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Climate change induced salinization and quality deterioration of groundwater resources in Pakistan; Current scenario and future prospects

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Abstract

Climate change has triggered various catastrophic events including groundwater salinization resulted in quality deterioration worldwide leading to the environmental degradation and posed threat to natural ecosystems. Pakistan is among the countries severely affected by the climate change. Most of the Pakistani depends on groundwater resources for drinking and irrigation purposes but no clear policy exists regarding judicious extraction and usage of groundwater. Over extraction and exploitation of groundwater along with climate change events have deteriorated the quality of groundwater in Pakistan and most of the part is salinized and has excess of soluble salts and other chemical, physical and biological contaminants. This paper reviews the impacts of climate change on salinization and groundwater quality and possible remedies and solution for this problem especially with the perspective of Pakistan. It is the need of the hour of the time to introduce climate smart agricultural practices at farmer level to stop overexploitation of natural resources and to reduce the agriculture share to climate change. Policies should be developed and existing policies should be strictly implemented for the judicious use of surface water and ground water resources to avoid the risks of water scarcity in near future.
Keywords: Water Security; Water Resources; Climate Change; Policy Framework; Salinization.

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1. Introduction

Long-term shifts in weather and climatic Patterns (i.e. temperature, precipitation patterns, radiations, wind patterns etc.) across the globe are termed as global climate change. It has a negative impact and put stress on various sectors and components of environmental, ecological, socio-economic and socio-political disciplines[1]. As per reports of International Panel on Climate Change (IPCC), about 0.74 °C temperature increment has been recorded in past century since 1906[2]. Models predict that by 2020, global surface temperatures will be more than 0.5 °C higher than the average of 1986-2005 initiating the complex and dreadful climatic events[3]. Disturbance in hydrological cycle caused by increased temperature and climate change influences groundwater resources directly or indirectly[4]. Climate change has an impact on groundwater aquifers both directly and indirectly via connections with surface water resources like lakes and rivers. Changes in groundwater recharge volume and distribution determine how directly climate change may affect groundwater resources. Due to this, accurately assessing the influence of climate change on groundwater resources necessitates precise calculations of groundwater recharge and reliable predictions of alterations in critical climatic factors[5]. Over-sized human population and climate change events trigger the deterioration of water quality i.e. chemical contamination, heavy metals toxicity, eutrophication, salinization and microbial contamination ultimately leading to the compromised and unsafe water resources[6].

Groundwater being the most exploited resource of water for irrigation, drinking and industrial purpose worldwide and its contamination and quality deterioration poses a serious threat and challenge to all the water sector stakeholders[7]. Country's economic development is reliant on various important components and water resource is one of those. In arid to semi-arid zones, water resources face quantitative as well as qualitative degradation under the action of climate change in recent decades[8]. Transpiration loss and evaporation of surface water results an increase in soil surface leading to imbalance hydrological cycle. As a result, these modifications may have an impact on the amount, timing, and intensity of precipitation as well as the movement and storage of water in reservoirs under the surface of the earth (such as lakes, soil moisture, and groundwater). Additionally, there can be unintended consequences like saltwater intrusion, declining water quality, a scarcity of potable water, etc. Surface water supplies are directly impacted by changes in significant long-term climatic elements including air temperature, precipitation, and evapotranspiration; however, it is more challenging and less well known how these variables interact with groundwater. Increasing rainfall variability may lead to longer and more frequent periods of high or low groundwater levels due to resource depletion and sea level rise, as well as saltwater intrusion in coastal aquifers[5].

Groundwater resource management and sustainable development relies on groundwater quality which is a major source of freshwater. Increase in demand of freshwater and overexploitation due to increasing population in developing countries put pressure on freshwater resources resulting in inferior groundwater quality and salinization is one of the quality parameter and indicator which is increasing worldwide[9]. Marine sources (e.g., marine transgressions, lateral seawater intrusion, connate saline groundwater, seawater sprays and incidental flooding by seawater), natural continental sources (e.g., soluble minerals, evaporation, geothermal origin and membrane effects), multiplicity sources and anthropogenic activities are the major sources of groundwater salinization[9]. However, climate change induced rise in temperature and depleted rainfalls are likely to accelerate the process of salinization in irrigated areas[10]. In many global regions, groundwater tables are declining due to climate change. Gaining streams change into losing streams when their water seeps underground. Groundwater quality and ecosystems are threatened by seepage of contaminated stream water[11]. Salinization and deterioration of quality of groundwater resources led by climate change is a serious threat to environment and ecosystem productivity and if the process proceeds for long time it may leads to unsafe consumption of water leading towards vulnerable state’s economy.

This paper reviews the climate change effects on groundwater resources in terms of salinization and water quality deterioration and its effects on health, environment and country economy. Pakistan is one of the most affected countries by climate change and numerous extreme climatic events have taken place here in recent decades. We have discussed the possible salinization and deterioration of groundwater quality due to these climatic events in Pakistan and processes involved in these phenomena. Existing institutional framework for managing climate change and water resource with possible strategies to minimize the effects of climate change with some case studies are discussed.

Climate Change Trends in Pakistan

Pakistan is an agricultural country situated in south Aisa and shares borders with Afghanistan, China, India and Iran. Over the past 200 years, Sub-continent is the most affected region due to climate change and extreme weather[12]. Pakistan majorly has a dry to semi-arid climate, and the country typically has a tropical continental climate with a broad range of temperatures and rainfall[13]. Highs of up to 49°C and considerably higher on the plains are common throughout the summer months of March through June. The nation's typical wintertime temperatures, which run from December through February, range from 4 to 20°C[14]. The country already encounters a variety of climate and weather-related natural hazards as a result of its diversified topography and variable tropical, continental climate (frigid winters and scorching summers). In Pakistan, there are frequent heat waves, flash floods, droughts, landslides and sea storms or cyclones. Climate change is predicted to enhance people's vulnerability and increase the frequency and intensity of these catastrophes[15]. According to Eckstein[12], Pakistan is one of the ten nations most susceptible to climate change. Cold waves, cyclones, droughts, floods and landslides are just a few of the extreme weather occurrences and phenomena that frequently occur in Pakistan. In winter, cold waves can occur in higher-altitude areas like Gilgit-Baltistan or Balochistan and Kashmir, where the combined effects of heavy snowfall, landslides, rain and below-average temperatures can have catastrophic consequences on people and cattle. For instance, 106 individuals perished as a result of these effects throughout the entire nation in January 2020, the majority of them were killed by avalanches and landslides that came along with intense rain and snow[16]. In addition to being frequent, flash floods can also cause landslides, especially during the monsoon season[17]. Finally, droughts are a common longer-term phenomenon that may have serious effects on sanitation and health systems, as well as food and water security. For instance, the Government of Pakistan estimates that a drought that began in 2018-2019 affected more than 5 million people[18]. Unpredictable rainfall, a protracted dry period, a variety of socioeconomic issues, including migration and population increase, as well as the predominance of rainfed agriculture, were all contributing causes to the drought[19,20].

I. Temperature variations and anomalies over the years

According to earlier studies, Pakistan's average maximum and lowest temperatures increased between 0.5 and 1°C from 1960 to 2007[21,22,23]. According to forecasts, Pakistan's average temperature would continue to rise and range between 3 and 9 °C by 2100[13]. The yearly mean temperature has risen by 0.57 °C during the last century. The maximum and minimum temperatures have increased since 1961 due to the accelerating warming trend; in other words, summer days have become intensified and winter days have warmed up. Between 1960 and 2007[13], the mean temperature of Pakistan's mountain ranges, dry coastal areas, and hyper-arid plains rose by 0.6 to 1.0 °C. The average temperature is expected to increase by 3-6°C by 2100, with a significant increase occurring after 2050, according to the emission scenario[13]. This suggests that Pakistan would see a higher temperature rise than the global average. The northern region, particularly the snow-covered areas, is expected to experience a greater temperature increase than the central and southern regions under all scenarios. By 2100, temperatures in the north could rise by 10–12°C, especially at high elevations, depending on emissions[15]. In Pakistan, heatwaves will increase in frequency and intensity while cold waves will trend downward in terms of frequency and size[14].

Changes in precipitation patterns

The winter and summer monsoons are two distinct periods that make up the rainy season. In the southern part of the nation, the southwest monsoon mostly brings rain to the eastern regions between June and September, while westerly disturbances primarily provide rain to the northern and western regions between December and March[13]. With only one and a half months of an active rainy period, Pakistan's summer rainy season is extremely brief since it is located at the western end of the Southwest Monsoon. However, according to Asian Development Bank[13], the Southwest Monsoon is responsible for almost 60% of Pakistan's annual rainfall. Less than 250 mm of rain fall each year falls across more than 75 percent of the nation. The southern inclinations of the northern sub-mountain area and the Himalayas are the locations that experience the 760–2,000 mm of rainfall annually and have the highest monsoon impacts. While summer rainfall increased by 18–32% across Pakistan's central monsoon region between 1960 and 2007, winter and summer rainfall decreased by 10-15% over the country's dry plains and coastal regions. Between 1901 and 2007, Pakistan had an overall 61 mm rise in yearly precipitation. Rainfall during the winter and summer monsoons has increased by 20.8 mm and 22.6 mm, respectively[13]. Predictions for Pakistan's rainfall show no discernible patterns of change. The Asian Development Bank[13] predicts that by 2050, the summer rainfall peaks will move to August while the winter rainfall maxima will move to March and last until 2100. For all emission scenarios, it is expected that the mean annual rainfall would rise until 2050 at a rate of 2-4 mm per day, with the northeastern region of the nation receiving the most rain. The rainfall pattern will change to the northwest and southern areas after 2050 and up to the end of the century[15]. With the exception of Sindh Province, most regions of Pakistan are expected to have a rise in extremely wet and very wet days, which will increase the likelihood and severity of floods[14]. Because there will be more dry days throughout the summer and fewer average rainy days, the earth will become drier and harder and less able to absorb surplus water during brief periods of strong rainfall[24].

Receding glaciers and its impact on water resources

Pakistan ranks among the most water-stressed nations globally, and the country's water supplies are extremely susceptible to alterations in the climate[17]. The main issues facing Pakistan's water industry are global climate change, seasonal and regional fluctuations in rainfall patterns, unpredictability in glacier melting and river flow. The hydrologic cycle has been disrupted by severe hydro-climatic occurrences, such as droughts and floods, which have a negative influence on water resources[25]. Large glacier masses in the upper Indus River basin provide summer meltwater. In Pakistan, human activities and ecosystems depend on water supplies from the upper Indus River basin, yet these resources are susceptible to climate change[26]. It is anticipated that the Himalayan, Karakoram, and Hindu-Kush (HKH) mountain ranges' glaciers and snow cover may thaw, with severe ramifications for the population living downstream[27]. The Indus River serves as a major supply of water for Pakistan. The Indus River is extremely vulnerable to climate change since it depends on glacial, snow and rainwater melt. Although future precipitation patterns in the majority of the nation are unclear, global and regional climate models are very definite about the increase in temperature, which might have a significant impact on water supplies[28]. According to hydrologic modelling, glaciers were responsible for one-third of the total flow, snowmelt was responsible for around

40%, and rainfall was responsible for the remaining flow. The hydrologic model's simulation of future river flows predicts major changes in both their amount and timing. Due to increased precipitation and glacier melt, river flows will increase by the middle of the century. According to simulations, the overall river flows are estimated to grow by 11% until 2050, with no forecast change in the hydrograph's morphology. The fact that glaciers lack sufficient bulk to support the glacial melt flow will lead this upward tendency in river flows to revert in the late 20th century. The modification will cause a flow reduction of 4.5% and a change in the date of the monthly peak flow from June to May[26]. Pakistan is heavily reliant on water supplies from the Upper Indus Basin's (UIB) hilly regions, particularly for irrigation. Astore and Gilgit, two of the five catchments that make up the UIB, will always run out of water, but Shyoke will only experience water shortages in the event that agricultural area is developed. It is also showed that Astore and Gilgit experience quite distinct effects of climate change. The influence of precipitation will reduce future water shortages over Astore by boosting winter streamflow, whereas non-climatic variables like population and agricultural expansion will do the same over Gilgit[29].

Water Resources of Pakistan and their uses

Like the majority of South Asian countries, Pakistan has both surface water reservoirs, including rivers, lakes, coastal regions, and subsurface water resources. Rainfall and precipitates that cause glaciers to develop are primary sources. The Tarbela, Mangla, and Chashma are the three largest water storage reservoirs in Pakistan, with a joint 18.92 million acre-feet (MAF) of storage capacity. Pakistan has 143 large and minor water storage reservoirs[30]. Since the majority of Pakistan's agricultural production depends on river water, the Indus River System (IRS) is vital to the country's survival[31]. Since it supplies a vital water supply to about 90% of Pakistan's food producing crops, the Indus Basin contributes more than 25% of the country's GDP. Pakistan's Indus Basin Irrigation System (IBIS), which includes the Indus, Chenab, Ravi, Sutlej, Jhelum and Kabul rivers, is one of the largest continuous irrigation systems in the world. 146 million acre feet (MAF) of water pass through the IBIS each year, While 106 million acre-feet of water is redirected to canals. Approximately 50–80% of Pakistan's normal river flows from the melting glaciers, while the remaining 20–30% is sourced from the annual monsoon precipitation. Water content for the two Eastern rivers, the Ravi and Sutlej, is 9.14 MAF, whereas 144.91 MAF of water is contained in each of the three Western rivers, the Indus, Chenab, and Jhelum. A total of 104.73 MAF of the available water is used for agriculture, 39.4 MAF typically flows into the Arabian Sea since storage space is at a premium, and 9.9 MAF is lost through system losses such evaporation, seepage, and spill during floods[32].

There are several reasons why water resources are becoming a major problem throughout the world, but most important among all are natural disasters. Pakistan is not exempt from a comparable threat of declining surface and subterranean water resources. The precipitation in the form of rainfall and the melting of glacial masses are the two main sources that can contribute the both above- and below-ground water[33]. The demand of water for household, industrial and agricultural purposes will all rise by 8% by 2025 as a result of this exponential population growth[34]. 5,000 m^3 of water were available per person in Pakistan in 1951, 1,100 m3 in 2005, and 800 m3 are anticipated by 2025[35]. According to the UN's estimations, Pakistan's water consumption is rising at an average annual rate of 10%[36]. This suggests that by 2025, the total amount of water available will remain within the same range of 240 to 258 km^3 [(37)]. For a water-scarce nation like Pakistan, it is estimated that 74% of the available surface water is drawn, while 83% of the groundwater is exploited for agricultural and various other purposes[38]. Due to population growth, water waste, and an insufficient water resources management system, there is a demand and supply mismatch that prevents the wise use of the water resources. Water shortage is becoming a significant threat to Pakistan's national security. It also produces social problems and inter-provincial strife in addition to water-related concerns with India[39,40].

Pakistan is the fourth-largest consumer of groundwater, where more than 90% of drinking, over 100% of industrial, and more than 40% of agriculture water requirements are satisfied by groundwater[25]. Surface water resources are adequate to irrigate 27% of the region, while groundwater is used to irrigate the remaining 73% either directly or indirectly. More than 90% of the total groundwater abstraction is used in the Punjab province. 1.2 million private tubewells are now operational throughout Pakistan, with 85% of them located in Punjab, 6.4% in Sindh, 3.8% in Khyber-Pakhtunkhwa, and 4.8% in Baluchistan.

About 60 billion m3 of groundwater have been extracted in Pakistan overall[41]. Studies have shown that the main environmental threats to the sustainable use of groundwater include things like increasing crop intensities, excessive groundwater extraction, insufficient awareness, chemical reliance in farming, industrial and urban expansion, acid rain from air pollution, and challenges with waste management, etc. These activities are deteriorating groundwater's quality and quantity at alarming rates. The main effects of poor planning and excessive use of groundwater reservoirs include abnormally low water tables in areas with fresh groundwater, the mixing of salty and fresh groundwater, an increase in the cost of pumping groundwater due to an increase in water depth, threats to agriculture from secondary salinization, etc.[25].

There is no comprehensive, trustworthy method in Pakistan for calculating groundwater extractions and the effects they have on the resource base. The few and infrequent measurement expenditures were uncoordinated, hindering thorough mapping and monitoring. Consequently, this has also impeded the measurement and management of water quality. As a result, it is difficult to direct groundwater usage towards sustainability and address emerging problems[42]. The establishment of the canal irrigation system in 1859 is largely accountable for the groundwater and soil salinization observed in the Indus Basin. The water table increased to 1.5 m below the soil surface with the construction of the extensive canal network. Groundwater irrigation that was used excessively added to the problem. Salinization has an impact on sizable portions of Sindh, Punjab, Baluchistan, and Khyber Pakhtunkhwa. In groundwater with increased TDS, sodium and chloride are discovered to be the major ions[43]. Groundwater extraction gone uncontrolled has seriously harmed the ecosystem. These include worsening soil salinization issues and quickly declining groundwater levels in the irrigated regions. More than 50% of Punjab's irrigated districts have groundwater levels below 6 meters, which has raised pumping costs and worsened groundwater quality. Despite intensive efforts, various salt levels damage around 21% of the irrigated area. For the sustainable use and management of groundwater resources, the authorities have passed a number of laws and regulations, but so far with little success. The main causes of inadequate groundwater management, in addition to lacking rule of law, absence of necessary data and information, a lack of political will, and institutional structures[41].

Socio-Economic Implications

Dependency of Pakistan economy on water resources

Although water is abundant in Pakistan, the sixth most populated nation in the world, water availability per person is rather low. Compared to most other nations, water usage is high and agricultural outputs are poor. If immediate reforms are made to increase water usage effective and service delivery, Pakistan may reap more economic, social, and environmental advantages from its water[44]. Majority of Pakistan's population relies on surface and groundwater resources primarily sourced from the Indus River basin. Approximately 92% of Pakistan's land area is classified as semi-arid to arid by climate[45]. Irrigated agriculture, the foundation of Pakistan's economy, is heavily reliant on water supplies coming from the upper Indus' mountain sources. Therefore, any alteration in the number of resources available due to socioeconomic or climate change may have a negative influence on both the environment and food security leading to the compromised economy. The availability of water per person and the ratio of withdrawals to runoff both indicate that Pakistan's water resources are already under a lot of stress and will continue to be so as the country's population grows[46]. Given that it accounts for around 20% of Pakistan's GDP and 44% of all employment, agriculture is a crucial pillar of the country's economy. More than 80% of the population depends on agriculture for a living, either directly or indirectly. About 22 mha, or 27% of the total land area, forms the foundation of the arable agricultural resources. There are 6 mha of rain-fed land and 16 mha of irrigated land. More than 90% of all agricultural and livestock production is produced in the irrigated area. In the Indus basin, the irrigated lands are situated along rivers[47]. The Indus River supplies water for about 90% of Pakistan's food production, contributing 25% to the nation's Gross Domestic Product. Pakistan may soon be in danger of experiencing a major food crisis due to problems with water security. The World Bank study for 2020–2021 indicates that by 2025, the projected water deficit is anticipated to escalate to 32%. leading to a food shortage of over 70 million tons. As river sharing has long been an issue for Pakistan, a water deficit might potentially lead to conflict amongst the provinces[48]. Even while irrigation accounts for the majority of water consumption in the nation, the four main crops (wheat, rice, cotton and sugarcane) that utilize 80% of the water provide just 5% of the GDP. It is tentatively estimated that poor water management costs 4 percent of GDP, or around $12 billion annually. These expenditures, which also include the costs associated with floods and droughts, are mostly caused by insufficient residential water supply and sanitation[44]. Access to groundwater has made it easier for farmers to withstand the whims of surface supplies, vary their cropping techniques, and convert erratic crop yields into longer-lasting agricultural output. The country's irrigated agriculture is, however, in risk due to the ongoing, unplanned, and unregulated groundwater withdrawal. Falling groundwater levels in many irrigated regions lead to higher pumping expenses and worsening groundwater quality. For smallholder farmers, this circumstance has rendered groundwater unavailable. Additionally, irrigated land is becoming more and more threatened by soil salinity issues, which are on the rise[41]. In areas lacking alternative water sources for irrigation, irrigation-induced salinity not only amplifies plants' water needs by hindering root penetration into the soil but also triggers excessive groundwater extraction. Conversely, regions reliant on surface water for irrigation and characterized by shallow water tables often face waterlogging issues[49]. Climate change, over extraction and exploitation of water resources, unwise use of water, population explosion, lack of policy implication for water resources management and political issues are all the main issues in managing and conserving water resources of Pakistan. As water is the main component for the irrigated agriculture and most of the country agriculture is irrigated, it is need of the time to manage the water resources of the country wisely to avoid the economy collapsed dependent on these resources.

Health implications related to water scarcity and degraded water quality

Water scarcity is not just a problem of diminishing natural resources; it is also a social phenomenon because it directly affects the general populace by leading to issues with food access, an increase in the demand for clean water, and health-related problems[50]. One of the most important risks to human health on a global basis is water pollution. Due to the exponential population expansion, fast industrialization, climate change and ineffective management of water resources, Pakistan's drinking water quality is steadily declining. The majority of Pakistanis are compelled to consume contaminated drinking water because they lack access to safe and healthy drinking water sources[51]. Due to poor water quality, sanitation and hygiene, water shortages and lack of sanitation facilities throughout the world, about 800 children die from diarrhea every day[52]. Pakistan is presently dealing with severe water shortages and pollution. The water crisis has now become a national mantra as the situation worsens. Ensuring access to safe drinking water remains a significant public health challenge in Pakistan, as the country battles with water quality and quantity difficulties[50]. The importance of water quality cannot be understated since it might influence public health in a certain area[53]. Due to the country's expanding population, water consumption has grown over the past several years[54]. Additionally, human activities like the increase of industrialization and agriculture have an impact on water quality[55]. Chemicals, microorganisms, industrial waste and poisonous compounds are some of the pollutants that make the country's drinking water dangerous[56]. Numerous waterborne diseases including skin allergies, renal failure, circulatory problems, gastrointestinal distress, cancer, blue baby syndrome, nervous system abnormalities and bone weakening are brought on by contaminated water[57]. Water is an essential resource, and everyone has the right to obtain affordable, clean drinking water. In Pakistan, the government's duty to guarantee safe drinking water for its citizens is compromised due to water shortages and pollution stemming from ineffective water management practices, thereby putting lives at risk[58]. High levels of arsenic in Pakistan's drinking water might have an impact on as many as 60 million people[59]. Community health surveys and studies indicate that in Pakistan, 40% of deaths and 50% of waterborne diseases are attributed to the consumption of poor-quality drinking water[60]. Additionally, in the previous 4 years, 1832 children are estimated to have passed away from water-borne illnesses and drought[61]. In Pakistan, methods of water disinfection such chlorination are either nonexistent or insufficient, and outside of a few areas, the public does not have access to clean water from water treatment facilities. The primary contributor to the nation's waterborne illness problem has been microbial and chemical pollution of drinking water[51]. The presence of inadequate and low-quality drinking water poses a significant public health concern. The discharge of dangerous industrial chemicals and untreated waste into waterways diminishes water quality and poses significant risks to human health.

Insufficient knowledge, obsolete treatments and apparatus, untrained workers, and inadequate inspections contribute to the problem. If this situation worsens, it could trigger a water crisis both nationally and internationally[62]. According to Ilyas et al.[63], only 20% of the population now has access to clean drinking water, with the remainder relying on tainted water that is mostly contaminated by sewage and to a lesser extent by pesticides, fertilizer, and industrial effluents.

Ground Water Salinization and Its Amplification with Climate Change

Extent of salinization in Pakistan

Growing salt levels in soil and water have become major worldwide problems that require context-specific solutions. An integrated strategy that takes into account the reasons, sources of salts, the level of salinization, and the socioeconomic environment is necessary to address salinization, which is marked by salt buildup[64]. Salinity affects 50% of irrigated lands and 20% of all cultivated land worldwide. In Pakistan, about 64% of agricultural output is lost due to salinity in salt affected soils, while 14% of irrigated area have been affected with varying levels of salinity[65]. Severe surface salinity affects almost 2.5 million hectares of irrigated land, with 3% of the afflicted areas in Punjab, 18% in Sindh, and 2% in NWFP. About 4% of Punjab, 10% of Sindh, and 2% of the NWFP are moderately saline areas. An area of around 4.5 million hectares of Pakistan's total 79.61 million hectares geographical area is thought to be impacted by salt stress[66]. Currently, varying degrees of salinity impact 21% of the total irrigated land, posing a danger to the sustainability of irrigated agriculture in the future, which is responsible for providing more than 90% of the nation's grain production. The Sindh province, where 22% of Pakistan's population resides, is the most devastated, with salinity affecting 43% of the region[41]. According to Qureshi[67], saline groundwater covers around 75% of Sindh and 17% of Punjab (TDS > 3000 ppm). The Indus Basin's tube wells, which pump roughly 70% water of the sodic or saline-sodic, are to blame for this degree of salinity. Saline groundwater is present in 16% of the Earth's total surface, or 24 million km^2, according to the global scale inventory created by the International Groundwater Resource Assessment Centre (IGRAC)[68].

Factors contributing to rising salinization

Soil salinization is caused by various natural as well as anthropogenic sources including weathering of parent material, rain and wind depositions, sea water intrusions etc. whereas anthropogenic activities are mainly irrigation with saline water, excess use of chemicals and poor management practices[69]. In Pakistan, groundwater was first extracted using a variety of techniques, including the open wells, Persian wheel, karezes and handpumps. However, throughout the 1960s, widespread tube well installation was started, which at initially helped to relieve waterlogging but ongoing expansion led to a high reliance on pumping water by farmers for their crops. The vast of tube wells pumped water of poor quality, which led to salt accumulation in soils and had an impact on agricultural fields. The deep unconfined aquifer underlying the Indus plain is composed of the alluvium deposited during the late Tertiary era. The aquifer has a thickness of more than 300 m and is heterogeneous and strongly anisotropic. There is hardly much natural drainage in the area[70]. Salinization of the soil and groundwater are two linked phenomena. Asia is the continent with the largest reported prevalence of saline soils, according to the scenario of the distribution of soil salinization by continent[71]. Various natural processes and anthropogenic activities have been examined in earlier research as the causes of groundwater salinization in coastal and inland locations[72]. The disturbance of naturally occurring salts in the stratigraphy, triggered by activities such as land clearing, well construction, and over-extraction, leads to the mobilization of these salts. This, in turn, results in the forthcoming rise of brines excessive use of fertilizers and irrigation runoff both contribute to processes affecting inland areas. However, Seawater intrusion, over-pumping groundwater, limited recharge, tidal infiltration, and inadequate land-water management lead to saline buildup in coastal groundwater[73]. The aquatic and terrestrial ecosystems are negatively impacted by groundwater contamination, which has a serious negative impact on human health. Due to a lack of clean water and the use of polluted water, millions of people perish every year. The quality of groundwater is under serious danger from manmade and natural causes. The main factors attributable to anthropogenic activity are the use of herbicides, insecticides, and fertilizers; waste from mining operations; industrial effluents; over-pumping; and disruptions in the river and canal networks. Natural processes also involve the breakdown of rocks and evaporation, especially in shallow aquifers where these processes cause the water table to rise, salt to accumulate, and seawater intrusion. It is imperative to concentrate on groundwater management and prevention against further degradation in light of all the negative repercussions[74].

The impact of salinization on agricultural productivity

About 500 million people worldwide are negatively impacted by the salinization of soils freshwater, especially in low-lying river deltas. Along with other salt-related consequences on human health that have gotten less attention and need for more investigation, the effects of salinity on water and food security, agricultural livelihoods, and other factors are extensively studied[75]. One or more of the functions of soil are compromised or lost as a result of secondary soil salinization, which is commonly defined as the buildup of water-soluble salts in the soil as a result of human activity. Particularly in arid and semi-arid parts of the world, soil salinization, along with its natural or primary form, appears as a significant environmental constraint limiting soil productivity, food security and agricultural sustainability[76]. Agricultural production is decreased by salinization when salt concentrations in the root zone surpass the crop's tolerance limits, inhibiting plant development[77]. Certain plants' germination rates, shoot and root lengths, and crop production all suffer when salt is present in the root zone. More recently, it has been shown that salinity conditions in soils affect crop yields through affecting soil microorganisms, with a clear detrimental impact on respiration[78]. Reduced respiration has an impact on the breakdown processes and nutrient cycling of microorganisms, which lowers crop production. While salinization-related decreased agricultural yields are widespread in low-lying deltas[79]. The two main ways that salinity affects plants are ionic toxicity (e.g., nutrient imbalance, hormonal imbalance, oxidative stress and increased susceptibility to pathogens) and osmotic stress, which initially inhibits plant growth by reducing the capacity of roots to absorb water[80]. Salinity stress has posed a deleterious effect on agricultural crop productivity hence compromising the food security worldwide. Salinization of groundwater induced by various anthropogenic activities and then irrigation with salinized groundwater increase the salt concentration in upper layer of soil leading to salinity development and soil properties disfunction. This affects the crop production hence food security of the country.

Adaptation and Mitigation Measures

Changes in water supplies are mostly caused by climate change, which also adds another stressor by impacting external causes. Water resources management can have an influence on climate change mitigation or adaptation policies and practices, and vice versa. A greater balance between mitigation and adaptation would help public policy, which has been dominated by mitigation thus far. Water is a measure of the repercussions of climate change, whereas carbon is a measure of its anthropogenic origins. The international community must strike a balance between spending for today's climate variability issues to avoid losses from droughts and floods and investing for tomorrow's expected challenges of increased climate variability and global warming.

Water resource management

The management of a sustainable water supply is essential for both human well-being and the health of the biological ecosystem[81]. Conservation of water resources is defined as an activity that includes instream flow rights, resource security and habitat conservation. To guarantee the long-term conservation of the available water resources and aquatic ecosystems, it entails the gradual decrease of pollution discharge, emissions, and losses[82]. Adoption of water resources management strategies that aim to strike a balance between their conservation and sustainable use is warranted given the susceptibility of both groundwater and surface water resources to pollution and overexploitation[83]. Groundwater supplies are affected by climate change; overpopulated regions have water scarcity problems, increasing temperatures, etc. It is vital to close the gap between water supply and demand through effective irrigation systems in order to address such environmental problems. The best management practices for sustainable water management include conjunctive use of groundwater and surface water, farmer training, government policies, public awareness of water conservation, institutional concerns and international collaboration[84]. Utilizing brackish or saline water, preserving groundwater levels, reducing secondary soil salinization and waterlogging, ensuring consistent water availability and increasing crop output are only a few benefits of conjunctive water usage[85]. Remote sensing (RS) technology has advanced quickly in recent years, enabling researchers to quickly gather sufficient data on hydrological state variables such as temperature, precipitation, water levels, soil moisture, flood extent, evapotranspiration, river discharge, flow velocity and land water storage over regional and global areas, particularly in remote areas where measurements are impractical or can only be made under extremely challenging conditions at a high cost. In order to simulate and evaluate water resources and water-related issues, this remote sensing data could serve as the input files for integrated hydrodynamics, hydrological, or hydrometeorological models. This would significantly aid in the more effective water resources management and development of hydrological models[86]. To oversee different water usage and fair pricing, the water regulatory authority should be turned into a statutory organization. In order to establish a volumetric pricing system in well and tube well irrigated regions as well as for surface irrigation, there must be a significant financial investment in the infrastructure for irrigation water delivery as well as the creation of operating plans. It is necessary to rationalize and simplify the existing system of revenue assessment and collection until a well-developed volumetric system is put into use. It is necessary to have an adequate electricity pricing strategy for rural regions and to charge a ground water conservation levy that covers the irrigation industry[87]. For the management and sustainable use of groundwater resources, Government of Pakistan has passed a number of laws and regulations, but so far with little success. The main causes of inadequate groundwater management, in addition to a lack of respect for the law, are the absence of necessary data and information, a lack of political will, and institutional structures. Pakistan must reevaluate its plans to make them more flexible to local circumstances. An appealing solution may be an integrated strategy to managing water resources that brings together appropriate government agencies, political leadership, academic institutions and other stakeholders[41]. To prevent major effects like famine, drought, loss of biodiversity and internal migration, the government has to focus urgently on water conservation and reducing water pollution[61]. The quality of rivers' water has been negatively impacted by the development in city density along river banks, which has resulted in fresh water abstraction. Consequently, for a sustainable water supply, water quality, water balance and water statistics are crucial. In addition, as large land is more productive than small land, the government should introduce sound land reforms. Categorically, effective and efficient strategies for the agriculture sector will improve the effectiveness of the nation's water management. Water policy aims to increase water efficiency while supporting the sustainable use of water resources[50]. Therefore, it is need of the time to wisely use and manage the water resources of country at public and government level to secure this precious resource for future generations.

Combating salinization

Salinization of groundwater due to anthropogenic and natural processes can raise salt levels above permissible limits for certain purposes or conditions. Groundwater salinization affects around 16% of the planet's surface area, which might have serious negative economic, social and environmental effects[88]. Although traditional reverse osmosis (RO) desalination can improve the quality of groundwater for drinking, it has drawbacks such uncontrolled brine release and faster groundwater depletion. A novel method that combines forward osmosis (FO), reverse osmosis (RO), and halophyte culture, in which the concentration of the RO reject brine used to irrigate Salicornia or Sarcocornia is ideally adjusted by FO. The FO also reuses wastewater, which lowers the volume of wastewater discharge and groundwater extraction[89]. In arid and semi-arid climates, irrigation-induced salinity, also known as dryland salinity, maybe mitigated by properly disposing of saline groundwater, building drainage systems, using mulch for crop residue, planting salt-tolerant species such as halophytes (deep-rooted trees use the groundwater and create bio-drainage), and applying molecular methods to enhance salinity[90]. Irrigation with salinized groundwater leads to the soil salinity development. Salinized groundwater can be desalinized for the drinking purpose and other purpose use but it needs to develop the cheaper techniques to desalinize groundwater. Whereas soil salinity can be tackled by the chemical, physical and biological methods as well. Saline agriculture and bio-saline agriculture are widely recommended for salt affected soils to generate good revenue from these problematic soils.

Climate Smart Agriculture

Climate change (CC) alters agricultural productivity and food systems, causing vulnerability and uncertainty threats among farmer community and decision makers[91]. It is indeed doubtless that climate change exerts notable challenges to worldwide food security, and this phenomenon has been envisaged to exacerbate in the coming years owing to livelihood pressure i.e., population rise, urbanization, economic development and increased prevalence of different dangers such as drought, enhanced warmth and floods. By 2050, it is predicted that approximately 9 billion people's living conditions will deteriorate, where poverty and hunger will be the predominant factors causing it substantially difficult to place food on the table[92,93]. As a result, numerous international organizations and institutes are collaborating with the Food and Agriculture Organization (FAO) and The World Bank will design agricultural systems to boost food production at all scales, from the regional to the global. Conclusively, a global shift from conventional agriculture to climate smart agriculture (CSA) has been encouraged by multiple institutions comprising stake holders i.e., research, investments, policy makers as well as along public, private and civil society[94,95].

Since, the definition of CSA is differentiated in technical and scientific publications, several definitions have been proposed by different sources such as agricultural scholars, organizations dealing with climate change, and several other research institutes. In this regard, Adesipo et al.[96] set together a number of keywords characterizing the main aims of CSA are transformation, knowledge, new technology, productivity, food security, sustainability, capacity building, vulnerability and emission reductions and profit[97]. They comprehensively defined CSA in terms of a transformative and sustained form of agriculture that attributes to enhance agricultural productivity in food system, based on key components of climate change i.e., mitigation, resilience, and adaptation along with smart and modern technological knowledge hence, enhancing profit and minimizing vulnerability via the reduction of greenhouse gas (GHG) emissions. Similarly, Engel and Muller[98] defined CSA as a precise and sustainable approach enhancing agricultural production via following different adaptation techniques while favoring adaptability to climate change and avoiding greenhouse gas emissions. Campbell defined CSA in terms of methods transforming agricultural systems for enhancing production and food security under climate change scenario. The CSA approach, as literature depicts, promotes the incorporation of climate change in considerations into the planning and implementation of sustained agricultural techniques, hence identifying trade-offs and synergies in between the three parts of CSA collectively known as food security, adaptation and mitigation, thereby, supporting decision making and CC related policy[99]. In particular, CSA supports effort to promote food and nutrition security thereby, following essential mitigation and adaptation strategies on the basis of its definition[94]. It supplies various enabling tools where several practices and technologies can be assessed concerning their findings particularly, food security and national development objectives under the climate change scenario. Furthermore, CSA incorporates the accumulated expertise in sustained agricultural development and participatory community-driven methods[99], it regards sustainable intensification as a cornerstone for enhancing productivity and income, alongside the implementation of existing measures to protect agricultural land. It also emphasizes the efficient utilization of poor agricultural system such as agroecology, conservation agriculture, small-scale irrigation, aquaculture sectors, ecosystem services, agroforestry system, nutrient management, soil/water conservation, landscape approaches, livestock, integrated crops, forestry and grassland management and best management practices involving zero tillage and breeds for enhancing food production and mitigation and adaptation measures[100]. Many of the documented CSA practices have been adapted in various countries of Africa including the purpose of combined fertility of soil management framework (integrated applications of organic and mineral fertilizers), for enhancing maize yield in Africa[101], Nigeria[102], Uganda[103] and Kenya[104]. Recently, CSA has emerged as a fundamental notion for most worldly organizations amidst the climate change, agriculture and development nexus. It has also been considered as a necessary tool for attaining sustainable development goals (SDGs)[105]. In short, CSA plays a significant role for mostly the rural farmers, who are at the blink of extreme weather and other climatic conditions. Various aspects of CSA research involving the joint venture of three pillars of CSA have been frequently reported in literature. Findings of Chandra et al.[100] regarding CSA was referred to as comparatively new with its main objectives emphasizing at framework description. CSA relies on the application of already available tools and devices related to conventional agriculture along with new and novel agriculture. however, these new techniques will disseminate within the whole agriculture. That is why, CSA is interpreted as smart agriculture or precision agriculture. however, the difference lies in their approach. Precision agriculture (PA) basically aims at input optimization[106] whereas, smart agriculture (SA in contrast, optimizes entire farming system[107,108]. CSA falls in smart agriculture category where further efforts are ensured besides the farming optimization. Broad definition of CSA involves the combination of impacts of various agronomic/farming practices along with the improvements of agricultural inputs such as seeds, water, pesticides etc.[109]. The CSA is often joined by sustainable intensification, which reflects intensive production in a more sustainable way[110].

Policy Framework and Institutional Structure for Water Resource Management

Since 2001, the institutional framework for managing and regulating Pakistan's water resources has been transferred to the province and then local levels of government. The disparity in per capita water usage between rural and urban areas is one of Pakistan's major water management concerns. The public sector underinvests in water supply and sanitation[113]. The National Water Policy (NWP) was released by the Ministry of Water Resources in April 2018 in order to address the problems with Pakistan's water resource management and to project the major goals to be accomplished by 2030. It presented the idea of "producing more crop per drop" and emphasized more sustainably using water resources[111]. The National Water Policy 2018 serves to formulate sustainable approaches to water resource management, rooted in the principles of Integrated Water Resource Management, guiding the development of plans and strategies. To promote universal access to clean drinking water and tackle the nation's food security challenges, the NWP aims to enhance both the quantity and quality of water resources in a sustainable method. It also recognizes the significance of provincial involvement and encourages them to develop their plans and strategies for water resource management. Implementing water management programs is now a provincial responsibility thanks to Pakistan's constitution's 18th amendment[112]. A bilateral water distribution agreement known as the "Indus Water Treaty (IWT)" regulates the sharing of water resources between Pakistan and India[32]. Water management and governance are the responsibility of a variety of institutional players in the provinces of Punjab and Khyber Pakhtunkhwa (KP). In rural and, in certain cases, metropolitan regions, the provincial Public Health Engineering Departments (PHEDs) construct drinking water supply projects. Water and sanitation services in urban areas are the responsibility of Tehsil Municipal Authorities (TMAs), however some cities have given this duty to Water and Sanitation Agencies (WASAs), which are also in charge of operation and maintenance. A significant distinction between the provinces of KP and Punjab is that, following construction, rural water supply systems in the Punjab are handed over to community-based organizations (CBOs) for operation and maintenance, but in KP, operation and maintenance are the responsibility of the PHED. In the two provinces, non-governmental organizations (NGOs) like WaterAid and Action Against Hunger also put in water supply and sanitation systems, frequently establishing regional water management organizations and governance frameworks[113]. According to The State Bank of Pakistan (2017), the challenge regarding domestic and industrial water supply is not primarily about water scarcity, but rather the complexities within the water management and governance system. This is marked by the presence of numerous authorities, overlapping responsibilities, and redundant efforts. In terms of both human resources and management systems, the TMAs and the WASAs both lack capacity[114].

Case Studies from Pakistan

Evaluation of groundwater quality of Punjab, Pakistan for irrigation using geospatial techniques and GIS Awais et al.[115] conducted a study in Punjab, Pakistan. The goal of the current study was to characterize groundwater quality zones for irrigation applications while also evaluating the spatiotemporal quality of groundwater in the Lower Chenab Canal (LCC) east sector. The chemical composition of groundwater samples from 289 observation wells was examined. To represent spatial variation and reduce estimation error in the data, a geostatistical method utilizing kriging interpolation was used. Groundwater quality maps were generated for both pre-monsoon and post-monsoon seasons by utilizing three key water quality parameters: electrical conductivity (EC), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC). The most appropriate semi-variogram models were found and cross-validated in order to characterize the spatial autocorrelation. For EC and RSC, the exponential model performed best, but the spherical model performed best for SAR. A composite water quality map was produced using overlay analysis, and it shows that 40% of the LCC area has high groundwater quality for irrigation, 49% has marginal quality, and 10% is unsuitable during the pre-monsoon and post-monsoon seasons. Only 3.75% of the groundwater in the Paccadala subdivision is excellent, compared to 100% in the Sultanpur irrigation subdivision. The study's findings may serve as a reference for planners and policymakers as they develop region-specific plans for sustainable groundwater usage.

Pakistan's Agro-Ecological Zones

Pakistan was classified into ten separate zones in an Agro Ecological zones (AEZ) exercise conducted by the Pakistan Agricultural Research Council (PARC) in 1980. The zones were determined according to physiography, climate, land utilization, and water accessibility. Punjab was further split into four main categories and eleven subzones. This approach yielded useful knowledge, which has since been put to use. However, taking into account the nation's water and land resources' fast fluctuations, as well as the climate, we need adaptive techniques to sustain and improve the shift during the previous 20 years in a sustainable manner to secure the security of the nation's food supply. Weather is a primary factor that has a significant impact on the health of the soil, plants, and water supplies. Based on the most recent data on natural resources, climate conditions, and agricultural markets trends, a team of scientists and researchers from the University of Agriculture Faisalabad and the University of Arid Agriculture Rawalpindi worked with FAO and the Government of Punjab Agriculture Department to delineate AEZs of Punjab. The incorporation of high-resolution datasets was essential for defining new AEZs at a 100-meter scale, specifically considering the country's fragmented landholdings, a departure from earlier AEZ assessments conducted in 1980, when the AEZ for conventional crops was determined only by using regional climatic data. The amount and quality of all accessible water, (including groundwater and surface water) the makeup and texture of the soil, as well as its organic matter content and chemical composition, the characteristics of the land use, the topography, the crop standards for more than 60 current and future crops in Punjab, and the economic suitability zones for the produce. A huge potential for crop diversification as well as sustainably increased agricultural output was highlighted by the new AEZs. The effective implementation of cropping systems and cultivation of crops within a specific area relies significantly on an understanding of the agro-climatic conditions and the resources accessible for agricultural production, thoroughly examining agro-ecological zones can enhance the profitability of smallholder farming and boost overall agricultural efficiency.

Conclusion

Pakistan is facing several issues caused by climate change and groundwater salinization and quality deterioration are one of those issues. Drinking inferior quality ground water, as groundwater serves as the primary drinking water source for the people of Pakistan, has given rise to various health problems in children and adult. Irrigation with low quality and salinized groundwater has a negative impact on soil as well as other natural resources compromising the agricultural production and economy of the country. Pakistan is predicted to be a water scarce country in near future. Water scarcity and water quality deterioration due to over exploitation and unwise use of water resources will lead to collapse of society and economy added by worse climatic events. Although, policies exist at national level to fight climate change and to conserve water resources but implementation of these policies is not well observed. Different strategies can be adopted to minimize the negative impacts of climate change on water resources quality deterioration and groundwater salinization along with policy implementation. Climate smart agriculture and continuous monitoring of groundwater extraction and quality may prove helpful for minimizing climate change impacts on water resources and reducing groundwater salinization. Therefore, it is recommended that climate smart agricultural practices and judicious use of groundwater resources should be adopted at farmer level by conducting extensive research programs to find alternatives and spreading awareness through mass media.

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