World water supply and use: Challenges for the future

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Abstract

Water is the most precious natural resource on earth. The amount of water available on earth is limited and some regions are already heading towards water bankruptcy. Rising population, climate change, conversion of agricultural land for biofuel production, and other processes further complicate the problem of adequate water allocation. This problem can be even more complex in transboundary river basins. This chapter presents the current state of water around the world and explores impending water challenges.

Glossary

Climate change Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

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Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Drought A drought can be meteorological, hydrological or agricultural. The American Meteorological Society's definition for the different types of droughts is: Meteorological and climatological drought is defined in terms of the departure from normal and the duration of the event. Drought is a slow-onset phenomenon that usually takes at least 3 months to develop and may last for several seasons or years. Agricultural drought links the various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential ET, soil-water deficits, and so forth. Agricultural drought is largely the result of a deficit of soil moisture. A plant's demand for water is dependent on prevailing weather conditions, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil. Hydrological droughts are concerned with the effects of periods of precipitation shortfall on surface or subsurface water supply, rather than with precipitation shortfalls directly. Hydrological droughts are typically out of phase or lag the occurrence of meteorological and agricultural droughts. More time elapses before precipitation deficiencies show up in these components of the hydrological system. As a result, impacts are out of phase with those in other economic sectors. Socioeconomic drought associates the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological drought.

Groundwater Water beneath the earth's surface, often between saturated soil and rock that supplies wells and springs.

Transboundary waters Sources of freshwater that are shared among multiple user groups, with diverse values and different needs associated with water use. Water, thus crosses boundaries, which can be different economic sectors, legal jurisdictions, or political interests.

Key points

- Freshwater is limited and several regions around the world are running out of it.
- Limited water resources may be a source of conflict in transboundary basins.
- Efficient management is necessary in the face of climate change and other challenges.

Introduction

Water—the liquid of life—like air and soil has no substitute. Life, as we know it, would not exist without water. The geosphere, the atmosphere, and the biosphere are all linked by water. Water, driven by solar energy, determines climate. It transforms and transports the physical and chemical substances necessary for life on Earth. Although 70% of the planet's surface is covered by water, most of it is saltwater; freshwater is limited and is not always where it is most required—neither in space nor in time. Water exists in several states: water vapor and clouds in the atmosphere; seawater in the oceans; icebergs in the polar oceans; glaciers and icecaps on the mountains; and fresh water in lakes, rivers, and aquifers.

There are significant continental and country differences in the availability of freshwater. These differences and the importance of water has grown to occupy national and international agendas. Many international organizations, such as the United Nations, the World Bank, the World Health Organization, the World Meteorological Association, the Stockholm International Water Institute, among others, hold regular conferences related to water issues. Awareness among scientists, political leaders, and citizens of the connections between climate change, water security, food security, environmental services, infrastructure needs, and sustainable water resource management increases every year. The message highlighted by all these efforts is that water is an increasingly scarce resource and that it is important to recognize and accept that the supply of water is finite and that it must be managed judiciously (Singh et al., 2014). Competition among agriculture, industry, and cities for limited water supplies is already constraining development efforts in many countries. At first glance, most of these water problems do not appear to be directly related to the agricultural sector. Yet agriculture has, by far, the largest demand for the world's water. Approximately 70% of the water withdrawn from rivers, lakes, and aquifers is used to produce food, feed, fiber, and fuel to sustain a rapidly growing population. Of increasing concern is the rapid depletion of fossil water in the limited recharge aquifers in many regions of the world. Water in these aquifers accumulated over thousands of years and cannot be readily recharged. Regions of concern include the western United States, northern China, northern and western India, Egypt, and North Africa (Pearce, 2006). As competition, conflicts, shortages, waste, overuse, and degradation of water resources grow, policymakers look increasingly to agriculture for solutions.

Drought, as a hydrological hazard, stresses water resources and has historically impacted a large number of people because it is geographically widespread. Droughts are insidious because they do not have a clear beginning like floods. They start slowly and their effects are not apparent for weeks, months, or even years. The southern plains drought of the 1930s in the United States (US) often described as the "dust bowl" lasted about a decade and was an agricultural, environmental, and human disaster. John Steinbeck in his 1939 novel *"The Grapes of Wrath"* chronicled the human suffering and migration of farmers fleeing the southern plains for California. More recently, a devastating spring 2010 drought in Southwestern China affected 60 million people and caused livestock and crop losses totaling about $5 billion. Ironically, in that same year floods in Northwest China impacted 300 million people, killed over 3000 and caused over $40 billion in damages. Correspondingly, Texas in 2011 experienced a major drought resulting in agricultural losses of nearly $9 billion (Combs, 2012). Although droughts have always plagued mankind and agriculture, they serve to heighten awareness on water issues and the need to use and manage water resources wisely.

As a prelude to sustainable water management for agriculture and food systems, this chapter briefly outlines water supply and use factors and challenges for the future. It begins by providing an overview of the physical and chemical uniqueness of water before discussing water location, availability, and uses. A section on "virtual water" provides information on the amount of water embedded in food, fiber, and other products. Impacts of drought and climate change on water availability are outlined. Issues with transboundary surface and groundwater resources sharing and management are also highlighted. These issues will become increasingly complex as the climate changes.

Water's physical and chemical properties

Water (H_2O) has a very simple atomic structure, consisting of one oxygen atom and two hydrogen atoms bonded together by shared electrons. The hydrogen side of each water molecule carries a slight positive electric charge, whereas the oxygen side carries a slight negative electric charge. This molecular polarity gives water its unique physical and chemical properties, allowing it to occur naturally as a liquid, a solid, and a gas.

The "bipolar" nature of water molecules gives water its special adhesion and cohesion properties. Hydrogen bonds cause water molecules to cohere and stay together and form high surface tension. Surface tension allows water droplets to form when placed on a dry surface or allows substances to float on water, while adhesion allows water to stick to other substances. These cohesive and adhesive forces play an important role in the movement of water from the soil matrix in the root zone to the plant's leaves. The forces create a pull as water molecules evaporating from leaves try to cling to water molecules below them. This movement of water across the plant also help transport dissolved minerals that plants need in order to grow.

The polarity of water makes it a good solvent allowing it to dissolve other polar substances. Hydrophilic (water loving) substances such as salts, acids, and alcohols dissolve in water and hydrophobic (water fearing) substances such as oils and fats do not mix well in water and are not dissolved. These properties affect the interaction of water molecules with other substances and thus every living organism on Earth. Water, as it flows through the air, the ground, or our bodies, carries valuable chemicals, minerals, and nutrients that help to sustain life.

Water has a unique thermal behavior. It has a high specific heat, which means that it can absorb a large amount of energy before it gets hot, and it also releases heat slowly. It is both a heat-transfer medium and a temperature regulator. It heats and cools more slowly than soil and is thus able to buffer large fluctuations in temperature, which helps moderate the climate. An example of the influence of water on the climate can be felt on areas near large water bodies. They tend to have warm autumns and cool springs because of the differential heating and cooling between land and water.

Water expands anomalously when heated; between 0 °C and 4 °C, water contracts and becomes denser, unlike most substances, which expand and become less dense as their temperature rises. Water is densest at 4 °C and becomes less dense when the temperature either increases or decreases with respect to this temperature. Ice is therefore less dense than cold water and hence floats over water. Floating ice slows the freezing process and acts as a blanket insulating water underneath. This ice layer further prevents large waterbodies from freezing and fish and other organisms are able to survive through winters.

Global distribution of water

The water paradox is that while 70% of the "blue planet" is covered by water, freshwater resources are very limited. About 97% of the world's water is saltwater—undrinkable and unusable without expensive and energy intensive desalination techniques—and only 3% is freshwater, of which only a relatively small portion is readily available to sustain human, plant, and animal life. Slightly more than two-thirds of this 3% is ice, located in the polar ice caps, glaciers and permafrost and is not readily available for human use (Table 1). While melting of polar icecaps may not increase the flow of freshwater, melting of interior glaciers may. The Himalayas contain the largest area of glaciers and permafrost outside of the poles (Gardner et al., 2013). Most of Asia's largest rivers flow from there and more than a billion people rely on river flow from this glaciated area. Of the remaining 30% that is not frozen, most is groundwater. Only about 1.2% of Earth's freshwater is surface water found in lakes, rivers, and streams. Although the 0.49% of surface freshwater that is in rivers appears as a tiny amount, it provides significant water for agriculture and domestic use.

The amount of water that is accessible for direct human consumption is minute compared to the total volume of water on Earth. This water is found in surface water bodies such as lakes, rivers, and stored in man-made reservoirs, and in underground aquifers shallow enough for easy and affordable retrieval. Most of these water sources are renewed by precipitation and can, to a certain extent, be considered renewable. Climate and geology affect the distribution of water on Earth, hence the uneven availability.

Table 1 Global water distribution.

Source	*Water volume (km^3)*	*% freshwater*	*% of total water*
Oceans, Seas, and Bays	1,338,000,000	–	96.54
Ice caps, Glaciers, and Permanent Snow	24,064,000	68.7	1.74
Groundwater	23,400,000	–	1.69
Fresh	*10,530,000*	*30.1*	*0.76*
Saline	*12,870,000*	–	*0.93*
Soil Moisture	16,500	0.05	0.001
Ground Ice and Permafrost	300,000	0.86	0.022
Lakes	176,400	–	0.013
Fresh	*91,000*	*0.26*	*0.007*
Saline	*85,400*	–	*0.006*
Atmosphere	12,900	0.04	0.001
Swamp Water	11,470	0.03	0.0008
Rivers	2120	0.006	0.0002
Biological Water	1120	0.003	0.0001

Note: % are rounded, so will not add to 100.

From Shiklomanov I (1993) World fresh water resources. In: Gleick PH (Ed.), *Water in Crisis: A Guide to the World's Fresh Water*. Oxford University Press: New York and Oxford.

Table 2 Richest countries in terms of water resources.

Country	*Total water available per inhabitant (km^3 year^{-1})*
Brazil	8233
Russia	4507
Canada	2902
Indonesia	2838
China	2830
Columbia	2132
USA	2071
India	1897

From Food and Agriculture Organization (2003) *Review of World Water Resources by Country*. Rome: Food and Agriculture Organization.

The total renewable water resources in the world are estimated to be of the order of 43,750 km^3/year. At the continental level, America has the largest share of the world's total freshwater resources with 45%, followed by Asia with 28%, Europe with 15.5%, and Africa with 9% (Food and Agriculture Organization, 2003).

Worldwide, there are water rich and water poor countries. The eight water-richest countries, listed in Table 2, account for 60% of the world's natural freshwater resources (Food and Agriculture Organization, 2003). The 10 poorest countries in terms of water resources per inhabitant are Bahrain, Jordan, Kuwait, Libyan Arab Jamahiriya, Maldives, Malta, Qatar, Saudi Arabia, United Arab Emirates, and Yemen. The difference between water resources per inhabitant for water-rich and water-poor countries can be explained with the help of an example: Brazil, a water-rich country, has 8223 km^3 of water per year per inhabitant versus Jordan, a water-poor country has only 0.75 of water per year per inhabitant.

Groundwater

Groundwater percolating beneath the earth's surface as soil moisture and contained in aquifers represents approximately one-third of all the world's freshwater resources. The area extending from the top of the land surface through the unsaturated soil to the top of the saturated water table is called the vadose zone. Soil moisture in the upper part of the vadose zone, which is the root zone of plants, is critical for food and fiber production. A very small part of the planet's freshwater is contained in this area (Table 1).

Water percolating through the soil may eventually fill all the voids to the point that the soil is totally saturated. The upper surface of this zone of saturation is called the water table. The saturated zone beneath the water table is called an aquifer. Aquifers are huge storehouses of groundwater. There are two types of aquifers: unconfined and confined. Unconfined aquifers are those into which water seeps from the ground directly above the aquifer. Confined aquifers are those in which an impermeable layer exists above the aquifer that prevent water from seeping into the ground from the surface directly above. Instead, water seeps into confined layers from recharge zones located farther away where the impermeable layer does not exist. Aquifers are also classified based on their size and the volume of water that can be extracted on an annual basis.

Table 3 Storage of water in groundwater basins by continent.

Volume (million km^3)	*Major groundwater basins*		*Minor groundwater basins*	
	% of land	*Volume (million km^3)*	*% of land*	
Africa	13.5	45	13.2	44
Asia	14.5	32	23	51
Australia	2.6	32	2.5	31
Europe	5.1	53	2.7	28
North America	3.2	15	12.4	58
South America	8.3	45	8.1	44

Source: BGR (2008) *Groundwater Resources of the World 1: 25 000 000, Statistics*. BGR: Hanover/UNESCO: Paris.

Approximately 35% of the earth's land area contains major groundwater aquifers and basins. Examples include the Ogallala in the United States, the Guarani in South America, the Great Artesian Basin in Australia, the Nubian in Africa, the Western Siberian in Russia, and the North China Plain Basin in central China. In addition to these major aquifers about half of the continents have minor or near surface aquifers (Table 3). Many aquifers exist under deserts where there is little precipitation. The water stored in these aquifers is geologically old water. Recently, satellite imagery and drilling helped to discover the Lotikipi Basin Aquifer—which by one estimate is roughly the size of Rhode Island—and the smaller Lodwar Basin Aquifer in Kenya. These aquifers contain an estimated 250 billion cubic meters of water (Kulish, 2013).

Freshwater lakes

Most freshwater lakes are located at high altitudes, with nearly 50% of the world's lakes located in Canada alone. The largest of these are as follows.

- The Caspian Sea is the largest enclosed interior lake but it is saline and not freshwater (Leeden et al., 1990).
- The 10 largest lakes by area (Downing and Duarte, 2009).

1.	Caspian Sea	Asia	371,000 km^2
2.	Lake Superior	North America	82,100 km^2
3.	Lake Victoria	Africa	68,800 km^2
4.	Lake Huron	North America	59,600 km^2
5.	Lake Michigan	North America	57,800 km^2
6.	Lake Tanganyika	Africa	32,900 km^2
7.	Great Bear Lake	North America	31,328 km^2
8.	Baikal	Asia	30,500 km^2
9.	Lake Malawi (Lake Nyasa)	Africa	30,044 km^2
10.	Great Slave Lake	North America	28,568 km^2

- The 10 largest lakes by volume (Downing and Duarte, 2009).

1.	Baikal	Asia	23,600 km^3 (about 20% of the world's freshwater)
2.	Tanganyika	Africa	18,900 km^3
3.	Superior	North America	11,600 km^3
4.	Lake Malawi (Lake Nyasa)	Africa	7725 km^3
5.	Lake Michigan	North America	4900 km^3
6.	Lake Huron	North America	3540 km^3
7.	Lake Victoria	Africa	2700 km^3
8.	Great Bear Lake	North America	2236 km^3
9.	Issyk-Kul (Ysyk Kol)	Asia	1730 km^3
10.	Lake Ontario	North America	1710 km^3

- The Great Lakes—Superior, Michigan, Huron, Erie and Ontario—located in the Midwest of the United States and shared with Canada are the largest surface freshwater system on the Earth. They contain about 21% of the world's surface water supply and 84% of North America's surface freshwater (US Environmental Protection Agency, 2012).
- Lake Baikal in Asia is the largest freshwater lake holding some 23,600 km^3 of water which is about 20% of the Earth's total freshwater (Downing and Duarte, 2009).

Rivers

Rivers are the arteries of the planet, delivering most of the fresh surface water people use. An estimated 263 international river basins cover about 50% of the Earth's surface, yet by volume they carry about 2120 km^3, or about 0.006% of fresh water (Table 1). The territory of 145 countries straddles international river basins. Some countries share their territory/boundary with only one other country while others may share it/them with several countries—13 basins are shared between 5 and 8 countries and 5 basins (Congo, Niger, Nile, Rhine, and Zambezi) are shared between 9 and 11 riparian nations. Transboundary river basins are home to approximately 40% of the world's population (United Nations, Department of Economic and Social Affairs, 2014).

At least 33 countries depend on other countries for over 50% of their renewable water resources. These countries include: Argentina, Azerbaijan, Bahrain, Bangladesh, Benin, Bolivia, Botswana, Cambodia, Chad, Congo, Djibouti, Egypt, Eritrea, Gambia, Iraq, Israel, Kuwait, Latvia, Mauritania, Mozambique, Namibia, Netherlands, Niger, Pakistan, Paraguay, Portugal, Republic of Moldova, Romania, Senegal, Somalia, Sudan, Syrian Arab Republic, Turkmenistan, Ukraine, Uruguay, Uzbekistan, Viet Nam and Yugoslavia (Food and Agriculture Organization, 2003).

Dams and reservoirs

The flow of water in a river is not constant. It is influenced by seasons and hydro-meteorological changes in the watershed. Dams are an efficient way to store water to meet demands during low rainfall seasons or periods of drought. Dams, diversions, and canals are present on about 60% of the world's largest rivers. The 45,000 largest dams around the world have a combined storage capacity of 6000 km^3. These dams provide water for agricultural, irrigation, domestic, and industrial water use, hydropower generation, and flood control. Dams help irrigate nearly 40% of agriculture around the world and 19% of the world's electricity is generated from water stored in dams. A third of countries rely of hydropower for their electricity needs (World Commission on Dams, 2000).

Although dams provide numerous benefits, they may also negatively impact river flow, existing water rights and access to water, the ecosystem (both aquatic and riparian), and even the livelihood of communities, especially downstream, striving on the river ecosystem for survival. Thus, the construction of new dams are often contested by funding and environmental organizations. Nonetheless, the construction of new dams continues: 46 new dams are planned for the Yangtze River basin in China, 27 in the La Plata basin in South America, 26 in the Tigris and Euphrates basin (Wong et al., 2007).

Water use

Agriculture is the largest consumer of water. It consumes 70% of the total water withdrawn, compared to only 19% for industrial use and 11% for municipal use. This ratio is skewed by a few countries with high water withdrawals. On average, the ratio of agricultural to municipal and industrial use is 59%, 23%, and 18% respectively (Food and Agriculture Organization, 2012). It is believed that irrigation started along the Tigris and Euphrates Rivers in what is now Iraq, in the desert valley along the Nile River in Egypt, and the Indus River in Pakistan. The Native Americans, in what is now Mexico and the southwestern United Sates, also used irrigation to support food production. Irrigated agriculture has expanded tremendously and currently supports 40% of crop production around the world. Table 4 gives the water use for agriculture, domestic, and industry across each continent. Except for Australia and Europe, agricultural water use dominates other uses on every continent.

Table 4 Water use by continent.

Continent	*Agriculture (%)*	*Domestic (%)*	*Industry (%)*
Africa	88	7	5
Asia	86	6	8
Europe	33	13	54
North and Central America	49	9	42
Australia	34	64	2
South America	59	19	23

From Food and Agriculture Organization (1996) *Report of the World Food Summit*. Rome: Food and Agriculture Organization.

Table 5 Leading irrigation countries.

Country	*Irrigated area (1000 km^2)*	*Irrigated land (% of cropland)*	*% of water withdrawals for irrigation*
China	2300	19	87
India	513	29	93
USA	490	11	42
Pakistan	163	80	97
Mexico	62	25	86
Egypt	33	100	86

From Gleick PH (2000) *The World's Water 2000-2001. The Biennial Report on Freshwater Resources.* Island Press: Washington, DC.

Asia, home to most of the world's population, is also the most irrigated. China, India, and the United States, the three most populous countries, have the largest areas under irrigated agriculture (Table 5), followed by Pakistan, Mexico and Egypt. A number of countries located in the arid region of the world (e.g., Saudi Arabia, Iran, Iraq, Israel, etc.) and central Asia are highly dependent on irrigation for their food and fiber needs.

The world's population is projected to increase by an additional 2–3 billion in the next 40 years. This will result in an increase in the demand of food supply and subsequently in the demand for water. With climate change, precipitation and hence water availability is expected to decrease, especially in the lower latitudes. Regions that are likely to be affected by climate change are also the most vulnerable in terms of water availability. To meet the food demand for the growing population, water use for irrigation is estimated to increase by about 19% by 2050. Technological (e.g. more efficient irrigation demand) and policy (e.g. use of genetically modified crops) interventions may, however, reduce pressure on agricultural water demands.

Virtual water and water footprint

Another perspective for analyzing water used in food production is virtual water. The virtual water content, which represents the volume of water that the produce has consumed throughout the growth cycle, gives an interesting perspective on the flow of water from major agricultural producing countries to those relying mostly on import.

The production of 1 ton of grain, on average, requires 1000 m^3 of water whereas the virtual water content of livestock product is much larger, as it includes the virtual water content of the feed crops consumed, the water that the animal drank over its whole lifetime, and the water used in the production of the final product. The production of 1 ton of beef thus requires approximately 15,500 m^3 of water (Hoekstra and Hung, 2002).

A country producing and exporting an array of food products is in fact exporting the water embedded in them beyond its boundaries whereas a country at the importing end is actually importing that embedded water and thus saving its own water, which can be put to other uses (Allan, 1997). Fig. 1 shows the international virtual water flows and virtual water balances for all countries in the world. From 1996 to 2005, the volume of international water flows related to agricultural and industrial products averages 2320 billion cubic meters. The main virtual water gross exporters were the United States, China, Canada, Brazil, Argentina, and Australia, whereas main gross virtual water importers where United States, Japan, Germany, China, Italy and Mexico (Mekonnen and Hoesktram, 2011).

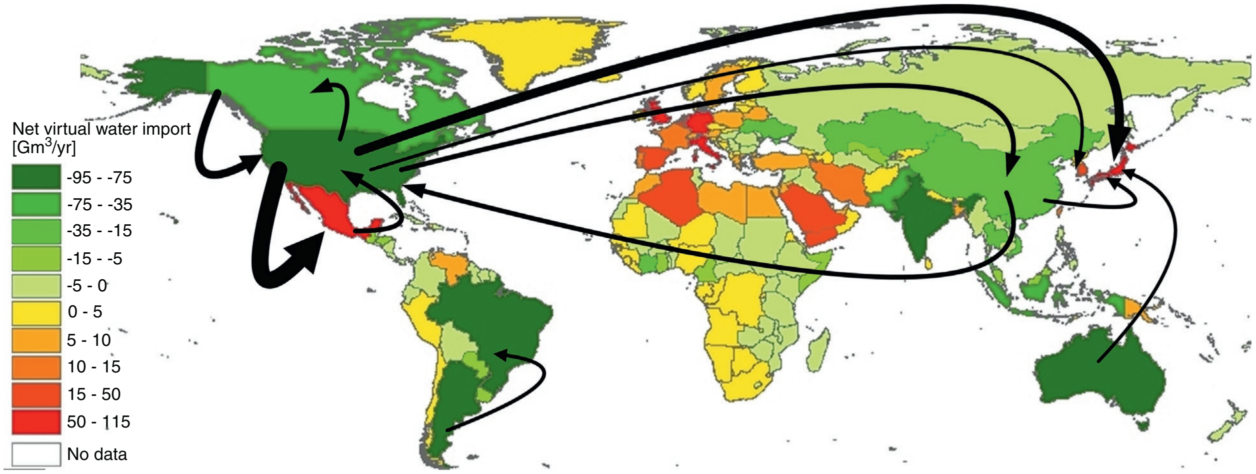

Fig. 1 Virtual water balance and direction of gross virtual water flows over the period 1996–2005. Map lines delineate study areas and do not necessarily depict accepted national boundaries. Reproduced with permission from Hoekstra AY and Mekonnen MM (2012) The water footprint of humanity. *Proceedings of the National Academy of Sciences* 109 (9): 3232–3237.

Reliance on food import can be an attractive option for water-poor countries, whereas water rich countries may produce and efficiently export more virtual water to other regions, thus replicating the logics of economies of scale (Mekonnen and Hoesktram, 2011). Virtual water could advocate for water conservation by discouraging the production of high water embedded products from water scarce regions and encouraging the water dependent economic activity in water rich regions. The decision-making process of international trade does not seem to be driven water efficiency use or water conservation efforts (Black and King, 2009; Ercin and Hoekstra, 2014). Food independence drives large scale agricultural production, and no country is willing to rely solely on import to meet its food needs. This sociopolitical need can easily lead to the misuse of limited available freshwater resources.

Climate

Local hydrometeorological variables (temperature, humidity, sunshine, atmospheric pressure, wind velocity, precipitation, etc.), and hence water availability, are influenced by the climate. Climate (or climatological normal) is a measure of the average pattern of the meteorological variables over a particular region and over a time period, usually 30-years. Discussions on the climate, in the context of water availability, include climate variability and climate change (or global warming). Climate variability pertains to the way the climate fluctuates around the long-term mean, while climate change refers to the long-term continuous change to a long-term statistically significant variation in either the mean state of the climate or in its variability.

Climate variability

The common drivers of climate variability are large-scale circulation patterns, sunspots, and volcanic eruptions. The former, however, is the most important one and it can dramatically alter the climate, weather and hydro-meteorological variables around the world. The time period of the resultant change can be in terms of months, years, or even decades.

El Niño-Southern oscillation

There are a number of climate variability patterns that influence local hydrometeorological conditions. The most important one is the El Niño-Southern Oscillation (ENSO). ENSO is a coupled ocean-atmosphere phenomenon related to sea surface temperature (SST) anomalies in the central and eastern equatorial Pacific and the associated sea-level pressure difference, the Southern Oscillation (Rasmusson and Carpenter, 1982). The Southern Oscillation is the fluctuation in air pressure between Tahiti and Darwin, Australia. Negative (positive) pressure is accompanied by sustained warming (cooling) in the central or eastern Pacific. ENSO has a recurrence pattern of 3–6 years and every event normally lasts for approximately a year. El Niño events are often, but not always followed by La Niña events, also referred to as the cold phase of ENSO (Trenberth, 1997). They have a direct effect on the hydrological cycle both regionally and globally, especially on precipitation patterns (e.g., Khedun et al., 2012; Piechota and Dracup, 1996; Regonda et al., 2005; Ropelewski and Halpert, 1987).

Regional effect of ENSO

The effect of ENSO is neither distributed uniformly across the globe—not even across a single continent—nor in time during its period of occurrence (Lyon, 2004). As ENSO cycles through its different phases (El Niño, La Niña, and neutral), its impacts vary both spatially and temporally (Fig. 2).

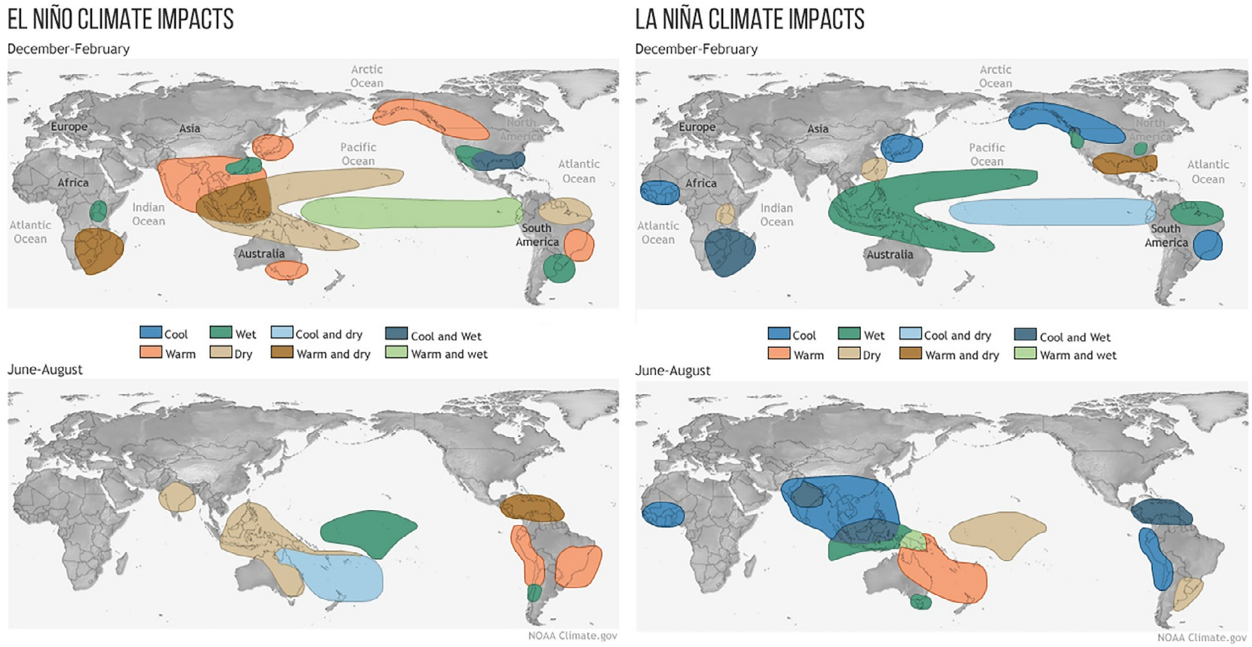

Fig. 2 Effect of El Niño and La Niña around the world. Map lines delineate study areas and do not necessarily depict accepted national boundaries. From National Oceanic and Atmospheric Administration, National Weather Service (2012) *Weather Impacts of ENSO*. Jetstream - Online School for Weather.

Africa

The effect of ENSO is mostly felt in the southeastern part of Africa and Madagascar and the eastern part along the equator. Dry and warm (wet and cool) conditions are felt during El Niño (La Niña) during December through February in the southeastern part while the eastern part benefits from higher (lower) precipitation. ENSO conditions influence the ecosystem and may affect rainfed agriculture and yield. Remote sensing studies on ecosystem variables confirm ENSO's influence: above normal normalized difference vegetation index (NDVI) were noted, indicative of a high biomass content, during the 1997/98 El Niño event in the eastern equatorial region along with wetter than normal conditions in the southeastern region while the southwestern region was dry (Anyamba et al., 2001, 2002).

Asia and Australia

El Niño causes abnormally warm and dry conditions during December through February over the region encompassing Southern Asia to Northern Australia. By June and August, the dry conditions extends to most of the eastern part of Australia, leading to an increase in the risk of bush fires (Fuller and Murphy, 2006; Williams and Karoly, 1999). Some1.75 million hectares was destroyed by bush fire in January and February 2003, an El Niño year (Bear and Pickering, 2006).

The relationship between ENSO and the Asian-Australian and Indian summer monsoon is well established (Charles et al., 1997; Kirtman and Shukla, 2000; Kumar et al., 1999; Yoo et al., 2010). The monsoon is associated with the biannual complete reversal of lower atmosphere wind regime over the Indian Ocean which results from the differential heating between the land and sea surfaces, and the presence of the Himalayas (Cadet, 1979). There is a negative correlation between ENSO and the Indian summer monsoon (weak monsoon arising from El Niño events). It causes a change in the precipitation pattern and has a strong impact on glacier-fed rivers. Ice cores from the Himalaya indicate that snow accumulation in the region is sensitive to the changes in the South Asian Monsoon (Thompson et al., 2000). These glaciers are the headwaters of several major rivers (e.g. the Huang He (Yellow) and Yangtze rivers in China, the transboundary Mekong, Ganges-Brahmaputra-Meghna, Indus, etc.) and they sustain the lives and economy of nearly 1.5 billion people in 9 Asian countries—the most populous region of the world.

Europe

The influence of ENSO does not extend into Atlantic Europe but its impact on Atlantic storm tracks can impact European weather (Schär et al., 1998). It is important to note that the geographical distance separating Europe and the central Pacific Ocean, where fluctuations in SST lead to ENSO, may make it hard to detect any association between ENSO and European weather using simple linear correlation techniques (Fraedrich, 1994). Warm (cold) ENSO episodes have been associated with enhanced cyclonic (anticyclonic) activities (Fraedrich, 1990). Warm events have been observed to produce more variable winter conditions, whereas cold events have had a more uniform response. The influence of ENSO on the glaciers of the European Alps, surface water reservoir for a number of important rivers, is almost negligible at the yearly timescale (Durand et al., 2009), but weak correlations may be detected on a multidecadal scale (Efthymiadis et al., 2007). Hence, the influence of ENSO should not be ignored in the water resources planning for the region.

North America

ENSO alters the path of the jet stream and hence affects the weather and storm tracks on the North American continent. El Niño causes a dip in the position of the jet stream in the Eastern Pacific which results in warmer winters in Western Canada and Southern Alaska and Northeastern US whereas the Southern United States has cooler and wetter weather. During the summer the southern part of Mexico becomes warm and dry. During La Niña, the dip in the jet stream shifts west of its normal position towards the Central Pacific. It causes cooler winters in Eastern Canada while the Southern United States becomes warm and dry.

The shift in the jet stream, during warm ENSO events, forces storms south of their normal position in the Pacific Northwest into California. Stronger El Niño events can force storms even further south into Southern California, while the Pacific Northwest becomes drier as the moisture flux is transported southward. California thus benefits from above average precipitation during El Niño and flash floods are very common (Mo and Higgins, 1998; Schonher and Nicholson, 1989). This influx of moisture also increases snowfall in the Sierra Nevada mountain range (Kunkel and Angel, 1999). In the Rocky Mountains, the effect of ENSO varies with opposite effects at the northern and southern ends (Baker, 2003). The Rockies can be divided into three sections: the northern Rocky Mountains in Montana, the central Rocky Mountains extending from southern Montana into central Wyoming, and the southern Rocky Mountain stretching from southern Wyoming into New Mexico and Arizona. El Niño (La Niña) winters bring higher (lower) snowfall in the southern Rockies (Kunkel and Angel, 1999). The effect of ENSO on the central and northern Rockies is less pronounced. In its cold (warm) phase ENSO bring higher (lower) snowfall over the Pacific Northwest in early and midwinter and over the northern Rocky Mountains in midwinter (Patten et al., 2003; Smith and O'Brien, 2001). The central Rockies receives 30% less heavy precipitation events (Gershunov and Barnett, 1998a).

South America

El Niño is associated with severe drought in Mexico and most of Brazil while Argentina, Paraguay and Uruguay benefit from increased precipitation. The coastal areas of Ecuador, Northern Peru, and Southern Chile also benefit from increased rainfall, but the mountainous Andes region suffers from drought which causes the glaciers to retreat. In La Niña conditions, however, this region receives a fourfold increase in heavy storm events as compared to non-ENSO years (Grimm et al., 2000; Haylock et al., 2006). ENSO events have also been found to influence extreme precipitation events in South America (Grimm and Tedeschi, 2009). This is an important observation as hydrological hazards are often associated with changes in extreme events associated with climate variability.

Other large-scale circulation patterns

Even though ENSO is the most well-known large-scale climate variability pattern, there are a number of other climate teleconnection patterns that affect, to varying degrees, local weather conditions and hence water availability. Their influence, either alone, or in conjunction with ENSO should not be discounted. Some of the most common ones include: the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation, the Quasi-Biennial Oscillation, the El Niño Modoki, etc.

In the US, for example, it has been found that PDO may modulate the effect of ENSO—El Niño (La Niña) during the positive (negative) phase of the PDO—and lead to stronger climate responses than when they are evolving in opposite phases (Gershunov and Barnett, 1998b). There is, however, a possibility that stronger El Niño and La Niña events result from random decadal variation of ENSO and may even be responsible for the PDO (McPhaden et al., 2006; Rodgers et al., 2004). Irrespective, knowledge of all the climate variability patterns that influence local climate conditions is important and can help forecasting precipitation and other climate variables that affect water availability (Chowdhury and Sharma, 2009; Devineni et al., 2008; Khedun et al., 2014).

Climate change

Earth's climate is constantly changing. Some of this change can be attributed to natural causes, such as changes in Earth's orbit, changes in solar activity, or volcanic eruptions, and anthropogenic impacts, resulting from a change in the composition of Earth's atmosphere. Since the beginning of the Industrial Era, human activities have led to an increase in the concentration of heat-trapping greenhouse gasses in the atmosphere, which has led to an increase in atmospheric temperature. In fact, the most likely reason for the recent observed warming, since the mid-20th century, is anthropogenic greenhouse gas emissions.

The greenhouse effect

According to the recent Sixth Assessment Report (AR6) from the International Panel on Climate Change (IPCC, 2023), the global surface temperature in the last decade (2011–20) was 1.09 °C warmer than the previous century, with larger increases over land. This change is driven, mostly, by emissions from human activities, as illustrated in (Fig. 3). It will continue to increase in the near term and future increase will depend on future greenhouse gas emissions. The temperature on Earth depends on the balance between energy entering and leaving the atmosphere. Incoming energy from the sun can be either reflected back into space or absorbed by Earth's surface. Some of the energy absorbed is released back into the atmosphere (infrared radiation). Greenhouse gases (water vapor, carbon dioxide, methane, etc.) absorb some of this energy which keeps the atmosphere warm. Earth's average surface temperature, without the greenhouse effect, would be 255 K (−18 °C), instead of the current 288 K (15 °C) which enables life to thrive. Paleoclimatological records from ice cores, corals, lake sediments, tree rings, etc. reveal that the concentration of greenhouse gases, especially carbon dioxide and methane, has fluctuated naturally over geological times, thus causing the climate to fluctuate between ice ages and interglacial periods. In recent decades, however, a marked increase in the concentration of carbon dioxide has been recorded. This increase has been attributed mostly to human activities, such as burning of fossil fuels, clearing of forests, and the use of gasoline dependent modes of transportation. The global monthly average concentration of carbon dioxide in the atmosphere has increased from a pre-industrial level of about 280 ppm (parts per million; pre-1750 tropospheric concentration) to 425.38 ppm (March 2024) (NOAA, 2024). The resulting increase in temperature is having a significant impact on the planet, affecting its land and marine ecosystems, the hydrologic cycle, sea-level, weather extremes and weather-related hazards, water availability, food and fiber supply, human health, and the economy among others.

Impact on the hydrologic cycle

As the climate changes, the amount of energy on Earth's surface increases, which leads to an intensification of the hydrologic cycle. A warmer planet implies that the water-holding capacity of the atmosphere increases; thus, leading to an increase in evapotranspiration. Higher evaporation from the soil implies less water for plants and a decrease in the recharge of groundwater aquifers which may result in a decrease in baseflow and hence less water in streams and rivers, lakes, and wetlands. An increase in evaporation from large water bodies such as lakes and the ocean, also implies more water in the atmosphere and an increase in global precipitation.

According to the IPCC (2022), records indicate that precipitation patterns across the world is changing. This increase, however, is not equally distributed, neither spatially nor temporally, across the planet (Fig. 4). Several regions are experiencing an increased in precipitation for part of the year and a decrease during other seasons. While the annual mean may not change by much, the change in the timing of rainfall may have serious implications for agriculture, especially where it is rainfed. Similarly, both global and regional evapotranspiration patterns are changing as a result of increasing carbon dioxide in the atmosphere. Two factors have contributed to increase in global terrestrial annual evapotranspiration: increase in atmospheric demand and vegetation greening. Regionally, the relationship between changes in carbon dioxide concentration and evapotranspiration is complex. A combination of factors—climate and atmospheric composition, land surface characteristics, and ecosystems—influence evapotranspiration. Higher carbon dioxide drives evaporative demand up but is counteracted by reduced stomatal conductance which in turn reduces transpiration.

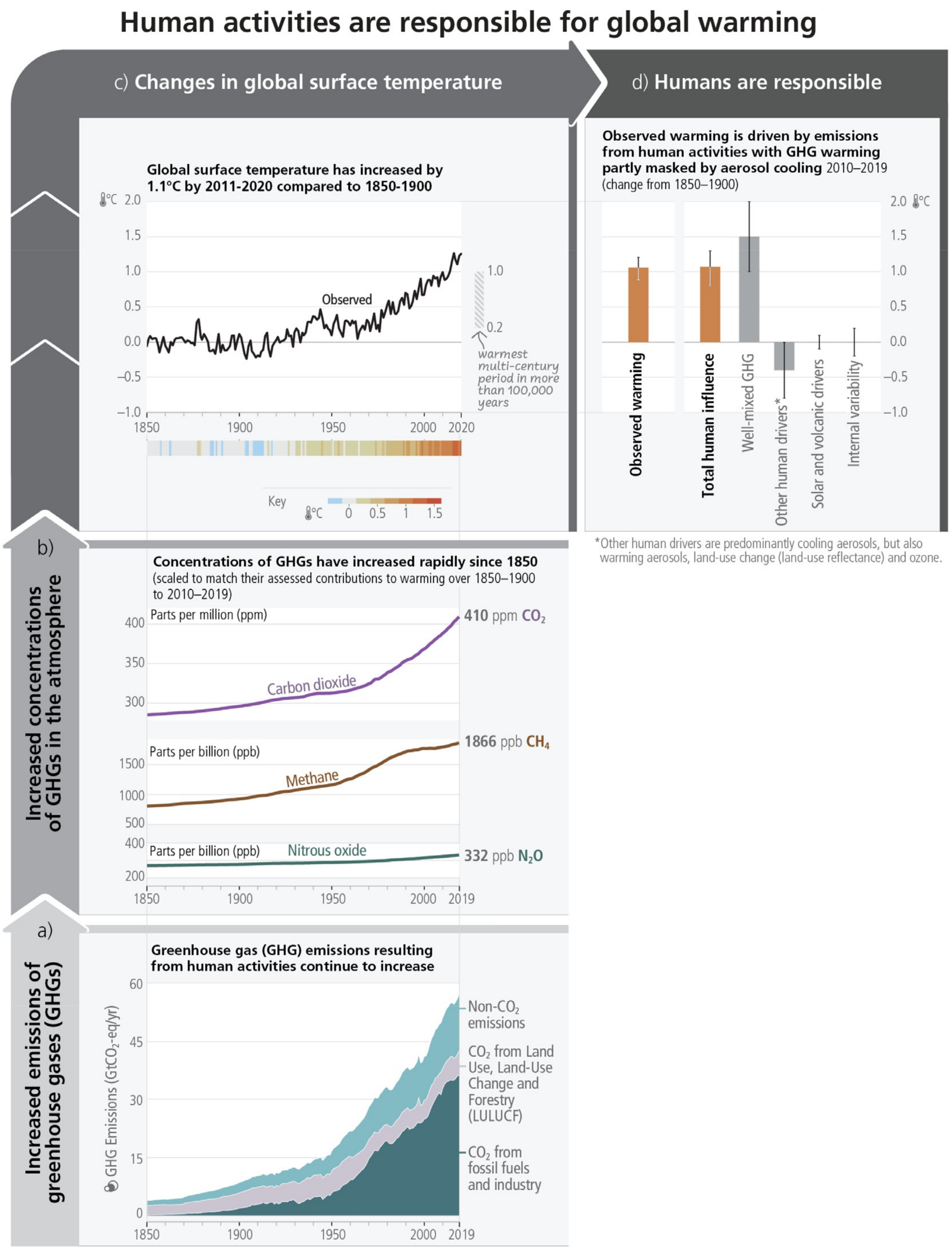

Fig. 3 The causal chain from emissions to resulting warming of the climate system. From IPCC (2023) Climate Change: Synthesis Report. *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC: Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Soil moisture is controlled by the difference between precipitation, and in some cases irrigation, and evapotranspiration. Regionally, soil moisture is increasing in some regions and decreasing in others, by as much as 20%. Decrease in soil moisture is more widespread and is mostly driven by increase in evapotranspiration than decrease in precipitation. Regions in the extratropical latitudes, including Europe, western North America, northern Asia, southern South American, Australia, and eastern Africa, are experiencing drier dry seasons (IPCC, 2022), and this trend will continue as the climate continues to change.

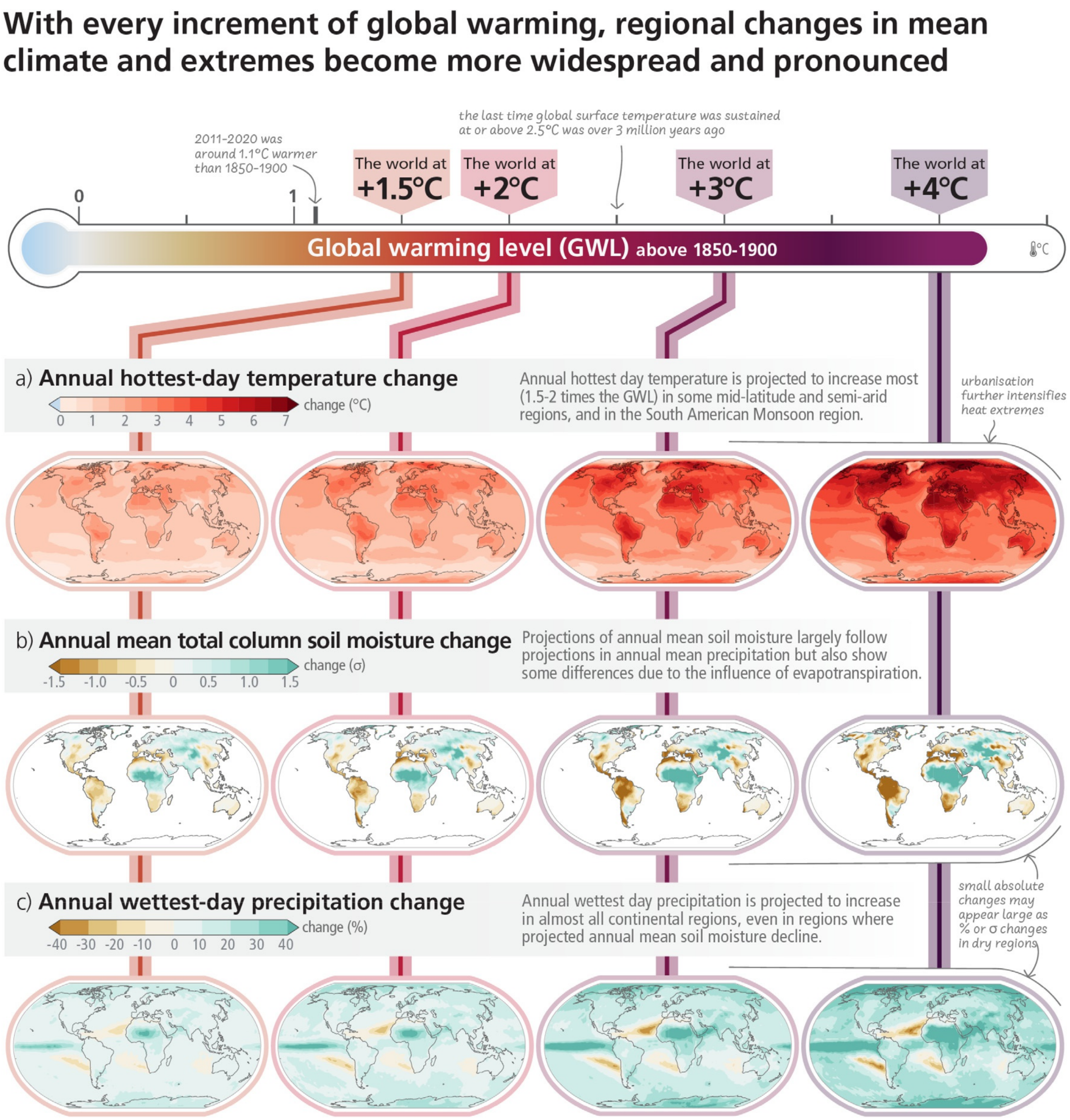

Fig. 4 Projected changes of annual maximum daily maximum temperature, annual mean total column soil moisture and annual maximum 1-day precipitation at global warming levels of 1.5 °C, 2 °C, 3 °C, and 4 °C relative to 1850–1900. From IPCC (2023) Climate Change: Synthesis Report. *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC: Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Effect on extreme events

An intensification of the hydrological cycle due to climate change implies that the frequency, intensity, spatial extent, duration, and timing of extreme precipitation events, evapotranspiration, tropospheric water content, and runoff may change (National Research Council, 2011), thus influencing the occurrence, nature, and return period of extreme events. Changes at both the lower tail (e.g., reduction in precipitation leading to droughts) and the upper tail (e.g., high intensity rainfall resulting in floods) of the range of observed values can be expected. These changes may be in the following three ways: (1) a shift in the mean which will result in less low-magnitude events and more high-magnitude events; (2) an increase in standard deviation and thus variability which equates with more low- and high-magnitude events; and (3) a change in the shape of the distribution where low-magnitude events remains almost constant but in high-magnitude events increase (IPCC, 2012).

Further, increase in the co-occurrence of multiple climate and non-climate related hazards, and their interaction, creating compound and cascading risks propagating across sectors and regions are of major concern. An increase in the frequency of compound extremes such as droughts and heatwaves will not only have an impact on agriculture and food production but also on health, ecosystems, infrastructure, livelihoods.

Water and biofuel production

Biofuel has often been touted as a panacea for climate change. It is a vital part of the renewable energy family. Biofuels are gaseous or liquid transportation or heating fuels derived from biological sources such as grains, sugar crops, starch, cellulosic materials and organic waste (De Fraiture et al., 2008). Biofuels include bioethanol and biodiesel. Bioethanol is produced by fermentation of sugar from plants, such as sugarcane, or from starch crops, such as corn, whereas biodiesel is made from vegetable oils or animal fats through a transesterification process.

Global biofuels production has been increasing steadily over the last decade—production rose from 16 billion liters in 2000 to more than 100 billion liters in 2011, and today, biofuel provides around 3% of road transport fuel globally (on an energy basis) (International Energy Agency, 2013). The transportation sector is a major consumer of petroleum fuels, hence substituting biofuel for fossil fuel offers several advantages—it is a renewable energy source, provides energy security by lessening dependence on foreign oil supply, allows a fair trade balance by reducing the financial burden, it is less polluting than petroleum fuel less sulfur, carbon monoxide and particulates, it reduces greenhouse gas (GHG) emissions, and biofuel, being usually a local industry, promotes rural economic and social development. These benefits have driven many countries to adopt policies that encourage local biofuel production (De Fraiture et al., 2008; Demirbas, 2007).

In the United States, the Energy Independence and Security Act of 2007 mandated the annual production of 56.8 billion liters of ethanol from corn by 2015 and an additional 60.6 billion liters of biofuels from cellulosic crops by 2022 (Dominguez-Faus et al., 2009). Around the world, Brazil already fuels a quarter of its ground transportation using ethanol derived from the fermentation of sugarcane (Somerville, 2006). India, driven by environmental and rural development considerations, hopes that biofuels will account for at least 20% of its diesel and gasoline consumption by 2017. However, increasing biofuel production raises several concerns, among which exacerbating the stress on water demand, which is already a scarce resource in many countries, is a major one.

Biofuel production impacts water in many ways—an enormous amount of water is required to irrigate feedstock crops, water is used during processing in biorefineries, and the quality of water bodies is affected by increased agricultural activities. These combined effects can be referred to as the water footprint of biofuel (Dominguez-Faus et al., 2009). The water requirements for biofuels production depend on the type of feedstock used and on geographic and climatic variables. Common crops that are used for biofuels production are corn and soybeans (primarily in the US), flaxseed and rapeseed (Europe), sugarcane (Brazil), and palm oil (South-East Asia). The most water-intensive aspect of biofuel production is the water used in irrigating feedstock crops, while the water used by biorefineries is generally similar to that for oil refining (U.S. Department of Energy, 2006). However, because water use in biorefineries is concentrated into a smaller area, the effects locally can be substantial. A biorefinery that produces 100 million gallons (378,541 m^3) of ethanol per year, for example, would use the equivalent water supply for a town of about 5000 people (National Research Council, 2008).

The water consumption of ethanol derived from corn grain is about 28 gal per mile (66 L km^{-1}) (King and Webber, 2008). This is in strong contrast with the water consumption for conventional petroleum gasoline and diesel of 0.07–0.14 and 0.05–0.11 gal per mile (0.16–0.33 and 0.12–0.26 L km^{-1}), respectively. Algae, another source of biofuel, is gaining much attention as, unlike corn or soybean, it does not compete with agricultural land for food crops and may produce 10 times more fuel per hectare. From a water requirement standpoint, however, it is not as efficient. Water consumption can vary anywhere between 3.15 and 3650 L of water for the amount of algal biofuel equivalent to 1 L of gasoline (National Research Council, 2012). The production of 39 billion liters a year, to meet a mere 5% of US transportation fuel needs, is currently unsustainable from a water requirement perspective. Table 6 shows some major biofuel producing countries, biofuel crops, and current and projected percentages of crop water used, and percentages of irrigation water need for biofuel production. It is clear that production of biofuel will divert more and more of the water currently being used for food production, thus putting additional pressure on water allocation. More efficient irrigation techniques may reduce water consumption and mitigate the effect of biofuel production.

Table 6 Major biofuel producing countries, sources of biofuel, and current and projected percentages of total water and irrigation water used for biofuel production.

Country	*Biofuel (billion liters)*	*Main biofuel crop*	*% of total crop water used for biofuel*		*% of irrigation water used for biofuel*	
	2030		*2005*	*2030*	*2005*	*2030*
USA and Canada	51.3	Maize	4	11	2.7	20
European Union	23.0	Rapeseed		17		1
China	17.7	Maize	1.5	4	2.2	7
India	9.1	Sugarcane	0.5	3	1.2	5
South Africa	1.8	Sugarcane	2.8	12	9.8	30
Brazil	34.5	Sugarcane	10.7	14	3.5	8
World	141.2		1.4	3	1.1	4

Adapted from De Fraiture C, Giordano M, Liao Y (2008) Biofuels and implications for agricultural water use: Blue impacts of green energy. *Water Policy* 10: 67–81. doi: 10.2166/wp.2008.054.

The production of biofuels not only affects water quantity but also affects water quality. Converting grassland to farmland requires both fertilizer and pesticide input and converting existing crops to biofuel will lead to an increase in nitrogen application (National Research Council, 2008). The water quality impacts of various crops can be compared based on fertilizers and pesticides application per unit of the net energy gain captured in a biofuel. Fertilizer requirement varies based on crop type. Corn requires the greatest amount of both fertilizer and pesticides. Between 24 and 36% of the nitrogen fertilizer applied to corn and soybean may be lost through runoff, sediment transport, tile drainage, and subsurface flow. This fraction may be a mere 5% during drought and as high as 80% during floods (Dominguez-Faus et al., 2009). Thus, if proper farm practices and management plans are not implemented, these chemicals can negatively impact neighboring rivers and lakes and hence affect water quality.

Transboundary water

According to the United Nations, there are 276 international rivers shared by two or more countries and 468 identified transboundary aquifers, of which 106 are in Africa, 135 in the Americas, 130 in Asia and Oceania, and 97 in Europe (IGRAC (International Groundwater Resources Assessment Centre), 2021). Transboundary river basins cover 50% of the earth's surface (excluding Antarctica) and channels 60% of global streamflow (Biswas, 1999). Some 40% of the world's population lives within transboundary lake and river basins and two billion people depend on close to 600 transboundary groundwater systems (IGRAC, 2015).

Transboundary waters and the role of the state

Worldwide, countries have found it more cost-effective to exploit water sources within their jurisdiction than to invest in water management strategies. The only remaining sources of water that can now be developed are mostly transboundary in nature (Biswas, 1999; Black and King, 2009).

Countries manage their shared watercourses considering their own national priorities, commonly overlooking water needs up- or downstream (Eckstein, 2017; Kreamer, 2012). As this tendency grows, pressure over management enhancement and institutional governance at national and international level challenges the state accountability to cope with contemporary transboundary issues and future threats (Suhardiman and Giordano, 2012; Tarlock, 2000). Even though the role of state actors as the key players in international water affairs is not questionable, it is agreed that their role has been insufficient when it comes to understanding the actual challenges pertaining to transboundary water management. There is recognition of participation of nonstate networks, institutional soft power alliances on decision-making processes and the existence of the scalar relationships and interactions between regional, national, subnational, and local influences (Sanchez and Eckstein, 2020; Sanchez and Kaiser, 2011; Zeitoun, 2013). The case of international organizations as key players in negotiations between coriparian river basins and the development of new governance scheme is well documented. The World Bank was a mediator in the signing of the Indus River Basin treaty between India and Pakistan; the United Nations Environmental Program (UNEP) on the Zambesi River agreement between its riparians; and the United Nations Development Program (UNDP) over the Mekong River Basin agreement (Biswas, 2011b; Eckstein, 2011).

Water interdependency: Conflict vs. cooperation

Management of transboundary water is very complex, and so far, only one-third of the transboundary river basins have a cooperative management framework. A transboundary basin can be a source of conflict and represents the potential for water wars or can represent an opportunity for cooperation among neighboring countries (Wolf et al., 2005). Despite the fact that water scarcity may give rise to tension over shared water resources (Kreamer, 2012), international cooperation has been more often the rule than the exception (Giordano and Wolf, 2003; UNESCO, 2013). Black and King (2009) noted that, between 1948 and 2008, 42 events related to transboundary river basins have led to hostile or military attacks, but 1743 events that have resulted in verbal discussion; cultural, economic, technical, and scientific cooperation; and, in some cases, the signature of an international water treaty. Since 2000, conflicts have been limited to infrastructure development and water quantity.

Even though it is clear that cooperative action may benefit transboundary neighbors, power asymmetry between parties has often been an impediment for effective cooperation over transboundary waters, which compromises water supplies and peaceful relations among parties (Ohlsson, 1995; Turgul et al., 2024). Of the world's 276 international basins, 166 do not have any treaty provisions covering them whatsoever. Only one third of the multilateral basins are entirely covered by a treaty provision and most of those are limited to bilateral agreements (Hussein et al., 2023). The United Nations International Convention on the Law of the Non-Navigational Uses of International Watercourses (1997) just received its final ratification in 2014 (United Nations General Assembly, 2005). Therefore, it is yet to be assessed if this development will actually make a difference in expanding bilateral and multilateral formal allocation treaties.

Climate change and transboundary water management

Climate change will only exacerbate present water disputes between countries as water availability and quality changes (Khedun et al., 2009; McCarthy et al., 2007; Nordas and Gleditsch, 2005). Thus, recognizing climate change as one of the challenges for transboundary water management, the actual international legal framework (bilateral and multilateral agreements) will also be adversely affected. Generally, transboundary agreements have not been designed to cope with increased climate variability, as they are often restricted by rigid definitions of water allocation rather than percentages. The certainty of climate variability results in an increased pressure over alternative governance structures, potentially diminishing the legitimacy of weak international agreements (Suhardiman and Giordano, 2012; Turgul et al., 2024). The declaration of the United Nations in 2013 as the International Year of Cooperation and in 2024 as Water for Peace Year foster states and other non-state actors to promote actions to achieve cooperation in water related goals in the face of multitude challenges.

Examples of transboundary water management around the world

There are numerous examples of transboundary basins that represent valuable examples of the challenges pertaining to transboundary water management. Examples include the following:

The Jordan River basin

The classic case of the Jordan River basin is constantly referred as one the most conflicted water regions in the world (Biswas, 2011a; Wolf, 2001). The Jordan River is shared by Israel, Lebanon, Syria, Jordan, and the Palestinian Authority. Aside from being the most water-scarce region in the world, the Middle East represents a region where political and ideological conflict has been permanently ruling the relationships among its coriparians. For Israel, adequate access to water to support a population that has increased 12-fold since 1949 and an agriculture highly dependent on irrigation, has been a constant concern over water resources allocation since the establishment of the nation (Giordano et al., 2002; Wolf et al., 2005). Likewise, high birth rates among Palestinians and Jordanians have put severe pressure on the already scarce water resources. In Gaza and the West Bank, the annual water availability per capita is below 100 m^3 (Israel less than 300 and Jordan around 100 m^3; Wolf et al., 2005). With rising demand and water constraints, conflicts between Israel and its riparian neighbors have oscillated from verbal exchanges to hostile armed conflicts over proposed water development projects (Wolf, 2000). However, even though historically Israel has been in a permanent state of conflict (sometimes at war) with its Arab neighbors, there are examples in which water has constituted the singular bond among them. The 1990 Treaty of Peace between Israel and Jordan described substantial provisions, principles, and cooperative mechanisms over their shared waters, regardless of conflicting conditions.

The Mekong River basin

The Mekong River Basin is shared by eight countries: China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. The magnitude of its challenging interdependency relies mostly on the fact that it is the major water supply in Southeast Asia, source of food and transport to more than 70 million people and home of the most diverse inland fisheries in the world (Black and King, 2009; Houba et al., 2012; Sneddon and Fox, 2006). To cope with the challenges of population growth, expanding irrigation, and hydropower generation, the Mekong River Commission was formed in 1995 between Cambodia, Laos, Thailand and Vietnam, with the godfathering effort of the UNDP (Biswas, 1999). Even though this Commission highlights the effort towards a cooperation scheme among coriparians to avoid water conflict, China, the most powerful country in the basin located upstream of the river, is not a signatory of the agreement. In fact, China voted against the resolution to establish the 1997 Convention on the Law of Non-Navigational Uses of International Watercourses (Biswas, 2011a). The expectations regarding the improvement of sustainable water use in the Mekong basin are not high, and the potential for conflict threaten the stability of the region (Biswas, 2011a; Houba et al., 2012). China, pressured by rapid population growth and water needs across all sectors, has already started the construction of a series of dams on the upper reaches without consultation with the Commission, thus threatening water supply for downstream users (Black and King, 2009; Sneddon and Fox, 2006). The power asymmetry between China and its neighbors does not give coriparians much hope despite the negotiation and mediation efforts of the UNDP.

The Rio Grande/Río Bravo River basin

The Rio Grande river basin, shared between Mexico and the United States, is the most water-stressed region on the continent (UNESCO, 2013). Population growth and intensive water use for irrigation, combined with drought, driven by a changing climate and new precipitation regime, are some of the most daunting challenges that water managers on both sides of the border faces (Lara-Valencia et al., 2023). However, despite power asymmetry between the two riparian countries, Mexico and the United States have been cooperating since the beginning of 1900s to efficiently and equitably share the waters of the Colorado and the Rio Grande basins (Sanchez-Munguia, 2011). Nevertheless, since the 1980s and more especially since the 1990s, drought conditions and climate variability have exposed the limitations of the 1944 US-Mexico Treaty. Industrialization and immigration, incentivized by the North America Free Trade Agreement of 1994, have accelerated population growth (quadrupled since 1945) and overallocation of water rights in the region has reached its limits (Mumme et al., 2024). The treaty (as most treaties around the world) does not consider climate variability scenarios in water allocation (Hurd, 2012). Further, with the region being in a perpetual state of drought it is uncertain if on the treaty provision pertaining to the timing of water deliveries (5-year cycles) from Mexican tributaries to the United States (Texas) will be satisfied. Moreover, transboundary groundwater, which is the primary source of water for around 12 million people, is not considered in the 1944 treaty (Eckstein, 2011; Mumme, 2000). These climatologic, hydrologic, and more importantly, institutional, and legal challenges, that govern the United States-Mexican conflict/cooperation relationship over shared waters of the Rio Grande expose the need to evaluate the adequacy of the 1944 Treaty under current and projected and future conditions.

Conclusions

Providing water to growing areas with limited supplies is a daunting challenge. Climate change further exacerbates water scarcity, especially in regions that are projected to receive less rainfall (Khedun and Singh, 2013a). Although distributional scarcity is a new reality, there is still time to adopt a new paradigm based on 'sustainable' water management practices. Practices must shift from supply development to demand and supply management incorporating more efficient agricultural irrigation, conservation, reuse, new technologies for water purification, smart improvements to infrastructure, water planning integrating economic and equitable use, and environmental factors with real participation by the widest realm of water users and communities (Brooks, 2005; Kaiser, 1996; Kaiser and Skillern, 2001; Khedun and Singh, 2013b; Wolf and Gleick, 2002). Like most paradigm shifts the practice of 'sustainable water management' will move slowly until accelerated by drought, climate change, and long-term water scarcity.

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Relevant websites

http://www.ipcc.ch/—Climate Change.
http://www.elnino.noaa.gov/—ENSO.
http://www.waterfootprint.org—Virtual water and water footprint.