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RESEARCH ARTICLE

TERRESTRIAL WATER SYSTEM & HYDROLOGICAL CYCLE ALTERATION ANTECEDENT TO ADVERSE CLIMATE CHANGE IN INDIAN SUB-CONTINENT A LITERATURE REVIEW

Arghadeep Dasgupta and Dr. Shyamoli Sen

Flt No: 5/4, 483 SKB Sarani, Kalindi Housing, Laketown

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ABSTRACT

Terrestrial water storage can be defined as the summation of all water on the land surface and in the subsurface. It includes surface soil moisture, root zone soil moisture, groundwater, snow, ice, water stored in the vegetation, river and lake water. Gravity Recovery and Climate Experiment has provided an unprecedented view of the terrestrial water storage variations at large scales. Extremes in water storage often are associated with droughts and flooding events because they are driven by the surplus or deficit of water. Water is a key prerequisite for human development. But only 0.5 per cent of water on Earth is usable and available as freshwater. Observing and understanding the water cycle and changes in the water cycle are essential to protect this life-enabling resource both now and in the future.

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INTRODUCTION

Terrestrial water storage, TWS modulates the hydrological cycle and is a key determinant of water availability and an indicator of drought. While historical TWS variations have been increasingly studied, future changes in TWS and the linkages to droughts remain unexamined. Using ensemble hydrological simulations, many researchers have concluded that climate change could reduce TWS in many regions, especially those in the Southern Hemisphere. Strong inter-ensemble agreement indicates high confidence in the projected changes that are driven primarily by climate forcing rather than land and water management activities. Declines in TWS translate to increases in future droughts. By the late twenty-first century, the global land area and population in extreme-to-exceptional TWS drought could more than double, each increasing from 3% during 1976–2005 to 7% and 8%, respectively. In this observation the study of inter-dependence relation of climate change with the adverse of TWS impact resulting in to severe drought is highlighted, which calls for the need for improved water resource management and resilient measures are highlighted. Globally, India recorded the highest loss in terrestrial water storage. Terrestrial water storage, TWS dropped at a rate of 1 cm per year in 20 years, 2002-2021, according to a new report 2021 State of Climate Services released by the World Meteorological Organization, WMO.

Corresponding author:** ***Arghadeep Dasgupta,
Flt No: 5/4, 483 SKB Sarani, Kalindi Housing, Laketown.

The biggest losses have occurred in Antarctica and Greenland. But many highly populated, lower latitude locations have also experienced TWS losses, according to the report. This includes India, where the TWS has been lost at a rate of at least 3 cm per year. In some regions, the loss has been over 4 cm per year too. India has recorded the highest loss in terrestrial water storage if the loss of water storage in Antarctica and Greenland is excluded. India is, therefore, the topmost hotspot of TWS loss, according to the WMO analysis. The northern part of India has experienced the maximum loss within the country.

Literature Review: Water on Planet Earth: Water found on or close to the Earth's surface is called the hydrosphere. The Hydrosphere is defined as a discontinuous layer of water at or near the earth's surface. It includes all liquid and frozen surface water, groundwater, and atmospheric water vapour. It is an essential resource for human survival, but its distribution and availability vary within countries and across the planet. Only 2.5% of the water on the Earth is freshwater, the rest is found in the oceans. Unfortunately, a lot of the freshwater is locked up in ice caps and glaciers so is unavailable for human use. This poses problems for people as freshwater is a scarce resource. About 71 percent of the Earth's surface is water-covered, and the oceans hold about 96.5 percent of all Earth's water. Water also exists in the air as water vapour, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers, and even in biological systems. The amount of water on planet Earth has been estimated at 1.386 billion cubic kilometres by NASA. The second issue with water availability is that it is in continuous movement across the globe. It moves in a cycle called the hydrological cycle. Global freshwater supplies are affected by three major factors. They are:

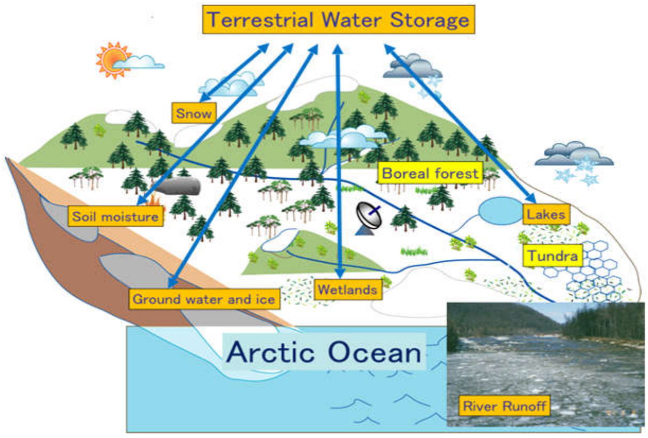

Figure 1. Terrestrial Water Cycle Source: e-Water solution

- Geology – This affects where water is stored and the location of aquifers and groundwater
- Climate – influences the availability of rainfall, snowfall and rates of evaporation. Climate can vary over time, with wetter and drier periods, hotter and colder periods. This can affect water availability.
- Rivers – which move or transfer water across river basins

Atmospheric stores of water: The atmosphere is the layer of gasses surrounding our planet. The atmosphere has water held in the air as gas, clouds, and precipitation. The Amount of water found in the atmosphere is only 12,900 km, 8% of all easily accessible freshwater. Most of this is found in the gaseous state, water vapour, which is a colourless and odourless gas. Water vapour is produced from evaporation or liquid water or from the sublimation of ice. Visible water can be seen in clouds - visible masses of water droplets or ice crystals suspended in the atmosphere.

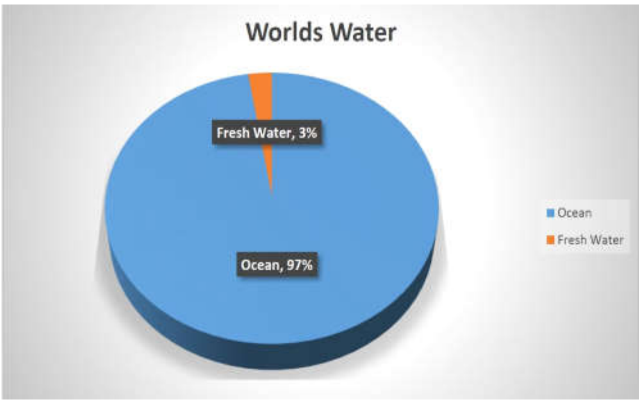

Figure 2. Worlds Water Distribution

Atmospheric water is very important despite it being one of the smallest stores of water on planet Earth. Some of the importance of atmospheric water is narrated bellow:

- It is a greenhouse gas that absorbs, scatters and reflects incoming solar energy and outgoing terrestrial energy, so plays a role in modifying our climate.
- It redistributes water around the globe.
- It helps to clean the air, removing impurities when it rains.

Warmer air can hold more water vapour that cooler air. For a 1°C increase in the air temperature, the atmospheric water content should increase by about 7%.

This means that water vapour levels in air will vary according to temperature around the globe, with high levels at the Equator, where there is available water for evaporation and lowest levels at the Poles.

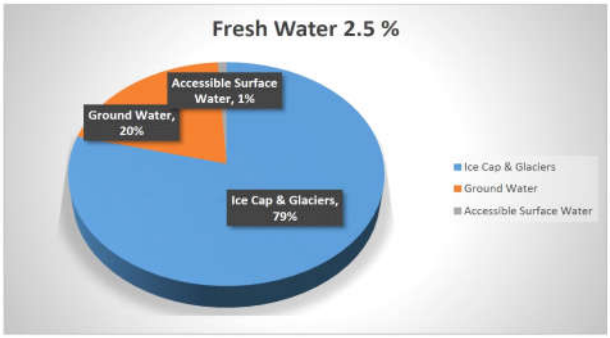

Figure 1. Fresh Water Distribution on Earth Crust

Cryosphere Stores of water: The Cryosphere includes all of the frozen water in the Earth's system. This means that frozen parts of ocean, glaciers, and ice sheets are all parts of the cryosphere. Frozen water can be found in the following forms mentioned below:

Sea Ice, this is ice that floats at the surface of our seas and oceans. The extent of this ice varies between summer and winter, growing in the winter and shrinking in the summer. The Arctic is an example of an area of extensive sea ice, and its extent and thickness has reduced in recent decades. Whilst sea ice has no impact on changing sea levels as it melts, scientists are concerned about its reduction. This is because sea ice reflects a lot of solar energy back to space as it has a high albedo, a measure of surface reflectivity. Without this ice, more solar energy is absorbed in these regions rather than reflected. Sea ice tends to freeze at temperatures slightly below 0°C because of the salinity of sea water.

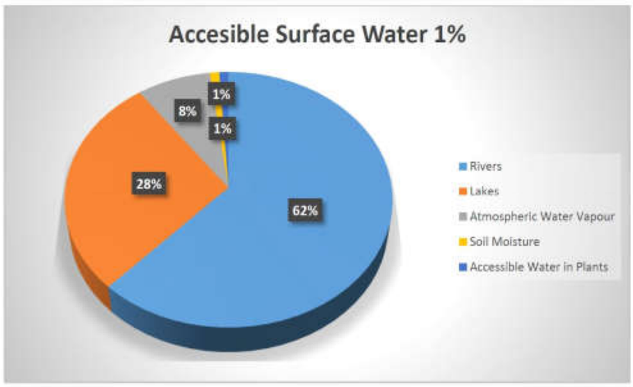

Figure 4. Accessible potable water for Human kind

Ice Shelves are another type of sea ice, they are platforms of ice where ice sheets and glaciers extend out over the oceans from the land. They are common in Antarctica and when the separate from the main ice sheet they become ice bergs. In 2017 a giant section of the Larsen C ice shelf in the Antarctic peninsula broke off, unleashing a 5,000 km2 iceberg, about a quarter of the size of Wales. Ice sheets, these are a mass of glacial land ice extending more than 50,000 km. The Antarctic ice sheet is one of the two polar ice caps of the Earth.

It covers about 98% of the Antarctic continent and is the largest single mass of ice on Earth. It covers an area of almost 14 million square kilometres and contains 26.5 million cubic kilometres of ice. The Greenland ice sheet, is a vast body of ice covering 1,710,000 square kilometres roughly 80% of the surface of Greenland. Together, Antarctica & Greenland ice contains more than 99% of the freshwater ice on planet Earth. If the Greenland Ice Sheet melted, scientists estimate that sea level would rise about 6 meters. If the Antarctic Ice Sheet melted, sea level would rise by about 60 meters.

- Permafrost, this is soil, rock or sediment that is frozen for more than two consecutive years. The thickness of this layer varies from just a few metres to over a kilometre in Northern regions of Canada and Russia. The permafrost generally was created during previous ice ages and is now under threat of melting due to global warming. This has the potential for a positive feedback loop as melting permafrost releases methane, a highly potent greenhouse gas.
- Ice caps, these are smaller than ice sheets and are a mass of ice that covers less than 50,000 km of land area, usually covering a highland area. They are found in mountainous areas such as the Himalaya and the Rockies, and are the source areas for many of the world's valley glaciers. These glaciers occupy many of the world's valleys and their meltwater is significant as a water source for millions of people.

Terrestrial or land-based water: Terrestrial water may be considered as falling into four broad classes:

- Surface water – the free-flowing water of streams and rivers, and the water of ponds and lakes
- Ground water – the water held in saturated strata below
- Soil water – the water held in association with air in unsaturated superficial layers of the earth.
- Biological water – all of the water stored in plant and animal matter on Earth.

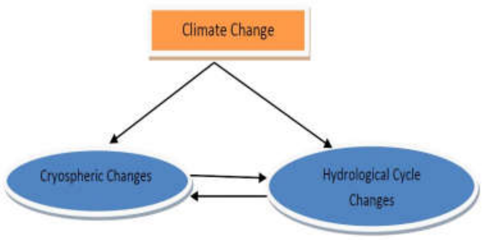

Figure 5. Climate Change altering Hydrological Cycles

The lithosphere is the solid outer section of Earth, including Earth's crust as well as the underlying cool dense and rigid upper part of mantle. This is the zone we are concerned with when considering terrestrial water. Only 3% of the World's water is freshwater and 79% is unfortunately locked up in ice sheets and glaciers. Another 20% of freshwater is found in the ground and needs to be accessed by drilling into the earth. Rivers and lakes are the most accessible water in the terrestrial system. Oceanic water: The Oceans are by far the biggest store of water. They dominate the amount of water available, 97% of all water is found in our oceans. Ocean water contains dissolved salts and ocean pH is 8.14 but is falling, linked to the increase in atmospheric carbon and ocean acidification. The world's oceans contain enough water to fill a cube with edges over 1000 kilometres in length. The oceans contain 326 million cubic miles, according to a recent study from the U.S. Geological Survey. The Water Cycle: The water cycle is also known as the hydrological cycle or the hydrologic cycle, and can be defined as the continuous movement of water on, above and below the surface of the Earth.

It is essentially a series of processes by which water is evaporated from the sea and eventually condenses and precipitates over the land, before returning to the oceans via various pathways. The amount or mass of water on Earth remains fairly constant over time but the location of that water into the major reservoirs of saline water, ice, fresh water, and atmospheric water is variable and depends on a wide range of climatic variables. Water on Earth moves from one reservoir or store to another, such as from river to ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, condensation, precipitation, infiltration, surface runoff, and subsurface flow. Movement between these stores often involves the water changing form between liquid, solid ice and vapour. The water cycle also involves the exchange of energy, which leads to temperature changes. When water evaporates, it takes up energy from its surroundings and cools the environment. When it condenses, it releases energy and warms the environment. These heat exchanges influence climate. The water cycle starts with water evaporating from the ocean, this warm moist air rises in thermals where it cools as it rises through the troposphere at the dry adiabatic lapse rate of 9.7°C per 1000m. As the air rises and cools it loses its capacity to hold water vapour as its relative humidity rises, and condensation occurs releasing latent heat. This forms clouds at the dew point, and these clouds are blown inland. Relief features can force the clouds higher, water droplets collide with one another and get bigger, and eventually the droplets are big enough to fall to earth as precipitation. This precipitation can be stored on the surface as snow or ice, or can be intercepted by trees and vegetation. On the trees or vegetation the water can be dripped off leaves, flow down the vegetation as stem flow or be taken up and lost as transpiration. The combined losses of water through transpiration and evaporation are known as Evapotranspiration. It could also fall straight into the ground where it can percolate into the soil then infiltrate into the rock underneath if the soil and rock are permeable. If the rock is not permeable or the soil stores are full then surface runoff will occur. This water will then work its way through the soil, soil flow or rock, through flow or over the land and into streams and rivers. These small tributary streams join together at confluences and the river will grow in size and strength. These processes are variable over time and space. Not all parts of the world have precipitation all year for example, some have noticeable dry seasons. Water resources across the world are under tremendous pressure due to human and naturally-induced stressors. These include population growth, urbanisation and decreasing availability of freshwater. Extreme weather events too have been responsible for the pressure on water resources realised across sectors and regions, the WMO noted.

Climate Change Impacts on Hydrological Cycle: The water cycle technically known as the hydrological cycle is the process that explains the circulation of water or cycling of water through the different parts of the earth namely the atmosphere, lithosphere and the hydrosphere, including the cryosphere. This circulatory process includes collection, storage as well as movement of water. In fact, storage is far more when compared to movement that can last for millions of years as is the case with freshwater stored in the ice caps and glaciers. The cycle goes through the following major processes even though there may be numerous micro processes that are entirely geographically dependent:

Step 1: Evapo – Transpiration

The water cycle literally starts with this step. It actually contains two processes i.e. evaporation and transpiration. First, evaporation is a process where water at the surface turns into water vapours due to the absorption of heat energy from the sun. Water bodies like the oceans, the seas, the lakes and the river bodies are the main source of evaporation. Through evaporation, water moves from hydrosphere to atmosphere. As water evaporates it reduces the temperature of the bodies. Transpiration is a process similar to evaporation. Soil absorbs some amount of precipitation. The roots of the plants absorb the water and push it toward leaves where it is used for photosynthesis. The extra water is moved out of leaves through stomata (very tiny openings on leaves) as water vapour. Transpiration is the process where liquid water is turned into water vapour by the plants. Thus water enters the biosphere and exits into a gaseous phase.

Step 2: Condensation – Sublimation: As water vaporizes into water vapour, it rises up in the atmosphere. At high altitudes the water vapours change into very tiny particles of ice /water droplets because of low temperature. This process is called condensation. These particles come close together and form clouds and fogs in the sky.Apart from evaporation, sublimation also contributes to water vapour in the air. Sublimation is a process where ice directly converts into water vapour without reaching the liquid water state. Sublimation takes place in higher altitudes under conditions of low temperature and high pressure. The main sources of water from sublimation are the ice sheets of the cryospheric zones of the earth comprising ice caps and glaciers on the mountains. Sublimation is a rather slower process than evaporation.

Step 3: Precipitation: The clouds made of condensation nuclei and water vapour then pour down towards the earth as precipitation due to wind or temperature change. This occurs because the water droplets combine to make bigger droplets through the process of coalescence. Also when the air cannot hold any more water, it precipitates. At high altitudes the temperature is low and hence the droplets lose their heat energy. These water droplets fall down as rain. If the temperature is very low, below 0 degrees, then the water droplets would fall as snow. There are other forms of precipitation that depend upon the prevailing temperature and pressure conditions such as drizzle, sleet and hail. This is how water enters lithosphere.

Step 4: Runoff and Collection: As the water precipitates on the earth, it leads to runoff. Runoff is the process where water runs over the surface of earth. When the snow melts into water it also leads to runoff. As water runs over the ground it displaces the top soil with it and moves the minerals along with the stream. This runoff combines to form channels, rivers and ends up into lakes, seas and oceans completing the process of collection. In this way water enters hydrosphere.

Step 5: Infiltration: Some of the water that precipitates does not runoff into the rivers and is absorbed by the plants or gets evaporated. It moves deep into the soil. This is called infiltration. The water seeps down into the underground aquifers, which increases the level of ground water table.

Figure 6. Image depicting Hydrological Cycle

Hydrological Cycle: Water evaporates from the land and sea, which eventually returns to Earth as rain and snow. Climate change intensifies this cycle because as air temperatures increase, more water evaporates into the air. Warmer air can hold more water vapour, which can lead to more intense rainstorms, causing major problems like extreme flooding in coastal communities around the world.

At the same time that some areas are experiencing stronger storms, others are experiencing more dry air and even drought. As temperatures rise, evaporation increases and soils dry out. Then when rain comes, much of the water runs off the hard ground into rivers and streams, and the soil remains dry. The resultant impact is an accentuated evaporation from the soil and an increased risk of drought. It is in fact the circulation of water that is one of the key determinants of interaction between the atmosphere, cryosphere, lithosphere and hydrosphere. Alteration in hydrology not only effects plants and animal species but also influences the delicate balance that ecosystems have achieved over the millions of years. Since water is one of the key variables of the climate system, climate change and global warming has resulted in maximum alteration of the hydrological cycle as such. Water cycle also acts as a medium of energy transfer through the biosphere. Therefore a slight disturbance to this cycle either leads to increase or decrease of water availability in different states such as solid, liquid or gaseous states that can lead to hazards and disasters such as floods, droughts, cyclones, glacial melt all endangering existing ecosystems.

Alteration of the Hydrological Cycle: The above diagram depicts two situations, all emanating from climatic changes, wherein, in a water excess scenario higher temperatures trigger higher evaporation rates as well as increased snow melt water that rise sea levels. All these factors ultimately lead to increased extreme events such as cyclones, storms, floods, etc. Contrarily, in a water deficit scenario, warm climate causes surface water as well as soil drying leading to extreme droughts and finally desertification. Both the situations cause changes in water availability that naturally hampers the

Hydrological cycle on the earth that is so very delicately balanced by all the existing processes. Indian scenario: In India, per capita water availability is reducing due to an increase in population. The average annual per capita water availability has been consistently decreasing. It reduced to 1,545 cubic metres in 2011, from 1,816 cubic metres in 2001. It is projected to further decrease to 1,367 cubic metres in 2031, according to the Union Ministry of Housing and Urban Affairs.

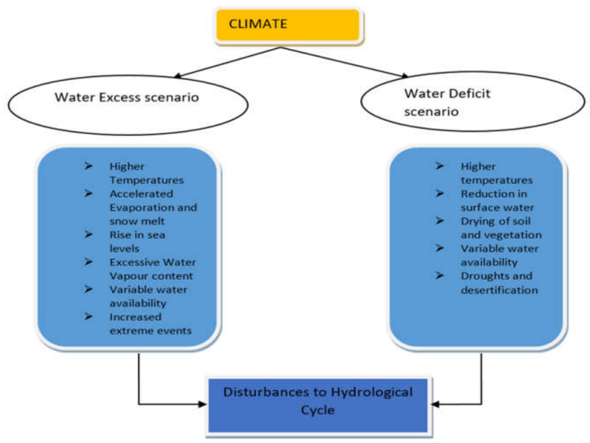

Figure 7. Flow Chart showing Hydrological Cycle

Five of the 21 river basins in India are absolute water scarce, per capita water availability below 500 cubic metres according to the Falkenmark Water Stress Indicator. Five are, water scarce, per capita water availability below 1,000 cubic metres and three are water stressed, per capita water availability below 1,700 cubic metres.

By 2050, six will become absolute water scarce and four will become water stressed, according to the State of India's Environment in figures, 2020. The terrestrial water cycle is influenced by a combination of multiple aspects including climate change, land use, land cover change, human water use and all these aspects are driven by natural and anthropogenic forces. Since the climate system is influenced by both natural and anthropogenic forces, it is necessary to distinguish the impact of natural and anthropogenic climate change on the terrestrial water cycle, Gudmundsson *et al*., 2017. Both natural and anthropogenic factors are responsible for land use, land cover change. The hydrological consequences of land use, land cover change cannot be seen simply as the impact of anthropogenic factor or natural factor on the terrestrial water cycle Fowler *et al*., 2019. It is important to disentangle hydrological responses to natural and anthropogenic land use or cover change. Human water use is mainly man-made, but it is inevitably influenced by natural factors as well. For example, irrigation water requirement may fluctuate with climate change and variability. Natural and anthropogenic impacts on water cycle and associated influences and feedbacks. As anthropogenic disturbance has reached unprecedented levels in recent decades, the terrestrial water cycle is undergoing rapid changes characterized as non-stationarity in hydrology, resulting in more extreme events, frequent water-related disasters, cryosphere melting, groundwater depleting de Graaf *et al*., 2019, rivers and lakes drying up, seawater intrusion, deterioration of water environment, and water scarcity. Although these water-related issues may occur at local or regional scales, the driving factors or influences and feedbacks are often global. Addressing such issues requires better integration of natural and social sciences based on Earth system science.

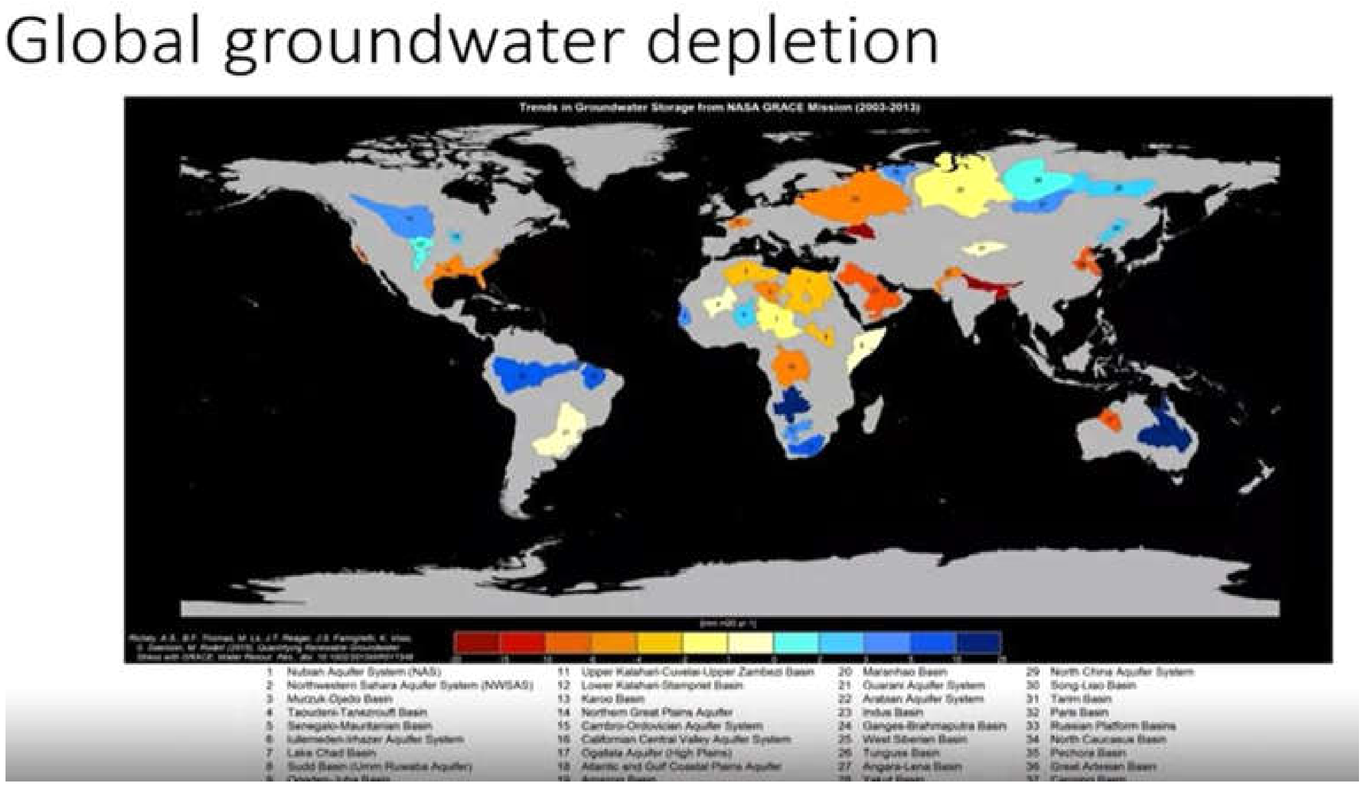

Figure 8. Image showing depleting water table Source: NASA

In the framework of Earth system science, natural and anthropogenic factors affect the water cycle, which in turn affects the Earth's environment. Global Change Hydrology, GCH research focuses on anthropogenic impacts on the terrestrial water cycle, the feedbacks to the climate system and human society, and the consequent water-related risk to human civilization. From the perspective of GCH, water-related hazards like floods, droughts, pollution and related issues cannot be seen as purely natural hazards because human has altered the characteristics of water hazards while suffering from the impact of the disasters and changing reactions and ways of coping with them Van Loon *et al*., 2016.

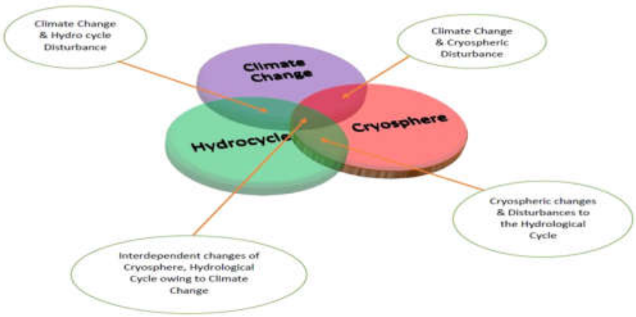

Figure 9. Interdependence of Hydrological Cycle Climate Change and Cryosphere

In the aspect of climate change, global warming has accelerated cryosphere melting, and the increasing recession of the cryosphere may feedback to the climate system and bring more extreme weather Tang *et al*., 2014. In the aspect of land use or land cover change, human transformation of landscape such as deforestation and afforestation together with biophysical forces such as physiological and ecological responses of plants to elevated atmospheric carbon dioxide concentrations would alter hydrological processes, contributing to flood hazards and drying up of rivers and lakes Feng *et al*., 2016; Fowler *et al*., 2019. In the aspect of human water use, massive abstractions from surface water and aquifer can exert considerable pressure for environmental flow provision, influencing sea level rise rates, threatening aquatic ecosystems and water environments de Graaf *et al*., 2019.

Addressing water risks mitigation and adaptation actions under global change: Global Change Hydrology, GCH is dedicated to understanding anthropogenic causes of water-related hazards and global water issues to guide humans to adjust their behaviour to achieve sustainable water resources management and the Sustainable Development Goals, SDGs of the United Nations by 2030. Under global change, rapid changes of the global water system may lead to increased threats of extreme events and trigger new types of water related disasters and risks. Meanwhile, population growth and socio-economic development have led to an increase in global exposure to natural hazards. Although physical exposure would increase, the vulnerability of social-ecological systems may be reduced by human society's response and prevention measures. Water engineering infrastructures today have provided human society certain capability of regulating the terrestrial water cycle at local and regional scales. The adaptive regulation of the water infrastructures to the rapidly changing global water system may offset the risks to some degree, while it will face a complicated trade-off between the adaption cost and original functions of the water infrastructures. Individual perceptions of the risks would influence risk-reducing behaviour, and therefore affect risk prevention Aerts *et al*., 2018. GCH research is taking human behaviour and socio-economic feedbacks into consideration, predicting change of water-related risks under global change, exploring adaptive water resources management for building resilience of social-ecological systems, putting forward global water governance arrangements.

Conclusion

One of the key questions of research pertaining to climate change and alteration in the Earth Hydrological Cycle is to scientifically ascertain mechanisms responsible for the changes in the terrestrial water cycle under global change. The main focus is to disentangle natural and anthropogenic influences on the terrestrial water cycle and to establish a sound scientific basis for addressing global water issues. There is an urgent need for rigorous scientific attribution of water cycle under global change. The priority challenges for Climate Change research are identified as:

- Disentangling natural and anthropogenic influences on the terrestrial water cycle.
- Development of scientific capability to detect, predict and adapt to change in the terrestrial water cycle in response to global change.

The underlying causes of water issues at local or regional levels are often global in the Anthropocene. While it is still impractical to measure all the processes and disentangle natural and anthropogenic influences on the terrestrial water cycle only by means of observation and experiment, numerical modelling has become an important means of research. Development of hydrological models that consider the influence and feedback of natural and anthropogenic factors within the Earth system modelling framework is a thematic research area of GCH research. Recently, there have been studies to represent water resources management and hillslope hydrological processes in the Earth system models and to develop integrated modelling framework of the terrestrial water cycle.

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