

Review

# Perspective Impact on Water Environment and Hydrological Regime Owing to Climate Change: A Review

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**Abstract:** This study summarizes reviews on climate change's impact on the water environment and hydrological regime. The results indicate a strong relationship between the climatological parameters and hydrological patterns. This relationship can be determined in two steps: (1) define the variations in climatological factors, particularly temperature and precipitation, and (2) measure the variations in runoff and inflows to streams and river systems using different statistical and global climate modeling approaches. It is evident that the increasing global temperatures have significant positive effects on runoff variations and evapotranspiration. Similarly, the increase in temperature has speeded up the melting of glaciers and ice on hilly terrains. This is causing frequent flash floods and a gradual rise in the sea level. These factors have altered the timing of stream flow into rivers. Furthermore, the accumulation of greenhouse gases, variations in precipitation and runoff, and sea-level rise have significantly affected freshwater quality. These effects are likely to continue if timely mitigation and adaptation measures are not adopted.

**Keywords:** climatological parameters; driving forces; water resources; hydrological regime; modeling approaches



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## 1. Introduction

To make water reserves more sustainable, it is necessary to determine how water quantity and quality would vary. Simulated data from regional models are a standard tool for predicting future water resources. Uncertainty and variability across models typically hinder the downscaling of large-scale water supply system predictions to small watersheds for water resource management decisions [1,2]. There is certain unanimity in stream behavior in different regions [3–5]. However, this is not the case for watershed effects. According to Fatichi et al. [6], natural climate variation may be more critical for variations in stream flow than systematic variability. Land use and anthropogenic variables also play a role in sustainable water resource management [5,7–10]. The determination of the impact of climate on stream flows has been a challenge in previous regional research [11–13].

Climate change affects the hydrological cycle by affecting precipitation, evapotranspiration, and soil moisture. A World Meteorological Organization (WMO) report (2021) indicated that the average global temperature has increased by 0.8 °C since 1880 ([https://library.wmo.int/doc\\_num.php?explnum\\_id=11178](https://library.wmo.int/doc_num.php?explnum_id=11178); Accessed on 5 November 2022). In 2021, the average global temperature was around 1.11 ± 0.13 °C above the level of 1850–1900 but less warm than some recent years. However, additional precipitation is dispersed irregularly across the planet. Certain parts of the globe may experience significant reductions in precipitation or significant seasonal variations. Thus, research on the impacts of climate change on diverse hydrological components is vital [14–16]. Meko and

Woodhouse (2005) observed the Sacramento and upper Colorado river basins [17]. They discovered that the seasonal flow from melting snow in the spring has decreased over time. Different studies confirmed this result by employing complicated statistical approaches and analyzing other basins [18–20].

Climate change alters the overall discharge regime of river basins and modifies the stream and base flow in channel systems. Establishing a multi-model set by considering multiple simulations through a series of global climate models (GCMs) has become a common approach for understanding climate disorders [21,22]. Arnell (1999) determined that climate change significantly impacts flood risk [23]. Previous studies have examined the flooding frequency over climate change using different projected climate scenarios [24,25]. However, the impact of climate change on hydrological regimes and river flows at the catchment scale is different from that at the regional scale [26–28].

Droughts and floods are observed to be a consequence of extraordinary spatial and temporal climate changes in Central America. This has been considered as a variability of climate “hot spots” [16,29,30]. It is critical to understand how climate change affects hydrological cycles and water resources. In this respect, four important drivers (Section 2) forcing climate change and the consequences on water resources have been discussed. This state-of-the-art review incorporates climate change’s impact on water resources and on hydrologic regimes (rainfall–runoff, river-flow system). In addition to the development of hydrological and climate models, downscaling strategies have been proposed to achieve geographical and temporal coverage for regional investigations of hydroclimatic change [30–32]. Fonseca and Santos [33] illustrated that to consider the uncertainties of future scenarios, it has become common practice to use climatic datasets produced by a multi-model group of regional climate models (RCMs) and forced by GCMs as inputs to run hydrological models (HMs). From the global scale to the local or basin scale, the chain “GCM–RCM–HM” is convenient for scenario-based information obtained by dynamic downscaling.

The objectives of this study are (1) to highlight the main driving forces behind climate change at a regional and global scale, (2) to describe the state-of-the-art methods to evaluate climate change and its impact on water and hydrologic regime, and (3) to describe the subsequent effects on water resources and the hydrological regime. A schematic design of the research is shown in Figure 1.

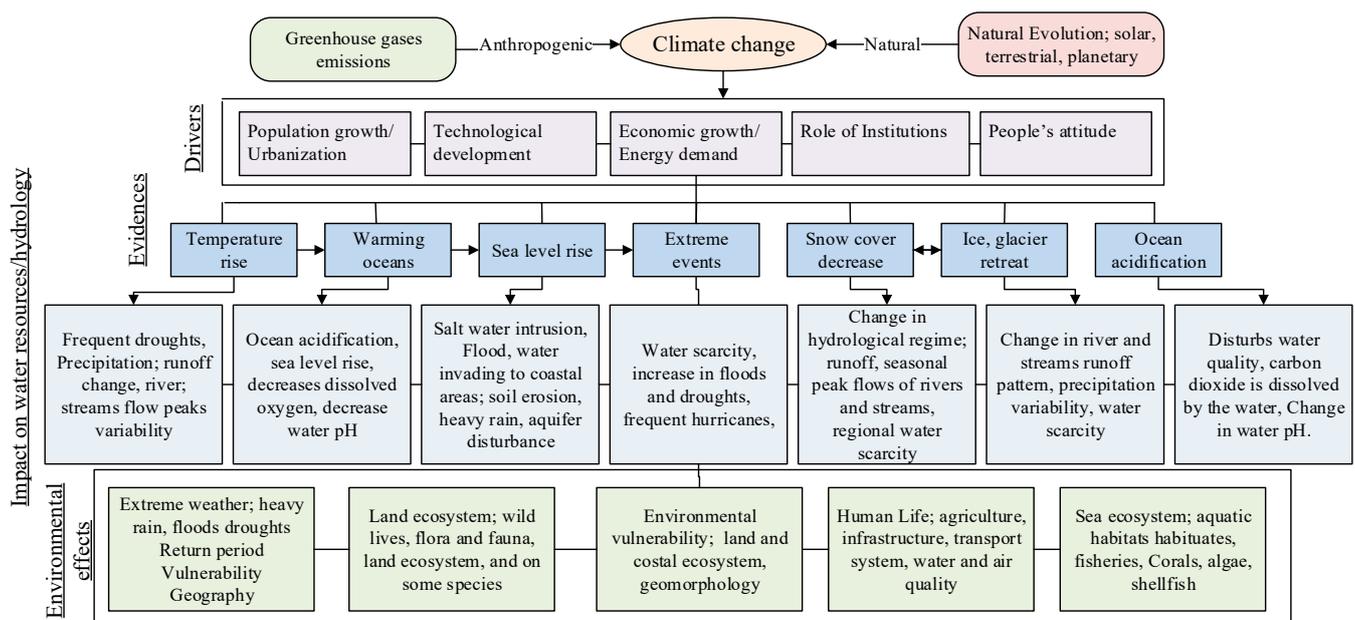
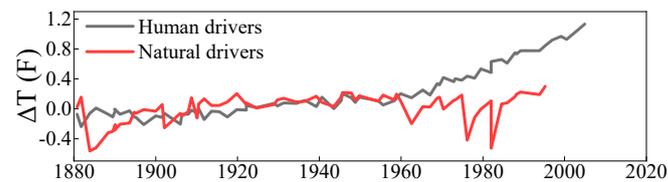


Figure 1. Schematic workflow of the reviews.

## 2. Driving Forces behind Climate Change

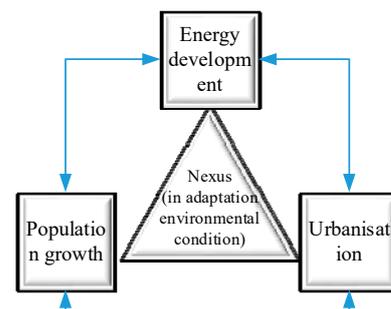
Climate change occurs through a complex set of interactive driving forces. According to the Intergovernmental Panel on Climate Change sixth assessment report (AR6; <https://wg1.ipcc.ch/index.php/ar6/sixth-assessment-report-ar6>; Accessed on 5 November 2022), human activity is the main driving force of climate change, whereas others contend that natural factors are also main causes. This ambiguity is due to inadequate data and methods to understand the phenomenon [34]. Both natural and human forces influence the Earth's temperature, but the long-term trend observed over the last century can only be explained by the impact of human activities on the climate (Figure 2). Natural phenomena such as fluctuations in solar radiation and volcanic eruptions also have an impact on the Earth's temperature. Similarly, Milankovitch cycles and El Niño Southern Oscillation (ENSO) are two other natural phenomena that are likely to change the Earth's temperature. Milankovitch cycles occur as the Earth orbits the Sun, and its route and axis tilt might alter slightly. El Niño Southern Oscillation (ENSO) is a pattern of shifting Pacific Ocean water temperatures (<https://www.metoffice.gov.uk/weather/climate-change/causes-of-climate-change>; Accessed on 26 October 2022). However, they do not describe the warming we have experienced over the previous century. In this regard, the following four important human drivers are discussed in detail. These are also summarized in Table 1.



**Figure 2.** Temperature difference from average due to natural and human drivers (Data source: U.S. Global Change Research Program, Fourth National Climate Assessment).

### 2.1. Population Growth

The human population increased from 1 billion to 7 billion in less than two centuries. Population growth has a direct relationship with the urbanization rate, and the growth of the urbanization rate in the past few decades is unprecedented. The two continents (Europe and Africa) are projected to be 56% and 64% urbanized, respectively, by the middle of this century [35,36]. In adaptation to environmental conditions, the nexus is shown in Figure 3.

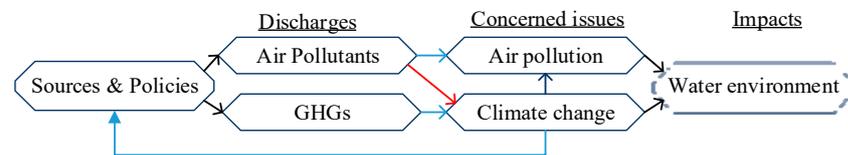


**Figure 3.** Conceptual diagram showing the nexus among population growth, urbanization, and energy development in the context of climate variability.

### 2.2. Technological Development

The evolution of technology has increased the use of fossil fuels, which is a major cause of the increase in the concentrations of CO<sub>2</sub> and other greenhouse gases (GHGs). Understanding the environmental impacts of technological changes is essential for sustainable economic growth. Popp et al. [37] indicated that technology transition has largely affected the environment. They conjectured that advanced technology would escalate air pollution. Technological advancement is the most important part in projecting future impact on global

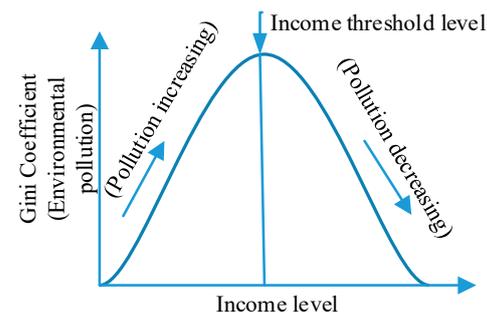
environmental challenges, such as climate vulnerability [37]. Climate change is directly linked to air pollutants. Certain pollutants, such as black carbon and ozone, contribute to global warming by trapping heat in the atmosphere (Figure 4).



**Figure 4.** Connection between air pollution and climate change.

### 2.3. Economic Growth

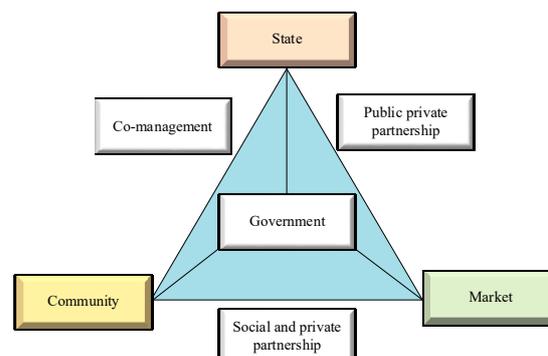
The nexus between economic development (GDP) and environmental sustainability has been long discussed. In particular, environmental objectives such as limiting global warming below a threshold (2 °C or 1.5 °C) have been challenging owing to continuous economic growth [38]. Industrial growth has recently negatively impacted the environment and increased GHG concentrations, toxic pollutants, and chemical spills [39]. Wu et al. [40] hypothesized that income inequality and per capita income have an inverted U-shaped relationship. This indicates that the degree of environmental pollution increases as economic growth approaches the threshold income level and then declines at the same rate (Figure 5).



**Figure 5.** The relationship between per capita income (PCI) and environmental pollution.

### 2.4. Role of Institutions

It is vital to effectively address the role of institutions (particularly local ones) in preparation for adaptation to climate variations if this adaptation is to help the most susceptible social groups. Previous research indicates that the success of adaptation normally depends on the type of existing institutions [41]. Conversely, previous research also highlights the factors that resist adaptation and indicates institutional hurdles as a main cause of ineffective adaptation to climate variation [42–45]. The failure of institutions to adapt to climate change has aggravated their climate vulnerability (Figure 6).



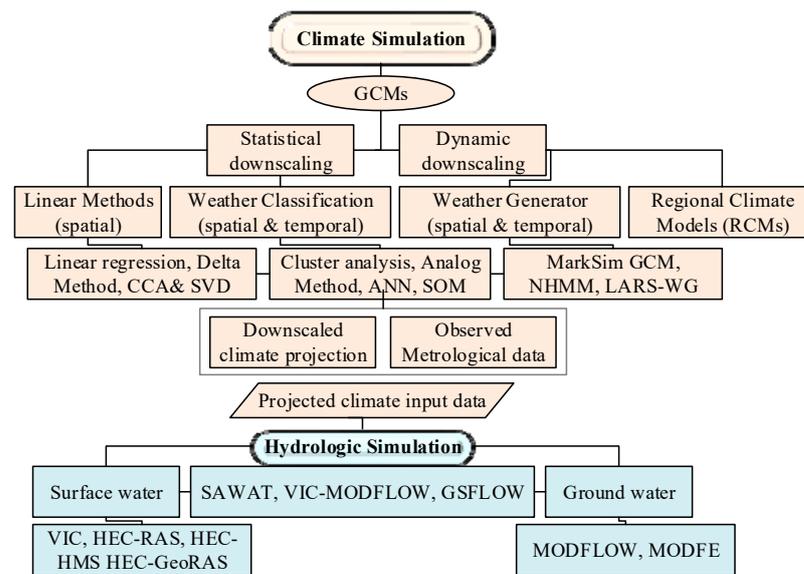
**Figure 6.** Institutional collaboration arrangements considering climate variability (aftser [43]).

**Table 1.** Summary of recent studies on major climate variability-forcing drivers.

Driver	Major Findings	Methodologies/Techniques	References
Population growth/Urbanization	I. Role of urbanization growth on pollutants emissions and energy intensity development	<ul style="list-style-type: none"> <li>Panel data techniques, Mean group estimation</li> </ul>	[35]
	II. Effects of urbanization and energy growth on China's environment	<ul style="list-style-type: none"> <li>Theoretical modeling approaches</li> </ul>	[46]
	III. Population increase and urbanization implications for climate change	<ul style="list-style-type: none"> <li>Statistical approaches</li> </ul>	[47]
	IV. Greatly rising water needs, greenhouse warming	<ul style="list-style-type: none"> <li>Numerical analyses, climate models</li> </ul>	[48] [49]
Technologic development	I. Carbon dioxide emissions in relation with technology change	<ul style="list-style-type: none"> <li>Empirical analyses, dual effects model</li> </ul>	[50]
	II. Possible environmental risks by large-scale seawater desalination plants	<ul style="list-style-type: none"> <li>Conceptual models, statistical approaches</li> </ul>	[51]
	III. Environmental change in response to technology evolution	<ul style="list-style-type: none"> <li>Theoretical and numerical models</li> </ul>	[37] [52]
	IV. Impact of technological advancement on photosynthesis phenomenon	<ul style="list-style-type: none"> <li>Agrometeorological model</li> </ul>	
Economic growth	I. Proposed relation between urbanization, economic development and environmental vulnerability	<ul style="list-style-type: none"> <li>Theoretical and simulation equation models,</li> </ul>	[53]
	II. Public perception against economic growth and environmental pollution.	<ul style="list-style-type: none"> <li>Empirical simulation</li> </ul>	[54]
	III. Developed a relation between CO <sub>2</sub> emissions and economic growth in EU-5	<ul style="list-style-type: none"> <li>Statistical analyses</li> </ul>	[55]
	IV. U-shaped relation between environmental deterioration indicators and per capita income.	<ul style="list-style-type: none"> <li>Empirical methods</li> <li>Linear model</li> </ul>	[56]
Institutions	I. Institutional challenges against climate change to improve agricultural productivity	<ul style="list-style-type: none"> <li>Qualitative methods</li> </ul>	[57]
	II. Efficiency of formal institutions to mitigate climate change impact	<ul style="list-style-type: none"> <li>Conceptual models</li> </ul>	[58]
	III. Facilitating in local level adaptation by the public/private institutional arrangements	<ul style="list-style-type: none"> <li>Qualitative approaches</li> <li>Qualitative and quantitative analyses</li> </ul>	[59] [60,61]
	IV. Effectiveness of local institutions in adaptation to climate variation		

### 3. State-of-the-Art Methodology

To assess the impact of climate on water resources and hydrology, it is necessary to first compute rainfall–runoff, analyze temperature variations, compute population increases within the basin, and then statistically evaluate the results [62,63]. Progressive downscaling approaches that can be used on the temporal and spatial aspects of climate have been used for projected climate scenarios. Statistical downscaling models are relatively computationally effective and have been applied on a large scale to determine the impacts of regional climate change, particularly in hydrological response evaluations [64]. Trzaska and Schnarr [65] categorized statistical approaches as linear methods (canonical correlation analysis), weather classifications (artificial neural network), and weather generators (non-homogeneous hidden Markov model (NHMM)). A conceptual methodological framework is shown in Figure 7.



**Figure 7.** Methodological framework to evaluate climate change impacts on hydrological regimes.

### 3.1. Determination of Variations in Climatological Parameters

Only cortical rain gauges have been used to collect the daily rainfall data [15,62,66]. Then, annual and seasonal rainfall was aggregated. However, there are two methods to identify the temperature and precipitation variations linked to climate change. Let us consider the hypothetical temperature and precipitation variations. Alternatively, data from the general circulation model (GCM) can be utilized [7,9,67]. Temperature is a crucial factor in regional meteorological variation.

GCMs depict connected atmosphere–ocean–ice–land systems. These models show how the atmosphere reacts to varying greenhouse gas concentrations [68–71]. Furthermore, a review of previous studies can help identify the most trustworthy and accurate GCM [72–74]. However, the geographical and temporal resolution of the GCM output data does not fulfill the hydrological model resolution criteria. The spatial resolution (approximately 100–300 km) is insufficient for handling complex hilly terrain and sub-framework scale events such as convective precipitation. Table 2 summarizes the current climate simulation research.

**Table 2.** State-of-the-art methods used to simulate climatological variables.

Climatological Parameters	References	Methods Used	Major Findings
Precipitation	[75] [76] [77] [78]	<ul style="list-style-type: none"> <li>Empirical modeling, theoretical approaches</li> <li>Intensity duration frequency (IDF) curves</li> <li>Simulation modeling approaches</li> <li>Integrated hydrological modeling; HydroGeoSphere (HGS)</li> </ul>	<ol style="list-style-type: none"> <li>Determined the rainfall intensity and average volume diameter</li> <li>Evaluated properties of hourly rainfall</li> <li>Estimated rainfall variation under climate change in different regions of UK</li> <li>Evaluated hydrological system in glacial regions</li> </ol>
Temperature variation	[79] [80] [81]	<ul style="list-style-type: none"> <li>RS and GIS; Landsat-8</li> <li>GCMs through representative concentration pathways</li> <li>ANOVA, and Mann–Kendall trend test</li> </ul>	<ol style="list-style-type: none"> <li>Measurement of temperature and land surface process</li> <li>Evaluated temperature and precipitation variation</li> <li>Pattern of temperature change and rainfall behavior</li> </ol>

Table 2. Cont.

Climatological Parameters	References	Methods Used	Major Findings
Air humidity	[82] [32] [32]	<ul style="list-style-type: none"> <li>Hygrometer, psychrometers, dew-point meter, evaporimeter and atmometer</li> <li>Three-dimensional computational fluid dynamics (CFD) modeling</li> <li>Humidity meter</li> </ul>	<ol style="list-style-type: none"> <li>Air humidity measurements</li> <li>Numerical prediction of air humidity</li> <li>Measured relative air humidity</li> </ol>
Wind speed/wind direction	[83] [84] [85]	<ul style="list-style-type: none"> <li>Linear multivariable model</li> <li>Time series models; mathematical model</li> <li>Time series method; empirical Bernstein copulas</li> </ul>	<ol style="list-style-type: none"> <li>Proposed idea of wind speed estimation</li> <li>Determined mean wind speed per hour</li> <li>Wind direction/wind speed simulation</li> </ol>
Solar/terrestrial radiation	[86] [87] [88]	<ul style="list-style-type: none"> <li>Commercial pyranometers</li> <li>Pyrheliometer, different modeling approaches</li> <li>Plastic scintillation counter</li> <li>High-purity germanium (HPGe) detector</li> </ul>	<ol style="list-style-type: none"> <li>Determined solar irradiance</li> <li>Solar and infrared radiation measurements</li> <li>Determined Terrestrial <math>\gamma</math> radiation</li> <li>Figured out environmental radioactivity</li> </ol>

### 3.2. Hydrologic Simulation

The climatological data of the first step (namely, temperature and precipitation) are then utilized to construct a hydrological model that forecasts fluctuations in hydrological parameters (i.e., infiltration, runoff, and evapotranspiration). Statistical hydrological models can be used to forecast future runoff values based on the characteristics of historical data. Models that characterize the relationship between streamflow runoff and climate factors (through regression or observational analysis) are examples of statistical models used to estimate the impact of climate change [89]. Table 3 summarizes the current rainfall–runoff simulation research.

Table 3. State-of-the-art methods used for rainfall runoff simulation since 2018.

References	Methods	Key Objectives	Major Findings/Contribution
1. [32] 2. [17] 3. [90] 4. [7] 5. [91] 6. [92]	<ul style="list-style-type: none"> <li>Fourier–Stieltjes representation approach</li> <li>Neuro-fuzzy setup for R-R modeling</li> <li>A method based on the integration of an adaptive neuro-fuzzy inference system (ANFIS) with principal component analysis (PCA)</li> <li>SWAT model</li> <li>Neuro-fuzzy setup for R-R modeling</li> <li>Stochastic modeling by using Fourier–Stieltjes representation technique</li> </ul>	<ol style="list-style-type: none"> <li>To evaluate changes in runoff discharge</li> <li>Rainfall–runoff modeling</li> <li>Runoff flow estimation</li> <li>Rainfall–runoff simulation in karst topography, curve number (CN) performance validity</li> <li>Time-based rainfall–runoff relationship</li> <li>Runoff modeling for small watersheds</li> </ol>	<ol style="list-style-type: none"> <li>Found that runoff discharge changes with the characteristic catchment size and rainfall time scale.</li> <li>Rainfall–runoff (R-R) model was calibrated in three various catchments kinds and sizes, and the results were compared with physical models.</li> <li>Emphasized flow routing aspects by challenging the GIS use based on the handling of rainfall input data.</li> <li>Predicted peak flow in Lijiang river basin.</li> <li>Performed streamflow simulations in different land use water basins.</li> </ol> <p>Concluded that:</p> <ul style="list-style-type: none"> <li>Runoff variability increases with rainfall time-scale characteristics variability;</li> <li>Constant mean travel time reduces the runoff discharge variability.</li> </ul>

#### 4. Consequences for Water Resources

Global warming is detrimental to the global freshwater supply. It has altered the overall hydrological cycle and, thereby, altered the quality, quantity, distribution, and timing of the available freshwater [93]. Water shortages are increasing constantly as a result of climate change, river discharge magnitudes and shifts, and population growth dynamics [49,94,95].

Deng et al. [75] illustrated that data from meteorological stations play a vital role in the study on climate variation vulnerability by providing better future climate projections and wet–dry conditions. Zhang et al. [32] examined data from the past 50 years collected from an arid region of the northwest. It was observed that most of the observation stations are established in lower elevation regions, and their number is small in hilly terrains. It is important to understand the hydrology of mountainous regions for long-term watershed management and sustainable water availability. In terms of water resource availability, downstream catchments are intimately linked to variations in precipitation and temperature at the upstream catchments [89,96]. Recent studies on the effects of climate change on water resources are summarized in Table 4.

**Table 4.** State-of-the-art research on climate variability and subsequent effects on water resource.

Response	References	Key Objectives	Impacts on Water Resources and Hydrology	Methods Used	Remarks
Global temperature change	[97] [98] [99] [100]	<ol style="list-style-type: none"> <li>To account for non-climatic influences in assessments of variations in global surface air temperature.</li> <li>Global and hemispheric surface trend analysis, as well as annual temperature anomalies.</li> <li>Prediction of global surface air temperature equilibrium changes.</li> <li>To examine the effects of rising CO<sub>2</sub> levels in the atmosphere on world hydrology.</li> </ol>	<ul style="list-style-type: none"> <li>In 2000, the global temperature is moderately high in the Pacific Ocean.</li> <li>Between 1861 and 2000, the global surface temperature increased by 0.61–0.16 °C.</li> <li>The subsequent reaction of precipitation to global surface–air–temperature change is 2–3 percent K<sup>-1</sup>.</li> <li>In the 2CO<sub>2</sub> experiment, the global and annual mean near-surface temperatures increased by 2.42 K.</li> </ul>	<ul style="list-style-type: none"> <li>GIS Analysis</li> <li>Optimal average technique</li> <li>Atmospheric model based on Hadley Centre’s GEM climate model</li> <li>Model of the overall circulation of the atmosphere Community Climate Model (CCM3)</li> </ul>	The global land surface, ocean, and air temperature have significantly increased over the last two centuries.
Warming oceans	[101] [102] [103] [3]	<ol style="list-style-type: none"> <li>To intensify the shifts in poleward warming due to an increase in greenhouse gases.</li> <li>Ocean acidification’s effects on marine organisms in conjunction with global warming.</li> <li>The role of non-genetic and genetic inheritance in determining organisms’ adaptive capability in a warming ocean scenario.</li> <li>The link between ENSO Modoki and conventional ENSO and the frequency of tropical cyclones (TCs) in the western North Pacific.</li> </ol>	<ul style="list-style-type: none"> <li>Accelerated warming in the Southern Ocean or a strong poleward spread of warmth as emissions increase.</li> <li>Reductions in survival, calcification, development, and abundance of marine creatures as a result of ocean acidification.</li> <li>Transgenerational effects could be extremely effective at mitigating the effects of ocean warming if temperature increases gradually.</li> <li>The effect of ENSO Modoki on TC activity should be considered when predicting TC activity in the context of global warming or when the region’s WNP negative heating anomaly is removed.</li> </ul>	<ul style="list-style-type: none"> <li>The Hadley Centre’s Sea Ice and Sea Surface Temperature datasets are examples of observed SST datasets.</li> <li>Meta-analysis</li> <li>Transgenerational plasticity (TGP) and quantitative genetics</li> <li>Simple baroclinic model</li> </ul>	Warming oceans lead to sea-level rise; moreover, hot oceans carry more CO <sub>2</sub> , which causes seawater to become more acidic.

Table 4. Cont.

Response	References	Key Objectives	Impacts on Water Resources and Hydrology	Methods Used	Remarks
Shrinkage ice and glacier retreat	[104] [105] [106] [105]	<ol style="list-style-type: none"> <li>1. Mass balance study of four Kangri Karpo glaciers.</li> <li>2. Acceleration of glacier retreat in non-polar areas over the twentieth century.</li> <li>3. Affected South Asian Rivers by Himalayan Glacier Melt</li> <li>3. Earth sciences and water resources include studying the hydrological cycle and snow and ice.</li> </ol>	<ul style="list-style-type: none"> <li>• The study discovered a significant loss of ice mass and rapid glacier retreat since the 1980s.</li> <li>• There has been widespread observation of broad glacier retreat that has been significantly more rapid since the mid-1970s. Due to increase in monsoonal precipitation and rise in temperature, the flow along the Himalayas arc increases by enhanced glacier ice melt.</li> <li>• Overall statement of prevalent glacier retreat is significantly quicker since the mid-1970s.</li> </ul>	<ul style="list-style-type: none"> <li>• Observation of glacier mass combined with detailed study</li> <li>• Physical processes (melting and sublimation)</li> <li>• Rating curve method, bulk hydrograph, cross-sectional measurements are being used.</li> <li>• Modeling studies, field measurements</li> </ul>	A significant ice and glacier retreat have been seen since the 1970s.
Sea-level rise	[107] [108] [109] [110]	<ol style="list-style-type: none"> <li>1. Relationship between global sea level variation and global mean temperature.</li> <li>2. The economic costs of climate change and benefits of adaptation at the city scale.</li> <li>3. The impact of rising sea levels on predicted storm surge water levels and frequency.</li> <li>4. Estimating SLR to estimate coastal recession.</li> </ol>	<ul style="list-style-type: none"> <li>• Sea level is rising from (75–190) cm for period 1990–2100.</li> <li>• Rising sea levels would exacerbate flood hazards.</li> <li>• It is based on an empirically determined link between temperature changes and sea-level rise. The only climate change impact that is considered is sea-level rise.</li> </ul>	<ul style="list-style-type: none"> <li>• Climate Model, R07</li> <li>• Rising sea levels increase flood risk.</li> <li>• An empirical link between temperature and sea-level rise underpins it.</li> <li>• Simple, deterministic method (Bruun rule), PCR model, probabilistic model, Dune erosion model</li> </ul>	A substantial nexus between temperature change and sea-level rise has been seen. From the late 19th century, the sea level rises significantly, which is likely to exacerbate hydro-hazards.
Extreme events	[111] [112] [113] [114]	<ol style="list-style-type: none"> <li>1. Impacts of changing extreme weather and climate events.</li> <li>2. In the absence of major anthropogenic warming, the best technique to analyze possible climate change impacts on disaster losses.</li> <li>3. Weather and climate extremes changes (frequency and temperature distribution).</li> <li>4. Changes in climatic extremes owing to anthropogenic CO<sub>2</sub> and aerosol emissions.</li> </ol>	<ul style="list-style-type: none"> <li>• Extreme occurrences will become more often, and societal infrastructure will become increasingly vulnerable to weather and climatic extremes.</li> <li>• It has been determined that anthropogenic climate change has had a major impact on economic losses caused by various weather-related natural disasters around the world.</li> <li>• It will have an impact on society and the ecosystem.</li> <li>• A rise in heatwave episodes across terrestrial areas is likely.</li> </ul>	<ul style="list-style-type: none"> <li>• Climate model studies</li> <li>• Systematic analysis or studies</li> <li>• Climate model, statistical characteristics</li> <li>• Dynamical or statistical downscaling coupled with atmosphere–ocean general circulation models.</li> </ul>	In extreme weather events, hydro-hazards (i.e., floods and droughts) are more likely to occur now and in the future.

Table 4. Cont.

Response	References	Key Objectives	Impacts on Water Resources and Hydrology	Methods Used	Remarks
Ocean acidification	[115] [102] [107] [116]	<p>1. Additional strategies to mitigate the potentially harmful effects of climate change in coastal marine systems are being developed.</p> <p>2. Occurrence of changes in marine ecosystems are caused by global warming and acidification.</p> <p>3. Global changes in parameters such as temperature, currents, and sea level fluctuation on coral reefs due to ocean acidification have unknown effects.</p> <p>4. Productivity and the relationship between corals and their symbiotic dinoflagellates. Reduced calcification rate of framework builders is a major threat to coral reefs. Examining the effects of bleaching state on organic productivity, which is expected to be influenced, and comparing the patterns of organic responses with effects on calcification rates.</p>	<ul style="list-style-type: none"> <li>It has been observed that climate shifts may result in large-scale community alterations.</li> <li>Why ocean acidification may reduce biodiversity and profoundly alter ecosystems; therefore, understanding how it affects creature fitness, sustenance, and success is crucial with this research approach.</li> <li>It causes bleaching (pigmentation loss) in two important types of reef-building animals, as well as decreased productivity in coral reef builders.</li> </ul>	<ul style="list-style-type: none"> <li>Physiological, morphological, and behavioral effects and transport processes</li> <li>Conceptual model, physiological principles</li> <li>Intertidal and subtidal SCUBA surveys, short-term laboratory experiments</li> <li>Effects of experimental ocean acidification</li> </ul>	Changes in pH due to ocean acidification are altering water ecosystems and functions.
Decrease in snow cover	[117] [118] [119] [120]	<p>1. In the Swiss Alps, the duration of snow cover is rapidly decreasing, as is the maximum HS and the frequency of DSP.</p> <p>2. Multi-dataset calibration using a quantile mapped ensemble of climatic states to generate watershed discharge scenarios. Multiple datasets were used to calibrate the hydrological model.</p> <p>3. The impact of four statistically determined coming climate events on water resources toward the end of the twenty-first century.</p> <p>4. Spatial and temporal variability of snow cover and snow water equivalent over Eurasia.</p>	<ul style="list-style-type: none"> <li>The snowpack reduction is most likely associated with the elevation increase in temperatures.</li> <li>The uncertainty in the glacial runoff was considerably reduced by linking the multi-dataset calibration.</li> <li>Due to the rising temperatures brought on by a changing climate, annual peak runoff occurs sooner.</li> <li>Temperature trends that vary from year to year or season to season</li> </ul>	<ul style="list-style-type: none"> <li>A bootstrap method</li> <li>Use of daily/annual HS data, filtering procedure</li> <li>HBV-light elevation models (DEMs), analysis of variance (ANOVA)</li> <li>GCM downscaling, future snowpack estimation, and runoff simulation</li> <li>NSIDC EASE-grid weekly SCE and monthly SWE data reliability and possible uncertainties</li> </ul>	Snow melting has altered peak runoff timing, and the uncertainty in the glacial runoff is significantly reduced.

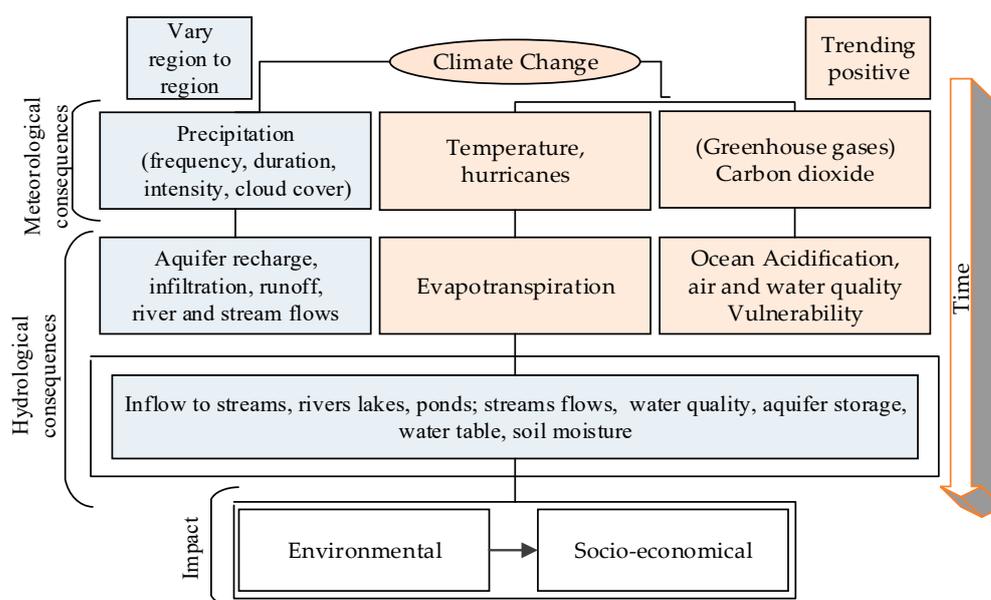
As global temperatures rise, more water evaporates, increasing atmospheric water vapor and more frequent, heavy, and severe storms in the coming years [97–100]. Hotter oceans can hold more CO<sub>2</sub>, causing seawater to become more acidic [101–103]. Rising temperatures cause alpine glaciers to melt, changing water availability to cause flooding [104–106]. Initially, when the glacier melts, more water flows downhill away from it. However, as the glacier melts, the water supply will be reduced, and farms, villages, and

towns may lose an essential water source [107–110]. Moreover, extreme weather events can also have an impact on water security. Problems can emerge from too much water, such as flooding, or too little water, such as droughts. Water resources will therefore decline as the seasonal snowpack declines and glaciers disappear. Furthermore, rapid snow melt in the spring can cause flooding, whereas delayed melting of snow and ice allows water to penetrate the ground [111–114].

#### 4.1. Impact on Hydrological Regime

Regional hydrological regimes have been altered or would be transformed because of climate change. Previous research has shown the influence of climate change on surface and groundwater, both at present and in the future [121,122]. Understanding river flow patterns is critical to watershed management and long-term sustainability. Pumo et al. [123] observed that the hydrological regime influences the form and behavior of river basins. However, meteorological factors (such as precipitation frequency and intensity) as well as seasonality influence streamflow regimes. Climate change influences precipitation intensity, magnitude, timing, and frequency [115]. According to NASA's latest assessment, storm-affected areas would experience more precipitation, whilst locations further from storm tracks are likely to see less precipitation and an increased risk of drought. In the future, climate change would have a significant impact on streamflow systems worldwide.

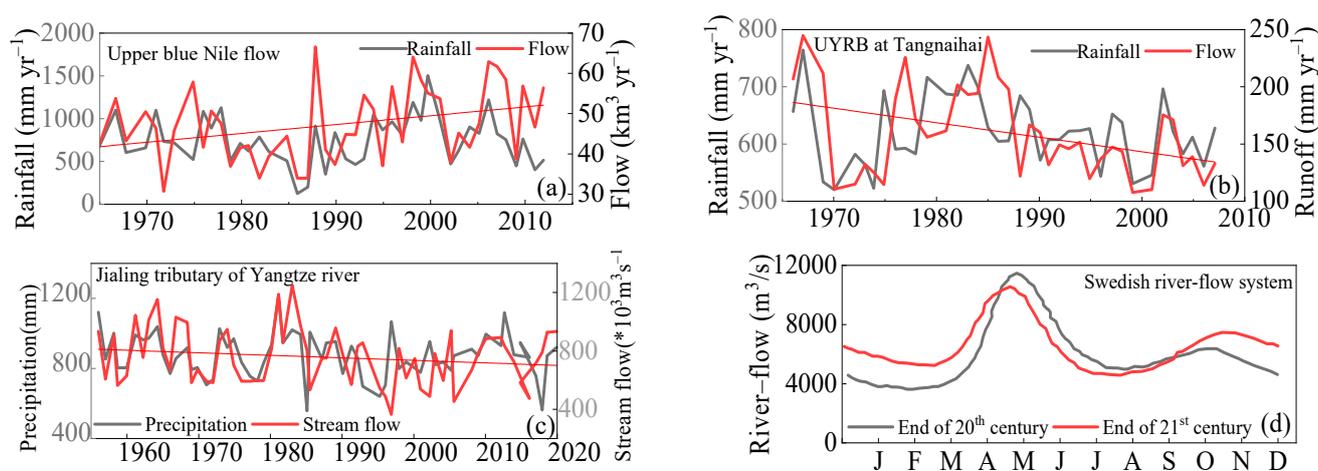
Generally, the critical global projections from the prior discussions are: (i) by 2100, average global temperatures are anticipated to rise by 0.5 °F to 8.6 °F, with a significant increase of at least 2.7 °F across all scenarios except the areas where greenhouse gas emission mitigation strategies are most active; (ii) precipitation patterns and storm occurrences, including rain and snowfall, are also likely to shift. Some of these changes, however, are less clear than those linked with temperature. According to projections, future precipitation and storm changes are expected to differ by season and region: (iii) future projections of sea-level rise vary from region to region. Still, the worldwide sea level is expected to increase faster in the next century than in the previous 50 years; (iv) glaciers are predicted to continue shrinking in size. The degree of melting is likely to accelerate further, contributing to sea-level rise; (v) the pH of the oceans is likely to fall even further by the end of the century as CO<sub>2</sub> concentrations rise in the near future; and (vi) the occurrence, magnitude, and duration of extreme events (i.e., floods and droughts) will increase in the future. Figure 8 shows the trends of the hydro-climatic variables.



**Figure 8.** Conceptual framework showing relative variations among hydrological and climatological variables in the climate change scenario with respect to an increase in time.

#### 4.2. Impact on River-Flow System

The impact of climate change on river-flow systems varies from region to region. The upper Blue Nile shows positive trends in the 30-year moving averages of the mean and standard deviation of annual river flow and annual rainfall (Figure 9a) [124]. Conversely, the Tangnaihai tributary of the upper Yellow River basin (UYRB) shows a significant decrease in a runoff with the rate of  $-11.6$  mm/decade (Figure 9b) [125], and Jialing tributary of the Yangtze River basin shows a negative trend in average annual streamflow with a change rate of  $1572.3$  ( $\text{m}^3/\text{s}/\text{a}$ ) (Figure 9c) [126]. Similarly, the flow peak (mean annual maximum flow) was found to be lowered by 15% across Sweden, and the annual redistribution of overall river flow to the sea accounts for 19% on average. Surprisingly, the same changing pattern is shown for the projected climate of the same region (Figure 9d) [127].



**Figure 9.** (a) Yearly rainfall time series based on a weighted average of rainfall stations and annual stream-flow time series averaged between June and May. (b) Yearly changes of rainfall and runoff in 1966–2009. (c) Yearly changes of precipitation and streamflow in 1965–2020. (d) Projected climate change (using a climate model ensemble) for 20th and 21st centuries.

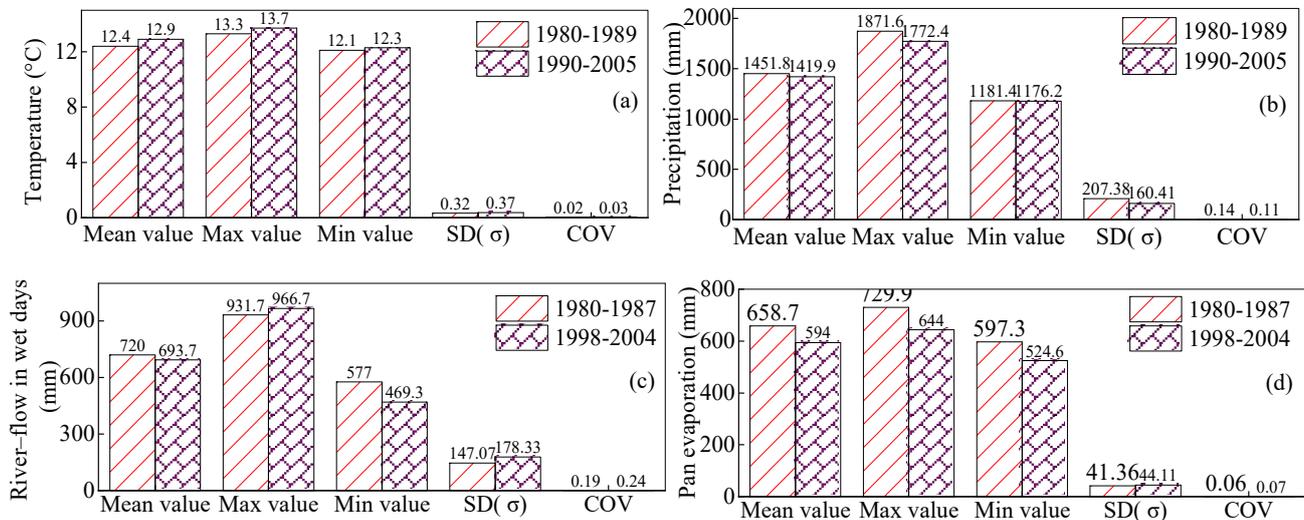
### 5. Worldwide Examples Showing Hydrological Impacts Caused by Climate Change

**Example 1: Qingyi River watershed, China.** The Qingyi River watershed is a pronounced hilly region upstream of the Yangtze River in China [128]. Climate change influences the hydrology of watersheds, particularly surface runoff variability. The water levels reduced dramatically from 1980 to 2004 [129–131]. Annual precipitation decreased significantly. Considering climate change, Liu et al. [132] concluded that increased precipitation on the western side of the watershed increases annual surface runoff, base flow, and evapotranspiration by 13%, 8.7%, and 1.1%, respectively. Furthermore, in the central region, evapotranspiration and surface runoff decreased significantly in the southeast. However, the increase in base flow was less, owing to variations in temperature and precipitation.

Evapotranspiration increased by 0.2% in the central region, owing to the substantial decrease in precipitation. The high temperature increased evapotranspiration. Moreover, evapotranspiration decreased by 3.1%, notwithstanding increased temperatures and precipitation to the northwest of the watershed. The variations in temperature, streamflow, and evapotranspiration are shown in Figure 10.

**Example 2: US Mid-Atlantic region.** The Mid-Atlantic is likely to show an increase in both temperature (T) and precipitation (P). However, the magnitude and direction of the increase varies between GCMs [131,132]. Precipitation (P) varied negligibly across the watersheds of the region, with a 1% coefficient of variation (COV) annually and seasonally [133]. The annual precipitation depth did not vary. However, the annual humidity and fall transition duration varied, and the non-growing and growing seasons were drier [134]. The watersheds exhibited similar variations in all the scenarios. Thus,

evapotranspiration was affected more by temperature, humidity, cloud cover, and wind speed. The statistical tests showed a positive variation of 8% in temperature.



**Figure 10.** Statistics for (a) annual temperature (T), (b) precipitation (P), (c) and streamflow in wet season in the Qingyi river basin and (d) evaporation at Pengshan meteorological station for different scenarios (Data source; [130]).

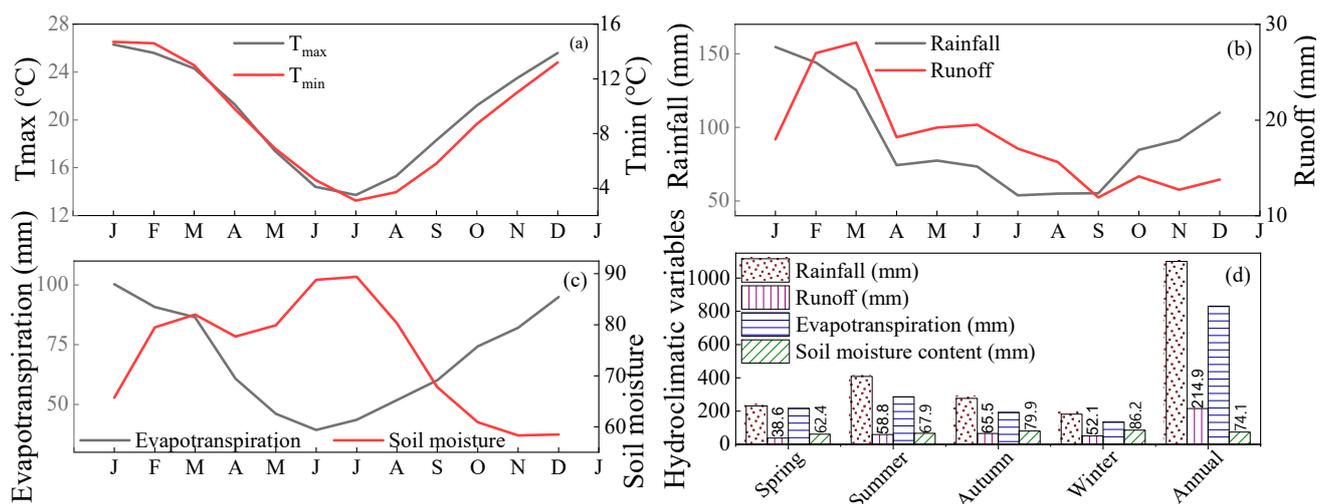
The water yield decreased in all the watersheds during the non-growing season. The parameter that varied the most was runoff, with COVs of 7%, 23%, and 26% in spring, growing season, and fall transition, respectively. The average annual runoff in the ten Mid-Atlantic watersheds was 1.05 mm/day, with a COV of over 9%. The statistics for the Cub and Cedar watersheds are shown in Table 5.

**Table 5.** Statics for seasonal variability of precipitation (P), runoff (R), evapotranspiration plus change in storage (ETDS), and water yield (WY) for Cub watershed (Data source; [133]).

Time Periods	Statistic	P (mm)	R (mm)	ETDS (mm)	Cub Run WY (mm)	Cedar Run WY (mm)
Annual	Mean	3.05	1.11	1.98	0.35	0.32
	Median	2.99	1.11	2.02	0.33	0.29
	SD	0.35	0.47	0.24	0.10	0.12
	COV (%)	17.3	42.4	12.2	27.9	38.9
Non-growing season	Mean	2.53	1.44	1.11	0.55	0.57
	Median	2.38	1.37	1.09	0.57	0.58
	SD	0.68	0.65	0.41	0.17	0.23
	COV (%)	26.8	45.1	37.1	29.8	40.7
Spring transition	Mean	3.02	1.61	1.45	0.51	0.48
	Median	2.95	1.39	1.52	0.46	0.46
	SD	0.99	0.85	0.49	0.16	0.21
	COV (%)	32.7	52.6	33.5	31.5	43.0
Growing season	Mean	3.34	0.75	2.62	0.21	0.15
	Median	3.27	0.61	2.58	0.18	0.13
	SD	1.19	0.54	0.62	0.11	0.11
	COV (%)	35.5	71.7	23.8	54.1	73.3
Fall transition	Mean	3.19	0.92	2.26	0.25	0.17
	Median	3.39	0.86	2.18	0.22	0.13
	SD	1.09	0.79	0.64	0.15	0.17
	COV (%)	34.2	85.9	28.1	60.3	95.1

**Example 3: Manning River basin, Australia.** Australia is referred to as the continent with the most variable climate [81]. This has had a significant impact on the country's water resources and ecosystem health. The Manning River basin is located on the central north coast of New South Wales and has a catchment area of 6630 km<sup>2</sup>. Zhang and Huang [135] determined that the mean annual temperature and mean evaporation of Manning River basin for 1977–2016 were 14.9 °C and 1305 mm, respectively. The basin receives an average rainfall of 1052 mm and has a runoff coefficient of 0.2.

Zhang et al. [32] determined that temperatures would be higher in the 2080s than in the 2040s on seasonal and monthly timescales. The largest median would increase by 1.6 °C by November 2040 and 3.8 °C by September 2080 for maximum monthly temperatures. In contrast, the lowest median temperature increase would be 1.1 °C by March 2040 and 2.5 °C by February 2080. On a seasonal scale, temperatures are likely to increase (a median increase of 1.5 °C by 2040 and 3.4 °C by 2080) in spring for both periods. Meanwhile, these are likely to decrease in the autumn of 2040 (1.3 °C) and summer of 2080 (2.9 °C). In addition, the projected largest runoff (monthly) is likely to shift from March to February compared with the baseline. The projected maximum monthly increase in runoff would be 6.9% in November 2040 and 31.1% in February 2080. Meanwhile, the maximum monthly decrease would be −16.7% in June 2040 and −205% in July 2080. Figure 11 illustrates the variability of hydrological and climatological variables in the Manning River basin.



**Figure 11.** Monthly (a–c) and seasonal and annual (d) variation in climatological and hydrological variables in Manning River basin in the period of (1977–2016) as a baseline [32].

## 6. Evaluation and Management of Water Resources

According to the aforementioned analysis, effective management of water resources is urgently required [30,136,137] against the stress of climate change, unequal temporal and spatial distributions, pollution, and overexploitation of water reserves [21,135–142]. Based on environmental risk assessments [20,104,143–149], resource evaluation management methods [7,150–152] should be applied to ensure the efficient utilization of water resources [153–155]. To save time and energy, it is necessary to switch from traditional to modern ways. In practice, the heat flow method or the thermal storage volume approach based on a shallow geothermal survey is frequently used to estimate the quantity of water resources. [156–159]. Shallow geothermal surveys including geological and geothermal field surveys partially follow conventional geothermal survey methods such as field investigations [160–162], drilling surveys, and laboratory or field tests [163,164]. Certain new innovative evaluation systems need to be proposed to replace the conventional approaches adopted in water resource management. This is because the water resource investigation's objective and task, considering climatic change, differ from the conventional ones.

Water resource monitoring and prediction are two significant aspects of risk evaluation [165–167]. Geographical information systems (GISs) and artificial intelligence (AI) are two remarkable technologies presently available in the field of resource evaluation and management. Assessments of water resource potential are based predominantly on GIS data. Many AI technologies can be used for resource evaluation and management, including the analytic hierarchy process (AHP) approach [145,168], deep learning neural networks, and long short-term memory (LSTM) [150–152]. Prior investigation is necessary to ensure the suitability of a specific AI method for the problem at hand. Therefore, it is important to consider the special characteristics of related problems [169]. The application of AI methods to water resource evaluation will become an important research area in the future [170–172].

## 7. Conclusions

This study summarized the impacts of climate change on water resources, hydrological patterns, and the key drivers of climate change. The review results indicate that climate change affects water resources more adversely than other deteriorating factors. The climate change scenarios affect evapotranspiration, precipitation, base flow, inflow to streams and rivers, and streamflow. Based on the above reviews, the main conclusions of this study are as follows:

- (1) The fast-growing population has increased the rate of urbanization, economic growth, and technological development. This is causing a significant increase in the concentration of GHGs in Earth's troposphere because of inadequate mitigation and adaptation measures. The temperature of the planet has increased owing to the increase in CO<sub>2</sub> and other GHGs. Climate variability is a key consequence of abrupt increases in temperature and GHG emissions. It affects water reserves and the overall environment. However, a lack of mitigating institutions and people's lack of environmentally friendly attitudes have increased climate vulnerability.
- (2) The variation in hydrological patterns and the water crisis are measured in two steps: (1) assess regional and local variations in climatological variables (i.e., temperature, precipitation, air humidity, and wind speed), and (2) evaluate the resulting pressure on hydrological parameters (i.e., runoff, inflow to streams and rivers, streamflow, base flow, and soil moisture) and water resources.
- (3) The literature review revealed that the temperature of Earth has been increasing regularly. The average global temperature has increased by 0.8 °C (1.4 °F) since 1880. This increase has adversely affected Earth's overall climate by causing frequent and abrupt extreme events (such as droughts, floods, hurricanes, tornadoes, and acid rain). However, the precipitation rate (particularly rainfall) has decreased in certain local and regional scenarios. This may cause freshwater scarcity in the future.
- (4) There is a strong relationship between the climatic variables and hydrological patterns. Increases in temperature and decreases in precipitation reduce surface runoff. This would result in low inflows to streams and rivers. In addition, soil moisture and infiltration rates would decrease. This implies that groundwater aquifers are not being recharged and that aquifer water budgets have been disturbed, thereby lowering the groundwater table. However, the increase in temperature has enhanced the melting rate of snow, ice, and glaciers at high altitudes. This has resulted in an average annual increase in sea level by 1.2–1.7 mm since 1900 and by 3.2 mm since 2000.
- (5) Climate variability has also caused deterioration in surface and ground water quality. Saltwater from the seas intrudes into fresh aquifers in coastal areas, owing to the decrease in groundwater level and increase in sea level. Saltwater intrusion affects the quality of groundwater. Similarly, in certain scenarios, freshwater quality has also been disturbed by acid rain caused by the high concentration of CO<sub>2</sub> in the atmosphere.

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