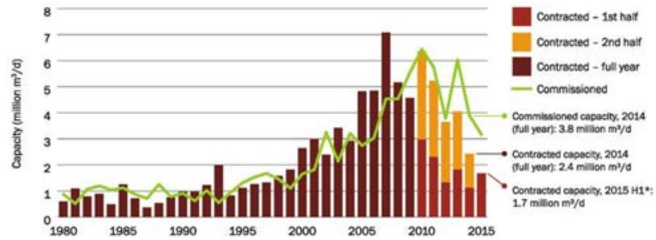
As of June 2015, according to the International Desalination Association (IDA) there were around 18,500 desalination plants in 150 countries worldwide, serving more than 300 million people, with some 300+ projects in the pipeline. These 18,500 desalination plants represent global freshwater production (commissioned) capacity of 87 million cubic meters per day (23 billion gallons per day). But this represents less than 0.01% of global water withdrawals of 3,800 $km^3$. Globally, desalination uses at least 75.2 TWh of electricity per year, or 0.4% of global electricity consumption (IRENA, 2012a). This is up from 2002, when there were 12,500 desalination plants worldwide with a production capacity of 14 million cubic meters per day of freshwater, less than 1% of global consumption at the time.

Figure 87. Global Cumulative Installed Desalination Capacity, 1965-2015




Source: GWI DesalData / IDA

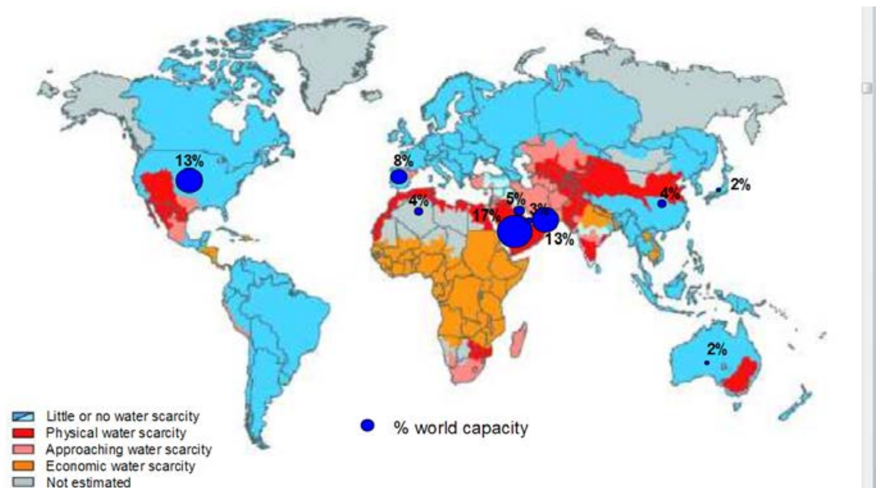
Figure 88. Annual New Capacity, 1980-2015




Source: GWI DesalData / IDA

Desalination capacity growth has slowed since 2008 due to lower levels of public financing for desalination projects, but began to recover in 2015. Most new projects use membrane technologies rather than thermal desalination processes, save for one multi-effect distillation (MED) expansion in Saudi Arabia recently.

Figure 89. Desalination Capacity in Selected Countries




Source: International Water Management Institute (2006), GWI DesalData/IDA (2009)

Around 70% of the freshwater in Saudi Arabia comes from approximately 30 desalination plants

However, water is an eminently local issue, so the prevalence of desalination varies widely by region: in Saudi Arabia, thermal desalination remains prevalent, in no small part due to cheap local energy supply; about 70% of freshwater in the region comes from some 30 desalination plants. As a region, the Middle East accounts for around half of global desalination capacity. The U.S., Spain, Asia, and Australia have significant desalting capacity too**.** The Carlsbad reverse osmosis desalination plant in San Diego, California is one of the larger new facilities that started up in late 2015, bringing drought-proof supply to the San Diego area, against the context of the severe California drought gripping the state (see construction costs and financing in Figure 90 below).

Most new plants use membrane technologies, with less than 5% of new capacity for thermal projects. In fact, even the planned Ras Abu Fontas A3 project in Qatar (with a capacity of around 164,000 cubic meters per day) saw a switch from multi-stage flash (MSF) to reverse osmosis (RO).

A few other projects are showcasing solar desalination, with the award of the Al Khafji project and four Masdar pilot projects, and the tender of several other projects: in the UAE, a solar-powered seawater reverse osmosis (SWRO) plant in Dubai and the Independent Water Project (IWP) in Ras al-Khaima, as well as the Aktau plant in Kazakhstan.

Figure 90. Carlsbad Reverse Osmosis Desalination Plant in San Diego, CA – Project Finance Sources and Uses

| Sources | Series 2012 Plant Bonds | Series 2012 PipelineBonds | Total |
|---|---|---|---|
| Series 2012 Bonds Par | 530,345 | 203, 215 | 733,560 |
| Series 2012 Bonds Premium (Discount) | 15,382 | 6,891 | 22,272 |
| Accrued Interest | 295 | 113 | 408 |
| Interest Income (2) | 942 | 428 | 1,370 |
| Equity Contributions | 167,044 | - | 167,044 |
| **Total Sources** | 714,007 | 210,646 | 924,654 |
| Uses | | | |
| Plant EPC (3) | 429,856 | - | 429,856 |
| Pipeline EPC (3) | | 144,473 | 144,473 |
| Power Substation Construction | 19,733 | - | 19,733 |
| **Total Construction Costs** | 449,589 | 144,473 | 594,063 |
| Interest on the Project Bonds During Construction (4) | 90,969 | 34,857 | 125,826 |
| Pre-Construction Costs (5) | | | |
| Engineering & Technical | 8,744 | 2,939 | 11,683 |
| Financing | 1,231 | 414 | 1,645 |
| Legal | 3,073 | 1,033 | 4,105 |
| Permitting/Environmental | 12,577 | 4,227 | 16,805 |
| Site Costs | 3,249 | 1,092 | 4,341 |
| Internal Staff & Office Costs | 10,609 | 3,566 | 14,175 |
| **Total Pre-Construction Costs** | 13,270 | 13,270 | 52,753 |
| Transaction Fees and Closing Costs | 26,308 | 3,646 | 29,954 |
| Environmental, Insurance and Misc. Costs (7) | 34,070 | 4,239 | 38,309 |
| **Total Fees and Other Costs** | 60,378 | 7,885 | 68,262 |
| Owner's Contingency | 20,000 | | 20,000 |
| Reserve Funds (8): | | | |
| Series 2012 Plan Bonds Debt Service Reserve (9): | 26,517 | - | 26,517 |
| Series 2012 Pipeline Bonds Debt Service Reserve | - | 10,161 | 10,161 |
| Working Capital Reserve Fund - Project Reserve Account | 11,500 | - | 11,500 |
| Working Capital Reserve Fund - Permanent Account | 4,340 | - | 4,340 |
| State Lands Commission Reserve (for Wetlands) | 3,700 | - | 3,700 |
| Ground Lease Restoration Reserve | 2,000 | - | 2,000 |
| WPA Reserve | 5,508 | - | 5,508 |
| **Total Reserves and Contingency** | 73,565 | 10,161 | 83,726 |
| **Additional Bond Proceeds** | 23 | 1 | 24 |
| **Total Uses** | 714,007 | 210,646 | 924,654 |

Source: California Pollution Control Financing Authority 2012

Technological improvements since the 1980s have brought down the cost of desalinating water from $1.50 per cubic meter to $0.60-1.00 today; these innovations have emerged across various parts of the RO process, such as pre-treatment systems, membrane efficiency, energy recovery systems, energy-efficient pumps, and energy recovery to harvest energy from residual water pressure. The surface area of membrane inside cartridges continues to expand, from 300 square feet of surface area to 450 square feet, increasing efficiency.

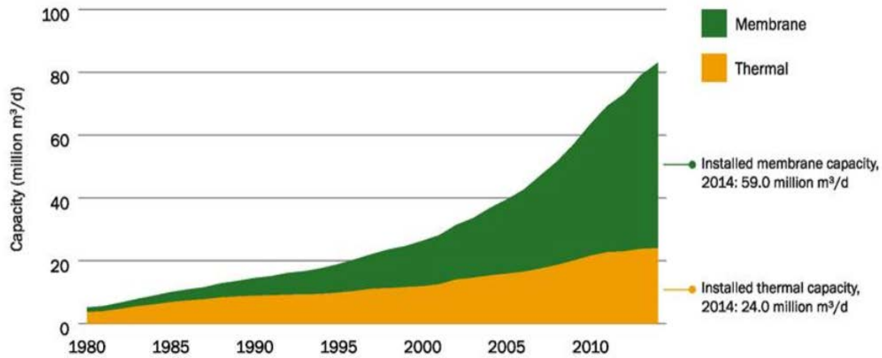
Figure 91. Further Comparisons Between the Economics of Various Desalination Processes for Differing Water Input Qualities in a 2003 Study ($ per cubic meter of freshwater)

| Reference Sources | MSF (Seawater) | MEE (Seawater) | TVC (Seawater) | RO (Seawater) | RO (Brackish Water) | ED ED (Brackish Water) |
|---|---|---|---|---|---|---|
| A | 1.10-1.50 | 0.46-85 | 0.87-0.92 | 0.45-0.92 | 0.20-0.35 | - |
| B | 0.80 | 0.45 | - | 0.72-0.93 | - | - |
| C | 0.89 | 0.27-0.56 | - | 0.68 | - | - |
| D | 0.70-0.75 | - | - | 0.45-0.85 | 0.25-0.60 | - |
| E | - | - | - | 1.54 | 0.35 | - |
| F | - | - | - | 1.50 | 0.37-0.70 | 0.58 |
| G | 1.31-5.36 | - | - | 1.54-6.56 | - | - |
| H | 1.86 | 1.49 | - | - | - | - |
| I | - | 1.35 | - | 1.06 | - | - |
| J | - | - | - | 1.25 | - | - |
| K | 1.22 | - | - | - | - | - |
| L | - | - | - | - | 0.18-0.56 | - |
| M | - | - | 0.46 | - | - | - |
| N | - | - | - | 1.18 | - | - |
| O | - | 1.17 | - | - | - | - |
| P | - | - | 0.99-1.21 | - | - | - |
| Q | - | - | - | 0.55-0.80 | 0.25-0.28 | - |
| R | - | - | - | 0.59-1.62 | - | - |
| S | - | - | - | 1.38-1.51 | - | - |
| T | - | - | - | 0.55-0.63 | - | - |
| U | - | - | - | 0.70-0.80 | - | - |
| V | - | - | - | - | 0.27 | - |
| W | - | - | - | 0.52 | - | - |

Source: Sandia National Laboratories Report, reviewing literature and information on desalination costs at the time (Miller 2003)

There are significant research efforts in membrane technologies, one of the most promising being forward osmosis (FO). This is similar to reverse osmosis – both technologies use a semi-permeable membrane to separate the water from dissolved solutes. But in reverse osmosis, the driving force is external hydraulic pressure from pumps that force water against the normal flow of diffusion of water (from lower concentration to the higher concentration solution side of the membrane); in forward osmosis, the water flows from the feed water across the membrane to a draw solution of higher concentration, thus saving on the energy used in pumping water at high pressure. Forward osmosis also enjoys less “fouling” of the membrane, as well as a higher rejection rate of many different contaminants. However, this technology remains in its infancy, and has yet to be commercially viable and grow to scale.

Figure 92. Desalination Capacity for Membranes and Thermal Facilities, 1980-2014




Source: GWI DesalData / IDA

Desalination can benefit from economies of scale, lower energy costs, and fostering competition in the sector

Areas of technological improvements and cost reductions come from a variety of avenues under research and development. In general, desalination can benefit from economies of scale, lower energy costs, and fostering competition in the sector. For thermal desalination processes, improvements can come through optimizing process design, improving thermodynamic efficiency, new materials, new construction, and transportation options. For reverse osmosis, improvements are happening in increasing surface area of membranes, raising salt rejection rates, extending the life-span of membranes, optimizing pre-treatment, and growing use of energy recovery.

For example, new directions include thinner graphene membranes, as well as nanotube technology, as well as smart sensors for optimization and automation of desalination equipment, which can also save some 33-50% of conventional desalination costs. Regulatory requirements for zero-discharge systems have spurred development of solutions for treatment of rejected salt and brine. Within the energy-water nexus, Water Standard has patents on ship-based desalination systems, to produce desalinated water for pumping into offshore oil reservoirs for enhanced oil recovery.

## Synergies of Desalination with Power Generation

Hybrid desalination plants combine fossil fuel power with desalination technology

One approach to improving the efficiency and economics of desalination is through the co-production of energy and water. Combined fossil fuel power and desalination plants – "hybrid desalination plants" – work well in the Middle East, where little freshwater is available. Examples include the Fujairah plant in UAE and Shoaiba plant in Saudi Arabia. Nuclear-powered desalination plants – in the dozens – could be built in the Middle East over the next 20 years, with 10 planned in Saudi Arabia alone. From a sustainability perspective, combined renewable power with desalination is a particularly appealing proposition. One such plant is being piloted in Spain; Abu Dhabi's Masdar announced plans to launch three new projects in this area, aiming to build a first large-scale commercial desalination plant powered by solar/wind/combo by 2020 (Newar 2013).

The advantage to these hybrid plants is that waste heat from power plant (steam) can be used as a heat source for (thermal) desalination. This improves overall efficiency as waste heat is used in the desalination process, while less water is needed for cooling purposes in the power plant, lowering energy costs overall.

The disadvantage is that such projects are more complex, particularly due to seasonal variability in power versus water demand — i.e. winter demand for electricity may be low, while demand for water is more consistent all year round.

Figure 93. Energy Savings from Various Desalination Techniques

| Technology | Percent savings potential | Potential electrical energy savings in public water supplies (million kWh/yr) |
|---|---|---|
| High-efficiency pump / motor systems | 10 to 30% of pumping energy | 2,600-7,800 |
| Pipeline optimization | 5 to 20% of pumping energy | 1,300-5,200 |
| Advanced membranes | 15 to 25% of treatment energy | 117-195 |
| Advanced ozone | 10 to 20% of treatment energy | 572-654 |
| Advanced ultraviolet | 10 to 30% of treatment energy | 515-544 |
| Advanced reverse osmosis | 50% of desalination treatment energy | 2,400 |
| Capacitive deionization | 50% of brackish water treatment energy | 1,000 |
| Membrane distillation | 66% of desalination treatment energy | 3,200 |

Source: USGS

## Innovations in Energy and Industrial Processes

The use of water for energy and industrial processes can be substantial, especially in water scarce areas. Water used for fracking has come under scrutiny over the years not only for the use of water, but also for the potential contamination of groundwater resources. However, traditional extraction and treatment technologies are being substituted for innovative and advanced water treatment equipment. Companies are developing more efficient ways to clean and recycle water that is used for drilling on site, as well as engineering more environmentally-friendly drilling solutions. For example, Ecosphere Technologies has developed a chemical-free technology that allows the oil and gas industry to recycle their produced water on site.[128]

The produced water sector is estimated to be an $8 billion global market

Citi's 2011 water primer report estimated the produced water sector to be an $8 billion global market, of which $5 billion is in the U.S. The produced water sector includes equipment and services engaged in treatment, lifting/pumping/reinjection, minimization, and off-site disposal of produced water. It is also interesting to note that some companies are doing away with water use in hydraulic fracturing all together. Praxair Inc launched DryFrac, which replaces the use of water in fracking with the use of liquid carbon dioxide ($CO_2$). Millennium Stimulation Services Ltd is testing a technique that uses methane instead of water to fracture shale gas wells[129]. Whether these methods are successful or not is dependent on the price of water in the region and safety considerations. More information on the treatment of produced water is found below.

Carbon dioxide ($CO_2$) and methane are already being used instead of water for enhanced oil recovery (EOR). The Permian Basin covering West Texas and southern New Mexico and the Weyburn demonstration project in Canada both use $CO_2$ for EOR. The benefits of this include (1) a reduction of water that is used for EOR; and (2) the re-use of $CO_2$ collected from industrial processes and/or power generation plants.[130]

[128] www.ecospeher.tech.com

[129] Bennett N. (2015). *Gas in, gas out: the waterless fracking alternative*, October 13, 2015.

[130] www.opec.org/open_web/en/905.htm

For industrial processes, Ecolab has been among the forefront of the chemical industry in growing a business dedicated to clean water (now ~21% of the company's sales), and the company believes it is a top supplier globally for chemical treatments for industrial water treatment. The company's global water business helps customers in industries like heavy manufacturing, mining, and paper save costs on water through pre-treatment, boiler, process, cooling, and post-application chemistry and technology solutions.

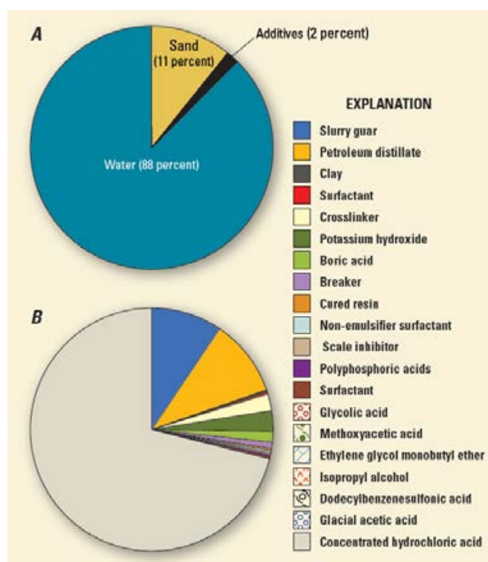
One of the key emerging technologies for the company is Traser 3D, which is an information management system which does real-time monitoring and management of water in industrial processes and reduces the need for manual sampling and testing of water. According to the company, 3D Traser technology has helped its clients save 114 billion gallons of water annually. However, for Ecolab, water-related sales are still 90% chemistry-related and technology/services are still an emerging business. Other key products which Ecolab sells for water savings include antifoulants, pre-treatment solutions, membrane treatments, coagulants, flocculants, and anti-foams.

## Treatment of Produced Water

Companies are developing more efficient ways to clean and recycle water that is used for drilling on a shale gas site. Some companies are also doing away with water completely for fracking

Treatment and re-use of produced water is currently challenging because there are a wide range of contaminants that vary from place to place and may change over time, each of which requires different treatment techniques. Produced water from oil and gas operations can contain natural contaminants, including radioactive isotopes like radium-226 and -228. It can be more saline than seawater and can include dispersed oil, dissolved organic compounds, bacteria, and other solids.

Figure 94. Relative Volume of Various Materials Used to Hydraulically Fracture an Oil Well in the Permian Basin in Texas, (of a total volume of 4.5 million litres)

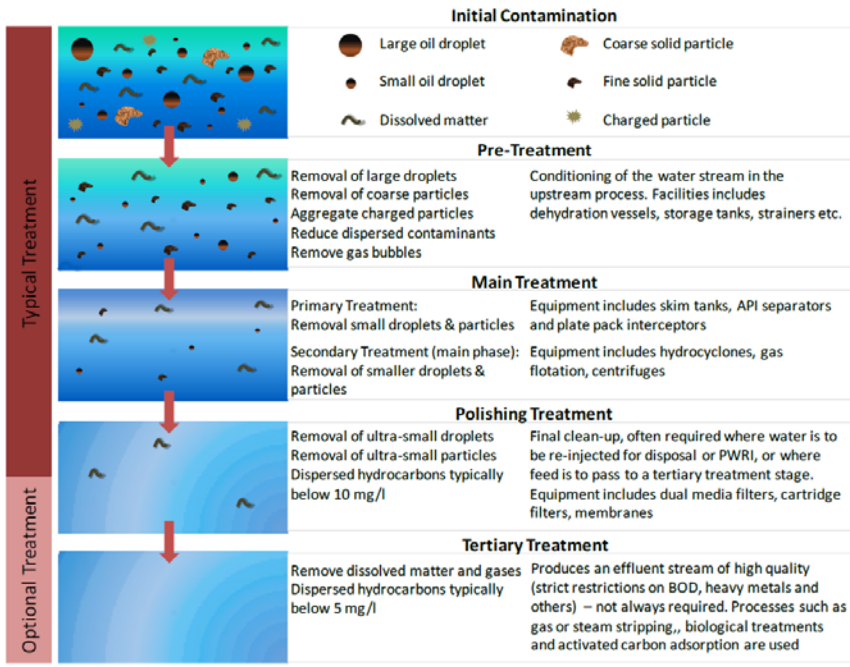



Note: A: relative volumes of water, sand, and additives used. B: relative volume of the specific additives used
Source: USGS, fracfocus.org

Important factors in water treatment include energy intensity, carbon footprint and water transportation

Different water treatment technologies have pros and cons for treating the various contaminants, particularly along the following dimensions: robustness, maintenance, weight and space considerations, installation, and requirements for skilled labor in operation and maintenance. Some technologies are more costly than others. Other important factors include energy intensity, carbon footprint, and water transportation (which tend to be expensive). On the whole, there is the need to balance best practices, capital costs, as well as weight and space and scheduling considerations (SPE 2012).

Figure 95. Typical Water Treatment Process in Oil and Gas




Source: SPE, Shell

Typical water management as part of oil and gas production involves several major steps, mainly to separate the water as byproduct from the primary product which is the hydrocarbons (see Figure 95 above), including pre-treatment, primary and secondary treatment, additional polishing and then tertiary treatment.

These treatments are implemented with a variety of water treatment tools that are widely used outside of the oil and gas sector too. Filtration involves various techniques ranging from nutshells to nanofiltration to membrane technology. And membranes are a key area of research and development, with advances in materials and design. For instance, materials range from polymers (cellulose, nylon, PTFE) to ceramics; designs include various kinds of cartridges as well as spiral-wound filter designs. But each of these technology types has pros and cons. For example, spiral-wound membranes may perform well, but may not be as robust and durable. Ceramics are sturdy, but expensive. Centrifuges are effectual but require significant maintenance.

Given the range of produced water contaminants and potential end-user requirements, various treatment technologies have differing pros and cons. Below we list some examples across three broad treatment categories: barrier technologies, chemical and electrochemical processes, and thermal processes.

Figure 96. Types of Treatment Categories for Produced Water

| Treatment Category | Type of Technology | Description |
|---|---|---|
| Barrier Technologies | Adsorption | Removes ~80% of heavy metal content with ~100% water recovery. Can be overloaded by organic content |
| | Ceramic Microfiltration / Ultrafiltration | Uses ceramic membranes that effectively remove suspended solids and non-dissolved organic carbon. It has low energy requirements but is an expensive technology |
| | Media Filtration | Uses materials like sand, coal, and walnut shells to remove carbons. Requires no energy consumption but frequent filter replacement |
| | Reverse Osmosis (RO) | Systems require high energy for pumping water at high pressure against the diffusion gradient. Effective at removing divalent ions, somewhat effective at removing monovalent ions and can remove organic compounds. Skilled technicians are needed for maintenance and membranes need to be replaced over 3-7 years |
| | Forward Osmosis (FO) | FO Membranes have a hydrophilic, cellulose acetate active layer cast onto either woven polyester mesh or micro-porous support structure. Is less energy intensive than reverse osmosis. |
| Chemical & Electrochemical Processes | Capacitive Deionization (CDI) | Effective in removing dissolved solids, is portable, requires little monitoring and skilled labor but is less effective in removing uncharged substances |
| | Electrodialysis (ED) & Electrodialysis Reversal (EDR) | Uses electrochemical charge to separate and can treat high concentrations of organic materials and microorganisms. Requires skilled labor to operate |
| | Oxidation | Uses oxidants to remove organics but chemical costs may be high and metering equipment is necessary |
| Thermal Processes | Multi-Stage Flash Distillation (MSF) | Evaporates water by reducing pressure, not by raising temperatures. Requires less pretreatment and feed conditioning versus membranes but infrastructure investment is significant |
| | Freeze / Thaw Evaporation (FTE) | Uses ambient air temperature below the freezing point of water and saline is sprayed to form ice crystals. When ice is melted it is highly purified water. Requires low temperatures. |

Source: Citi Research

The profile of treated water could be linked to the water into which it is discharged to ensure compatibility with the body of water it's being released to

Further solutions include passive constructed wetland systems that use biogeochemical processes to remove potential pollutants like oil and grease, salts, dissolved organic compounds, suspended solids, metals, and radionuclides. This fits with the broader concept of indirect potable reuse, where treated water could be discharged into a water body that is used for other uses, potentially including drinking water in the future. One consideration is to make sure the treated water profile is appropriate for the water into which it is discharged. Even if a technique like reverse osmosis outputs very pure water, post-treatment may be required to ensure the solution chemistry of the reuse water is compatible with any bodies of water that it will be added to, like aquifers. It is like too much of a good thing - very low levels of total dissolved solids and low calcium-to-sodium ratios can create other problems like dispersion of clays, clogging of aquifers, leaching of heavy metals from soil or aquifer formation into the water, and thus may need lime addition or blending with local surface water to minimize undue impacts to existing water sources.

Over time, direct potable reuse for drinking water may also face issues with public acceptance**,** while the entity treating produced water may be discouraged by legal liability risks. Further studies of produced water treatment should be carried out to ascertain the safety for drinking use, conducting ongoing toxicity assays and seeking to better understand any possible chronic toxicity from organic and other potentially toxic compounds.

## Economic Considerations for Produced Water

Conditions are mostly conducive to local disposal of produced water or reuse in oil and gas production vs. treatment

Economic and regulatory considerations keep the current focus of produced water management on disposal and local reuse in oil and gas operations. Produced water is considered a byproduct of oil and gas production, and requires clear water rights or water pricing to sell onto other users. Combine this with high costs of treatment and transportation of water, and regulations that mainly cover injection for disposal, and the conditions are mostly conducive to local disposal or reuse in oil and gas production. In the U.S., Sourcewater has developed a clearinghouse to match up water sellers and possible buyers, which is a start for helping reuse outside of the most common approaches. But on the whole, if the cost of treating produced water is higher than disposal, the volume of reuse should remain minimal.

Figure 97. Costs of Produced Water Management and Treatment by Method

| Method | Estimated Cost ($/bbl) |
|---|---|
| Surface discharge | 0.01-0.08 |
| Secondary recovery | 0.05-1.25 |
| Shallow reinjection | 0.10-1.33 |
| Evaporation pits | 0.01-0.80 |
| Commercial water hauling | 0.0-1-5.50 |
| Disposal wells | 0.05-2.65 |
| Freeze-thaw evaporation | 2.65-5.00 |
| Evaporation pits and flowlines | 1.00-1.75 |
| Constructed wetland | 0.001-2.00 |
| Electrodialysis | 0.02-0.64 |
| Induced air flotation for de-oiling | 0.05 |
| Anoxic/aerobic granular activated carbon | 0.083 |

Source: Hagstrom et al 2016

The costs can range wildly across management or treatment options and technologies, from as low as $0.01-$0.08 per barrel of water for surface discharge to $0.05-$2.65 for disposal wells to $2.65-$5.00 for freeze-thaw evaporation (FTE). Assuming a water-oil ratio of 7:1, disposal costs are some $0.07-$.56 per barrel of oil, which is minimal versus the wellhead price of oil, even in the wake of the recent oil price decline.

The high cost of water treatment technologies could be prohibitive based on the oil price environment

But for treatment technologies that reach $4-5 per barrel of water, this can reach $28-$35 per barrel of oil, which is prohibitive in the current environment and weighty even in the best of times for oil prices (for instance, in the period of $110 oil price in 2011-2014). An appropriate selling price for water would improve these considerations, but is not a current feature of most water policy environments. Most outlooks for oil prices for the next few years are in the $40-70 per barrel range, meaning water treatment costs need to be well below $4-5 per barrel of water range to be considered (short of being able to charge for supplying produced water).

Centrally located treatment facilities or disposal wells require pipeline or truck transportation

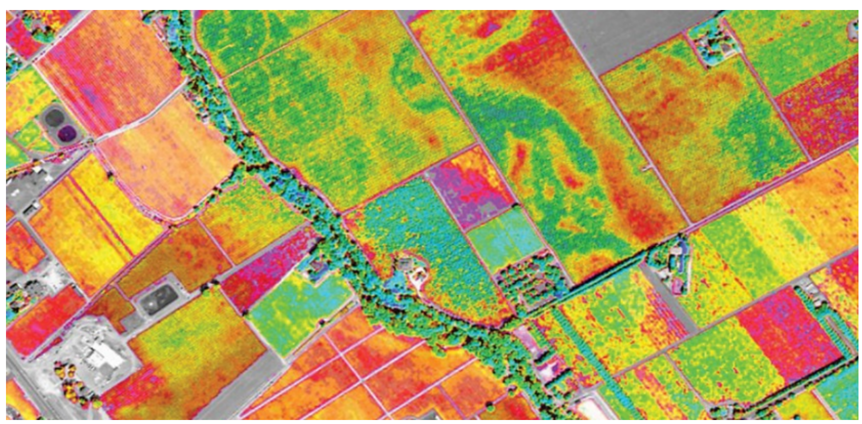
In general, transportation of water is expensive, but centralization of treatment facilities can enjoy economies of scale**.** Point-of-use treatment usually enjoys lower fixed cost investment, while centrally located treatment facilities or disposal wells require pipeline or truck transportation. Water pricing can also influence the use of transportation as areas as potable water and water for agricultural irrigation might be expensive in an area due to drought, making transportation of water to this area affordable and the price of water might well be high enough to warrant regulation-forced water treatment.

## Water Innovations in the Agriculture Sector: Satellites and Precision Agriculture

Biotechnology and precision agriculture are two new novel mechanisms that are being used in food production and can reduce water use

The use of water technology in agriculture has in the past focused on efficient irrigation techniques such as the use of drip or micro-spray irrigation. Over the last decade, other novel techniques such as agriculture biotechnology and precision agriculture are being used in food production. The introduction of biotechnology, such as plant genomics, now gives crop companies the tools to grow drought-tolerant crops. Innovations in hardware and software allow farmers to collect real-time data on weather, soil, and crop maturity that could help them make smarter decision on the use of fertilizers and water. Sensors are placed throughout the field to measure the humidity and temperature of the soil, and pictures of the fields are taken using satellite imagery and drones. Satellites are also being used to track and monitor groundwater use — experts are using NASA's Gravity Recovery and Climate Experiment (GRACE) to track changes in groundwater from space, detecting shifts in gravity. Using this data, scientists and policymakers are able to create an accurate database of the change in groundwater storage in water basins on a month-to-month basis. For example, Famiglietti (2014) used GRACE to measure and monitor terrestrial water storage change around the world and has concluded that most of the aquifers in semi-arid and arid zones (including Central Valley, North China Plain, and Gurani Aquifer in South America), which are important for the agriculture sector, are experiencing rapid rates of groundwater depletion.[131]

Figure 98. Satellite Imagery Used for Precision Agriculture



Source: Image taken from: http://www.xyht.com/enviroag/satellite-imagery-precision-agriculture/

Within the seeds and precision agriculture industry, companies like Monsanto and Pioneer (DuPont) have commercialized corn seeds which help farmers protect their crops during periods of water stress or drought. Monsanto's product, DroughtGard, is a biotech trait. The goal of the product is to expand the area which farmers can plant corn, moving into drier or more drought-prone areas like the western U.S. cornbelt, including North/South Dakota, Nebraska, and Kansas. According to the company, DroughtGard seeds produce ~3% more corn per acre. While the initial commercial launch of Droughtgard, which was first launched in 2013, has been relatively small, the company is continuing to develop the product and in 2015 advanced the next generation of Droughtgard to Phase 3 research & development trials.

[131] Famiglietti J.S (2014), *The global groundwater crisis,* Nature Climate Change, 4, pp 945-948

For Pioneer, its drought corn product, Aquamax, is not a biotech trait, but instead is corn seed bred specifically for growing in water-stressed environments. Its own second-generation product is in Phase 2 research and development trials. Syngenta also has a drought-tolerant corn seed product called Agrisure Artesian. In precision agriculture, much of the focus for companies like Monsanto, Pioneer, Agrium, and others has focused on planting advice, soil fertilizer monitoring, weed/insect control, and weather, although water management could be a longer-term opportunity.

## Other Innovations Still Under Research

There are a number of water technologies that are still being researched and have not yet been commercialized. The EU has provided funding of $50 million under its program called 'Water Innovation in Action.' Examples of such research include: (1) Biometal Demo - the development and feasibility of novel biotechnologies for the treatment of metal polluted wastewater; (2) SmartWater4Europe - the development of integrated solutions for the smart management of water distribution networks in the EU; and (3) WEAM4i - the development of a water and energy smart grid for irrigation and a decision support for an ICT-platform and others.[132]

Advanced materials such as graphene are being researched to develop new water infiltration technologies

Advanced materials such as graphene are also being researched with the intent to develop new water infiltration and desalination technologies. Professor Irina Grigorieva from the University of Manchester has stated that goal "is to make a filter device that allows a glass of drinkable water made from seawater after a few minutes of hand pumping".[133] Researchers at MIT have also discovered that the use of graphene for water filtering purposes reduces the energy use in desalination by 15% for seawater and up to 50% for brackish water.[134] There is a huge potential for such technology to be used in countries that do not have the financial infrastructure to fund large desalination plants.

There is little question that technology plays a critical role in forming part of a successful solution to the world's emerging water problems. Desalination plants and water treatment plants have provided a regular supply of potable water to many water-scarce countries. New innovations such as smart meters can encourage efficient water use and provide real-time information to consumers; mobile phones and cloud computing can enable access to water in many rural communities at a cheaper cost. Agriculture precision and drought resistant crops allow farmers to collect real-time data, reduce fertilizer use and maximize their water use.

[132] http://europa.eu/rapid/press-release_MEMO-14-34_en.htm
[133] http://www.manchester.ac.uk/discover/news/graphenes-love-affair-with-water
[134] http://news.mit.edu/2015/desalination-gets-graphene-boost-jeffrey-grossman-1102

# Case Studies

# Bringing it All Together - Case Studies of Singapore and Israel

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Head of Singapore & Malaysia Research

## Water is Strategically Important- A Case Study of Singapore

Water is important everywhere but it is extremely precious commodity in Singapore due to the country's lack of natural water resources – despite strong rainfall (up to 2400mm/year), Singapore has limited land to catch and store the rainfall. It runs a water strategy that spans across four main sources, collectively known as the "Four National Taps" – water from local catchment areas, imported water, recycled water or NEWater, and desalinated water.

### Demand to Double in 50 Years; Supply Must Catch Up

As of 2015, Singapore's current per capita domestic water consumption is about 151 liters per day. The Public Utilities Board (PUB), Singapore's national water agency, expects total demand of water currently at 1,955m liters/day, to more than double by 2061.

Figure 99. Sale of Potable Water in Singapore

| Sale of potable water | Unit | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2004-15 CAGR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Domestic | Mil m3 | 251 | 253.3 | 256.3 | 264.2 | 271.4 | 277.8 | 281 | 281.3 | 284.4 | 286.7 | 291.2 | 297.1 | 2% |
| Non-Domestic (Industrial) | Mil m3 | 189.2 | 186.9 | 191.3 | 191.3 | 191.2 | 190.1 | 195.1 | 197.2 | 206.5 | 211.9 | 215.1 | 217.6 | 1% |
| NEWater | Mil m3 | 19 | 26.6 | 29.6 | 49.2 | 66 | 72 | 96.4 | 102.4 | 111.4 | 114.1 | 117.1 | 124.8 | 19% |
| Industrial Water | Mil m3 | 38 | 39.1 | 40.9 | 29.3 | 23.7 | 21.9 | 24.5 | 23.1 | 25.3 | 27.6 | 27.6 | 25 | -4% |
| Total Sales | Mil m3 | 497 | 506 | 518 | 534 | 552 | 562 | 597 | 604 | 627.6 | 640.3 | 651 | 664.5 | 3% |
| Volume (Million m3/day) | Mil m3/day | 1.362 | 1.386 | 1.419 | 1.463 | 1.513 | 1.539 | 1.636 | 1.655 | 1.719 | 1.754 | 1.784 | 1.821 | |
| Volume of Used water treated | Mil m3 | | | | 536.2 | 516 | 515.5 | 542.1 | 558 | 575 | 585.2 | 571.1 | 574.8 | |

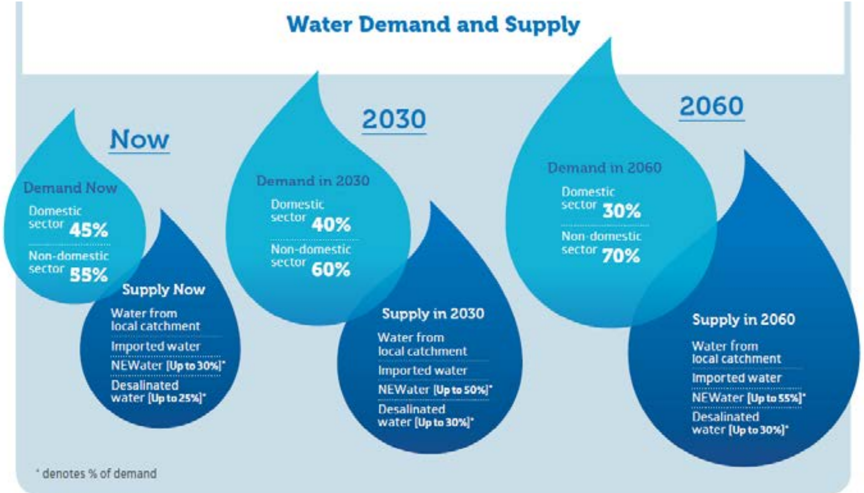
Source: Ministry of Environment and Water Resources, Citi Research

From 2004 -2015, NEWater potable water has grown at a compound annual growth rate (CAGR) of 19% versus the traditional water sources of reservoirs, water catchment areas and imported water.

### By 2060, Capacity of NEWater and Desalination Will Likely Increase by 3x and 10x, Respectively

The current imported water agreement with Malaysia which was signed in September 1962, contributes to around ~40% of Singapore's total water supply, and is expected to cease by 2062 (the first agreement signed in October 1961 expired in 2011). Imported water can supply up to 60% of Singapore's water needs. To cater to the increasing demand from both the industry and population growth, Singapore plans to increase its NEWater and desalination capacity by 3 times and 10 times, respectively by 2060. This suggests that treated water will likely increase ~5 times (i.e. grow at a CAGR of 3%) over the next 50 years.

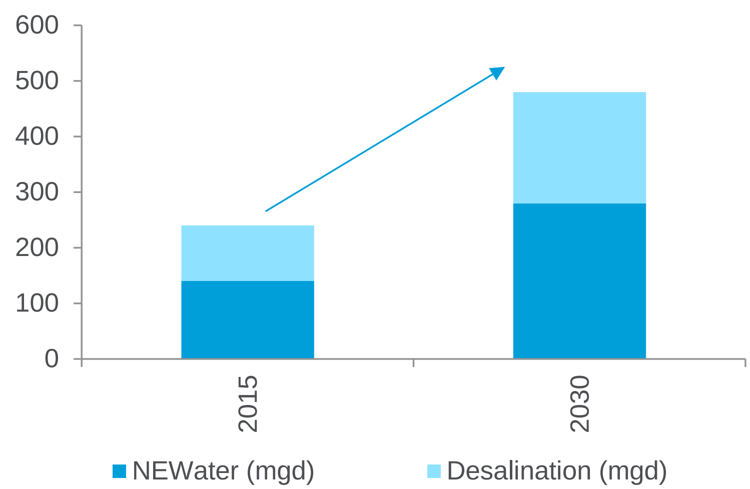
Figure 100. Singapore Water Demand and Supply




Source: PUB, Company reports

According to the PUB, by 2062 when the second water agreement with Malaysia ends, Singapore is expected to rely on up to 85% of its water needs from treated sources – mainly NEWater (55%) and desalinated water (30%), with the rest coming from local catchment and imported water.

Figure 101. Water Capacity Outlook – Supply growth mainly from NEWater and Desalination




Source: PUB, Citi Research

Singapore currently has four NEWater plants, with a fifth one slated to be completed by 2016. For desalinated water, Singapore has 2 desalination plants (SingSpring and TuasSpring) with 2 more desalination plants in the pipeline (to be located in Tuas and Marina East). The potential of a fifth desalination plant is being explored on Jurong Island.

## Used Water Superhighway – Infrastructure for NEWater

A national network to help with the collection of wastewater that can be recycled has already been mostly built – the deep tunnel sewerage system (DTSS). With the deep tunnel sewerage system, Singapore has built an efficient and cost-effective solution to meet its needs for used water collection and treatment.

Singapore's deep tunnel sewerage system allows for used water to be treated and discharged into the sea or purified for potable water

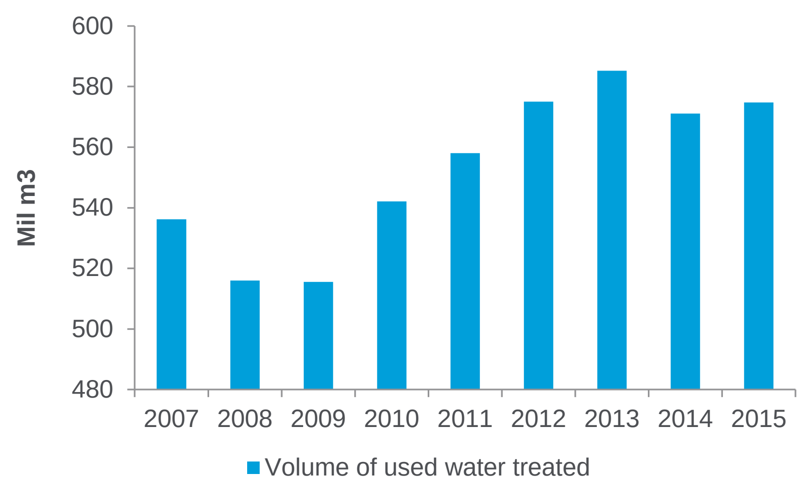
The heart of the system currently lies in the Changi Water Reclamation Plant where 800,000 cubic meters of used water can be treated daily and either be discharged into the sea or be channeled to NEWater factories, where it is further purified into potable water.

Construction of the DTSS spans over two phases: Phase 1, which was completed in 2008, involves the 48km North and Spur Tunnels, 60km of link sewers, the Changi Water Reclamation Plant (WRP) in the east, and deep sea outfall pipes to serve Singapore's eastern and central parts. Phase 2, to be completed by 2025, extends the DTSS system westwards, with 40km of tunnels and 60km of link sewers.

Figure 102. Used Water Superhighway – Wastewater is Being Channeled to Changi and Tuas


Source: PUB

Figure 103. Volume of Used Water Treated

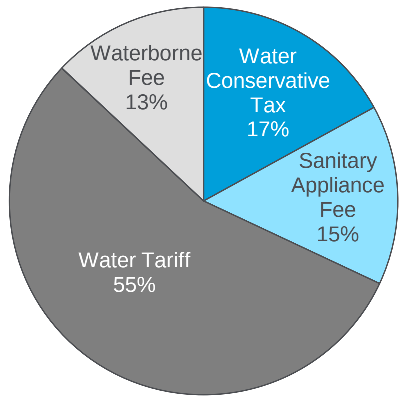



Source: Citi Research, MEWR Key Environmental Statistics

## Water Tariffs – How Water is Being Charged in Singapore

For the average household in Singapore, there are four layers of water charges, namely a water tariff itself, a water conservative tax, waterborne fees, and a sanitary appliance fee. About half of the charges for a typical consumer go to the water tariff, with the rest going towards tax, waterborne fees, and sanitary appliance charges. We believe water charges in Singapore are adequate enough to attract and fund new investments in the sector, coupled with attractive returns for suppliers.

Figure 104. Breakdown of Typical Household Water Bill




Source: Citi Research, PUB

## Israel: A Case Study and a Model for a Thirsty World

**Seth M. Siegel**
Author of the New York Times bestseller "Let There Be Water: Israel's Solution for a Water-Starved World" (St. Martin's Press, 2015). He writes and speaks widely on water issues. Connect with him at www.sethmsiegel.com and on Twitter @sethmsiegel

With growing water shortages, countries and leaders will need to identify ways to avoid the worst of the problems that a long period of scarcity will present. Israel – a nation that is 60% desert and which has a rapidly growing population and economy – provides a model for countries large and small, rich and poor.

Israel achieved independence in 1948 and, correctly anticipating a rapid growth in its population from displaced Jews around the world relocating to Israel, the country's founders deemed water security an existential issue nearly as important as the creation of an effective military. By focusing on water utilization decades before others (and despite a 50% decline in rainfall since 1948), Israel today has an abundance of water and likely the world's most sophisticated, multi-dimensional water system. Not only does Israel now have all of the water it needs for its current domestic use, it also has a robust agricultural sector that grows nearly all of the country's fruits and vegetables – and with water to spare to grow crops for export worth billions of dollars each year.

### What did Israel do and how did it do it?

There was no silver bullet or magical solution in what Israel did. It took vision, courage, sacrifice, and lots of experimentation. Success often grew out of failure but also out of a sense that, for the sake of the nation, there was no choice but to succeed. In my book, *Let There Be Water: Israel's Solution for a Water-Starved World*, I identify more than a dozen choices, techniques and processes which, combined, helped Israel to achieve its hydro-security. Even if not every country can or will adopt everything Israel did in water, every country has something to learn from the Israel experience. A few highlights:

(1) Israel has built a water-respecting culture. Even with its current surplus, Israel actively encourages conservation in school and in society at large. Parents teach their children and children reinforce the learnings from school with their parents. The national mindset – "Use all you need, but don't waste even a drop" – is the fruit of decades of public education.

Israel's water is regulated and managed by an apolitical water authority run by technocrats and water professionals

(2) Israel takes governance of its water so seriously that it has largely cut politicians out of the equation. The country's water is regulated and managed by an apolitical water authority run by technocrats and water professionals. Their mandate is to allocate water and to build new infrastructure in the best interests of the nation as a whole rather than biased in the favor of key stakeholders (like farmers or developers) who have established special relations with politicians. Further, Israel, which is, in most cases, a free-market country prohibits private ownership of water, reposing all rights to it in the government in the name of the people. Until water problems grow into a crisis, it is unlikely that countries like the U.S. will shift from private ownership of water to government ownership, even if private owners, especially farmers, often engage in wasteful water practices.

(3) In every country, agriculture is the largest user of water. In the U.S., it accounts for between 70% and 80% of the national annual water consumption. In less developed countries like Egypt, Ethiopia, and Iran, agriculture uses as much as 90% of the total. Early on, Israel realized that to most effectively save water, agricultural use of water would have to be re-thought. As a result, Israel developed a revolution on the farm with new seeds that thrive on the salty, brackish water otherwise seen as useless. Crops grown in whole or in part with brackish water in Israel include tomatoes, melons, peppers, and cucumbers.

Further, in the 1960s, Israel developed and introduced drip irrigation in place of the wasteful flood irrigation technique, still the most common form of irrigation in the US and around the world. Drip irrigation requires less than half as much water for an equal or larger yield. No field in Israel has been flood irrigated since the early 1970s, with 75% of all crops in Israel now drip irrigated.

75% of all crops in Israel are drip irrigated, which requires less than half as much water as flood irrigation

(4) Israel leads the world in the use of so-called "manufactured water." This water comes from numerous sources. The two largest categories are treated sewage and desalinated water. Nearly 90% of Israel's wastewater is treated to a very high level of purity and then reused for agriculture — the next highest user of reclaimed water is Spain at about 25% with the U.S. below 10%. In addition, Israel has long been a world leader in desalination technology and relies on desalted seawater to make up for any shortfall in water needed. A now-private former government company recently built what is the world's largest, lowest-cost per gallon of water desalination plant in Soreq, Israel and a similar facility near San Diego, California which is the largest desalination plant in the Western Hemisphere.

Manufactured water in Israel (62%) far exceeds water from natural sources like rivers, lakes and aquifers (38%). This gives Israel a redundancy and safety net during inevitable dry periods. Although both desalination and wastewater treatment are energy-intensive processes, greater efficiencies are being regularly developed in Israel and elsewhere. For example, the Soreq facility in Israel utilizes an algorithm to make use of off-peak electricity that would otherwise go to waste. And looking forward, many of the places with water scarcity concerns are located, as is Israel, in sunny locales. Lower cost photovoltaic energy production can be counted on in the near future to augment the energy needed for production of manufactured water.

More than 200 new water-tech companies have been started in Israel in the past ten years

(5) Aside from drip irrigation, reuse of sewage, and desalination, Israel, as a matter of national policy, encourages the creation and development of water technologies that save water or make more efficient use of it. Every municipal water utility and farm can receive bonuses from the government for serving as a beta site for new technologies. Qualifying inventors and entrepreneurs can receive up to 85% of their R&D budget for two years from the government. More than 200 new water-tech companies have been started in Israel in the past ten years, adding to the cluster mindset that Israel has important water ideas to use itself and to share with the world.

Globally, water is a $600 billion industry, making it bigger than biotech and telecommunications and just a touch smaller than the worldwide pharmaceutical industry. About three-quarters of those sales go for valves, pipes and pumps, and most of what utilities do. But it is in the other 25% where the future of water – and the future of the water business – lies. As high tech fills all parts of our lives and as the internet of things becomes an everyday reality, so, too, it will be in water. Expect to see ever better ideas in desalination, membranes, leak minimization, filtration, water security and valve-to-control-room communications everywhere, and especially coming from Israel. That Israel excels in each of these categories was a matter of accident and evolution, but it is likely to grow into an ever more important business category for Israel, and Israel is as likely to be an important destination for cleantech investors as it has become for governments and utilities that want to see best practices in water management in real world settings.

(6) Likely most valuable of all, Israel uses price to tamp down demand while using those water fees to pay for cutting-edge infrastructure and technology. Unlike in most of the world where a fanciful price unrelated to the real cost of sourcing, cleaning and transporting water is charged, in Israel, consumers and farmers pay the real cost for the entire water system, infrastructure included. With price as an incentive, farmers now seek out water-efficient crops and technologies, and even affluent consumers are careful in how they use water, most especially in the kinds of gardens they plant.

(7) A typical seven-minute shower in Israel costs less than ten cents, but even at that low price, many Israelis turn off the shower while lathering and shampooing. In this example, the marketplace meets conservation education while what goes down the drain gets treated and reused a theoretically infinite number of times in a perpetual loop between agricultural fields, the dinner table and the toilet.

100% of water and sewage fees in Israel go to a locked box, assuring that such consumer payments don't get diverted for other municipal budgetary needs

The cost of Israel's water comes to about a penny a gallon for fresh water and a fraction of that for reclaimed wastewater. Thanks to clever financing of infrastructure, that penny multiplied billions of times is sufficient to cover all water system costs. One hundred percent of water and sewage fees go to a locked box assuring that such consumer payments don't get diverted for other municipal budgetary needs, as happens too often elsewhere. In the U.S. and around the world, prices go from zero to a flat monthly fee to even more than is paid in Israel. But not enough water systems keep all water fees and use them exclusively for the maintenance, expansion and innovation of the water system.

With the U.S. government projecting that 60% of the world's land mass and 40 of the 50 US states are likely to endure water shortages by 2025, there isn't much time to plan, finance and build the water systems needed to prevent higher food prices, social unrest, a change in global stability and even the potential of a mass migration of hundreds of millions forced from their homes by failed water systems.

Israel started poor and as it moved up the development scale, it built water systems to match the coming need. Today, Israel is an OECD country. It has water experiences and technologies to share with rich countries and poor ones. But no lesson is more important than the need to not delay in addressing what could be one of the greatest challenges of our time: assuring an adequate supply of water needed for us all to live our lives safely and, ironically, without the need to think about our water.

# Conclusion

When people talk about water, they assume that the responsibility of its management lies with the state or local institutions. However, many companies, whether they produce food, fiber, energy or minerals, also have an important part to play in managing this resource.

The scarcity of water can have a huge effect on businesses. For example, U.S agriculture giant Cargill reported a 12% drop in 2014 fourth quarter profits as a four-year drought in the U.S. Southwest damaged pastures to raise beef, while European multinational Unilever estimated that natural disasters (linked to changing climate which in turn led to food price hikes, water scarcity and reduced productivity in their agriculture supply chain) cost the company around $400 million annually[135]. In 2003, Electricite de France had to shut down the operations of a quarter of its nuclear plants due to water shortages caused by a heat wave. The closures triggered electricity price increases of 1,300 percent and led to almost $300 million in losses for the French company.[136] Mining exposure to water scarcity can lead to unanticipated drops in production — evidenced when water restrictions contributed to a 2% fall in output at BHP Billiton's Excondida mine, the world largest copper mine.[137] The list goes on and on.

The good news is that companies are realizing the importance of water for their operations and investing in this valuable resource. For example, Nestle put aside $43 million for water-saving and wastewater treatment and U.S. automaker Ford built a $25 million water treatment plant at its Pretoria assembly plant in South Africa to increase its water re-use on site.[138] Mining companies globally spent over $12 billion on water infrastructure in 2014 alone which is an over 250% increase on what was spent in 2009.

With the demand for water expected to increase over the years, it is imperative that we implement adequate solutions to the efficient use of water in many areas. The path to water innovation and other solutions has been slow in the past due to many issues included the complexity with the way governments manage water resources, low water pricing, unnecessary regulatory restrictions, complicated water rights, lack of access to capital and the complexity of most water systems.[139] There is a need to sort out these problems and create solutions that will benefit the use of water resources for all. Both demand- and supply-side solutions are needed. Advanced countries should be investing in their aging infrastructure and strengthening their water institutions to develop efficient pricing systems, tradable permit systems, etc. The priority for emerging markets is to invest in new infrastructure needed to provide clean water to its residents and price this water efficiently to ensure continued economic growth. Investing in well-needed infrastructure could bring economic benefits in terms of jobs and well-being to the area in question. The flip-side to this is inadequate investment and lack of integrated plans, which could ultimately lead to job losses and a loss of economic growth.

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Technology also has an important part to play in the management of water. The demand for clean water has never been greater, and the need for wastewater treatment plants, desalination plans, precision agriculture, and others will increase in the future. This is a huge opportunity for a number of companies working in these areas and an excellent opportunity for local and regional government, private investment and others.

We have been discussing global water management for many years with slow progress happening in many countries – what is definitely clear is that with dwindling supplies of available clean freshwater and an increase in the demand for water over the next decade, the era of 'free and cheap' water for all needs to come to an end.

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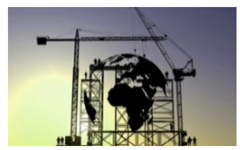

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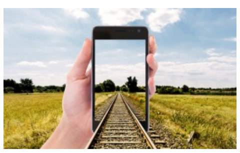

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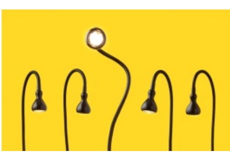

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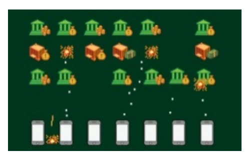

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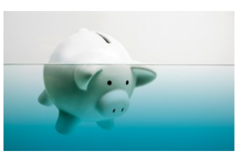

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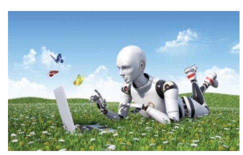

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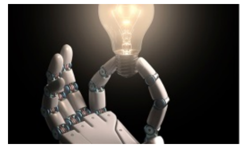

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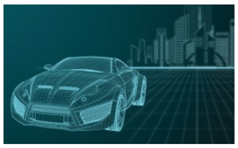

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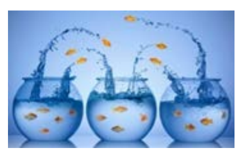

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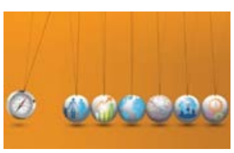

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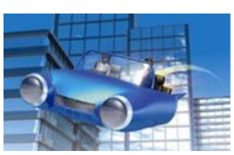

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## Key Insights regarding the future of Water

### INFRASTRUCTURE

In the last decade there has been a lack of investment in water infrastructure and it is estimated that globally $7.5 to $9.7 trillion is needed over the next 20 years to deliver sustainable water and sanitation services. / New financing instruments are surfacing allowing various types of institutional investors to invest in infrastructure projects.

### SUSTAINABILITY

Given that water is more a local than a regional or global phenomenon, regulation can become complex. It is difficult for governments to adjudicate conflicting claims to water while rationing existing water supply and finding ways to grow it. / Both regulation and cooperation are needed to facilitate water pricing and usage, as seen with Israel's government declaring property rights to all water above or below the ground, including rainwater.

### TECHNOLOGY

Technology has always played an extremely important role in the management of water but hasn't been able to stop a potential water crisis. / Smart water management tools, efficient desalination projects, drought resistant crops, and precision agriculture all seek to alleviate some of the challenges in the water sector.