

Climate change and its influence on groundwater resources

S. Panwar* and G. J. Chakrapani

Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India

Climate change is commonly discussed at national and international levels. It directly affects the water cycle and thus life on Earth. The effect of climate change on surface water has been known for quite sometime now, however research is still in its infancy on the effects of climate change on the subsurface water. This review provides an insight into the factors responsible for climate change, its effects on groundwater quantity and quality on a global scale with emphasis on Indian groundwater resources and anticipated mitigation strategies.

Keywords: Aquifers, climate change, groundwater zones, mitigation strategies, sea-water intrusion.

CLIMATE change affects the components of water cycle such as evaporation, precipitation and evapotranspiration and thus results in large-scale alteration in water present in glaciers, rivers, lakes, oceans, etc. The effects of climate change on subsurface water relates to the changes in its recharge and discharge rates plus changes in quantity and quality of water in aquifers. Climate change refers to the long-term changes in the components of climate such as temperature, precipitation, evapotranspiration, etc. The major cause of climate change is the rising level of greenhouse gases (GHGs) in the atmosphere such as CO₂, CH₄, N₂O, water vapour, ozone and chlorofluorocarbon. These GHGs absorb 95% of the longwave back radiations emitted from the surface, thus making the Earth warmer. Except CO₂, the effects of other GHGs are minor because of their low concentration and also because of low residence times (e.g. water vapour and methane). The rise in CO₂ level causing global warming was first proposed by Svante Arrhenius, a Swedish scientist in 1896 and now it is a widely accepted fact that the concentration of CO₂ is the primary regulator of temperature on the Earth and leads to global warming. The temperature of the Earth is continuously rising; between 1990 and 2005, the temperature increased by 0.15–0.3°C per decade; 11 of the 12 warmest years were noticed during 1995–2006 and in the future a rise of 0.2°C per decade is projected¹. Climate change has an adverse impact on the Indian groundwater reservoirs and hence, better management and mitigation strategies for minimizing the threats are necessary.

*For correspondence. (e-mail: sugandha.panwar@gmail.com)

Factors causing climate change

Both natural and anthropogenic factors control climate change. The role of man is always overemphasized because of the accelerated climatic effects in recent times. However, natural processes play a much bigger and significant role as has been observed during the entire lifespan of the Earth. Figure 1 shows that climatic conditions were not the same throughout the history of the Earth.

Natural causes

The natural causes of climate change include the Earth's axial and orbital changes, changes in the strength of the Sun, plate movements, asteroid collision and chemical weathering. Each of these factors has been discussed briefly in the following:

Changes in the strength of the Sun: The strength of the Sun is measured by the number of sunspots visible on its surface. The concentration of CO₂ decreases with the cooling of oceans and increases with their heating, proving that the Sun is a primary driver of climate on Earth². The first satellite measurement carried out in 1978 pointed out that solar radiation varies by 0.5% during every 11 years. This factor has been proved by the satellite measurements, however the 11-year span concept is still not well understood and accepted³.

Earth's axial and orbital changes: The change in the tilt of the axis of the Earth affects the amount of solar radiation received on the surface; it shows a latitudinal difference and thus results in seasons on Earth. The Earth's axial tilt at present is 23.5° and varies between 22.2° and 24.5°. Increase in the tilt amplifies seasonal differences and decrease in the tilt results in the reduction of seasonal differences and thus affects Earth's climate³.

The Earth's orbit is also not constant and varies from circular to eccentric, and also changes the distance between the Sun and Earth, thus resulting in variable solar radiations received by the Earth and in climate change.

Plate tectonics: Seafloor spreading moves the continents at a steady rate, thus changing the latitudinal positions, which leads to predictable changes in climate. The

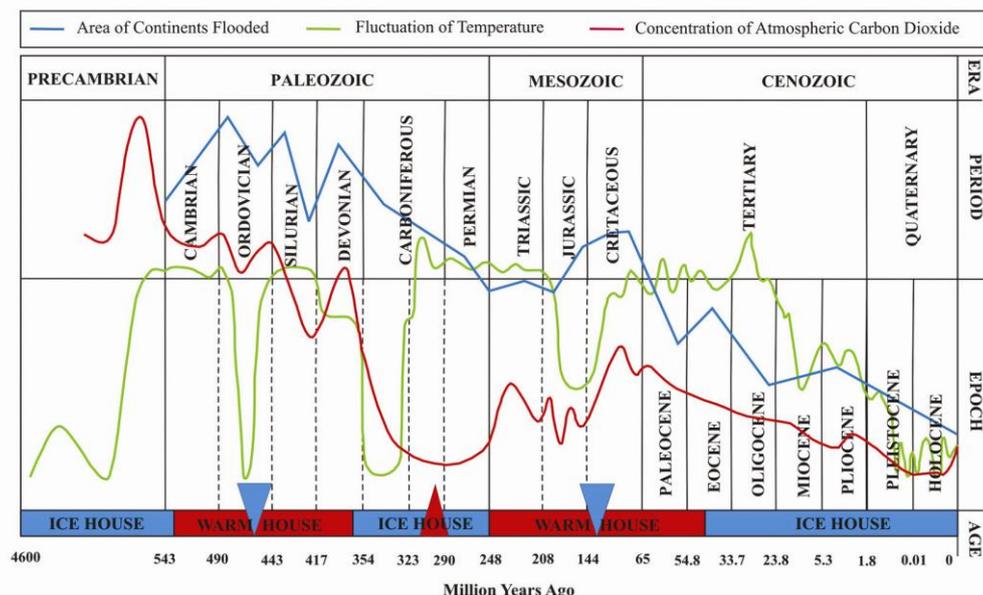


Figure 1. Climatic fluctuations all through the geological timescale (adapted from Nahle²).

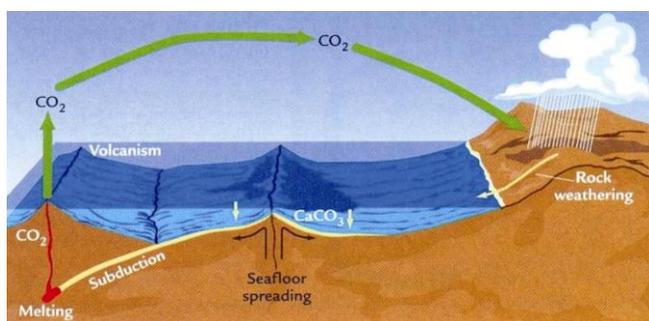


Figure 2. Global carbon cycle and CO₂ pool in different reservoirs (adapted from Ruddiman³).

position of south magnetic pole during 430 m.y. ago coincides with the climate change that has been observed, which showed the occurrence of large-scale glaciations in the modern-day Sahara Desert. Volcanic eruptions also change the composition of the atmosphere by ejecting SO₂, CO₂, water vapour and pyroclastic materials. BLAG hypothesis and uplift-weathering hypothesis are used to explain the relation between the plate tectonics and climate change processes.

(i) BLAG hypothesis: Berner⁴ stated that the rate of seafloor spreading controls the rate of CO₂ delivered into the atmosphere and thus the temperature on the Earth. Faster rate of seafloor spreading results in faster subduction and release of more CO₂ into the atmosphere and oceans. Slower rate of seafloor spreading results in the opposite effects. The carbon cycle governing the CO₂ concentration is shown in the Figure 2. The changes in the seafloor spreading can alter the rate of subduction and magma generation and thus the concentration of CO₂ in the atmosphere.

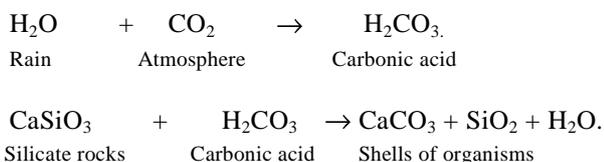
(ii) Uplift-weathering hypothesis: In the late 1980s, Raymo *et al.*⁵ observed that the global mean rate of chemical weathering is highly affected by the availability of fresh rocks and mineral surfaces for the weathering process to attack, and proposed that this exposure affects the climate-related factors both locally and globally. The uplift of the Himalayas during the Miocene and the consequent chemical weathering has been cited as an example of a driver for climate change. Factors such as mass wasting, steep slopes, earthquakes, heavy precipitation and glaciers in the uplifting areas increase the exposure of fresh rocks and accelerate chemical weathering. Accelerated chemical weathering draws more CO₂ from the atmosphere and cools the Earth. Conversely, during times when the upliftment is slow, CO₂ remains in the atmosphere and causes warming. The plate tectonic event such as subduction and collision of continental plates cause upliftment. Similar to the BLAG hypothesis, this theory also does not fully explain some events such as the short glaciation in the Sahara, which occurred nearly 440 m.y. ago³.

Asteroid collision: This has been held responsible for destruction of large forms of life in the geologic past and also caused instant climate change. However, such large-sized (greater than 10 km radius) impacts are rare and arrive on the Earth only after every 50–100 million years³. The Earth has experienced such events during the Permian–Triassic boundary and at the Cretaceous–Tertiary boundary which resulted in mass extinctions and in the beginning of a new era.

Chemical weathering: The changes in CO₂ concentration in the atmosphere can be related to the chemical

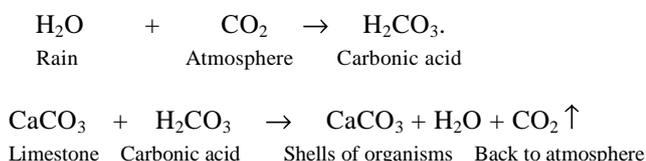
weathering processes, which include hydrolysis and dissolution.

The process of hydrolysis involves weathering of continental crust (mainly silicate minerals) by the action of carbonic acid such as



These reactions show CO₂ uptake from the atmosphere getting deposited in the shells of the organisms and as limestone deposits, thus controlling the CO₂ concentration of the environment. Although this process takes place during long intervals of geologic time, it still accounts for approximately 80% of the 0.15 gigatons of carbon buried each year in ocean sediments³.

The process of dissolution involves the dissolution of the carbonate deposits by the action of carbonic acid as



This process of dissolution occurs at a much faster rate than hydrolysis of silicates. Unlike hydrolysis, it plays no role in the net CO₂ removal from the atmosphere.

The process of chemical weathering regulates the Earth's temperature through a negative feedback mechanism (Figure 3). Chemical weathering is dependent on temperature, precipitation and vegetation conditions. During warm house, temperature, precipitation and vegetation increase, which enhances chemical weathering, thus allowing rapid CO₂ drawdown from the atmosphere resulting in reduction in the warming. During icehouse, because of low temperature on the Earth, chemical weathering shows opposing effects, thus acting as the Earth's thermostat. The concept of chemical weathering

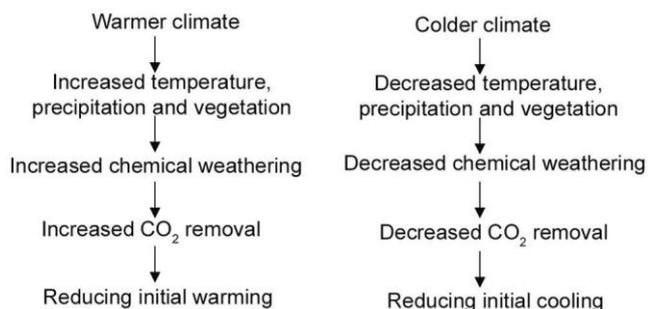


Figure 3. Negative feedback mechanism of CO₂ concentration regulating Earth's temperature.

is best suited to explain the climate change events due to changes in solar insolation and changes in rate of plate movements³.

Anthropogenic causes

The Earth has experienced rise and fall of CO₂ several times, but the rate of increase has never been so fast in its entire geologic time as it has been in recent times. Since the Industrial Revolution in 1750 up until 2009, an increase of approximately 38% in the atmospheric level of CO₂ has been noticed⁶. Figure 4 shows the rise in CO₂ concentration from 280 ppm in 1750 to 379 in 2005 (refs 1 and 6) to approximately 395 ppm at present, indicating the role of man in increasing the global atmospheric CO₂ levels. Humans have influenced the CO₂ kinetics in the atmosphere at an accelerated rate. The IPCC reports state that human activities have tremendously influenced the global water cycle by impacting the global carbon cycle. The CO₂ annual emission in the 1970 was 21 gigatons by human activities, whereas in 2004 it increased to 38 gigatons, almost 80% increase in just three decades. CO₂ also represented 77% of total anthropogenic GHG emissions in 2004 (ref. 1). Hence, in all probability the largest impact on global climate has been wrought by humans.

Human activities that are causing climate change include industrialization, use of fossil fuel, urbanization, excessive agriculture and livestock and land-use land-cover changes. Figure 5 shows how land use controls the ambient temperature of the Earth. Due to rapid industrial growth, every nation has tremendously increased its road connectivity thereby reducing vegetative cover. The Paved (asphalt and concrete) surfaces have higher surface temperature than those with vegetation cover⁷. More and more creation of concrete upper crust leads to heat island effect, which affects both the surface and subsurface temperatures⁸.

Effect of climate change on water cycle

The global water cycle is primarily driven by the atmospheric circulation and wind patterns. Climate change

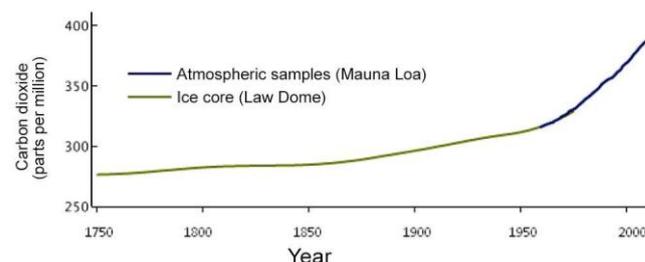


Figure 4. Increase in CO₂ concentration in recent times (from NASA Earth observatory⁶).

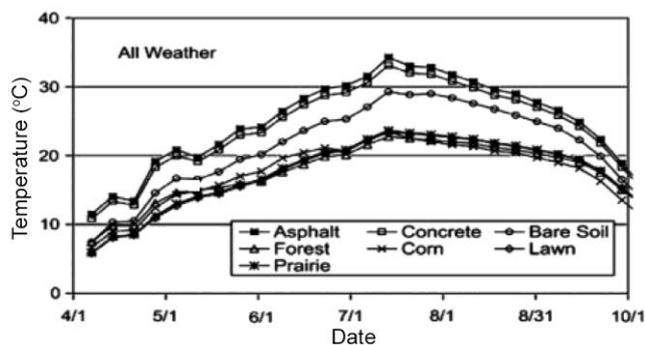


Figure 5. Average weekly surface temperature for seven land uses calculated with climate data from St Paul in 2004 (adapted from Taylor and Stefan⁷).

leads to changes in precipitation and evapotranspiration rates, which show a direct effect on the quantity and quality of both surface and subsurface water. Increase in temperature increases the capacity of the atmosphere to hold water and thus precipitation rate may increase^{1,9}. However, its effect on climate is spatio-temporal, being controlled by local or regional factors such as topography, vegetation, wind velocity, etc. Hence, both an increase and decrease in the precipitation rate is envisaged^{1,9,10}. As evapotranspiration is dependent on the vegetation, soils types and on the amount of water available^{11–13}, it may also be expected to show spatio-temporal changes^{1,9,10}.

Effect of climate change on groundwater zones

Groundwater is directly affected by changes in the rate of precipitation and evapotranspiration. The response of groundwater to climate change may be less compared to surface water, however, it is still a matter of concern because groundwater is one of the largest available resources of freshwater and potable water on Earth. It is estimated that approximately 30% of global freshwater is present in the form of groundwater^{14,15}. Todd¹⁵ divided the groundwater occurrence in two zones – zone of aeration and zone of saturation. The effect of climate change on both the zones has been discussed in the following.

Zone of aeration

This zone is above the phreatic surface and is divided into soil water and vadose zone.

Soil water zone: This zone is important as it supports vegetation and all biogeochemical reactions. Climate change has an adverse effect on this zone. Higher temperature leads to higher evapotranspiration rates, resulting in less moisture content in this zone. Little or no moisture in the soil leads the penetration of solar radiation into the deeper soils and increased dryness in soils, resulting in

severe droughts¹⁶. The high precipitation in wet climate change scenario will increase surface run-off and in promoting rapid soil erosion. Less infiltration, high evapotranspiration and high run-off will have a great impact on the water availability in this zone, which will affect the entire plant and animal kingdom. Because of change in evapotranspiration patterns in this zone, the rainfall pattern will also be affected. The transpiration process which holds 80–90% of overall evapotranspiration¹³ on Earth will show various changes depending on the regional vegetation. The increase in CO₂ will increase the stomatal resistance of some plants to resist water and prevent transpiration and thus rainfall. However, in other plant genera, the CO₂ increment will promote plant growth and hence the increase in area of transpiring tissue may result in higher transpiration and precipitation¹¹. Seneviratne *et al.*¹² have shown that less soil moisture will increase soil suction making it difficult for plants to uptake moisture from the soil.

Vadose zone: This is the dynamic zone which undergoes complex interactions between hydrologic and geochemical processes that control the quality and quantity of groundwater percolating down to saturated zone^{17,18}. Changes in vadose zone due to climate change can be computed by studying the variations in major cations, anions, trace elements and isotopes from the pore water. The results vary from aquifer to aquifer and from region to region, and are used to distinguish changes due to climate change and human-induced perturbations¹⁷. Due to increase in surface temperature, groundwater temperature will increase. The change in temperature will affect pore water chemistry, residence time and volume of water in matrix and fractures¹⁷, and thus the composition of the water. These changes in the water chemistry will be spatio-temporal depending on both the water composition and underground lithology. The increase in recharge rate will help in mobilizing the contaminants into greater depths. As an example, in semiarid and arid regions, increased infiltration can mobilize large, pore-water chloride and nitrate reservoirs affecting the quality of water¹⁹. The diurnal temperature fluctuations may be detectable at depths of less than 1 m in the unsaturated zone and seasonal fluctuations at depths of 10 m or more⁷, indicating that the climate change effects depend on depth and are slow in the deep vadose zone.

Zone of saturation

Groundwater in the saturated zone is important as it is less polluted and has no effects of evapotranspiration. The sensitivity of this zone depends on the depth of the water table; shallow aquifers are more vulnerable to climate change than deeper aquifers. This zone responds to climate change by showing changes in its amount, quality and flow of water depending on the trends of precipita-

tion, evapotranspiration, recharge and discharge. The response of the saturated zone will be more in terms of storativity, as this property depends on the volume of water²⁰. It is generally observed that climate change has less effect on this zone in comparison to human activities on groundwater exploitation, such as excessive pumping, reduction in recharge rate and contamination.

Effect of climate change on aquifers

The two types of aquifers, i.e. confined and unconfined will show alterations in some of their properties during climate change. It has been noticed that severe dry periods can alter the properties of aquifers such as transmissivity and storativity^{21,22}. Larocque *et al.*²¹ observed that during dry periods, the conductive channels such as fractures and fissures may become desaturated and the pressure pulse of water within the aquifer will be transmitted slowly, whereas during the wet season, fractures get fully saturated and transmit pressure pulse rapidly. Thus, the changes in recharge pattern will affect the specific storage of an aquifer.

In a climate change scenario, unconfined aquifers of semiarid and arid regions are considered to be more vulnerable than aquifers of wet regions. In dry areas, there is a shift in the annual balance between precipitation and evapotranspiration, whereas the aquifers of wet regions may renew themselves because of high precipitation²³. Confined aquifers are sensitive in less rainfall scenario as they are totally dependent on recharge rate, and hence their vulnerability is also more because of increasing population and increasing demand for land. In case of extreme aridity, their vulnerability becomes higher if the potentiometric surface falls below the upper confining beds and results in converting confined aquifers to unconfined aquifers.

Effect of climate change on recharge and discharge

Recharge of an aquifer is important as it provides continuity of appreciable quantity of groundwater forever. Recharge of an aquifer depends largely on the type of soil, vegetation, amount of precipitation, surface temperature, wind speed, evapotranspiration, run-off and discharge patterns. Hence, recharge is expected to show spatio-temporal changes either by increase or reduction in water availability⁹. The changes in recharge patterns will affect discharge patterns, which will have a direct impact on groundwater supplies and on surface water availability. The effect of climate change is considered to be worse for semiarid and arid regions, where the recharge will be lesser in a climate change scenario^{23,24}.

The sensitivity of recharge depends on how the temperature and precipitation are related. In a cold or wet and

cold-wet scenario, the relationship is directly proportional, i.e. high temperature results in high precipitation and high recharge, and hence moderate changes are noticeable in water balance components. However, in case of dry scenario, the temperature and precipitation are inversely related to each other, as high temperature will result in less rainfall. Hence, the effects in case of dry scenario will be severe²⁴, implying that the aquifers of semiarid and arid regions are more vulnerable to climate change. Changes in recharge patterns will also alter the quality of water by affecting geochemical reactions and movement of water in the vadose zone.

Under a varied climate change scenario, spatio-temporal variation in precipitation, evapotranspiration, and recharge and run-off will directly affect the discharge patterns. Under wet climate scenarios, run-off is considered as a most sensitive component and the combined effect of increased precipitation and high discharge will increase the risk of flooding. Under dry climate scenarios, recharge will be the most sensitive component as evapotranspiration will increase while both recharge and discharge will decrease in all seasons, resulting in decline in groundwater level²⁴.

Increased discharge from melting of glaciers in the Himalayas will increase the risk of flooding in the catchment areas affecting major parts of North India, Pakistan and Bangladesh. Due to changes in discharge, the quality of groundwater will be adversely affected, since during high discharge all the pollutants will be mobilized and may reach groundwater level. Increase in groundwater discharge may also lead to increase in sea level. Increase in the sea level deteriorates the water quality by increasing the salt content in the coastal and continental aquifers, resulting in health problems and drinking water scarcity¹.

In the case of a dry climate scenario, generally the water level will fall and this will affect the needs of the people and may result in increased use of energy to extract water. The conditions will be worst for arid and semiarid regions of the world. The increase in groundwater pumping and loss of groundwater storage from aquifers resulted in land subsidence in many Asian cities such as Osaka and Bangkok^{8,9}. In future, the increase in discharge and decrease in recharge will make land subsidence a much bigger problem.

Effects of climate change on groundwater quality

With the use of modern technology, the water needs can be fulfilled by better exploration and extraction methods. However, quality assurance of groundwater is much more essential as it relates to the various uses of water. The groundwater quality relates to the physical, chemical and biological properties of the aquifers, which are controlled by climatic fluctuations.

As has been mentioned earlier, changes in the recharge rate and the groundwater temperature in the vadose zone affect its pore water chemistry, contaminant transport and residence time, thus affecting the quality of water¹⁷. Under a climate change scenario, the following events can deteriorate the groundwater quality. During the wet scenario, increased infiltration can mobilize large pore-water chloride and nitrate reservoirs in the vadose zone of semiarid and arid regions¹⁹. Increase in recharge leads to the dissolution of carbonates; increase in Ca content may increase the hardness of groundwater. During a dry scenario, the increase in total dissolved solids may deteriorate the groundwater quality by increased salt content. The higher saline water may also result in scaling of industrial boilers.

Effect of climate change on sea-water intrusion

Coastal regions support approximately one-quarter of the global population²⁵, and are under a constant threat of sea-water intrusion. The three major reasons for the sea-level rise are: expansion of oceans on warming, increase in discharge due to melting of glaciers and excessive pumping due to human settlements along the coasts.

Excessive pumping can lead to sea-level rise by increasing the width of the dispersion zone as shown by Sherif and Singh²³. Excessive groundwater extraction can also lead to land subsidence^{8,25,26} in the coastal regions, which allow sea water to intrude the continents. The unsustainable groundwater extraction by humans can result in adding extra water into the sea, as water ultimately makes its way to the oceans^{26,27}.

Global average sea-level rose at an average rate of 1.8 mm/year between 1961 and 2003 and about 3.1 mm/year from 1993 and 2003 (ref. 1). Figure 6 shows the increasing rate of sea-level rise.

Greenland, Antarctica and Arctic, and mountainous glaciers are losing extent and thickness of ice at a fast rate. At the Arctic, ice has shrunk 2.7% per decade, with a larger decrease in summer with 7.4% since 1978, as the average temperature in the Arctic is increasing almost twice the rate of the world temperature¹. Figure 7 shows the decrease in September sea ice at the Arctic.

Estimations show that if the global warming continues at the same rate, approximately 4000 km² of the low-elevation delta lands will be submerged under sea water, resulting in loss of groundwater reservoirs^{23,25-27}. The rise in sea level is said to have a great impact on the mangrove forests of the world and aquatic life, affecting the fish stocks and planktons^{1,28}. It is estimated that 30% of coral reefs could be lost in the next 10 years, which will affect the food web of the aquatic environment. The sea-level rise will change the world map because of submergence of many coastal mega cities of the world such as California, Hong Kong, Mumbai, etc. A rise of 1.5 m rise

at sea level will lead to a submergence of 16% of Bangladesh²⁹ and a rise of 1 m is expected to be enough for the complete submergence of the Maldives. In Grenada, just 50 cm rise in sea level will result in 60% loss of its beaches¹⁰.

Sea-water encroachment in coastal aquifers can be controlled by adopting engineering measures such as subsurface barriers, e.g. dikes and sluices as used in the Netherlands^{16,30}. But it may not be possible for smaller countries like the Maldives and Bangladesh to invest large sums of money for such measures. This indicates a direct relationship between vulnerability and economy. Because of high temperature, the frequency and intensity of cyclones will increase, which will pose great threats to the people residing in the coastal regions¹. The increase in the melting of glaciers, variations in atmospheric pressure and groundwater pumping, will result in groundwater salinization in coastal aquifers of the world, which will limit its use for drinking and agriculture purposes. As recharge is expected to be less, the interface between the sea water and freshwater in the coastal aquifers will move up and sea water will be encountered at shallow continental depth. Increased salinity of groundwater may induce dissolution of some constituents which are otherwise stable under freshwater conditions, thus changing its quality. The high concentrations of Hg in the aquifers of South Italy are due to sea-water intrusion³¹.

Effect of climate change on groundwater resources of India

India's groundwater status and utilization

India accounts for 2.45% of land area and 16% of the world population, whereas only 4% of freshwater resources of the world are available in India, of which 38.5% is groundwater³². In the 1940s, India was utilizing less groundwater compared to USA and Europe, but by 2000, India utilized around 220–230 billion m³ year⁻¹, over twice that the USA³³ (Figure 8). The groundwater resources in India are important, as they supply 80% of domestic needs and more than 45% of total irrigation requirement³⁴. The estimated average precipitation in India is 4000 BCM (billion cubic metres) – 1869 BCM flows into rivers and 1123 BCM occurs as utilizable water, of which surface water has a share of 690 BCM and groundwater contributes 433 BCM^{32,35}.

The per capita water availability is continuously declining from 5176 m³ in 1951 to 1820 m³ as on 1 March 2001 and 1703.6 m³ on 1 March 2005 (ref. 35), as the resource is limited but the shareholders have increased many folds. Population thus has put severe pressure on the water resources and distribution. Urban population utilizes more water per capita and also in total amounts than rural population. Recent estimates show that 60% of

Sea level

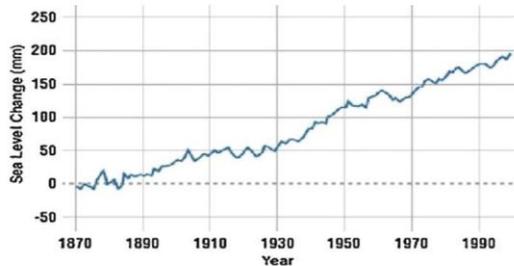
Data updated 2.23.11

GROUND DATA: 1870-2000

Data source: Coastal tide gauge records.
Credit: CSIRO

RATE OF CHANGE

↑ 1.70 mm per yr*



*estimate for 20th century

SATELLITE DATA: 1993-PRESENT

Data source: Satellite sea level observations.
Credit: CLS/Cnes/Legos

↑ 3.27 mm per yr*

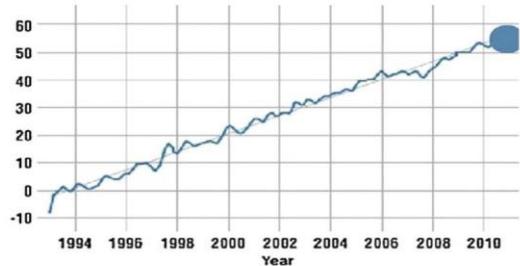
Inverse barometer applied and seasonal signals removed.
*estimate for 1993-2010

Figure 6. Global sea-level changes in recent times (adapted from Vijaya VenkataRaman *et al.*²⁸).

Arctic sea ice

Data updated 2.23.11

AVERAGE SEPTEMBER EXTENT

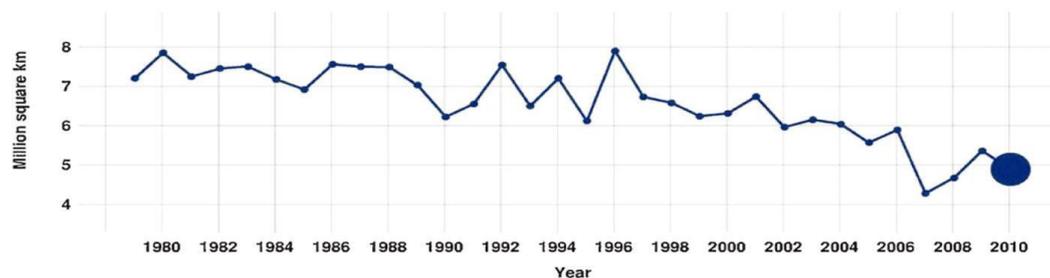
Data source: Satellite observations
Credit: NSIDC

Figure 7. Arctic sea-ice level in recent times (adapted from Vijaya VenkataRaman *et al.*²⁸).

Indians will live in urban areas by 2050, and so high increase in water demand is expected in future³⁶. Table 1 shows the increase in water demand from all sources based on population increase (low and high growth scenario).

A study conducted on 5723 blocks by the Central Groundwater Board of India (CGWB) in 2004 states that 1615 blocks are semi-critical, critical or overexploited. The number of exploited blocks in 1995 was 4%, which increased to 15% by 2004 (refs 32 and 35).

The data presented in Table 1 are based on population increase and developmental progress of India. They do not include the climate change scenario, which may make the situation much worse.

Climate change effect on Indian groundwater resources

About 85% of the rural water supply in India is dependent on groundwater and due to unplanned discharge of groundwater; the levels are continuously falling down³²⁻³⁷. Groundwater level in Gujarat, Rajasthan, Punjab, Haryana

and Tamil Nadu has shown a critical decline. Groundwater decline has been registered in 289 districts of India³⁷. The water table in Ahmedabad is falling at a rate of 4–5 m every year; in some parts of Delhi a lowering of 10 m has been noticed. Even in Kerala, where the monsoon intensity is high, water table has fallen¹⁶. It has been predicted that an average drop in groundwater level by 1 m would increase India's total carbon emissions by over 1%, because for the withdrawal of the same amount of water there will be an increase fuel consumption¹⁶.

Many parts of peninsular India, mainly the Western Ghats are likely to experience increase in precipitation; however, the increase will show spatio-temporal variability. Due to melting of the Himalayan glaciers, the Indo-Gangetic Plains will experience increased water discharge till 2030s (ref. 33) but will face gradual reductions thereafter. This increase in precipitation may show higher flooding, devastating major parts of India. At present northern India is losing groundwater at a rate of $54 \pm 9 \text{ km}^3/\text{year}$ (between April 2002 and June 2008). This rate of high run-off and low recharge will lead to degradation of aquifer in the northern plains of India³⁸. A 1°C rise in temperature will increase the water demand

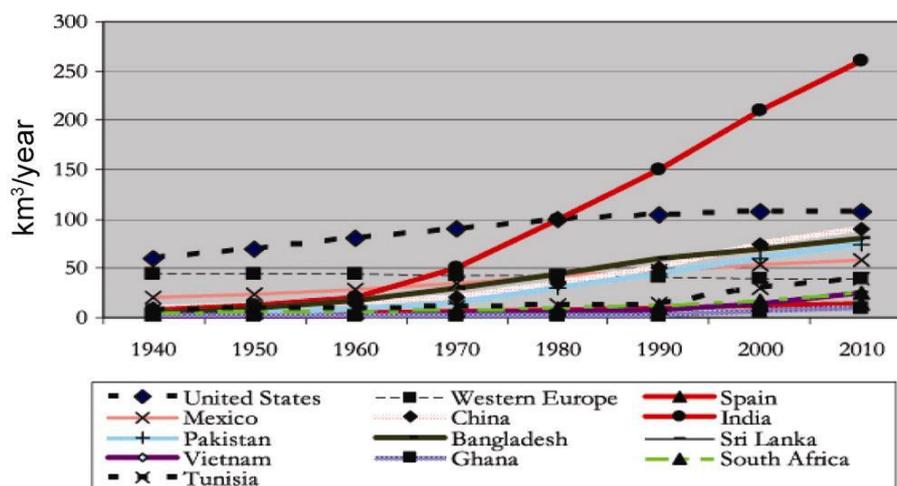


Figure 8. Growth in agricultural groundwater use in different countries (from Shah³³).

by 313.12 MCM for arid regions of Rajasthan²⁸. As a result of high temperature, the intensity of cyclones will increase and as India has a long coastline of 7517 km, the effect will pose a great threat to the population residing in the coastal regions³⁰. Sea-water intrusion has been observed in several coastal states of India, such as Tamil Nadu, Puducherry and Gujarat (Saurashtra), which is not only engulfing the land but also the groundwater reservoirs.

The changes in precipitation and evapotranspiration trends, droughts, floods and tropical cyclones will have a negative impact on agricultural production. In India, winter precipitation is projected to decline in the future, and hence will result in increasing the demand of water for irrigating rabi crops³⁰. Kharif crop production will also have to cope with heavy floods and droughts³³. Increased temperature will favour the growth of weeds and their shifting to the higher latitudes. As a result, environmental stress on crops may increase, which may become more vulnerable to insects, pathogens and weeds. The effect of weed growth on yield suggests losses in the range 28–74% in rice and 15–80% in wheat³⁹, and these drawbacks shall have an adverse impact on the nation's economic growth and GDP. India is highly sensitive to climate change in terms of its effect on water supply for irrigation needs^{36,37}.

Mitigation strategies to reduce effects of climate change

Groundwater is a renewable natural resource, and hence it can be replenished by better groundwater management and governance policies. India as a country of more than a billion population and high cattle and other domesticated population has a challenging task of conserving groundwater without affecting the needs and its development progress. The following measures can be adapted for the sustainable utilization of the groundwater reserves.

Behavioural and structural adaptations

Behavioural adaptation implies the way people utilize their groundwater resources. It depends on the people and their lifestyle. For example, using buckets and not showers for bathing and use of recycled water for agriculture. Structural adaptation implies building infrastructure or techniques that can minimize the risk of climate change on groundwater and increase storage capacity of aquifers, e.g. rainwater harvesting, artificial recharge of aquifers, underground dams, reservoirs and check dams, etc⁴⁰.

Promoting groundwater governance

Groundwater governance involves the role of multiple stakeholders from different sectors, including scientists, policymakers, and users for managing groundwater resources⁴⁰. It works on a set of policies or decisions that manages and develops groundwater resources and protects aquifers. Local groundwater governance can be an effective way of managing groundwater resources as the individual is also involved in it and if the action is taken at the micro watershed level, it will be an important step in the protection of groundwater resources.

Defining groundwater risk zones and climate change mapping

Spatio-temporal effect of climate change on aquifers should be assessed and based on this risk assessment of each aquifer should be rated and actions and policies should be designed accordingly. Climate change mapping on different resources will give better results and answers about the vulnerability and risks involved over time for a specific area. Research should also be promoted to fetch better results from the positive effects of climate change, with the aim of reducing the negative effects.

Table 1. Annual water requirement for different uses (in BCM; from Jain³⁶)

Uses	Year					
	2010		2025		2050	
	Low	High	Low	High	Low	High
Irrigation	543	557	561	611	628	807
Domestic	42	43	55	62	90	111
Industry	37	37	67	67	81	81
Power	18	19	31	33	63	70
Inland navigation	7	7	10	10	15	15
Environment – ecology	5	5	10	10	20	20
Evaporation loss	42	42	50	50	76	76
Total	694	710	784	843	973	1180
Population (million)	1286	1333	1286	1333	1346	1581

Promoting afforestation

Trees are the sinks for CO₂ on the Earth, and to minimize the effect of global warming, afforestation is the best way, with the aim of reducing deforestation. Land-use development planning should emphasize on planting more trees and increasing recharge area.

CO₂ sequestration

Due to unusually large amounts of CO₂ added to the atmosphere, carbon cycle is insufficient to maintain the balance. For example, annual carbon emissions from the use of fossil fuels in USA accounts for 1.6 gigatons, whereas the natural annual uptake is only about 0.5 gigatons, i.e. 1.1 gigatons per year remains in the atmosphere⁴¹. This extra CO₂ is responsible for global warming, which can be trapped in forests, grasslands, oceans and in the sedimentary formations such as coals. However, this sequestration processes is also beset with many environmental issues and concerns.

Conclusions

Global climate change is not a new phenomenon. The effect of climate change poses many threats; one of the important consequences is bringing about changes in the quality and quantity of the groundwater resources. The recent global warming caused by the increased emissions of GHGs to the atmosphere by anthropogenic processes, has its effect on continental surface water, oceans, ocean productivity, vegetation, etc. In addition, it has a significant effect on the energy cycle and groundwater. We perceive the immediate climate change effects in terms of floods, drought conditions, glacial melts, etc. The effect of climate change is significantly more on the semiarid, arid and coastal aquifers of the world. In India, the vulnerability is extremely high because of overexploitation of the groundwater and accompanied land subsidence in

urbanized areas. Since the recent global climate change phenomenon is more or less an established fact, it is time we focus our attention on the dire consequences it may bring to various Earth processes and face the challenges of climate change in more realistic ways. Groundwater is one of the most utilized resources in India for drinking and irrigation purposes. The climate change effects on groundwater resources in our country should be assessed under these new environments for better planning and management of this vital resource.

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