Chapter

Sustainable Water Flows in Era of Climate Change

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Abstract

The flow of water in rivers is of paramount importance to maintain supply of food and energy requirements to a great extent. The minimum flow in perennial rivers is subjected to groundwater availability, it is further replenished by the water added through precipitation. Climate change not only increases the melting of glaciers and sea level rise, but also influences the surface water flow and quality. As agriculture is directly affected by changing precipitation pattern, the reduction in water resources and untimely addition of water, both act havoc to the food production process. This interconnection makes agriculture even more vulnerable to the scenarios of global warming and climate change. Studies on food-energy-water nexus has opened new avenues of research in sustainable water management. The role of sustainable flow of water in rivers is highlighted which needs to be understood in era of climate change.

Keywords: surface water flows, ground water, climate change, sustainability

1. Introduction: Era of climate change

The surface water has been the cradle of civilisations since the beginning of human history. The social and economic well-being of human beings is directly affected by availability of fresh water. The use of water in domestic, agriculture as well as industrial sector has increased the stress on fresh water. The major fresh water sources, the rivers, are turning into water bodies unfit for proper use. The pollutants have also reached the groundwater and contaminated the clean water source. Climate change is another threat posed on the availability of fresh water. Change in the climate during the last few decades is described by the changes in variables of climate such as temperature, humidity, wind velocity etc. in different parts of the world. This climate change is caused by the warming of the earth's atmosphere as a result of increasing greenhouse gas (GHG) emissions, change in land-use pattern and emission of aerosols and other pollutants through various anthropogenic activities. Thus climate variability in a particular region may be observed at hourly and daily basis in addition to monthly, seasonally, annually and decadal variability [1].

Climate change will cause significant impact on our water resources since it is directly related to changes in patterns of precipitation. The effects of climate change are already visible in many parts of the world. Many countries in the world are negatively affected by the impacts which range from increased frequency and intensity of floods and droughts, severe water scarcity, increased intensity of erosion, retreating glaciers, sea level rise, decreasing snow cover, increased sedimentation in water bodies, deteriorating quality of water and damaged ecosystems [2]. The impact of climate change on surface waters, as studied for Moldova, East Europe, has shown increase in temperature and precipitation from 1945 to 2011. The annual average temperature was predicted by climate models to increase by 2°C between 2010 and 2039, and up to 3°C by next thirty years. However, the predictions for precipitations indicated that total amount of precipitation could decrease steadily or remain stable by the end of the century, with seasonal variability [3].

The human populations are exposed to various climate change related risks. The modifications of climate often result in unpredicted cyclones, storms, floods, droughts and heat waves and with increased intensity. The water availability in surface water bodies get altered as a consequence; modified river flow regime and altered ground water recharge play a significant role. Indirect effects of changing climate causes siltation of reservoirs, coastal floods and salt-water intrusion in coastal aquifers are most common occurrences (**Figure 1**). These various factors are interrelated and they affect the human population intensely and in most unpredictable way [1]. Various sectors which directly depend on water resources, such as agriculture, hydropower, navigation etc. are getting affected and have devastating societal impacts like effects on health of large scale of population and economy of many countries [2].

1.1 Extreme events

Extreme events have caused major disasters in many parts of the world in last couple of decades. A stronger link is detected between the changing weather patterns and warming of the atmosphere. Extreme heat and drought with changing seasons are being experienced in many tropical and sub-tropical regions. The number of flood disasters have increased several times [4]. Storms and flash floods have increased frequency in mountainous regions [4, 5]. In tropical and sub tropical regions, the event of extreme rainfall is anticipated on land because of increasing convective activity during summer monsoon. Warmer atmosphere facilitates heavy moisture bearing clouds and rainfall is intensified. Extensive and continuous rainfall have triggered disastrous effects such as landslides, subsidence and submergence under water. The annual flows would become more unstable, spring and flash floods will become more common and increase the peak flow [3]. The run-off is expected to increase in many parts of the world. Increased snowfall and frigid weather are also linked with moisture in the warmer atmosphere. The non-climatic factors of human actions have exposed and increased the vulnerability, making these regular events more hazardous. The geographical location and socio-economic dynamics play a very important role in turning extreme events into disasters.

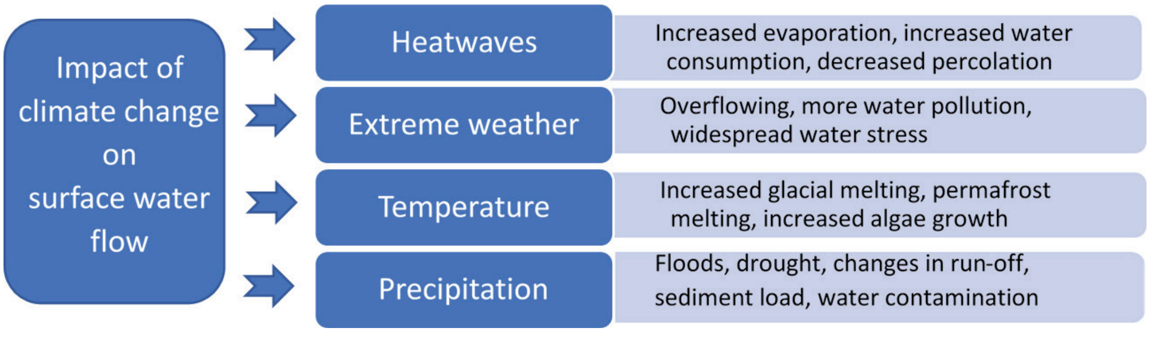

Figure 1.
Climate change impacts on flow of surface water (adapted from UNECE guidance document).

1.2 Effect on water quality

Surface water temperature increase will increase properties such as solubilisation, dissolution, and evaporation in the surface water bodies. Increased temperatures will also favour degradation of chemical and organic compounds, complex formation and their reactions, and bring about transformations in the chemical property of water to a much higher degree. As Arrhenius equation explains, kinetics of a given chemical reaction can be doubled for a temperature increase of 10°C, Increased temperature of water bodies due to high atmospheric temperature may alleviate dissolution of substances and decrease the dissolved gases in water. Depletion of the most important dissolved gases, oxygen, also affects the quality of water [6]. The increase in temperature and accommodating extreme inflow has a definitive effect on the quality of water due to mixing of pollutants, sediments, pathogens, pesticides, salt, organic carbon, nutrients etc. The surface water bodies are at the receiving end of the heavy contaminants through run-off which changes the quality of water. Extra heat released by anthropogenic causes, industrial processes, directed to water bodies, cause change in water quality called thermal pollution. Hence the quality of surface water is compromised due to increased heat as well as its calamitous effect on the physical and chemical properties of water and added contaminants. This negative impact is more pronounced to the aquatic ecosystem and the health of human population [7].

1.3 Effect on the flow of water

Climate change influences many characteristics of flowing surface water and is anticipated to have great impact on river regimes. The water levels of the rivers, flow velocity, residence times and overall hydraulic characteristics are affected as a consequence. This eventually brings changes in wetted areas of rivers, overflow patterns and affect habitat availability and connectivity [8]. Frequent and intensified flooding is expected as the run-off load and overall peak flow is increased. More intense rainfall and flooding is expected to increase the load of suspended solids and sediment yields [9, 10]. The impact of extreme events is severe on rivers in upper courses, leading to releasing heavier number of sediments which are carried downstream in suspended state and as fine sediments from land. Erosional capacity of heavy flow increases many times. Such changes have great influence on downstream habitats and ecology. Increased suspended load in the surface water is also a potential cause of bacterial (*Escherichia coli*) and harmful heavy metals [11] pollution. As studied in many parts of Europe, the key factor controlling the ecosystem behaviour is the hydrological and geomorphological processes in the region [12]. The carrying of sediments is beneficial for the upland stream ecology as it leads to wider range of habitats, meandering side channels and deeper sediment zones to support aquatic life. Enhanced habitat restoration due to varying flow regime of the rivers was found through extensive study of German river systems [13]. Sustained flow in rivers is difficult to maintain due to unpredicted extreme events of precipitation.

2. Sustainable water flows

Changes in the flow of river due to channel straightening, disconnect with flood plains, dam construction and loss of river ecology has a great impact on the overall ecology of the river, climate change is added problem. Fresh water ecosystems were studied through PRINCE (preparing for climate change impacts on freshwater ecosystems) project in UK which has shown that changes in climate have directly affected the aquatic ecosystems [14]. The changes in climate including changes in duration, frequency and magnitude of precipitation, especially extreme events, influences the aquatic ecosystems through episodic pulse effects. Combined with the changes in water velocity and dissolved oxygen content of the water bodies, the effect of temperature becomes more pronounced for fishes, amphibians, as well as birds. The more conspicuous effect would be on migratory or dispersal patterns between ecosystems such as between marine and freshwater, long-distance migrants or across watersheds. Hot summers with limited rainfall eventually decrease the amount of dissolved oxygen, particularly in standing waters, and rivers in middle and lower courses, where re-aeration in less. In addition, such water bodies also have high amount of nutrients resulting in profuse plant growth but leading to low oxygen levels which can be threat to fishes and invertebrates of water bodies. On the other hand, the high flow of storm water improves oxygen levels, but increases the contaminants such as pesticides and fertilisers. Such conditions take a toll on vulnerable sections such as ephemeral ponds, ditches and small water bodies which are most affected due to changing conditions. The sensitivity and resilience of the surface water ecosystem gets effected due to magnitude, variability, frequency and mistiming of the water flow and quality.

Surface water resources like lakes, rivers and reservoirs, as well as frozen water in glaciers and snow covers, the internal renewable water resources, receive water from total precipitation and upstream streamflow produced. The aquifer recharge is also dependent on the same. Ratio between total precipitation and total streamflow, runoff ratio, vary from country to country and is a factor of terrain, the mountainous region and steep terrain produce more run-off [15]. Hence total renewable water resources are the sum of internal renewable resources and surface run-off water. The upstream and island countries like Bhutan and Sri Lanka respectively have minimum run-off component whereas Bangladesh receives more than 90% [1]. The risks with water bodies gradually get worse with the climate change. Studies in tropical and sub-tropical regions have predicted increase in extreme flows due to climate change [16]. Land use induced by climate change may increase the erosion rates. Use and managing water resources which are differentially affected by modified rainfall patterns, temperature increase, and sea-level rise are very crucial in the times of climate change.

Hydrological impacts on river systems are aggravated due to climate change. The prime cause of reduced water flows is the increased water extractions, also a consequence of global warming. Overexploitation of both surface and ground water has affected the surface water flows more predominantly. The health of the rivers has been severely impacted due to consumption being overpowering. The per capita water availability has sharpy declined in many countries in the recent past [17]. With growing economy and ever-growing population, this is expected to become worse [18, 19]. The microscale studies on effect of climate change on different rivers or studies at global scale showing anthropogenic stresses on river systems, have not been thorough in understanding the situation in most countries, the meso-scale analysis of cross-continental basin-scale comparisons have revealed that water extractions from the rivers of past and present, have exceeded the projected impacts of climate change to much larger extent [20]. This finding realises the importance of effective water governance to reduce present water stresses and further deterioration because of decline in water flows and consequences of climate change. The current water-use practices consume water at the expense of natural water flows [21, 22]. With the threat of climate change, the policies to reduce consumptive use of water and maintain sustainable in-flow water uses for a longer time need to be encouraged. The water allocation management plan should share the variability equally between the users and the environment.

3. Climate change impacts

3.1 Floods

Floods are not only the excess flow of water in rivers during rainy season, but also the flash floods which are induced by changes in rainfall pattern and temperature rise. Such flash floods are expected more frequently in the mountainous regions as a consequence of convective activity during monsoon, collapse of natural ice or debris deposited due to landslides or sudden subsidence of glacial lake. The global warming has accelerated the melting of glaciers in Himalayas and number and size of glacial lakes have increased [5, 23]. The outburst of the glacial lake is anticipated due to moraine deposition, and flash floods play havoc to such conditions. It is disastrous for thousands of people living downstream and are capable of paralysing hydropower projects [24].

The more common riverine floods are still a disaster in many parts of the world and climate change has increased its probability. It has long-term effects on land-use, economy, and development of the effected region. Naturally, the floods are essential feature of a river life cycle and is highly required for the nutrients carried down through silt and water, which is beneficial for the crops like rice. However, the increased in the frequency and intensity of rainfall has resulted in longer flood duration and greater spatial extent. The frequent flooding damage crops, delays cropping cycles, spreads infectious diseases and damages properties and land.

The sea-level rise due to warming of atmosphere and increased frequency of storms in sea has aggravated the coastal floods making them more damaging. The low-lying lands get completely submerged everytime and the adjoining coastal lands face severe agricultural losses. The frequency and severity of coastal storms has increased, and cyclone have become more common, posing a serious threat to the coastal regions. The subsidence and retreating of delta are other consequences due to increase in silt load of the rivers in the coastal region [5, 18].

3.2 Droughts

Increasing water demand and increasing water scarcity in areas due to climate change have made regions even more vulnerable to droughts [24, 25]. The reduction in groundwater recharge is more prominent due to altered flow and changed rainfall patterns. The discharge in the rivers which are snow-fed will face huge changes in pattern as the peak season discharge will be smoothed throughout the year and extended in the early part of the year. Hence during the peak summer season less water will be available, along with increased rate of evaporation, for irrigation and hydropower projects [26]. This problem will increase as the temperatures increases, owing to enhanced evapotranspiration, increased water demand by crops and greater risk of drought stress, siltation of reservoirs and reducing storage capacities of the reservoirs [27].

3.3 Groundwater

Groundwater is the major source of freshwater, estimating up to one third of the total freshwater withdrawals, and is crucial for agriculture, industry as well as domestic requirement [28]. The groundwater also sustains the baseflow of surface waters such as rivers, lakes and wetlands and help them to survive during low or no rainfall period. On the other hand, the water table is maintained by percolation of rainwater and leakage from surface water such as lakes, streams and wetlands.

Hence, the groundwater recharge is highly dependent upon climate, land cover, terrain and geology of the region. The amount of precipitation and evapotranspiration is decided by the climate and vegetation cover, and the water percolation in the soil also depends upon the type of soil and underlying rocks [29]. It is the surplus water after run-off and evaporation, which enters the repository of ground water. At higher altitudes, the spatial distribution of snow and ice is largely affected by climate change, less accumulation of snow and earlier melting. In winter season this effect causes more precipitation and increased frequency of rainfall plus snow events. The overall impact is that the recharge regime of the groundwater is changed in this era of water scarcity and global warming, and it does not get replenished with sufficient water [30, 31].

Groundwater storage is the prime source of freshwater which has been stored since decades and is one of the cleanest sources of water. The reserves of groundwater act as buffer for the surface water supplies and provide a sustainable flow in surface water bodies under climate variabilities, however, there is a limit to their natural resilience due to withdrawal exceeding the recharge rate [32]. The recharge is in areas which allow inflow by infiltration of excess rainwater and surface water bodies, also includes irrigation practices in agriculture, water seepage of wastewater or storage water. Natural outflows include discharges in springs, wetlands and lagoons, most prominently extraction through borewells. The balance between inflow and outflow in groundwater determines the maintenance of the water table. The sustainability of groundwater depends upon the balance between its recharge and discharge; climate change would affect this balance in case of increasing aridity and overexploitation, decreasing the recharge rate. The lesser and more intensive rainfall may increase the water table of an area, even higher than their previous level, and damage the crop and property. It will also deplete the soil moisture, cause soil compaction, soil erosion and will further reduce the infiltration capacity and groundwater recharge.

Another important consequence is saline water intrusion in coastal aquifers and reduced flow in delta region. Many coastal countries are at the risk of climate-related groundwater contamination [1]. As the sea-level rise, the aquifers and wells are affected by saltwater intrusion and contaminate the drinking water source [33]. Extensive pumping of groundwater due to increase water demand in warm temperatures, accelerates the pollution of aquifers through lateral movements of saltwater or contaminants. The geogenic contaminants including arsenic, uranium, fluoride [34, 35] can be hazardous for living beings. Agricultural additives, fertilisers and pesticides also infiltrate to the groundwater and make it toxic. Domestic wastewater and other industrial effluents are increasingly reaching the groundwater and changing its quality. This will further deteriorate the situation as it will lead to excessive pumping from tube wells and water withdrawal from upstream rivers. This phenomenon of sea-level rise, depleting aquifers, increased water demand will accelerate the groundwater pollution and is already happening in many parts of the world [36, 37].

4. Indirect risks

The indirect risks of climate change phenomenon are closely interrelated and affect each other dynamically, creating a situation of environmental emergency. The extent of the risks and its effect on the human civilization may yet to be fully understood, as the stressors may have cumulative effect [38]. Hence feedback loops and synergies of indirect stressors need to be understood to safeguard against disasters. Some possible interconnections are as following:

4.1 Urbanisation

Land encroachment, high population and overexploitation of fresh water resources affect the environment most potently. Increasing industrial as well as other wastes and irresponsible dumping of wastes, add to the havoc of water contamination and increasing greenhouse gases, the cause of global warming and climate change.

4.2 Changes in land use pattern

Increasing temperature and changes in hydrology of a region bring about changes in the vegetation and land use pattern of a particular region. On the other hand, poorly planned land use is the arching factor behind increased incidences of disastrous conditions like flooding. Flooding in urban areas can be controlled by restricting urban development in low-lying flood-prone areas and floodplains of adjoining rivers, appropriate wastewater management released by high populated areas. Environmental degradation along with poor planning of land use can result in major disasters due to climate change.

4.3 Agriculture

Deterioration of soil due to extensive agriculture practices, unregulated irrigation and use of excessive fertilisers and pesticides have adverse effect on environment, particularly water bodies. Major changes in the water demand of irrigation due to climate change is expected. Practices such as clearing of forest for agriculture, cultivation on steep slopes, combined with overgrazing by cattle stock, unsustainable use of pastures and scrublands, have aggravated the conditions created by climate change. Soil degradation and erosion reduces the water absorbing capacity of soil and increases surface run-off. This will further increase the destructive effects of flash floods, siltation of downstream water reservoirs and also reduces groundwater recharge. Change in water quality and quantity as a result poses insecurity and the threat of food scarcity, hence increasing the vulnerability of poor farmers of arid and semi-arid regions.

4.4 Population growth and migration

Demographic changes due to increasing climate refugees increases the stress on the host land, adding to the problem of environmental degradation and making lives of people more vulnerable. Settlement along the rivers is more prone to disaster of floods, more damaging to the temporary or semi-temporary infrastructure for living. This also adds to the contamination of surface water and creates stress on dwindling freshwater resources. Social inequalities, less opportunities for livelihood, economic weakness, food insecurity and political instability causes fundamental threat to human life posing serious repercussions to the environment. Global demand of fresh water is sharply increasing primarily due to increasing population.

4.5 Growing energy consumption

It will trigger increasing demands of energy and stress on hydropower, thermal power and nuclear power to produce more energy. Inadequate infrastructure towards energy generation also comes with a risk of water stress, wastage of water, release of pollutants and major accidents. Increasing soil erosion and other extreme events such as flash floods, mud water flow has caused severe siltation of the reservoirs which will effectively reduce the capacity of hydro power generation. It also reduces the capacity of meeting water needs for irrigation and other activities during dry season.

5. Conclusion

IPCC Report 4 [5] has clearly emphasised on the linkage of atmospheric warming to the large-scale changes in the hydrological cycle, increase in the water vapour content, changing in the patterns of precipitation, increased frequency and intensity of precipitation, reaching extremes of dry season and flooding, reduced snow cover, enhanced melting of ice and reduced permafrost, changes in soil moisture content and increased runoff. A remarkable spatial and inter-decadal variability in the precipitation has been observed. The events of intensive precipitation have increased worldwide on one hand, and area classified as very dry land has increased to double on the other hand. The snow cover and water stored in glaciers have decreased considerably. This ice melting related phenomenon with snow-fed rivers, run-off in glaciers and increased number of glacier lakes have been observed in last few decades. Such changes have also been associated with disastrous flash floods, landslides, riverine floods and heavy mud flow. Sustainability of the surface water due to delicate hydrological cycle seem to be disrupted beyond cure.

Climate change models are predicting increased precipitation in higher latitudes and decreased precipitation in subtropical and lower mid-latitude regions, increasing disparity and creating extreme conditions in different parts of the world. As a result, increase in average river water availability and run off is predicted in the higher latitudes and a decreasing trend towards dry tropics. Reduction in the water supplies in glaciers causes reduced water availability in rivers, hence creating water stress conditions.

Freshwater resources are also influenced by many non-climatic drivers such as changes in the patterns of population, food consumption and production of food and other products. The economics of water pricing, technology and societal views towards value of freshwater ecosystems also plays a role [2]. Thus, climate change is one of the many factors causing future water stresses, effecting sustainable water flows. The socioeconomic and technological changes along with demographic changes can prove to be more effective towards water management in most regions of the world and on most time scales. Talking about the effect of extreme events, the impacts more often depend upon the socioeconomic vulnerability. The development pattern, wealth distribution, demographics and environmental conditions determine the severity of such disasters like extreme weather events and migration of disease vectors.

The water management practices presently in action are not enough to cope with the impacts of climate change and may not be able to assess and manage risks such as devastating floods, human health, food insecurity, damaged ecosystems and inadequate power supplies. The current variability in climate is impossible to predict completely and plan for long term adaptation strategies. The effect of climate change stress in tropical and sub-tropical regions is more pronounced and a threat to sustainable surface water flow. The indirect stressors such as population growth, urbanization etc., will aggravate the conditions. The challenges posed by changing climate in the past can be a good guidance for planning for the future. The management practices based on projected hydrological changes may help to avoid disastrous events and bring situation under control. The adaptation strategies for maintaining sustainable flow of surface water require integrated strategies for both demand and supply sides. Improving water-use efficiency, recycling of water, water harvesting, water conservation, water metering and water markets may be valuable efforts in this regard. Integrated water resource management, expanded use of economic incentives and providing framework adaptation strategies in administrative systems, across socio-economic barriers are the key factors. Integrated approaches must be at appropriate scales to be effective in practice and to provide total environmental solution. Such mitigation methods will not only reduce the impact of global warming but will also reduce the stress of adaptation to changing climate.

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