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REVIEW ARTICLE

How does the climate change effect on hydropower potential, freshwater fisheries, and hydrological response of snow on water availability?

Shan-e-hyder Soomro[1,3,4] · Abdul Razzaque Soomro[2] · Sahar Batool[2] · Jiali Guo[1,3] · Yinghai Li[1,3] · Yanqin Bai[3] · Caihong Hu[4] · Muhammad Tayyab[3] · Zhiqiang Zeng[1] · Ao Li[3] · Yao Zhen[3] · Kang Rui[3] · Aamir Hameed[3] · Yuanyang Wang[3]

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Abstract
Globally there is already a lot of pressure on water resources because of climate change, economic development, as well as an increasing global populace. Many rivers originate in the mountains, where snowfall fluctuations and the global climate's inherent unpredictability affect the hydrological processes. Climate change sensitivity has been recognized in recent years and would affect hydropower, such as humidity, cloudiness, and precipitation, that are considered; global warming emerges as one of the most important contributors to climate change. The Yangtze River supports rich biodiversity and provides important ecosystem services for human survival and development. In addition, climate changes, particularly short-term and long-term precipitation and temperature fluctuations, influence the snow regime and the hydrological development of river flow response at the basin and sub-basin scales. More precise this review focused to understand the hydropower potential, freshwater fisheries, and hydrological response of snow dynamics in snow-dominated basins.

Keywords Climate change · Hydropower potential · Freshwater fisheries · Water resources availability · Snow

Introduction

Global warming emerges as one of the most important contributors to climate change (Abbass et al. 2022). Its effects on hydropower production and water supply are substantial. As the global average temperature rises, it changes the way rain falls around the world (Wasti et al. 2022). Earlier spring snowmelt is one consequence of these changes, which has direct consequences on hydropower production. Hydropower is threatened by the global warming that has been widely proven. Low-capacity, high-elevation hydropower reservoirs are particularly vulnerable to temperature fluctuations. When temperatures rise, snow melts faster, and seasonal rainstorms tend to be heavier, also it comes to reducing carbon emissions and increasing power grid flexibility; hydropower is indispensable (Johansen 2023; Han et al. 2023). Due to repeated droughts in hydropower-rich countries like China, Brazil, Turkey, Canada, and USA hydrocapacity utilization was lower than typical in 2021, marking the first time in two decades that hydropower generation had fallen (Cuartas et al. 2022). Capacity increases in 2021 reaching 35 GW and China holding 66% of the capacity growth are positive signs for the future of hydropower despite the slow development of hydropower output due to persistent droughts (Demetriou and Hadjistassou 2021). China occupies the eastern region of Eurasia, and its geography resembles a ladder that slopes gently into the ocean from west to east. The terrain helps generate rain, and it also serves as a transportation and economic connector between eastern and western regions. There is a lot of hydropower because rivers generally flow from west to east with a steep decline. Southwest rivers have great potential for hydropower generation because of their high runoff volumes and steep gradients. Additionally, runoffs and significant drops are abundant in rivers draining the central south, the southeast, and the northeast. However,

Shan-e-hyder Soomro, Jiali Guo and Yinghai Li have contributed equally to this work.

1st corresponding author: Yinghai Li, 2nd corresponding author: Jiali Guo, and 3rd corresponding author: Shan-e-hyder Soomro.

Extended author information available on the last page of the article

in the northern and eastern plains, hydropower is often not attractive due to low river flows or a lack of falls. Rivers have been crucial to human movement, settlement, agriculture, forestry, fisheries, industrialization, and commerce throughout history (Brierley and Brierley 2020). The ecosystem of the river provides a variety of services that are necessary for the well-being, health, livelihood, and survival of humans (Fu et al. 2022; Zhang et al. 2023). It is now a concern on a worldwide scale that the rate at which biodiversity is dwindling, as well as the effects this has on the activities and services provided by ecosystems (Shin et al. 2022). The majority of the world's major river systems are confronted with significant difficulties regarding the maintenance of fisheries and the preservation of biodiversity (Reid et al. 2019). Floodplains in Europe are becoming degraded as a result of heavy human use, such as agriculture. The Yangtze River Basin, which consists of the main river and its numerous tributaries, is the third biggest river basin in the world (Fig. 1). Eastern, middle, and western China are all represented, with a total of 19 provinces, municipalities, and autonomous regions included, and it drains a total of 1,810,000 km^2 of China (Sun et al. 2023). Rich biodiversity is supported by its geological history, ecological circumstances, and human activity (Ding et al. 2023) that provides China's ecosystems with enormous benefits (Li et al. 2023a). There are around 400 different fish species in the watershed, and over half of them are indigenous (Feng 2023). As of 40% of China's GDP is produced in the Yangtze River Basin, and the basin provides sustenance for one-third of China's total population (Kang et al. 2023). Yet, the region's biodiversity has suffered greatly as a result of extensive industrialization (Chen et al. 2023) the aquatic environment of the Yangtze River could collapse without preventative steps. The world's mountainous areas are the basic source of surface water and groundwater replenishment (Zhang et al. 2022b). Interactions between the climatic, cryospheric, and hydrological systems establish the water balance in mountainous places (Tang et al. 2023). The hydrologic processes in mountainous regions under the influence of the climate significantly from those found in other cryospheric regions and dry or wet climates, because of orographic enhanced precipitation, temperature variability, and partitioning of rain and snow with elevation, as well as the high seasonal variability of the snow cover (You et al. 2020; Yin et al. 2023b). The occurrence of snowfall from the mountain zone can be observed during the spring and summer seasons, when precipitation is infrequent. As a result, this particular phenomenon serves as a significant source of water for numerous individuals residing in the neighboring lowlands. Most of this winter's precipitation falls as snow in the highest elevation locations, while mixed precipitation falls in the mid-elevation areas (Notarnicola 2020). Agriculture is a major source of revenue and employment in virtually these areas, and snowfall delivers runoff during the crop-growing season when irrigation is most needed. However, the pressures of a growing population, more irrigation, and climate change are putting a strain on water resources (Riaz et al. 2020; Liu et al. 2023). According to the initial intergovernmental panel on climate change (IPCC) assessments, regions have been designated as climate change "hot zones." New data also suggest that the pace of air warming rises with altitude, raising concerns about climate change in regions. Because snow accumulation and ablation are extremely sensitive to air temperature, the impact of atmospheric warming is predicted to be significant in snow-dominated watersheds (Barnett et al. 2005). The academic research on climate hydrology pays very little attention to mountain hydrology, with notable exceptions. Meteorological forcing (energy and mass fluxes) and land surface physiography influence snow dynamics (topography and vegetation) (Mazzotti et al. 2023). Indeed, climate change effect on hydropower potential, freshwater fisheries, and hydrological response of snow on water availability directly impact on countries' economic development. Therefore, this review addresses this need by reviewing the appraisal of climatic changes in Asia and Europe.

Climate change effect on hydropower potential

The expeditious progression of economic globalization has resulted in an innovative energy transformation that encompasses the gradual reduction in the utilization of conventional primary energy sources, such as coal, oil, and natural gas. A sustainable and eco-friendly energy framework should be implemented in a progressive manner to gradually supplant the existing energy framework, which engenders significant environmental degradation. Environmental issues arising from the utilization of fossil fuels, including acid rain, the greenhouse effect, and ozone depletion, are substantial determinants that impede the advancement of the worldwide economy. As a result, the attention of governments, the scientific community, and the general populace has been captured. Consequently, it is imperative to establish a novel energy generation framework. China, being the most populous developing nation, plays a pivotal and indispensable role in the alteration of the worldwide energy configuration. Coal serves as the primary means to meet the energy demands of China; nevertheless, its availability demonstrates an annual decrease, with the present level of 64% being acknowledged as the most minimal in the nation's past. The utilization of non-fossil fuel and sustainable energy has experienced a substantial growth, whereby

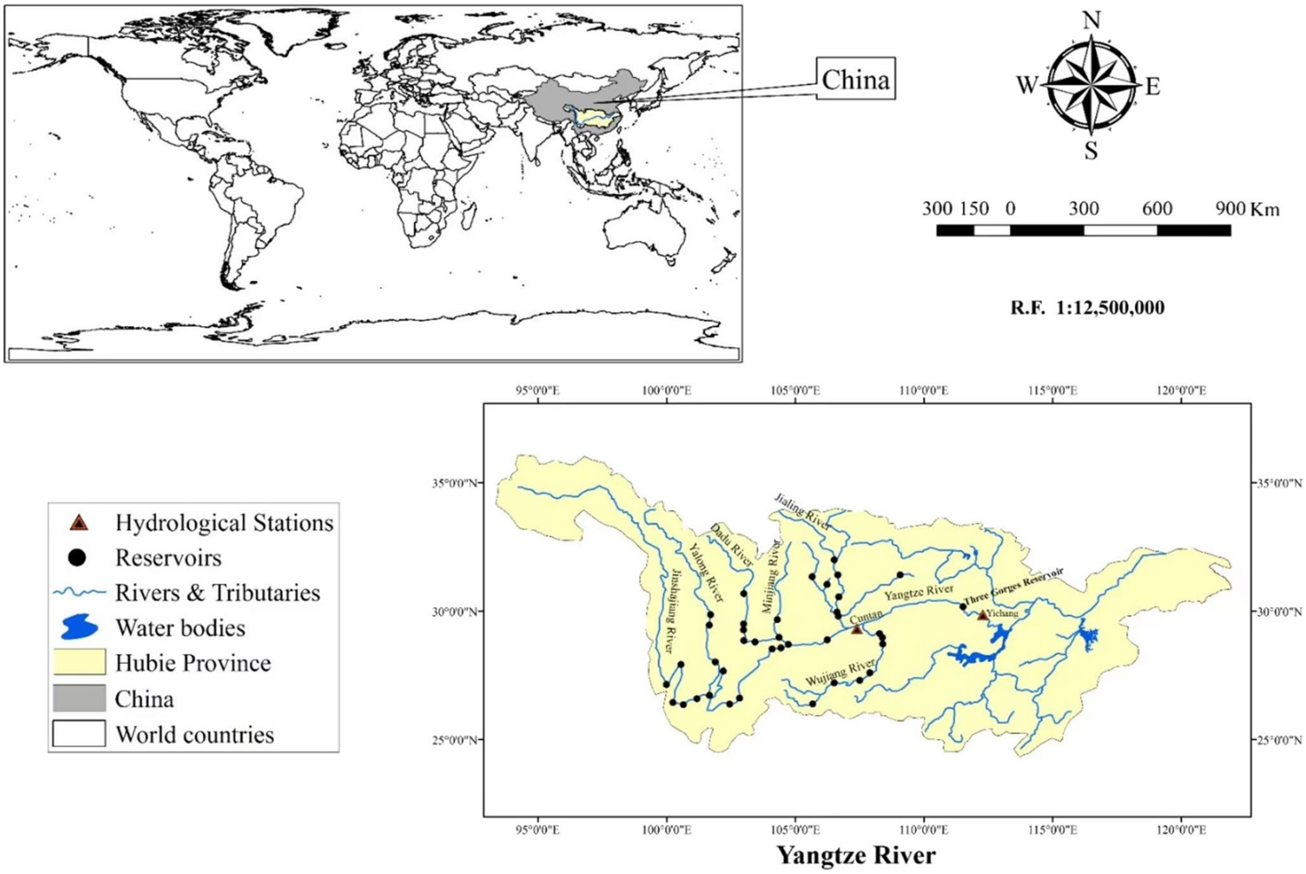


Fig. 1 The great Yangtze River of China (Soomro et al. 2023)

the proportion of renewable energy in the worldwide aggregate has escalated from 2 to 7% over the span of a decade. Hydropower assumes a pivotal function in facilitating the advancement of China's electric power sector (Zhu et al. 2022). To make the most of their limited resources, states must prioritize sustainable development, environmental protection, and the efficiency of energy structures. In addition to facilitating irrigation and flood management, a full-fledged hydropower project also includes ancillary projects that can boost local transportation and economic growth. After constructing a large hydropower station, it is difficult to resume basic production because the plant's operation will alter the local climate and the surplus electricity generated during the rainy season would be wasted in transmission. A multitude of studies, encompassing both domestic and international contexts, have been undertaken to investigate the subject of hydropower. Schulz and Saklani (2021) explained the purpose of this discussion is to provide a comprehensive analysis of the importance of hydropower development in Nepal, while also highlighting the relevant issues that require thoughtful deliberation in the country's hydropower development endeavors. Manzano-Agugliaro et al. (2017) provide a concise overview of the historical progression of hydropower development in Austria, with a specific focus on the energy structure and consumption patterns within the country. The objective is to underscore the significant role that water and electricity play in Austria's socio-economic fabric. It shows the political, economic, and ecological difficulties of hydropower in the future. Many academics have studied China's hydropower expansion, including (Brown et al. 2008; Liu et al. 2016; Yin et al. 2023c) emphasized that the technology is more developed, is used for power generation of high-quality energy, and has a higher energy conversion density and efficiency than other renewable energy sources such as wind energy, solar energy, biomass, and other renewable energy sources (Panwar et al. 2011). Wang et al. (2020) worry that things will only get worse if China's coal-dominated energy sector keeps producing more carbon emissions, and that we would not be able to achieve our global emission reduction objectives unless we aggressively push low-carbon energy, especially hydropower. In this part, the author details about the hydropower development in China, including the famous Three Gorges Project and the pumped storage power station, as well as the current limitations on hydropower development in China. It has elucidated the trajectory of development, identified the problems encountered, and assessed the future prospects of small-scale hydropower in China. In this part, there is a comprehensive analysis of hydropower development and situation of hydropower development in China.

Hydropower growth

The commencement of hydropower growth in China took place at a relatively advanced stage in comparison with other countries. The first hydroelectric facility in the world was established by France in 1878. The first hydroelectric station in the USA was successfully constructed on the Fawkes River in Wisconsin in 1882. Europe's first commercial hydropower station, the Tewoly dam, was built in Italy in 1885. It is safe to say that many countries started paying attention to hydropower in the early 1890s, and not just in North America and Europe. China's first hydropower project, Shillong Dam, was erected in 1910 on the outskirts of Kunming in Yunnan Province. The installed capacity of this hydroelectric plant stands at 6000 kW following a series of seven upgrades in the year 1958 (Sun 2020). Currently, the Shillong Dam Hydropower Station remains operational. The hydropower station incorporated cutting-edge international technology, equipment, and managerial practices, while also establishing China's inaugural hydropower team. China's hydropower sector witnessed tremendous expansion until the advent of the "new China." A significant milestone in history was achieved by the construction of the Xin'An River Hydropower Station situated on the upper segment of the Qian Tang River. The hydroelectric station listed above is a noteworthy achievement in China's hydropower sector, since it serves as the country's first major station that demonstrates domestic design, equipment, and construction methods. At the same time, major hydroelectric projects were launched along the Xinfeng River in Guangdong. For context, the Hunan Zhexi dam was more than a hundred meters in height. Gutian, Yunnan, Sichuan Yili River, Guizhou Longxi River, Beijing Maotiao River, and Yongding River have all begun work on small- and medium-sized cascade reservoirs on the Fujian River. The Fujian Gutian Creek Station holds the distinction of being the inaugural cascade hydropower station and the first underground powerhouse within the realm of hydropower stations in contemporary China (Zeng et al. 2017). The station is outfitted with two sets of 6000 kW turbines and four turbine generator units, consisting of 12,000 kW and 500 W units from Taiwan. At the same time that the Xin'An River Hydropower Station began operations, the Sanmenxia Hydropower Station on the Yellow River began operations. Training staff in China's hydropower industry benefited from lessons learned during the Sanmenxia Hydropower Station's development. The station's operational history has played a significant role in fostering a methodical and scientifically oriented approach to the advancement of hydropower in China. The ongoing advancement of socialism has enabled the incorporation of hydropower station construction into the policy formulation agenda. The Liujiaxia Hydropower Station, a notable hydroelectric power plant and the first establishment in China with a capacity exceeding one million kilowatts, was initiated during the implementation of the "First Five-Year Plan" in China. The policy that was put forth during the period of hydropower development played a significant impact in facilitating the adoption and utilization of this particular energy source. Additionally, it is worth noting that the Three Gorges Dam (Fig. 2), initiated in 1994, boasts several remarkable features, including the largest set of five locks worldwide, the highest concrete arch RCC dam, and the highest CFRD. The hydropower industry has made notable advancements in the production of large-scale hydropower machinery and the attainment of substantial installed capacity. These achievements have been facilitated by several methods, including information transfer, digestion and absorption, and independent innovation. Moreover, the incorporation of the innovative technology has resulted in notable progressions in the field of hydropower engineering, as seen by the widespread adoption of cutting-edge materials in the development of hydroelectric infrastructure.

China's use of hydropower has rapidly expanded in the modern era. The passion for the development of hydropower in all its forms is being fully mobilized as countries continue to encourage power system reform (Fig. 3). As of 2004, China's hydroelectric system had the biggest installed capacity of any country at more than 100,000 MW. While the Three Gorges Hydropower Station nears completion, work has begun on other large hydropower plants. In 2010, China's hydropower capacity surpassed 200 million kilowatts, a new record. The installed capacity of China's hydropower sector surpassed 300,000 MW in 2015. China already has the largest hydropower installed capacity and is rapidly becoming the world leader in hydropower innovation and development.

Hydropower resources in China

Unlike non-renewable energy sources like coal, oil, and natural gas, hydropower resources rely on the potential and kinetic energies supplied by rivers and lakes. There is a strong correlation between rivers, evaporation, and precipitation, all of which contribute to hydropower reserves. Because of variations in rivers, evaporation, precipitation, and other factors, hydropower supplies are not uniformly distributed over the world. According to the World Energy Council (Elavarasan 2019), renewable energy resources can be classified into three distinct categories based on statistical data pertaining to hydropower resources. These categories include theoretical reserves, potential for technological advancements, and prospects for economic development.

Fig. 2 Three gorges dam (https://news.cgtn.com/news/2023-09-04/Three-Gorges-Dam-ship-locks-log-record-monthly-cargo-throughput-1mPzDGYCwow/index.html)

The assessment of hydropower potential in rivers involves the utilization of both average river runoff and river descent measurements to ascertain the overall hydropower capacity of rivers (Kuriqi et al. 2019). The completion of the change in mechanical and electrical energy is hindered by the magnitude of losses incurred. Consequently, it is possible to advance the technology to operate at a level that is lower than the available hydroelectric resources. Technology plays a pivotal role in the use of hydroelectric resources, providing significant benefits like as cost efficiency and less loss due to flooding. According to statistical data, the implementation of hydropower station projects demonstrates both technical feasibility and economic viability, as supported by the existing water resources. China possesses a considerable abundance of hydroelectric resources. Nevertheless, it is worth noting that the allocation of hydropower resources in China exhibits an inherent imbalance when considering the contextual factors at play. Hence, the usage of suitable treatment techniques is vital for promoting the progress and efficient utilization of water resources. In Figure 4 the data presented illustrate the statistical information pertaining to the distribution of hydropower resources across different regions within China. The southwestern portion of the country is recognized as the primary geographical area housing significant hydropower resources, encompassing both practical and theoretical reserves. In accordance with prevailing perspectives, the prioritization of technology advancement or the level of economic growth can be deemed paramount within a given nation. Theoretical reserves in the northwest region are placed second, suggesting a notable disparity in quantity when compared to the reserves in the southwest region. When opposed to the Northwest, the Central-South region (which includes Central China and Southern China) has less potential for hydroelectric resources. It is worth noting, nevertheless, that the central-south region is technically and economically ahead of the northwest region. Regional differences in technical and economic growth are subject to variation as a result of several causes, including the utilization of hydroelectric resources, enhancements in topographical conditions, advancements in technology, economic conditions, and contextual constraints.

The development of hydropower in China has a history spanning over a century, although it had significant advancements and achievements particularly after the year 1950. Nevertheless, China has not yet presented comprehensive data regarding the extent to which it has exploited and utilized its hydroelectric resources. The degree of development and utilization of hydropower resources can be assessed globally by examining the percentage of yearly electricity generation attributed to hydropower technology. Hydropower resources in China can be more accurately represented using this way. The hydroelectric plant in the

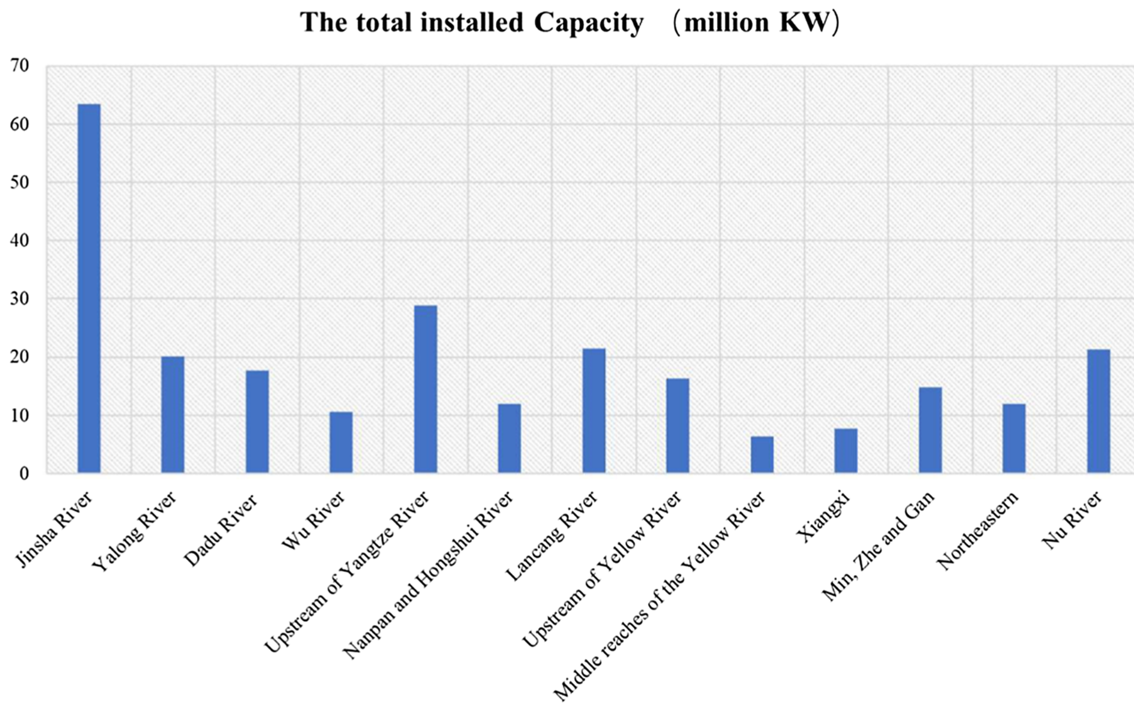


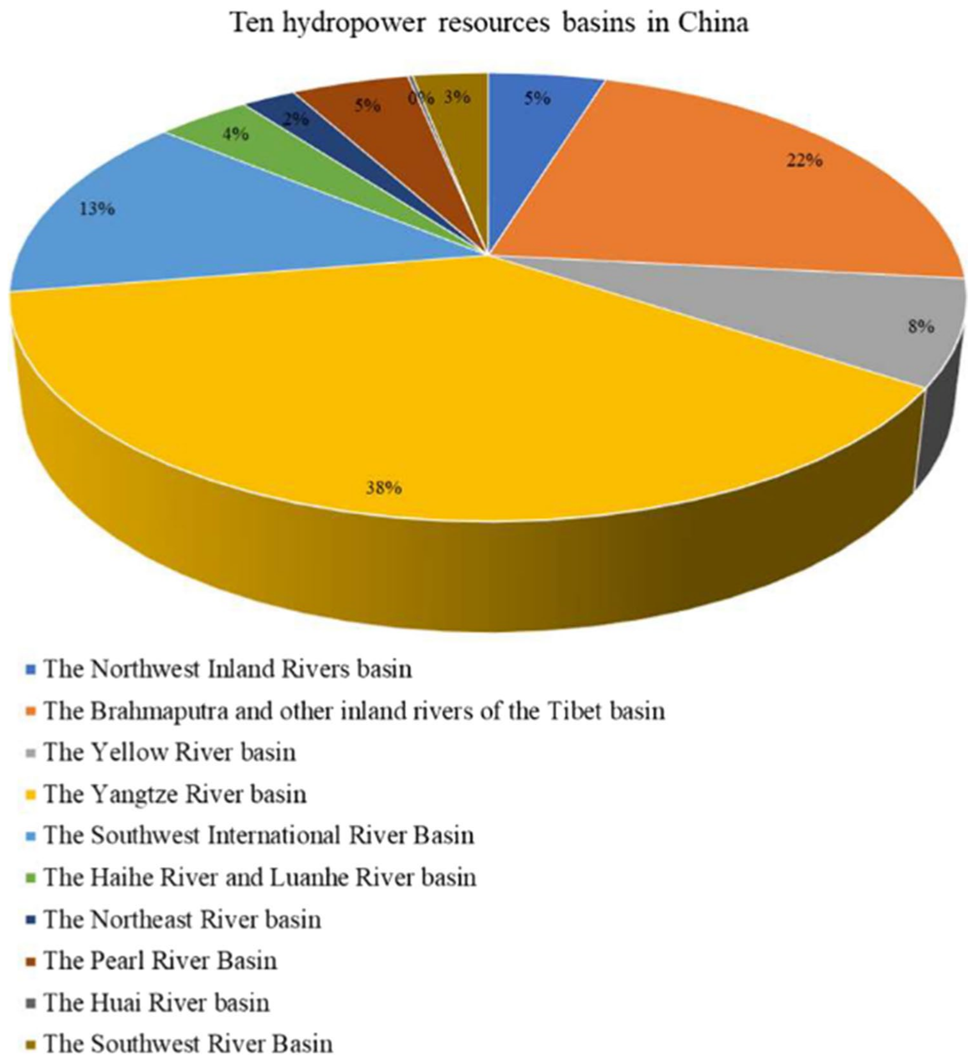
Fig. 3 China's hydropower installed capacity (Xiao et al. 2023)

Yangtze River Basin possesses the highest installed capacity, constituting 53.2% of the overall installed capacity in the nation (Wang et al. 2022b). The Three Gorges Hydropower Station, located in the lower reaches of the Yangtze River, is renowned as the largest hydropower installation in China. The renowned hydroelectric power stations of Danjiangkou and Ankang are situated along the course of the Han River. Wujiang is home to a number of prominent hydropower stations, including Goupitan, Thring, and Shatuo. Qingjiang and Yuanjiang are home to numerous medium- and large-scale hydropower facilities. The technological applications employed in the Huaihe and Haihe River basins exhibit potential for the development of the hydropower industry. However, it is worth noting that the current technology possesses a limited capacity. The Brahmaputra River basin is widely acknowledged as the second largest river basin globally, surpassed only by the Changjiang River. Furthermore, it is worth noting that the Brahmaputra River basin harbors substantial hydroelectric potential. However, the comprehensive investigation of the region remains unfinished due to various issues, including the challenging mining circumstances.

Sustainable development of small hydropower

Achieving sustainable development at the turn of the twenty-first century has become a pressing concern since it requires simultaneous improvement of the environment and the economy. The world community has taken notice of the growing worry over small hydropower plants despite the fact that they use a sustainable and clean energy source. Furthermore, the implementation of small hydropower projects with their relatively short construction periods and financial requirements is a significant approach to addressing poverty in marginalized regions characterized by remoteness, ethnic diversity, and economic deprivation (Hennig et al. 2013). The western part of China possesses a significant abundance of minor hydropower resources. The Yangtze River Basin holds the highest position in terms of watershed and contributes to 43.2% of the overall installed capacity in the country. China's approach to small hydropower development includes the consideration of proximity as a network characteristic, with the aim of addressing energy and environmental challenges and alleviating poverty, particularly in developing nations (Kishore et al. 2021). He et al. (2022) according to a Chinese small hydropower industry specialist, the global community's long-term goal for electric power distribution is the widespread use of clean, renewable energy sources. The concept of small hydropower involves placing emphasis on the sustainable use of water resources. Consequently, small hydropower exhibits perpetual viability. During China's 13th Five-Year period, there has been a strong emphasis on promoting the growth of small hydropower in impoverished regions. This initiative aims to expedite the construction of environmentally friendly hydropower projects, including the completion of the Global Environment

Fig. 4 Regional water resources in China (Xiao et al. 2023)



Facility (GEF) and expansion initiatives. Furthermore, there is a strict adherence to ecological and environmental protection measures, with the goal of facilitating the scientific development and sustainable utilization of resources in a manner that promotes livelihood improvement, peace, environmental preservation, and harmonious coexistence.

Impact of climate change on hydropower sustainability

There is no doubt that climate change over the next several decades will have potentially severe implications on water supplies and hydropower, notwithstanding large uncertainty in the results and predictions of different models' output (Hamududu and Killingtveit 2017). Hydropower's potential sensitivity to climate change has been recognized in recent years, and as a result, some quantitative assessments of hydropower's technical potential have been created. But few studies have actually looked at how climate change would affect hydropower specifically. When other elements, such as humidity, cloudiness, and precipitation, are considered, global warming emerges as one of the most important contributors to climate change. Its effects on hydropower production and water supply are substantial. As the global average temperature rises, it changes the way rain falls around the world. Earlier spring snowmelt is one consequence of these changes, which has direct consequences on hydropower production. Hydropower is threatened by the global warming that has been widely proven. Low-capacity, high-elevation hydropower reservoirs are particularly vulnerable to temperature fluctuations. When temperatures rise, snow melts faster, and seasonal rainstorms tend to be heavier, it was observed with particular worry that countries in the Himalayas rely on high-altitude hydropower (Krishnan et al. 2019). Under magnetic storm conditions, the thermospheric atmospheric density experiences significant fluctuations, which have a negative impact on spacecraft control (Yin et al. 2023a). More water is collected due to the increased snowmelt and seasonal precipitation; however, this is not helpful for hydropower generation or the safety of areas downstream. Because the surplus hydraulic state biases the optimum operating condition, an overfilled waterhead in front of the turbine results in low generating efficiency. Low-elevation plants are more susceptible to weather fluctuations than high-elevation hydropower plants. The quantity of water available for usage in hydroelectric plants is typically impacted by precipitation runoff. Temperature increases, in addition to precipitation, cause adjustments in electricity generation. Hydropower resource or hydropower generation has been shown to be similarly sensitive to changes in precipitation and temperature in many studies. Batoka Gorge scheme's elasticity of energy output to changes in temperature and precipitation has been estimated, and the results are displayed by Harrison et al. (2006). There was a 0.44 degree drop in temperature and a 0.77 percentage rise in rain. The results showed that the case study was more reactive to changes in precipitation than in temperature (Jamali et al. 2013). The data and isolines from the 2080s showed that a change of 1 degree Celsius in temperature had the same effect on hydropower as a change of 3 percent in precipitation. This means that in order to keep hydropower production at its current level, an additional 3% of precipitation is needed for every 1 °C increase in temperature. Temperature and precipitation are two crucial direct elements, but there are also many indirect aspects to consider. Their impact on hydropower's ability to adapt to climate change is minimal, but quantifying it is tricky. Water demand for other applications, such irrigation and water supply for residential families and industry, increases as a result of climate change that could have unintended consequences for water availability for energy reasons (Khan et al. 2017). A higher evaporation potential means that more liquid water will turn into a gas in the lower atmosphere as the temperature rises. Consequently, the available water supplies for hydropower could be reduced due to the temperature-driven increase in evaporation from reservoir surfaces. As a result of an increase in total soil evapotranspiration, the demand for irrigation water tends to rise in agricultural regions when temperatures are high and precipitation is unpredictable. This phenomenon persists irrespective of the constant cumulative precipitation during the period of plant growth. Furthermore, it is crucial to note that the quantity of water is not the only significant variable. The alteration of water quality can significantly affect the output of hydropower. Periodic increments in precipitation intensity might lead to heightened turbidity levels in the water flowing toward the hydraulic generator. Rivers provide abundant fresh water resources, shape rich alluvial plains, and provide habitats for organisms (Li et al. 2023b). The influx of material originating from upstream will result in an escalation of turbine erosion. Additionally, the implementation of this measure would result in an escalation of the expenses associated with the clean-up process, as well as a decrease in the operational lifespan of the turbine and its overall efficiency in power generation. Ultimately, it is quite probable that global warming will be accompanied by severe weather events (Gong et al. 2023). The heightened vulnerabilities associated with landslides, glacial lake outbursts, and floods underscore the criticality of incorporating enhanced flow management through reservoir regulation and water management practices. Increases in irrigation and overall electricity demand during particularly warm and dry weather will put a higher strain on the available water supply for power generating. There are other climate change impact elements to hydropower, especially considering the substantial municipal use of water resources. Future management of the hydropower resource must take fish and wildlife preservation into account to safeguard the survival of rare or threatened species in the river system and along the river banks. Because there is a finite amount of water, competition arises between the many uses of the system.

China hydropower challenges

The hydropower development in China has transitioned into a new phase of advancement. On a technical level, the nation has constructed a number of technologically complex and massive hydropower plants. There have been significant advances in the design of hydropower stations, their construction, and the technology used in their operation and management. However, China is confronted with a myriad of obstacles that impede the ideal advancement and utilization of hydropower. China's rapid expansion of its hydropower transmission capacity was helped by the country's careful planning and construction of sizable hydropower bases. As a result, hydropower transmission has an impact on China's electricity resource distribution. According to (Soomro et al. 2023), the core challenge faced by large-scale hydropower transportation lies in effectively leveraging the mutual compensation between inter-basin cascade hydropower stations to optimize the consumption of hydropower and address the variations in grid load characteristics between the sending and receiving ends. This approach allows for the maximum utilization of hydropower resources and facilitates the management of peak electricity demand. The rate of development of the hydropower system inside the Sichuan power grid has experienced a significant increase (Shen et al. 2019). Nevertheless, the problem of neglected energy remains a grave concern. Based on an analysis of the power system level in Sichuan region and the balance between abandoned energy power and idle capacity of hydropower stations, it is projected that the issue of abandoned energy in the region will persistently escalate from 2016 to 2020. If appropriate actions are not taken into consideration, the maximum value of 35 billion kWh, which will be approximately 8.64% of the total power generating capacity in the year 2020, will be attained (Xue et al. 2020). The issue of consumptive difficulties in hydropower generation is of considerable magnitude, and its resolution remains a basic challenge that has yet to be effectively addressed. The issues pertaining to the Sichuan hydropower region serve as a microcosm that exemplifies the prevailing challenges associated with resource consumption in China (Lingying et al. 2019). Hydropower curtailment can be attributed to various factors, with the primary causes being the disparity between supply and demand, as well as the challenging water power consumption scenario. The southwestern regions possess abundant hydropower resources and favorable circumstances for their development. Nevertheless, the economies of these regions exhibit a low degree of development and suffer from a lack of structural diversity. The inadequate management of the substantial power producing capacity in the southwest region has led to a significant amount of abandoned energy resources. Several factors, such as the mismatch between the building time of grid projects and electricity generation, the lengthy approval schedule for large grid projects, and issues related to land acquisition and demolition, are negatively impacting the progress of the construction project. The oversupply of coal-fired power in China is concurrently impeding the growth of hydropower Zhang et al. (2022a). Hydropower is commonly acknowledged to be significantly influenced by natural climatic conditions. To guarantee a consistent power supply, it is imperative to establish dependable thermal power units. The rapid construction of thermal power stations has led to an excess of thermal power generation capacity, hence limiting the market space for clean energy and renewable energy sources. The issue of overcapacity in power generating in China mostly stems from the surplus of coal-fired power stations, while there is currently no surplus capacity observed in the realm of renewable energy generation (Zheng et al. 2021). In order to address the complex issue of energy development, the official publication of the 13th Five-Year Plan for power development (2016–2020) is imperative to implement stringent regulations on thermal power generation within the country, accompanied by the implementation of many policies aimed at effectively managing the administrative approval process for new power projects. The over-reliance of China's energy system on coal, in contrast to the efforts of industrialized countries to decrease coal usage, has emerged as a distinct disparity. Simultaneously, China can alone curtail the advancement of coal in order to alleviate the inherent conflict arising from surplus capacity. The development of pumped storage power stations has not met the anticipated objectives, and the total operational efficiency is suboptimal. The pumped storage power station exhibits characteristics of flexibility and cost-effectiveness when employed as a large-scale energy storage mechanism. The operational efficiency of the plant has been adversely impacted by many factors such as overcapacity, thermal power fluctuations, and other causes of power peaking. These issues have resulted in a decline in storage utilization rates and have had a negative impact on plant pumping activities. Hence, the hydroelectric system in China has the capacity to effectively allocate and utilize a wide array of resources. Nevertheless, the magnitude and scope of the hydroelectric project are substantial, hence leading to an inevitable detriment to the local ecosystem. The construction of hydropower stations inevitably necessitates the utilization of extensive land areas, leading to the destruction of vegetation. Consequently, this process contributes to the loss of arable land and exacerbates issues related to water and soil erosion. The construction of the dam has resulted in alterations to the wildlife habitat of the river and reservoir, leading to the destruction of animal and plant life in the affected area. The construction of a hydropower station has notable environmental implications, including the generation of noise and dust that can impact the surrounding ecosystem. Additionally, the earthmoving activities associated with the construction process might have consequences for the geological environment. The rise in groundwater levels in the vicinity of the reservoir has the potential to result in land submergence, thus leading to modifications in the natural environment of the region. As a result, the natural ecological framework is disrupted, leading to the potential for the reservoir to trigger seismic activity or other geological catastrophes. China has undertaken measures to address the aforementioned challenges through the formulation and strengthening of relevant laws and regulations, as well as the supervision of the execution of water conservation and hydropower initiatives. In order to promote economic growth, initiatives focused on environmental protection are implemented with the aim of mitigating illicit activities that have detrimental effects on the environment. China has implemented suitable incentives and consistently conducted assessments and evaluations of water conservancy and hydropower projects within the domain of water resource systems. The majority of China's hydropower resources are located in the southwest, an area with lower population density and lower rates of reservoir migration and flood damage. As a result, there are plentiful water resources and favorable conditions for growth in this region. Nevertheless, the geographical characteristics of this region are predominantly hilly, which consequently poses challenges in terms of infrastructure construction and significantly increases the expenses associated with development. The rivers located in the southwestern region are typically considered to be international rivers, thus necessitating substantial efforts in their development and exploitation. Consequently, the presence of illogical and cross-border conflicts in the realm of economic development pertaining to hydropower projects in Southwest China has led to suboptimal levels of development and use of hydropower stations (Sun et al. 2019). In China, the development of extensive reservoirs has typically exhibited a delay in comparison with the building of downstream cascade hydropower plants during periods of high precipitation. Moreover, the capability for regulating water levels during the dry season has been found to be inadequate. The expansion of hydroelectric facilities throughout the calendar year results in an imbalanced energy contribution, characterized by substantial energy wastage during the wet season due to mismanagement of resources, and insufficient resources and power generation capacity during the dry season (Wang et al. 2022c). China's electricity quality from hydropower is heavily impacted by the country's laxity in developing huge reservoirs and its inability to adequately respond to changing conditions. Construction of hydropower plants necessitates the use and flooding of large tracts of land, necessitating the evacuation of nearby inhabitants. Water conservation and hydropower engineering construction both benefit from hydropower resettlement. The work is complex not only in terms of economic recompense migration, but also in promoting the social development of those who will be touched by the initiative. One of the major issues affecting the development and building of hydropower stations in China is reservoir resettlement (Zhao et al. 2020). According to the findings of this study, it is difficult to provide an enhanced immigration compensation standard not only to protect the rights and interests of investors, but also to raise resettlement funds and effectively modify the distribution structure of these funds. The compensation funds set aside to help the impacted immigrants should be prioritized.

Strategies for hydropower growth and long-term sustainability

The consequences of climate change on hydropower are permanent, but there are several ways to lessen the blow and safeguard the vitality of hydraulic resources in the face of this threat. Improvements in technology, models, methodologies, and algorithms have allowed for more exact and accurate climate change planning and forecasting. To what extent may climate change impacts on hydroelectric resources be mitigated, and how can long-term sustainability in hydropower development are encouraged: Efforts have been undertaken by many institutions and groups to address climate change and mitigate its effects through the difficult process of increasing the proportion of hydropower output. In order to mitigate the effects of global warming, it is imperative to significantly decrease greenhouse gas (GHG) emissions across all areas of economic development. There exist numerous mitigation strategies that can potentially contribute to the attainment of this ambitious objective. Hydropower, being a form of renewable energy, holds considerable importance in the overall global energy equilibrium due to its minimal greenhouse gas (GHG) emissions during the power generation phase. However, it should be noted that GHG emissions are produced during the manufacturing process of hydropower systems. The amount of greenhouse gas (GHG) emissions during the building phase may be reduced in comparison with its overall impact in mitigating GHG emissions throughout the entire lifespan of hydropower generating. Hydropower, with wind power and solar energy, serves as a dependable and supplementary energy source within the overall power supply infrastructure. The integration of hydropower into a hybrid energy supply system comprising wind and solar power sources enhances the overall stability of the system. The current era is witnessing a significant phase of global energy use. The imperative trajectory for future energy development, in light of climate change consequences and the pursuit of global sustainable development, lies in the robust advancement of hydropower and other renewable energy sources. Increased hydropower generation within the energy system will result in a reduction in the consumption of fossil fuels and, thus, a decrease in the release of greenhouse gases into the atmosphere. Hence, a viable approach to address the issue of climate change involves expediting the progress of hydropower expansion, with particular emphasis on regions such as Africa, Asia, and Latin America. The energy development rate in these locations remains below 30%, indicating a significant untapped potential for exploration and development. As discussed earlier, SHPs play a key role, not only in rural energy generation, but also to mitigate climate change impacts. Some small hydroelectric power (SHP) plants contribute to the emission reduction efforts of developed countries as part of the clean development mechanism (CDM) established under the United Nations Framework Convention on Climate Change (UNFCCC), specifically in the context of the Kyoto Protocol. The utilization of Small Hydropower (SHP) technology can also prove to be advantageous for energy development in developing nations. Furthermore, the use of SHP can yield significant advantages when combined with other renewable energy sources, such as solar energy and wind energy, particularly in geographically isolated regions. The optimization of these advantages can be achieved by the implementation of multi-energy, complementary power generation, which is contingent upon the particular technology, management practices, and site attributes.

Optimizing hydropower operation and management

Significant emphasis should be placed on the implementation of adaptation strategies aimed at effectively managing the diverse climate conditions. This discussion focuses on two primary approaches pertaining to the operation and management of hydropower generating in order to effectively respond to the challenges posed by climate change. One potential approach is improving the efficiency of cascade hydropower stations or individual hydropower stations equipped with reservoirs in order to optimize their performance. The implementation of scheduling optimization techniques has the potential to effectively mitigate water spillage by efficiently managing available capacity and storage resources. There is a persuasive case made by Eyer and Corey (2010). The data indicate that the yearly incremental advantages of increasing capacity were more pronounced for storage as compared to generation. The study analyzed the Dry scenario, which demonstrated a 20% reduction in runoff compared to the historical hydrology baseline. However, by efficiently managing storage and production facilities within their current capabilities, the overall decline in revenues across the system was found to be less than 14%. The optimization of scheduling for a set of hydropower stations situated on a river or basin presents a straightforward approach to effectively harnessing water resources at various levels. Additionally, this approach enables the adjustment and compensation for the impacts experienced by individual stations as a result of interannual climate variability throughout the year. In this particular scenario, the primary objective is to enhance the operational pattern of hydropower systems in order to get the highest possible revenue, considering the constraints of restricted capacity and the availability of ancillary services (Pérez-Díaz et al. 2015). An additional alternative, which does not preclude the previous option, entails undertaking a comprehensive risk assessment pertaining to the effects of climate change on hydropower production, as well as formulating a contingency strategy to address climate-related extremes. The effects of global warming on hydropower are primarily manifested in modest changes to the mean climate, which may be more easily managed. However, the occurrence of extreme weather events, such as floods and droughts, poses significant challenges to the production, transmission, and distribution of hydropower output. The unmistakable manifestation of climate change is readily apparent in the frequency and severity of extreme weather events at the regional level. Hydropower systems are subjected to significant stress and elevated risk as a result of these circumstances. Hence, it is of utmost importance for hydropower planners and decision-makers to conduct a thorough analysis of the possible risks associated with climate extreme events during the operational phase. It is imperative to build emergency strategies under various extreme conditions, as indicated by hydrological model forecasts and predictions. Through the optimization of power generation operation and management, hydropower stations can enhance their efficiency, resulting in augmented generation revenue and substantial socio-economic contributions to society.

Climate change impact on freshwater fisheries

Freshwater aquaculture in China

Aquaculture in freshwater environments around the world recent studies has analyzed the current state of freshwater aquaculture on a global and regional scale (Edwards 2015; Jiang et al. 2022). Freshwater aquaculture has played and continues to play a preeminent role since aquaculture became a key contributor to the food fish basket worldwide (Jia et al. 2018). However, if seaweed production was not considered, the latter's share would be much larger. Figure 1 clearly demonstrates that China holds a dominant position in worldwide freshwater aquaculture production. Furthermore, China's contribution to aquaculture sector has consistently grown over time and presently remains on an upward trajectory (Hu et al. 2021). In addition, China's share in worldwide freshwater aquaculture production peaked in the early 1990s and averaged 61.2% from 1981 to 2011 (Wang et al. 2016b). This highlights the significance of freshwater aquaculture to global aquaculture and China's preeminent role in the former. In China, aquaculture makes use of all of the country's rivers, lakes, and even man-made reservoirs and ponds. The area dedicated to freshwater aquaculture ponds has experienced a notable increase over the years, with a particularly significant growth observed from 1991 onward (Wang et al. 2015). In contrast, the area allocated for aquaculture purposes in reservoirs has witnessed a minor reduction. Since the 1990s, there has been a significant rise in the extent of paddy field aquaculture, also known as rice-fish culture, which is a longstanding and customary practice in China (Wang et al. 2018; Yuan et al. 2022); however, it is increasingly being embraced within the cultural practices of esteemed species, such as crayfish and mitten crab. Net cage culture is the prevailing aquaculture method employed in China's reservoirs, lakes, and rivers (Liu et al. 2018). There exists a significant range of variation in the dimensions and composition of net cages, as well as a corresponding diversity of farmed species. For example, the exotic channel catfish the cultivation is predominantly conducted within net cages situated in reservoirs located in the north-western region of Hubei province. The present geographical region has suitable temperature conditions that promote the growth and development of the species. This farming method is primarily aimed at satisfying the lucrative international export market. However, the area used did not always correspond with the trends in overall production across different environments.

Status of Yangtze River fish

In the middle of the 1940s, the first comprehensive survey of Yangtze River fish was done, and it found that there were roughly 2000 different species in the Yangtze River Basin (Chen et al. 2020b). One of the largest freshwater fish is the Chinese paddlefish, which has been caught traditionally for millennia. Fish-based measures of biological integrity have been used in a number of Yangtze River fishery resource assessments (Liu et al. 2021b). Liu et al. (2021a), He et al. (2011) reported from the Yangtze River basin and compared the outcomes of studies conducted on its lower and upper portions. This proved that the two largest freshwater lakes in China, Dongting and Poyang, located in the middle reach of the Yangtze River, were in terrible ecological condition, due to the distinctive geographic location and climatic characteristics of the Tibetan Plateau (Zhou et al. 2022; Luo et al. 2022). Ecological functions in the Yangtze River basin have been severely degraded, as was noted at a symposium held in Wuhan in 2018 to encourage the development of the Yangtze River industrial belt. The middle and lower portions of the river have experienced significant declines in trends, with all regions being classified as poor according to survey data from 2008 (Zhang et al. 2020a). Total output, abundance, and productivity have all been on the decline in the six provinces through which the Yangtze flows since 1954 (Du et al. 2011), according to the Yangtze River Fishery Resources Management Committee. After changing by around 200,000 metric tons per year in the 1980s, the yearly catch was cut in half by the 1990s (Zhang 2010). It is important to note that no major efforts were taken to regulate effort throughout this time; therefore, the decline in abundance must have been caused by natural causes rather than management decisions. Total catch numbers mask the seriousness of the situation for many high-value species. For instance, in the Jiangsu region of the Yangtze River, the yearly capture of the pufferfish was 409 tonnes in 1959 (Fig. 5), but has since dropped to around 100 tonnes (Chen et al. 2020b). Now more than ever, hatchery-reared fry is essential to the success of commercial fisheries for this species. Seasonal shad catches averaged 300–500 tons per year in the 1960s and peaked at 1,575.75 tonnes in 1974 (Chen et al. 2020a). While production has increased somewhat in recent years-possibly as a result of stricter management regulations the overall decline is still substantial, and it represents a significant opportunity cost to the economy and the ecosystem.

Biodiversity pressures

Zhang et al. (2020b) ranked the Mekong, Ganges, and Yangtze Rivers as having the greatest, second-highest, and third-highest fishing pressures, respectively. Damming, water pollution, overfishing, channel engineering, and sand quarrying are only few of the many human activities that have had a significant and varied impact on the Yangtze River system since the 1950s (Wang et al. 2016a), with cumulative impacts. Implications for the river's rehabilitation are at stake due to the difficulty or impossibility of reversing the consequences. In the last few decades, the Yangtze River Basin has seen remarkable growth in reservoir construction and hydropower production (Zhong et al. 2020). Blocking fish migration pathways, altering hydrological conditions, and altering river habitats all contribute to this loss of output by having a negative impact on fish survival and reproduction (Gao et al. 2022). The current process of natural spawning is contingent upon the conditions of the environment situated beneath the Gezhouba Dam, whereby the likelihood of successful spawning is significantly diminished (Tao et al. 2012). The Chinese sturgeon's spawning grounds in the middle and lower parts of the Yangtze River have experienced a further reduction in area as a result of the impoundment of the Three Gorges Dam (TGD) since 2003 (Zhang et al. 2019). The spawning circumstances are subject to many impacts resulting from alterations in several elements, such as flow rate, water level, riverbed sediment composition, water temperature, and dissolved oxygen. Efforts aimed at mitigating declines in fish supplies through the implementation of restocking initiatives have yielded only limited achievements (Zhang et al. 2020c). The pollution levels in the Yangtze River have experienced a significant surge since the 1970s, primarily attributed to the substantial growth of agricultural and industrial sectors, coupled with insufficient efforts to reduce pollution (Ding and Liu 2019). The origins of water pollution in the Yangtze River can be classified into four main categories: non-point sources, point sources, mobile sources, and solid waste. Non-point sources are present throughout the course of the river, particularly due to the discharge of pesticides, nutrients, and sedimentation resulting from agricultural activities. The Yangtze River is characterized by the presence of point sources, which encompass industrial discharges as well as home and municipal sewage outputs. Mobile sources mostly stem from the significant pollution caused by shipping activities, sewage discharge, and improper waste disposal in the Yangtze River. Solid trash primarily consists of industrial waste, but it also includes domestic garbage originating from various areas situated along the river (Wang et al. 2022a). A significant portion of the discharges originate from sources that undergo treatment operations before being released. However, due to the large number of these sources, serious pollution accidents occur with high frequency. The over exploitation of juvenile and adult fish populations has led to the persistent occurrence of recruitment overfishing in numerous species (Chen et al. 2020a). The primary factor attributed to the significant reduction in fishery resources in the middle and lower sections of the river is widely acknowledged to be

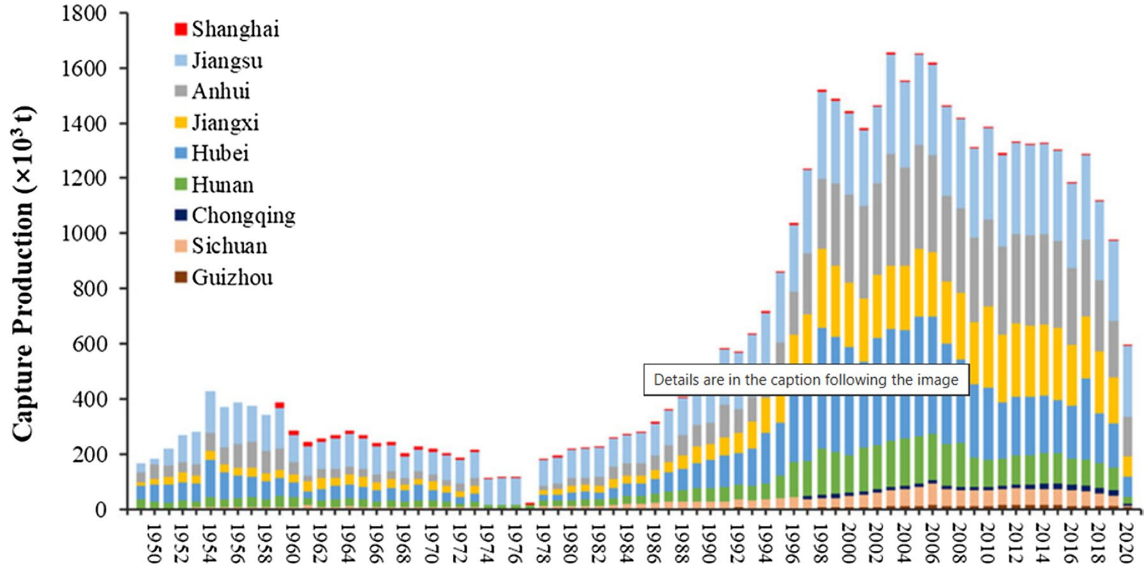


Fig. 5 Amount of capture production in the Yangtze River Basin (Yin et al. 2022)

the lack of comprehensive catch management (Zhang et al. 2020b). Nevertheless, the feedback regarding the existing protective measures suggests that the regulation of fishing catch can only lead to a limited restoration of the fishery resources in the Yangtze River.

The effects of climate change on aquaculture and implications on sustainability

The effects of climate change on aquaculture production and the consequences for the sector's long-term viability are discussed in greater depth below. It is widely agreed upon that aquaculture production does not happen in isolation, but rather it has crucial connections to other food production systems (Troell et al. 2014), noticed that a strong link exists within and between the goals of fisheries, aquaculture, and agriculture systems, and that this must be recognized if the growing demand for aquatic goods is to be met sustainably. The major ways in which the aquaculture industry contributes to greenhouse gas emissions are the use of fossil fuels in power generation, transportation, and the manufacture of feed (Boyd et al. 2020), when compared to other areas of food production; however, this sector's impact seems disproportionately minor. Recent estimates by IPCC (Friedlingstein et al. 2022) demonstrate that net anthropogenic GHG emissions were from agriculture, forestry, and other land uses. It is estimated that animal production, especially livestock husbandry, accounts for 45% of agriculture's overall net contribution (Herrero et al. 2016), which produces the most greenhouse gases overall mostly methane, carbon monoxide, and nitrous oxide (Rehman et al. 2020). However, CO2 from aquatic animals' respiration is aquaculture's primary greenhouse gas emission (Raul et al. 2020). Still, there is a lack of information about the pathways and contribution of aquaculture output to global GHGs emission; thus, more research is needed. Fishing's net impact is on food production, especially in terms of carbon dioxide. The global fisheries industry is responsible for an estimated 28% of the growth in GHG emissions that occurred between 1990 and 2011, with a 2011 contribution of 4% (Parker et al. 2018). Significant technological advancements have recently been made in aquaculture, allowing the industry to increase existing production in order to meet the expanding demand for aquatic products (Olsen et al. 2012). The sustainability of food production systems as a whole is being threatened by climate change, and aquaculture is no exception (Ahmed and Turchini 2021). According to (Ahmed et al. 2019), the impacts and reactions to climate change are intrinsically related to the goals of sustainable development, which strike a balance between environmental protection, economic growth, and social welfare. This indicates that tackling the consequences of climate change is crucial to achieving sustainability in aquaculture output. Although sustainability can be defined in a variety of ways (Lam et al. 2020), can mean organizing our material, intellectual, social, and environmental assets so that present and future generations have access to what they need to thrive (Coulthard et al. 2011). Therefore, aquaculture must be able to endure for future generations if it is to be considered sustainable (Boyd et al. 2020). According to (Bridson et al. 2020), environmental, economic, and social indices can be used to evaluate aquaculture systems' long-term viability. Indicators of environmental sustainability include things like pollution control, biodiversity preservation, and the effective use of natural resources (Moldan et al. 2012). The ability of aquaculture to provide benefits to communities, such as food security, employment, equality of income and opportunity distribution, and inclusion of vulnerable populations, is central to social sustainability, while the efficient use of financial resources, economic feasibility, resilience, and the generation of funds for re-investment are central to economic sustainability (Kennedy and Corfee-Morlot 2012). Despite the importance of economic and social sustainability, these two aspects have received far less attention in the existing literature on aquaculture sustainability (Osmundsen et al. 2020). Researchers need to look into the potential social and economic impacts of climate change on the long-term viability of aquaculture output in the future. Many recent studies suggest that the consequences of climate change on aquaculture may vary across regions, economies, climate zones, production strategies, and cultivated species (Maulu et al. 2021). For example, (Ficke et al. 2007) producers in developing countries and poorer economies were expected to feel the effects more strongly than their counterparts in rich countries. Abisha et al. (2022) indicated that freshwater, brackish water, and marine producers can anticipate different impacts from climate change. The risks associated with climate change are expected to have a greater impact on small-scale farmers than on large-scale producers due to higher production costs associated with farm management and a dearth of recovery support networks (Collares-Pereira et al. 2004). Aquaculture production methods and the full value chain are vulnerable to the effects of climate change (Cochrane et al. 2009). Therefore, climate change may be seen more as an involuntary risk that causes vulnerability on the socio-economic development and raises stress, particularly on food demand and supply and the livelihood system of the farmers. Rising temperatures, ocean acidification, diseases and harmful algal blooms, changes in rainfall/precipitation patterns, sea-level rise, the uncertainty of external input supplies, changes in sea surface salinity, and extreme climatic events are all predicted elements of a changing climate that threaten production and sustainability in the aquaculture sector (Khalid 2022). Since aquaculture, like any other farming method, is defined in time, place, and scale, and thus has a fair amount of maneuverability, these factors will not have the same impact on productivity in every setting (Iversen et al. 2020), also having an impact on fish populations at various stages of their existence. The complexity of adaptation planning in the aquaculture sector is exacerbated by the fact that we know relatively little about the impact of any given consequence and even less about the impact of any given combination of consequences. The environment's temperature has a significant impact on the development of aquatic organisms (Guo et al. 2023). Most fish, especially cold-water species like the Atlantic halibut, Salmon, and Cod, and intertidal shellfish, are expected to die out at higher rates with the estimated 1.5 °C rise in average global temperature this century (Khalid 2022). In light of this, extended temperature stress has the potential to impact aquaculture productivity in a number of ways, the most prominent of which is likely to be. Most finfish and shellfish species are also likely to experience changes in their metabolism and physiology, eating behavior, and growth performance (Cascarano et al. 2021). Furthermore, the increase in ocean temperatures and subsequent acidity of the oceans gradually diminishes the capacity of the ocean carbon sink, and the large-scale vegetation restoration project on the Loess Plateau increased the ecosystem carbon (C) stocks and affected C budget in arid and semi-arid ecosystems (Yang et al. 2023). This leads to changes in the hydrology and hydrography of water systems, as well as the occurrence of red tides (Zhang et al. 2022c). The aforementioned consequences have the potential to result in escalated management expenditures and diminished productivity, hence posing a significant risk to the economic and social viability of aquaculture production. The issue of environmental sustainability can be influenced by thermal stratification in deep water bodies caused by temperature fluctuations. This stratification can impact the dispersion and availability of nutrients within the water. Additionally, in the event of upwelling, aquaculture producers operating in open waters may experience significant economic losses (Maulu et al. 2021). Nevertheless, there remains a scarcity of data on the physiological reaction of economically significant species to increasing temperatures. The available knowledge is mostly focused on a restricted number of species and is predominantly centered on adult life stages. Consequently, there is a lack of understanding of the impact of rising temperatures on early developmental stages, including embryos, larvae, and fingerlings. Conversely, periods of elevated temperatures (within the acceptable range for species) have the potential to extend growing seasons, particularly in temperate climates, so facilitating the proliferation of thermophilic aquatic species, like the Giant tiger prawn, Tilapia, Oysters, and Mussels (Abbass et al. 2022). Warmer seasons are expected to encourage the growth of aquaculture production in chilly places like the Arctic (Bricknell et al. 2021). Temperature increases may also present chances to cultivate new species and advance advancements in genetic improvements of aquatic animals (Ficke et al. 2007). Social sustainability will be aided by higher production levels and more job openings, while economic sustainability will benefit from higher earnings and lower management expenses. Although this may jeopardize environmental sustainability in the case of hybridization with species in natural waterways, it can only be accomplished with the help of recent developments in molecular biology and the application of practical methods of genetic improvement in aquaculture. Increased rainfall (Flooding) and times of low or no rainfall (Drought) will have opposing effects on aquaculture productivity and sustainability. Flood control schemes and the scale of drainage facilities are closely related to the occurrence of rainstorms and the tide level of an outer river, so it is necessary to study the probability of the occurrence of rainstorms and the tide levels (Gao et al. 2021). The patterns of flooding events are difficult to anticipate; the dangers associated with droughts occurrences are likely to increase with 2 °C of global warming compared to 1.5 °C. Production hazards in lowland areas will rise if the amount of rainfall increases, especially if it comes in the form of heavier events (Marambe et al. 2015). The dangers associated with fish ponds encompass the potential loss of fish due to flooding, the infiltration of undesired species into the ponds, and the structural impairment of ponds caused by infilling and erosion of walls (Abisha et al. 2022). The potential consequences of introducing invasive fish species and deteriorating water quality as a result of mixing pond water and wild fish pose significant threats to the environmental sustainability of aquaculture operations. In addition, the depletion of fish populations in ponds poses a significant challenge to the social and economic aspects of maintaining sustainable aquaculture practices. This is mostly due to the adverse impact it has on the financial returns of producers, potentially leading to poverty within affected communities. According to (García et al. 2019), the percentage of fish lost during episodes of severe flooding is contingent upon the specific species and the age of the individual specimens. The authors additionally noted that there is a tendency for percentage losses to diminish as fish age increases. Nevertheless, it is important to acknowledge that a rise in precipitation can potentially expand the acceptable areas for aquaculture ponds that depend on rainwater in low-lying tropical countries. Nevertheless, it is imperative to do further research in order to examine the potential impact of altered precipitation patterns on various fish species and their distinct life phases, particularly those that hold economic significance.

Proposed strategies

While adaptation is widely recognized as a feasible short-term approach to addressing climate change, its successful implementation may encounter many obstacles. For instance, a failure to recognize the implications of climate change on producers, taking into account their specific regional context, environmental conditions, level of awareness regarding climate change, population dynamics, community dynamics, economic circumstances, and existing industry (Ahmed et al. 2019). Without considering these issues, it is likely that the effectiveness of adaptation methods for producers and stakeholders in the aquaculture sector will be limited (Lebel et al. 2021). In order to effectively tackle this issue, it is imperative for governments, particularly in countries that are more susceptible to climate change impacts, to acknowledge and include this reality into their policy frameworks pertaining to climate change interventions. This will enable them to adequately address the requirements of producers within their unique circumstances. Hence, it is imperative to allocate more efforts and resources toward the producer groups who are most susceptible to vulnerabilities. Additionally, as noted by previous research, the likelihood of successful adaptation is increased when producers are informed about the factors that drive adaptation and the routes via which it impacts their operations. Furthermore, monitoring a comprehensive range of impact indicators and employing adaptive decision-making strategies also contribute to the effectiveness of adaptation efforts. In recent times, numerous models have been employed to forecast the ramifications of climate change on food production systems, encompassing aquaculture (Cubillo et al. 2021; Soto et al. 2019). Nevertheless, inaccurate estimates have the potential to hinder the effective adaptation of aquaculture producers to the impacts of climate change. The ability of aquaculture producers to adjust to climate change is expected to be contingent upon the availability of precise future estimates pertaining to various systems within the aquaculture sector. The provision of inaccurate and prejudiced assessments of the possible risks linked to climate change has the potential to misinform policymakers and aquaculture producers, leading to a failure to implement essential precautionary measures. In order to mitigate biases inherent in climate models, it is imperative to minimize reliance on subgrid parameterizations to the greatest extent feasible. Alternatively, if such reliance cannot be entirely eliminated, it is crucial to explicitly communicate the associated uncertainties. The authors moreover propose that forthcoming models ought to prioritize sustainability and possess a transnational scope, encompassing the effective utilization of computing and technology. In addition, a number of projections indicate that aquaculture producers in developing nations will be the most impacted, due to a lack of adaptive capacity (Dabbadie et al. 2019). Hence, it is highly recommended that international collaboration is prioritized to facilitate improved financial and technological accessibility, as well as bolstering local capabilities in developing nations and regions that are particularly susceptible. This would enable more effective measures to be undertaken. The implications of climate change on the entire aquaculture value chain are finally becoming apparent. Current literature largely ignores the commerce and marketing of aquatic products since it is not directly related to the production system. The extent to which the aquaculture industry will be impacted, and thus our adaptation choices, cannot be adequately assessed because scientific studies have focused on such a restricted subset of the problem. Therefore, it is imperative that future research and models consider the entire aquaculture value chain.

Characteristics and anatomy of snow

Basics of water, ice, and snow

The hydrology of snow is significantly influenced by the physical and chemical characteristics of water (Granados et al. 2020). It is the molecular structure of a water molecule that determines its properties including its melting point, density, specific heat, freezing points, adhesion, cohesion, solubility, and viscosity. Water is a dipolar molecule with two hydrogens and one oxygen atom, and a negative charge (Mghaiouini et al. 2020). Each hydrogen atom has a nucleus with one charged particle and one negatively charged electron. Oxygen has a nucleus that consists of eight protons as well as eight uncharged neutrons, and it is surrounded by eight electrons. All these ten charged particles align to establish five orbitals: one pair leftovers strongly affiliated through the oxygen atom in the interior or 1st shell, two-electron pairs construct the covalent O–H bonds, and two sets denote two so-called lone sets of electrons (Peterman and Cordes 2021). The morphology of the water molecule, with its cloud of turning electrons, can be best illustrated as a quite rotund molecule, with a position between the H–O–H branches of approximately 104.5 °C for water and approximately 109 °C for normal hexagonal ice molecule (Todaro et al. 2022). The ice's hexagonal lattice structure results from hydrogen bonds (Ignatov et al. 2014). Snow hydrologists encounter the hexagonal Ih form of ice, but it can exist in at least ten other forms depending on the conditions of temperature and gravity at the ground's surface. Water has been found to exist in a quasi-liquid state on the surface of crystallized ice at temperatures below freezing (Kim 2017). Layers of this liquid may be as thin as one or a few molecules thick, or they may form as small islands on the ice. Subfreezing chemical reactions may be triggered by a liquid-like thin coat of surface water of ice, which also gives ice its slickness. Crystals made from hexagonal Ih ice have smooth basal planes on the top and bottom, as well as six prism faces (Pounder 2013). Sections that lead to the typical hexagonal snowflakes found in nature grow faster on the crystal's rougher edges between its crystal faces or facets. The snow density can be defined as the quantity or volume of ice and water per unit volume of snow. There are various forms of structures created due to different levels of densities (Table 1).

Anatomy of snow crystals

Snow crystals, sometimes called snowflakes, are crystalline materials of ice that develop from water vapor. They develop in abundant quantities in the environment and are widely recognized for their complex, symmetrical patterns (Caravello et al. 2006). To begin with, every snowflake has an ice core that forms when a cloud droplet freezes around a dust particle. Dust particles act as nuclei for water droplets to freeze when the temperature is between –6 and –15 °C (underneath the freezing point of water) (López-Moreno et al. 2008). The seed crystal then begins to collect water vapor molecules that are in the vicinity. They get encased in the crystal and help it expand. It takes the crystal around 30 min to grow to its full size before it falls out of the cloud because there is no more water vapor to feed it. Snow crystals are the scientific name for an ice crystal that has developed this manner. Figure 6 illustrates some stages of natural snow crystal formation. After a crystal has grown over a period, only the facet surfaces that are sluggish to develop remain (Caravello et al. 2006). Irrespective of the original form of the crystal, it will ultimately become facetted. For crystallization, the molecule attached to the lattice decides which surfaces develop slowly and, therefore, which lattice planes form facets. The procedure of faceting is the method by which the geometry of a water molecule is translated to the geometry of an enormous crystal of the same material.

Origin and principles of snow hydrology

When it comes to snow hydrology, history suggests that we have only recently developed a technical understanding of it (DeWalle and Rango 2008). However, there is some evidence to suggest that snow played an important role long before that. A surprising amount of early knowledge of the relationship among river flows the freezing, as well as thawing of water, can be observed with references to the ideology of the ancient Greek philosopher Anaxagoras (500–428 BCE) (Koutsoyiannis et al. 2021). A cooperative snow investigation program was established in 1944 by the US army corps of engineers (US Army Corps of Engineers) in collaboration with the US Weather Bureau during the era of World War II in the US Army Corps of Engineers (Coates and Morrison 2015). It was decided to organize the snow investigations to address specific snow hydrology issues that were being experienced utilizing both agencies at the time. To encounter the snow hydrology goals of both organizations, it was determined that basic research in the physics of snow was required. A widespread laboratory program was established throughout the western USA, and observations began to be collected in 1945 (Mote et al. 2018). The analysis of these data served as the foundation for developing the fundamental relationships and application methods that were used to develop solutions to the most challenging snow hydrology issues. A multitude of snow organizations and research watersheds have been established in countries other than the USA. A typical subalpine spruce-fir forested watershed, the Marmot Creek Basin (9.4 km^2), approximately 80 km west of Calgary, Alberta, Canada, had

Table 1 The snow characteristics at different levels of density

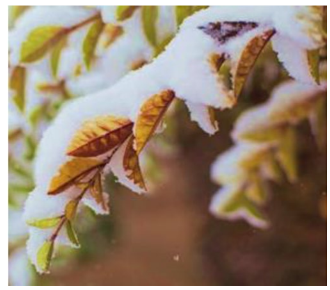
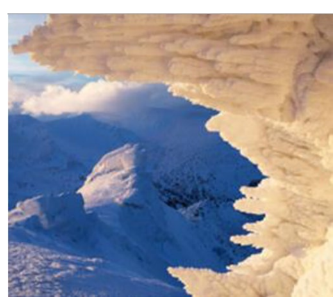
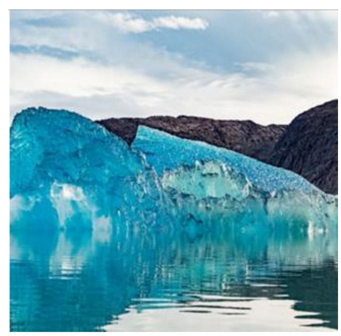
Density (kg m^{-3})	Characteristics	Form created	Image	References
50–100	Snow is an accumulation of packed ice crystals, and the condition of the snowpack determines a variety of qualities, such as color, temperature, and water equivalent	Fresh snowfall		Jeffries and Adolphs (1997)
100–200	Snow is light and fluffy because of its low moisture content	Powder		Passow et al. (2012)
200–300	Snow that perseveres on the ground every year. Powder snow is dry new snow, which is comprised of loose and fresh ice crystals	Perennial snow		Hughes (2018)
300–500	It can be compressed into a solid mass that resists further compression and will hold together	Compacted snow		De Wrachien et al. (2006)
500–550	It is a young, granular type of snow that has been partially melted, refrozen, and compacted, yet precedes the form of ice	Neve		Frick (2012), Maggiore (2022)

Table 1 (continued)

Density (kg m^{-3})	Characteristics	Form created	Image	References
550–830	It partially compacted granular snow that is the intermediate stage between snow and glacial ice	Firn		Hughes (2018)
830–917	It might look like the entire surface of the bubble is freezing, but what you're seeing is the innermost layer of water	Frozen bubbles with ice		Catalan (1989)
917	Rime ice forms when supercooled water liquid droplets freeze onto surfaces	Hard rime		Fikke et al. (2008)

also been instrumented in 1962 to investigate the water balance of the basin (Golding and Stanton 1972).

Factors affecting snow hydrology

Topographical effects on snow hydrology

As there are more snowfall episodes and less evaporation and melt at higher elevations, the depth of seasonal snow cover typically rises. Thus, a strong linear relationship amid seasonal snow cover in addition raise within a specified elevation band may often be discovered at a specific site in a mountainous region (Xu et al. 2022). Even along certain transects, the rate of change in water equivalent with elevation might vary dramatically each year. Elevation alone is not a causal element in snow cover delivery, and a variety of additional factors such as slope and aspect must be taken into account to correctly understand distribution patterns (Elder et al. 1991). Major accretions arise on slopes (sheltered from the wind) and in unexpected depressions since snow depth diminishes with distance along a slope orientated in the route of predominant winds. The impact of aspect on the surface energy exchange process and melting has a major influence on snow distribution patterns (Fayad et al. 2017).

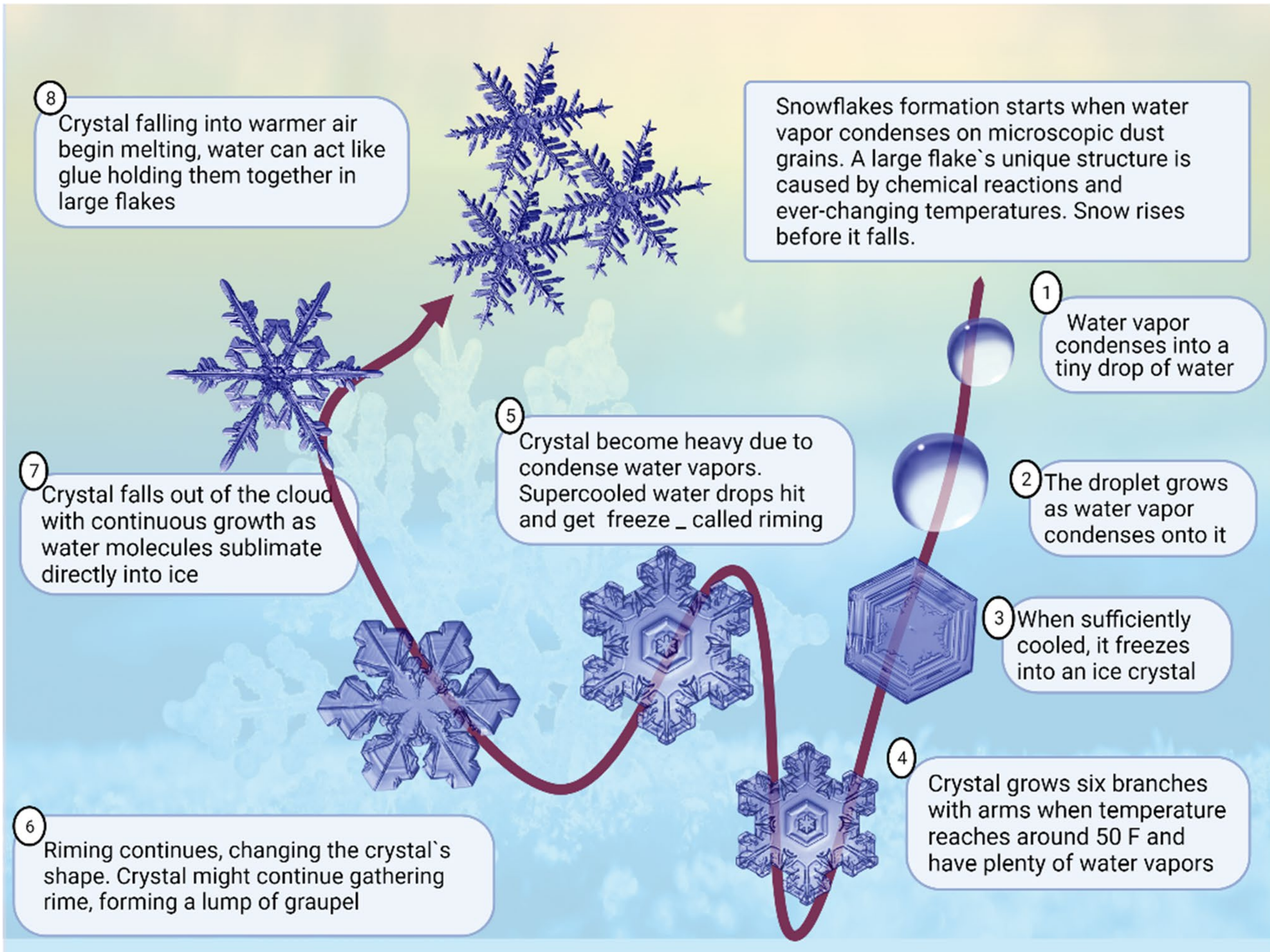


Fig. 6 Demonstration of various stages of snow crystal formation

Climatic factors affecting snow hydrology

Heat and wind are important climatic parameters in addition to precipitation. The temperature of the atmosphere has an impact on precipitation type, melting/freezing, and snowpack internal metamorphosis (Bravo et al. 2008). The new snow's crystal structure and packing degree are determined by the air temperature at the time of the snowfall. It is easy to move light crystals in the snow when temperatures are low, but wet and dense snow at 0 °C is more difficult to move (Vieira et al. 2003). Air temperature typically drops as the altitude rises, while precipitation typically rises, so there is an increase overall in the snow with altitude. Because of this, snowpacks in high-lying areas can be substantial, while there is little or no snow in low-lying areas (Theakstone 2013). Because of the way the wind moves snow around, it has a significant impact on the amount of variation in snow water substitute that occurs. Furthermore, wind plays an important role in regulating the energy transfer between the atmosphere as well as the snow surface, which in turn affects how quickly water evaporates and melts before freezing again. The impact of moving air and impacting particles harden and compact snow during a windstorm (Linares et al. 2020). The literature stated that once the insulating snow cover is gone, the climate will be drastically altered. Snow cover also has a significant impact on climate, hydrology, and biological systems because of its effect on the surface energy balance (e.g., reflectivity), water balance (e.g., water conservation and release), thermal regimes (e.g., insulation), vegetation, and trace gas fluxes (Fig. 7). As a result, the catchment has an uneven or skewed distribution of snow (Bravo et al. 2008). Snow accumulation and ablation are the two main factors that influence mountain snowpack dynamics. There is a balance between snowfall and ablation, with the former being primarily driven by precipitation and the latter being primarily driven by temperature. Both deposition and ablation are influenced by the near-surface wind.

Vegetation and snow hydrology

The impact of vegetation on snow cover dispersal is mediated by its effects on surface roughness and wind speed, and, as a result, on snow erosion. It is often seen that the distribution of snow in a heavily wooded area is less irregular than the distribution of snow in a bare landscape (Morán-Tejeda et al. 2010). The amount of snow that accumulates in a forest is determined by the density of the canopy, the significant percentage of the ground surface that is endangered (shaded) through vegetation, and the types of trees, deposition, the surface energy interaction, and the interception of snowfalls (Rodà 1999). Even though deciduous trees end up losing their leaves in the winter, coniferous forests have a greater capacity for interception. Evaporation and sublimation reduce snowfall, which has a knock-on effect on the energy stability at the ground's surface (Karas 1997).

Locations of MDM zone

The MDM region includes low and medium–high mountains in the northern Mediterranean near the edges of major mountain ranges, such as the Pyrenees and Alps, as well as high mountains in the south. It also includes low and medium-height mountains in the northern Mediterranean near the edges of major mountain ranges, such as the Pyrenees and Alps (Gentili et al. 2015). The climate is the Mediterranean, with warm summers and precipitation concentrated in the winter months, with higher precipitation than elsewhere in the Mediterranean. Crop production is limited in much of the zone because of poor soils and steep terrain, although these, along with vineyards, are significant locally. Extensive grasslands are still common and used for cattle and sheep grazing, although they are in decline with consequent scrub invasion, particularly of broom and Cistus species. Climate change adaptation and mitigation measures are necessary to limit the potential consequences of the supply of ecosystem services to society (Bangash et al. 2013). However, to achieve these goals, coarse quantitative assessments of the consequences must be conducted, the variability of forecasts must be assessed, and regional and local-scale models must be developed to fine-tune the predictions produced at coarse scales (Flaounas et al. 2013). This is expected to have a substantial influence on the physical,

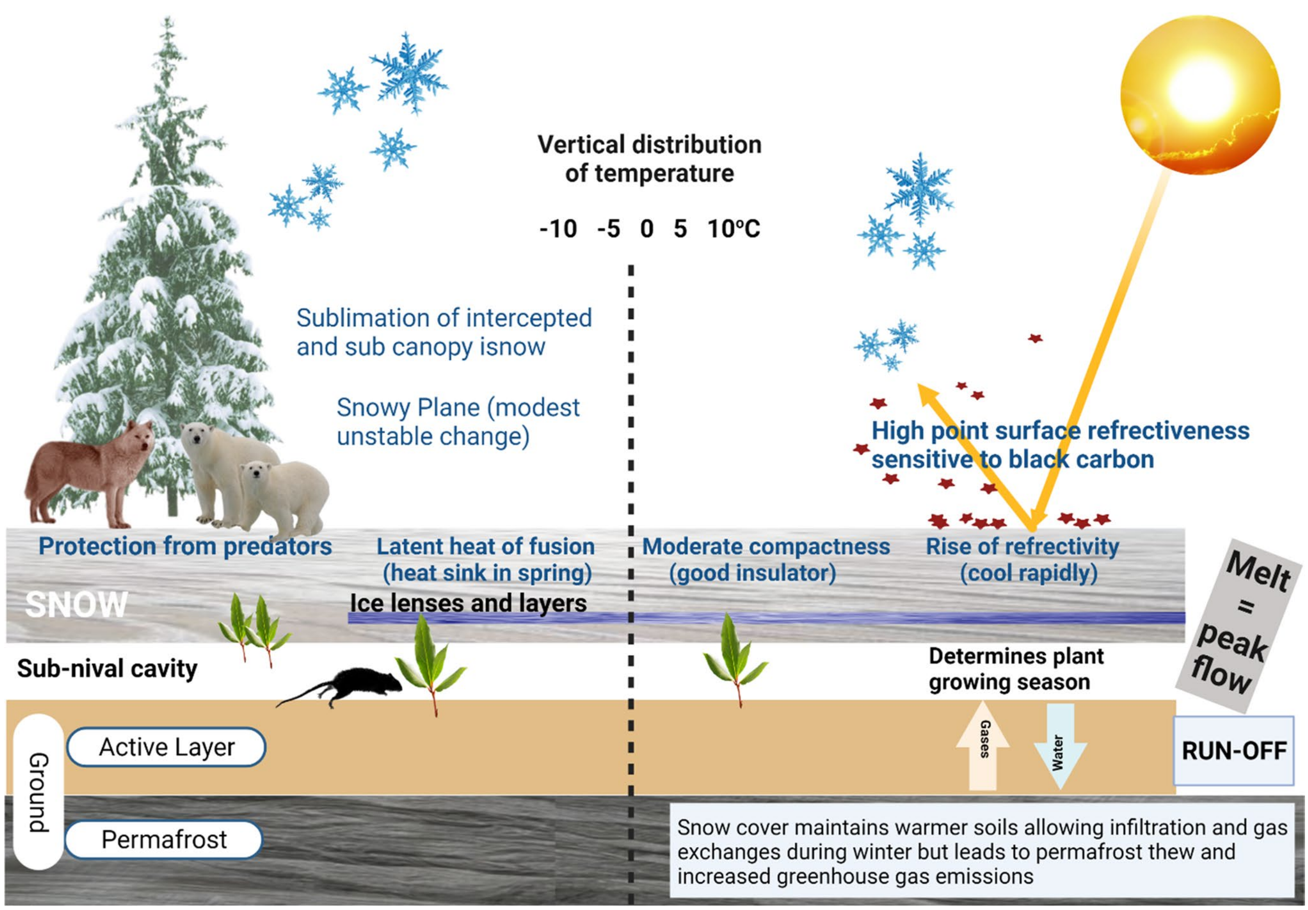


Fig. 7 Schematic representation illustrating the significance of snow to climate, hydrology, ecosystems, and snow

biological, and social realms, as evidenced by projected warming being much larger than that seen throughout the twenty-first century. However, there is still some uncertainty in climate change forecasts, and accounting for this variability is critical. Aside from addressing the technical aspects of this unpredictability, communicating the significance of these uncertainties is a difficulty.

Climatic factors affecting snowfall at MDM region

Snow is an important part of the Earth's surface energy balance. Climate changes, particularly short-term and long-term precipitation and temperature fluctuations, influence the snow regime and the hydrological development of river flow response at the basin and sub-basin scales (De Girolamo et al. 2022). The relationship between climate and flow patterns is critical in mountainous locations, where slight temperature differences, for example, may have an enormous influence on precipitation (which can be rain or snow), snowmelt, and sublimation/evaporation as a result, flow fingerprints might be quite diverse (Assouline et al. 2008). The effects of climate variability on snow and hydrological regimes are more visible in semiarid high mountain regions. Because of their particularly extreme conditions, in which the high variability of annual and seasonal climate regimes is typically propagated to and amplified by river flow (Pérez-Palazón et al. 2018). This is true throughout the MDM regions (Fig. 8), where alpine and semiarid environments coexist. The long-term and medium-term effects of climate variability (i.e., 20- and 100-year time scales) horizons, respectively) hydrological regimes in such locations are being evaluated using various techniques on various spatiotemporal scales (Francioni et al. 2022). The most extremely rapid losses of snow (both in-depth and duration) occur in mid-elevation areas (e.g., sub-alpine zones) and areas with Mediterranean/maritime climates (e.g., the Australian alpine zone), where mean air temperatures are near freezing and snow is primarily temperature-limited (Papadakis 2012). In areas where snowfall is restricted by precipitation (e.g., high northern latitudes), shifts in regional and international atmospheric streamflow are driving increased snowfall. However, over the next 50 years, these regions are expected to experience diminished spring snow and short flowering seasons (Slatyer et al. 2022).

Techniques of snow hydrology at Mountainous region

As snow is kept in a basin intended for a prolonged length of time before entering the runoff process, the manifestation of precipitation in the solid formula (snow), as opposed to the liquid form (rain), causes a change in the drainage basin reaction to the intake of water (Camera et al. 2020). Snowfall and the associated seasonal snow cover are a significant supply of water in many parts of the world. Excessive snowmelt runoff can create floods, but insufficient snowmelt is frequently the precursor to subsequent drought (Michaelides et al. 2018). Snowmelt and accumulation contribute to the hydrological cycle in moderate to cold areas, as well as in tropical highland basins. Snowmelt and accumulation have a significant impact on the runoff regime, resulting in substantial seasonal fluctuation (Senter et al. 2017). Models that take into account hydrologic systems' continuous dynamics were developed in concept in the early 1960s. Using digital computers to model hydrologic processes quantitatively in a watershed within the limits of existing knowledge and computer constraints, the Stanford Watershed Model was the first integrated effort (Sánchez-Canales et al. 2012). During the past several decades, a multiplicity of hydrological modeling has been suggested, and many of them are now being employed for a range of various purposes. Some of them are mentioned in Tables 2 and 3. These models have shown to be useful tools for water management challenges (e.g., flood forecasting, water balance studies, and calculation of design floods), and the growing public responsiveness of environmental issues has provided further motivation to hydrological modeling (Romano et al. 2018). With data for precipitation, air temperature, and potential evapotranspiration, the HBV technique can be used to visualize the runoff process in a catchment. The HBV is an abstract precipitation-runoff model that is used to imitate the runoff progression in a catchment using conceptual precipitation-runoff representations. Snow gathering, snowmelt, real evapotranspiration, retention in soil moisture and groundwater, and discharge from the catchment area are all calculated by the computer model (Ali et al. 2022). Water surface is usually saturated, which results in a serious effect on the bottom echo signal (Zhou et al. 2021b) and high-quality waveform decomposition, as one of the most critical cores of light detection and ranging data processing has become increasingly interesting (Zhou et al. 2021a). Based on the specific characteristics of the modeled output, manual calibration is a protocol wherein the various subjective modifications to classical parameters are made, typically in sequence. It is possible to obtain a good set of estimates for model parameters by manually calibrating the model. According to the number of free variables and the degree of parameter interaction, the method, however, is a tedious and time-consuming process. Furthermore, because of subjective alterations to constraints, the effectiveness of manual standardization is highly dependent on the individual performing the calibration. In order to obtain good parameters with the model, the user must have a significant amount of experience with it. However, even though these parameters are different, they produce nearly identical output results. Given the information for decision-making, it is challenging to expressly assess the

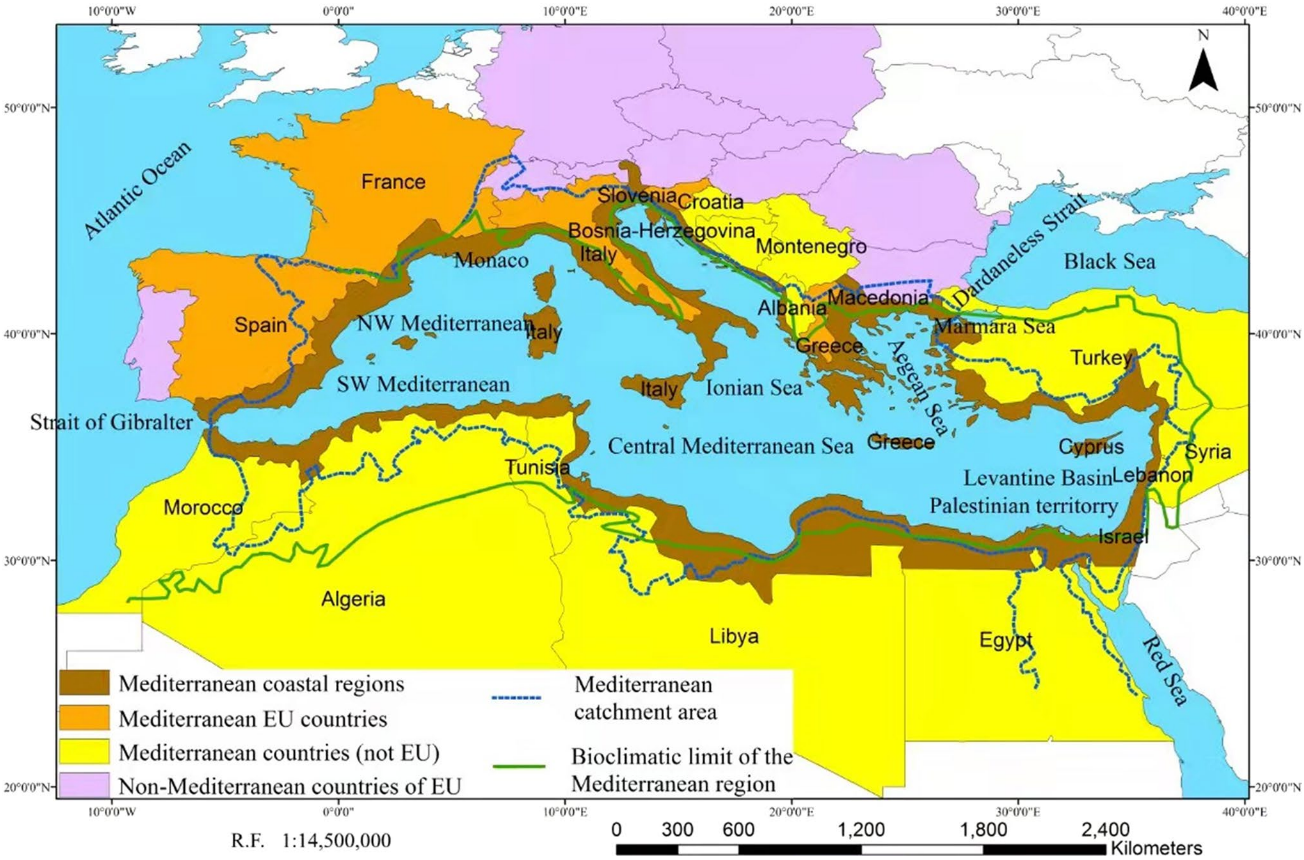


Fig. 8 The map showing Mediterranean coastal regions, Mediterranean EU countries, Mediterranean countries other than EU, and non-Mediterranean countries of EU

Table 2 Some important techniques of snow cover and snowfall measurements in MDM region

Evaluation classification	Approach name	Parameter measured	References
Remote Sensors (B: Satellite)	Natural terrestrial gamma radiation, Visible photography Microwave Radar Multispectral images	Water equivalent Snowcover Snowcover Water equivalent, Snowcover Depth, Snowcover	Bech et al. (2013)
Simple linear measurement	Graduated snow ruler Snowboard	Depth Depth	Molina et al. (2014)
Calorimetric method	Freezing, alcohol solution, or dilution calorimetric methods	Liquid water content (Weight base)	Redjaimia and Rached-Kanouni (2021)
Gravimetric method	Precipitation gauges a. non-recording bucket b. Recording weighing/tipping bucket c. electronic balance Snow samplers (snow tubes) Snow pillows and snow triangles	Water equivalent Water equivalent Snowfall rate Water equivalent, Snowfall rate Depth, Water equivalent Water equivalent	Herrero and Polo (2016)

level of confidence that can be placed in the simulations generated by models. Techniques for automated calibration are those wherein the computer modifies variables in a formulated way while only applying a clearly defined objective function as the only input (Nearing et al. 2005). The application of a programmed model standardization process necessitates the assortment of (a) a calibration given dataset, (b) a goodness-of-fit quantity (objective function),

Table 3 Techniques used for the fortitude of the water content of snow MDM region

Approach/techniques	Performing rule	Advantages	References
Relative permittivity	Capacitance or TDR measurement in snow varies because of an enormous difference in dielectric constants of liquid water and ice	It can be used for determining the density and the wetness of snow by a single measurement	Fiorillo et al. (2015)
Dilution	Reduction in electrical conductivity of a solution because of dilution by snowpack liquid water is measured	The dilution method has received renewed attention and appears quite promising. This type of measurement used NaOH solutions and was adapted to dye solutions	Nikolaidis et al. (2013)
Melting calorimetry	The energy required to melt a mass of ice is recorded when warm water is applied to the snow sample	The melting calorimetric method has been considered a benchmark technique, but because it is cumbersome, rather slow, and requires very precise measurements of temperature, it is not suitable for routine field use	Akitaya (1985)
Freezing-point depression	Freezing-point depression in a salt solution is applied to a snow model and liquid water is measured	The freezing point depression is a function of the pore radius since there also exists a connection between pore water pressure and pore radius	Rudels and Oceanography (2010)
Centrifugal	Centrifugal force is used to disperse the liquid water from ice in a snow sample	The free water in the snow sample was drawn out by the centrifugal force through the cylindrical gauze of the cage and ran down along the sloping wall of the collector	Denis et al. (2001)
Alcohol calorimetry	Temperature depression is measured as the snow sample melts in methanol at 0 °C	It appears to overcome many of these difficulties but still requires sophisticated apparatus which is not readily available	Fisk (1986)
Freezing calorimetry	The energy liberated after the liquid water in snow is frozen by a freezing mediator is measured	One effective method for measuring the liquid water content of snow is freezing calorimetry	Jones et al. (1983)

(c) an automatic measurement exploration procedure (optimization algorithm), (d) a section of the parameter space to be searched (feasible parameter space), and (e) a validation technique, among other things (tests to regulate the degree of uncertainty enduring in the model) (Collados-Lara et al. 2019; Zhou et al. 2021c). The two most major advantages of automated calibration are the speed with which it can be performed and the ease with which it may be used. Automatic calibration has grown more significant as a consequence of the widespread availability of fast and powerful computers, as seen by the enormous variety of computer optimization approaches now accessible. Because the client is not required to intervene during the discovery process for the ideal parameter configuration, automated calibration may be regarded an analytical tool that can be utilized by anybody, even people who are not technically sophisticated.

Existing challenges of snow dynamics at mountainous regions

Seasonal snow can fall in temperate climates at higher elevations as latitude decreases. Snow becomes the major supply of water in these mountainous locations throughout the year, dictating its availability and timing. During the dry season, snow is an important source of water supply for human consumption, irrigation, and the survival of species and ecosystems (Zacharias et al. 2007). Any discussion or management choice about water usage and sustainability in these drought-prone areas must be founded on a correct understanding of snowpack dynamics. A significant study has been conducted on snow dynamics, particularly on the description of the energy balance that drives the many ablation mass fluxes that affect the snowpack (Herrero and Polo 2016). Generalization is more challenging in mountainous locations because energy balance varies with height, aspect, and plant cover since these factors affect local temperature, wind exposure, and shadowing of solar and long-wave radiation (Herrero et al. 2009). In the MDM zone, these climatic variables are subject to the typical erratic weather patterns. Because of this unpredictability, the timing of yearly snowmelt might change from a single typical major springtime melting cycle to many mid-winter partial or complete melting cycles (Vihma 2014). In semiarid settings, snow dynamics so depend on the energy status of the snowpack that effective modeling typically causes physical techniques that compute the energy balance. Many of the issues encountered while verifying models and measuring real evaporation are related to the difficulties of obtaining measurements in harsh winter conditions typical of high mountain regions (Rana and Katerji 2000). To begin with, it is difficult to keep automated ground sensors functioning for long enough to collect large data series over years. The geographical diversity of the snowpack makes it impossible to generate a meaningful assessment of the snow processes, which vary significantly over small distances depending on aspect and elevation (Fayad et al. 2017). Satellite pictures are an excellent source of dispersed data; however, they often only give direct information on the presence or absence of snow. The water vapors exchange between the snow surface and the atmosphere is one of the mass balance fluxes of snow, and it is closely related to the latent heat balance. Depending on the phase of the snow, evaporation and sublimation of water from the snow surface occur alternately (Materia et al. 2022). The rate of evapotranspiration is determined by the vapor pressure gradient between the snow surface and the air, which is primarily controlled by the local wind strength, and therefore by the complex turbulent processes that occur in the boundary layer. As a result, it is one of the most complex fluxes involved in the energy balance of the snowpack, both in terms of measurement and simulation (Boudhar et al. 2016). Numerous studies have been conducted to measure and estimate evapotranspiration losses from snowpacks in wooded and unforested regions (Gaona et al. 2022; Elliot et al. 2016; Casirati et al. 2023). It is fairly unusual in this type of topography to have times of strong wind and low humidity, which cause significant evapotranspiration rates. According to scientists the increased solar radiation and rising air temperatures promote evapotranspiration as long as the snowpack is cool and snowmelt does not dominate the ablation process (Fayad et al. 2017; Chaouche et al. 2010; Vicente-Serrano et al. 2015).

Conclusion

This review paper has provided a comprehensive analysis of the potential consequences of climate change on the productivity of aquaculture and the following implications for the long-term viability of the sector. The aquaculture industry is commonly regarded as the primary solution for managing the ongoing rise in worldwide demand for aquatic products. However, this sector is encountering rising obstacles due to the impacts of human-induced climate change, both presently and in the foreseeable future. The potential effects on aquaculture are expected to comprise both positive and negative outcomes, with the latter outweighing the former in terms of significance. Furthermore, it is crucial to acknowledge that climate change presents a substantial peril to the worldwide food provision. However, the particular risks encountered by aquaculture are expected to differ based on various factors, including geographical or climatic zones, national economy, water environment, production processes, production scale, and the specific species being cultivated by aquaculture producers. To optimize resilience and productivity in the face of climate variability, aquaculture producers must promptly adapt to available alternatives and simultaneously implement necessary modifications in their production practices over an extended timeframe to mitigate associated impacts. The current study provides a thorough analysis that extensively investigates several aspects related to the impact of climate change on hydropower production, aquaculture productivity, and water availability on snow-dominated area. However, it is important to note that there are certain limitations that have been identified, which emphasize the need for more research in important areas. The potential responses of commercially significant species at different life stages to climate change impacts are also unclear in the context of the value chain under discussion. With this knowledge in hand, producers may make informed decisions about whether or not to switch to species that are more resistant to the effects of climate change. However, there is not enough hard data to back up claims that climate change will negatively affect the long-term viability of aquaculture output in the existing literature. Furthermore, the bulk of studies have shown a bias toward investigating sustainability's environmental aspects while generally ignoring its social and economic dimensions. It is crucial to take a holistic approach to predicting the effects of climate change on aquaculture and successfully mitigating these repercussions, especially in light of the growing aquaculture industry and the mounting evidence that climate change is real. Therefore, it is likely that the effectiveness of mitigation and adaptation measures would improve if they were put into practice. However, improvements in research are needed for this project to be carried out successfully, especially in regions that are more vulnerable to negative impacts due to their low adaptability. Therefore, it may be claimed that economies with less income have more to gain from working together internationally.

Authors' Contribution All authors have an equal contribution.

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Data Availability All data are included.

Declarations

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Consent of participate Not applicable.

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Authors and Affiliations

Shan-e-hyder Soomro[1,3,4] · Abdul Razzaque Soomro[2] · Sahar Batool[2] · Jiali Guo[1,3] · Yinghai Li[1,3] · Yanqin Bai[3] · Caihong Hu[4] · Muhammad Tayyab[3] · Zhiqiang Zeng[1] · Ao Li[3] · Yao Zhen[3] · Kang Rui[3] · Aamir Hameed[3] · Yuanyang Wang[3]

✉ Shan-e-hyder Soomro
shanhydersoomro110@hotmail.com

✉ Jiali Guo
jiali.guo@ctgu.edu.cn

✉ Yinghai Li
liyinghai@ctgu.edu.cn

Abdul Razzaque Soomro
soomroabdulrazaque2@gmail.com

Sahar Batool
saharbatool110@hotmail.com

Yanqin Bai
958634286@qq.com

Caihong Hu
hucaihong@zzu.edu.cn

Muhammad Tayyab
dr.mtayyab@outlook.com

Zhiqiang Zeng
zeng_zhiqiang@ctg.com.cn

Ao Li
1461234001@qq.com

Yao Zhen
1054561037@qq.com

Kang Rui
kangrui1440@qq.com

Aamir Hameed
aamir.mphil.geo@pu.edu.pk

Yuanyang Wang
wangyuanyang911@163.com

1 Hubei Key Laboratory of Intelligent Yangtze and Hydroelectric Science, China Yangtze Power Co., Ltd., Yichang 443000, China

2 Department of Energy System Engineering, Quaid e Awam University of Engineering Science and Technology, Nawabshah Sindh 67480, Pakistan

3 College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang 443002, China

4 College of Water Conservancy Science and Transportation, Zhengzhou University, Zhengzhou 450001, China