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Omid Bozorg-Haddad *Editor*

Climate Change in Sustainable Water Resources Management

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Preface

One of the most important and complex concerns of the present and future centuries is climate change. The phenomenon of climate change is not confined to our era, and evidence indicates that the Earth has faced climate change in different periods, although this issue in the present era attracts the attention of many of the world's scientific and political societies. Any change in the climate can be due to natural climatic change or the result of human activities. Such a change can occur in temperature, rainfall, humidity, weather patterns, wind, radiation, and other climatic variables. However, even a small change in the climate conditions can lead to tangible changes in hydrology and the sensible water resource systems. The impacts of climate change on water resources include the changes in rainfall and runoff patterns, sea level, land use, water demand, and many other aspects. The negative effects of this phenomenon on water resources can cause irreparable damages. Thus, identification of these effects and their reasons is essential. Investigation of such changes can facilitate the studies on a series of hydroclimatic, economic, and social problems such as droughts, floods, foods, and human migration.

In this book, to gain a comprehensive understanding of climate change, water experts can benefit the content of three separated sections according to their background. In the Part I, basic concepts of climate change, its natural and anthropogenic drivers, and its effects on water resources, from both quality and quantity aspects, are discussed. Results of the accredited researches show that greenhouse gases take the first place in the consistent growth of the radiative forcing and the Earth's energy level since the 1950s. Increasing temperature and decreasing precipitation have reduced the discharge of surface runoffs in different parts of the world, which leads to a decline in the level of groundwater aquifers. In Part II, climatic scenarios and IPCC reports are discussed. In order to analyze future climate conditions in water resource studies, we explain several categories of climate models, including Energy Balance Models (EBMs), radiative-convective models, and General Circulation Models (GCMs). Being most comprehensive, GCMs have been widely applied for future climate change projections using different scenarios of population growth, greenhouse gas emissions, and land-use changes. As the final step in climate change studies, downscaling method, including statistical and dynamic, is explained thoroughly. The last Part focuses on water resource modeling under clime change conditions. To broaden the viewpoint of experts on available mitigation and adaptation measures, numerous case studies of all continents on the earth are presented. Generally, this book is arranged in a manner to meet the need of readers with diverse background through choosing the most appropriate section.

Karaj, Iran Omid Bozorg-Haddad

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Chapter 1
Overview of Climate Change in Water Resources Management Studies

Omid Bozorg-Haddad, Saba Jafari, and Xuefeng Chu

1.1 Introduction

In general, climate change takes place whenever the climate condition in a region changes compared to its long-term behavior (Karamouz and Araghinejad 2005). The rise of global temperatures and the changes in precipitation patterns are the effects of climate change, which lead to a decrease in streamflow. Global climate change in the future also is a threat to the world's water resources, which makes it difficult to access these resources.

Mirza et al. (2003) examined the impacts of global warming and climate change on the possibility of flooding of the Ganges–Brahmaputra–Meghna (GBM) river basin in Bangladesh using four General Circulation Models (GCMs). The output of the GCM models was used as an input of the Mike11-GIS hydrological model. Their results showed an increase in the average of maximum discharges in the GBM, which potentially led to flooding.

Rosenzweig et al. (2004) assessed the influences of the changes in agricultural water demand and the availability of water induced by climate change on irrigation reliability using a series of models, including the Water Balance (WATBAL) model for water supply, the Ceres-Maize Index Model, the Soygro model, and the Cropwat

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model for product operation, and the Water Evaluation and Planning (WEAP) model for water demand forecasting, evaluation, and planning. These models were used in conjunction with different climate change scenarios to evaluate the adaptation strategies of water resources in major agricultural areas in Argentina, Brazil, China, Hungary, Romania, and the United States. The results showed that even in relatively water-rich areas, the effects of global warming on agricultural water demand and the increased water demand due to urbanization would require improved irrigation technology and water management.

Zhao et al. (2005) investigated the response of climatic variables to greenhouse gas emissions in South Africa by using the outputs of three GCMs and B2 scenarios from the set of Special Report on Emission Scenario (SRES). The simulations for most parts of South Africa indicated that by the end of the twenty-first century, rainfall would drop by 8.2%. Bates et al. (2008) found from their study on the Tsha Rolpa Glacier Lake in Nepal that due to rising temperatures in recent years and the melting of the lake's glaciers, the lake's water area increased from 0.23 km^2 in 1957 to 1.65 km^2 in 1997, which added about 100 million m^3 of water to the lake. Since the water in the lake was maintained only by its icy masses, the increase in this volume elevated the risk of devastating floods.

By analyzing the effects of climate change on river flow in Northern China, Zhenmei et al. (2008) also examined the trend of annual flow changes in the past 50 years using the Mann–Kendall test. They found that climate change reduced the average annual flow rate by 64% and decreased the amount of rainfall. Traynham et al. (2010) assessed the effects of climate change and population growth on the water resources system of the Puget region in the United States. The response of the water resources system to future water demands under the influence of climate change was examined for different cities in the Puget area. Three GCMs and two emission scenarios were used to assess the region's water supply over a 75-year period. The performance of the water supply system in each city was determined by the reliability and firm yield criteria. The results showed that climate change would reduce the future system's yield, and the existing operation policies needed to be changed to meet the future demand.

Tabari et al. (2011) studied the average, maximum, and minimum annual trends of rainfall and temperature series at 13 stations in western, southern, and southwestern Iran for the period of 1966–2005 to understand how global warming affected the regional climate. Their results showed that the average, maximum, and minimum annual temperatures increased 0.412, 0.452, and 0.493 °C per decade, respectively, while the rainfall time series exhibited different changing patterns (i.e., increasing–decreasing trends) throughout the region. Their study also indicated that there was a need for more research on human impacts on the environment as a factor of climate change.

Georgakakos et al. (2012) assessed the adaptive reservoir management strategies under climate change in the Central Valley of Northern California. The reservoir management assessment included the adaptive policy with the developed Inform Decision Support System (INFORM DSS) and the current policy obtained from the Department of Water Resources Planning Simulation (DWRPS). Two sets of hydrological data were compared for basic and future periods. The results showed that the adaptive management under both basic and future conditions was effective in mitigating the adverse effects of climate change and reducing the system's vulnerability.

Ashofteh et al. (2012) evaluated the effect of climate change on the reservoir inflow and the tail water demand by utilizing three scenarios in East Azerbaijan, Iran. The monthly series of temperature and rainfall were achieved from the third version of the Hadley Centre Coupled Model (HadCM3) under the A2 scenario (Mendoza-Ponce et al. 2021). The obtained data were input to the recognition of UHs[1] and IHACRES.[2] A monthly runoff series was simulated for the period of 2026–2039, and the required water volume was estimated. The simulation of reservoir operation with the WEAP showed that the reliability for the future period decreased by 4% compared to that for the base period (1987–2000) and that the vulnerability and flexibility increased by 38% and 4%, respectively. The optimal operation of the reservoir was also determined by LINGO, which showed that in the future, the reliability decreased by 21% and, in contrast, the vulnerability and flexibility increased by 31% and 14%, respectively.

Alvarez et al. (2014) examined the effect of climate change on the administration of some reservoirs in a basin in Quebec, Canada and the adaptation strategies. For this purpose, a method was developed, which combined the HESPs,[3] a SOM,[4] an ANN[5] model, and a WBM.[6] The RCM[7] was used for the base period (1961–2000) and the future period (2041–2070). Their results showed that providing adaptive solutions in the future would reduce the risk of flooding and the vulnerability of the system under climate change.

Zareian et al. (2014) examined the effects of climate change on the inflow of the Zayandeh-Rud reservoir in Iran by using different various weighting approaches. The AOGCM15 was selected to study the effects of climate change on temperature and precipitation of the upstream area in 2015–2074. The modelling results were compared with the observation data in 1971–2000, and three patterns of climate change (ideal, moderate, and critical) were determined. The meteorological data were downscaled for 2074–2015 with the Lars-WG model, and then the IHACRES hydrological model was used to predict the monthly inflows of the reservoir for different climate change patterns, which were further used for the optimization of the downstream water resources.

Ahmadi et al. (2015) studied the rules of adaptive operation of Karoon-4 Reservoir in Iran with climate change. The HadCM3 model under Scenario A2 was used to predict the future temperature and precipitation, and the IHACRES model was also

[1] Unit Hydrograph.

[2] Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Streamflow Data.

[3] Hydrological Ensemble Streamflow Prediction.

[4] Stochastic Optimization Model.

[5] Artificial Neural Network.

[6] Water Balance Model.

[7] Regional Climate Model.

used to simulate the incoming flow to the reservoir. The rules of operation were extracted by the Non-Dominated Sorting Genetic Algorithm (NSGA-II), and the reservoir was operated adaptively and non-adaptively to climate change. The results showed that adaptive operation with climate change increased the reliability and reduced the vulnerability related to hydropower generation.

Moursi et al. (2017) evaluated the effects of climate change on water deficit in the Sevier River basin in Utah using a decision-scaling framework. In their study, 31 general circulation models (GCMs) were used for predictions to assess the vulnerability of water deficit in 2000–2099, which was defined by using an index to measure the ratio of available water to the agricultural water demand predicted by the AquaCrop model. The results revealed that the GCMs showed an increase in available water for agriculture in the basin and also indicated a significant risk of agricultural water deficit in 2025–2049 with the RCP4.5 emission scenario, which emphasized the need for adaptive strategies.

Khare et al. (2017) evaluated the effect of climate change on soil erosion in the Mandakini Basin in India. The rise of rainfall intensity, apart from other factors such as land-use change, led to an increase in soil erosion. In their study, the future precipitation generated by downscaling the GCMs data was used to determine the impact on soil erosion, which was estimated by the Universal Soil Loss Equation (USLE). They found that soil erosion in the future exhibited an increasing trend due to an increase in precipitation.

1.2 Symbols and Definitions

ANN:	Artificial Neural Network.
AOGCM:	Atmosphere–Ocean General Circulation Model.
AR4:	Fourth Assessment Report of IPCC.
AR5:	Fifth Assessment Report of IPCC.
CMIP:	Coupled Model Inter-Comparison Project.
CMWG:	Climatic Models Working Groups.
CRU:	Climatic Research Unit.
DSS:	Decision Support System.
DWRPS:	Department of Water Resources Planning Simulation.
FAR:	First Assessment Report of IPCC.
Flexibility:	A combination of other performance criteria [Reliability× Resiliency× (1-Vulnerability)].
GCMs:	General Circulation Models.
GHG:	Greenhouse Gases.
GHGES:	Greenhouse Gas Emission Scenarios.
GIS:	Geographic Information System.
HadCM3:	Third Version of the Hadley Centre Coupled Model.
IHACRES:	Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Stream flow Data

IPCC:	Intergovernmental Panel on Climate Change.
LARS-WG:	Long Ashton Research Station Weather Generator.
RCM:	Regional Circulation Model.
RCPs:	Representative Concentration Pathways.
Resiliency:	How quickly the system recovers from failure.
RF:	Radiative Forcing.
SAR:	Second Assessment Report of IPCC.
SDM:	System Dynamics Model.
SRES:	Special Report on Emission Scenarios.
TAR:	Third Assessment Report of IPCC.
UNEP:	United Nations Environment Program.
USLE:	Universal Soil Loss Equation.
Vulnerability:	How severe the consequences of failure may be.
WATBAL:	Water Balance Model.
WEAP:	Water Evaluation and Planning System.
WGEN:	Weather Generator.
WGMS:	World Glacier Monitoring Service.
WMO:	World Meteorological Organization.

1.3 Significance of the Study

Climate change is a serious threat to human societies, which is potentially irreversible. According to the Intergovernmental Panel on Climate Change (IPCC) (Mandal 2017), the Earth will warm and its surface temperature could rise 0.6 °C during the twentieth century, and based on the greenhouse gas emissions estimates, the temperature will increase 1.0–3.5 °C by 2100. By the end of the twenty-first century, global warming will be greater than it has occurred in the last 10,000 years (IPCC 2001). Undoubtedly, in the coming years, due to the increase in human activities, greenhouse gas emissions will increase, which will intensify the change in climatic variables. On the other hand, even if the emission of greenhouse gases is stopped now, due to the long shelf life of greenhouse gases that have already been released into the atmosphere, humans would face climate change in the twenty-first century. Among the 16 most threatening factors for humans in the twenty-first century (e.g., food shortages, poverty, drought, floods, and nuclear weapons), climate change ranks first (Martin 2007). Studies show that countries in low latitudes will be disturbed further from the negative consequences of climate change (Lane et al. 1999). Climate change has affected economic growth in such a way that it can bankrupt up to one-fifth of the economy unless an effective measure is taken (Peston 2006). Generally, climate change in the future could have dissimilar effects on water resources, environment, industry, health, agriculture, and all other systems that interact with the climate system (Ashofteh 2014). Therefore, it is necessary to identify the negative effects of this phenomenon on the intended systems, and adaptive strategies should be anticipated to deal with them. Since the phenomenon of climate change and its effects on water resources are one of the most important challenges for water resources managers (Mendoza-Ponce et al. 2021), a number of relevant studies have been conducted since the late twentieth century. Various climatic models have been developed and used to simulate the affecting processes and to predict the future climate conditions for a variety of possibilities scenarios (Nouri-Tirtashi et al. 2015).

According to IPCC Technical Paper VI, the frequency and severity of borderline events such as droughts and floods are increasing due to climate change (Bates et al. 2008). The regions with higher forecasted rainfall are at a greater risk of flooding (Solomon et al. 2007). The climate change effects are also reflected in the changes in surface runoff and groundwater levels. It is estimated that the average change in runoff due to climate change is more than the precipitation amount at most, which is higher in arid regions than in humid areas (Lettenmaier and Gan 1990). Therefore, the increased intensity of extreme events such as droughts and floods induced by climate change is undeniable. Thus, examining the influences of climate change on water resources (Mandal et al. 2019a, b) is one of the necessities for water resources planning and management (Karamouz and Araghizejad 2005). Evidence of the influences of climate change shows that in addition to analyzing the occurrence of this phenomenon, special attention should be paid to its impacts on the water resources planning and management at a basin scale. This can be achieved by changing the way for data acquisition and processing based on the variability of basin data, paying attention to long-term scenarios affecting the change of basin water resources, and paying attention to extreme hydrological values. It is aimed to optimize available water resources. In this regard, it is important for the managers of water systems to provide necessary operation policies by considering the needs of consumers in the best way based on the available water resources. Instead of considering current conditions only, optimal adaptive policies that take into account climate change conditions should be adopted and implemented for the future.

1.4 Basic Principles

Climate is the average of climate conditions in a place, including its constituent factors such as temperature, rainfall, and humidity. In other words, it is the long-term average climate of an area (Bradley et al. 1985). Climate change is the change in climate that lasts for a long period of time (e.g., decades or longer). This term can be defined as any change in climate over time (IPCC 2007a, b, c). This change can be in the averages of temperature, rainfall, humidity, wind, radiation, and other variables. Climate can get hotter or colder, and the average of each variable can increase or decrease over time. This complex long-term global atmospheric-oceanic phenomenon can be influenced by natural factors such as volcanoes, solar activity, oceans, and atmospheres that interact with each other or by human activities (Buchdahl 1999).

1.5 Climate Change and Dangers Ahead

In recent decades, greenhouse gases (GHG), especially carbon dioxide (CO2), have increased dramatically due to the growth of industries and factories since the beginning of the industrial revolution and the increase in fossil fuel consumption, deforestation, and land-use change (Carter et al. 2007). Continuation of this trend and the increase of greenhouse gases have increased the average temperature of the Earth, resulting in global warming and changes in other climatic variables such as rainfall. That is why the most important factor in climate change is the increase of greenhouse gases. By changing climatic variables, other systems affected by these variables, such as water resources, agriculture, environment, and economy, will also change (Mearns et al 2010). However, this study will focus on water resources. According to various reports of the World Glacier Monitoring Service (WGMS), mountain glaciers have been exposed to melting since 2005, which is more than three times faster than the one in the 1980s. As a result, the average diameter of 30 glaciers in the world has been reduced by 60–70 cm. Studies show that rising water levels, along with the increase of glaciers melting, will exacerbate flooding (IPCC 2007a, b, c). Satellite data show that since 1978, the average number of polar glaciers has dropped by 2.7% every ten years. In addition, Rothrock et al. (1999) determined that the sea ice thickness has considerably decreased. As shown in Fig. 1.1, six different regions experienced a decrease in the thickness of sea ice between 1993 and 1997 compared to the data in 1958–1976.

Many studies on assessment of the effects of climate change indicate that many years between 1995 and 2006 are the warmest years in the global surface temperature record (since 1850). The updated 100-year temperature linear trend (1906–2005) of

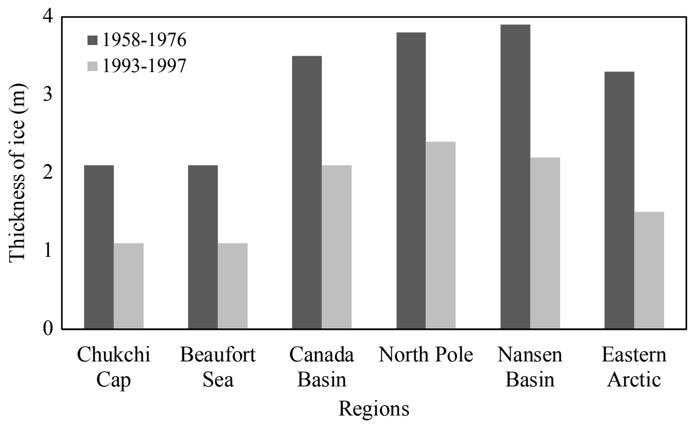

Fig. 1.1 Changes in thickness of the sea ice in six different regions (Based on Rothrock et al. 1999)

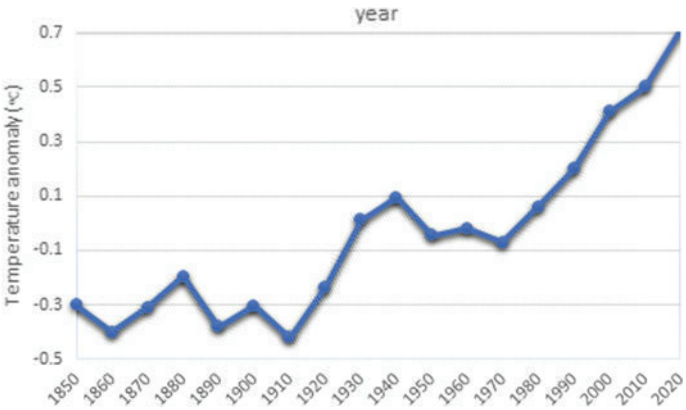

Fig. 1.2 Observed changes in global average temperatures 1850–2020 (Based on Jones and Palutikof 2006)

0.74 °C per year (0.56 to 0.92 °C) is greater than the corresponding trend for 1901–2000 provided in the TAR of 0.6 °C (0.4 to 0.8 °C) (IPCC, 2007a, b, c). According to the climatic research unit (CRU), Fig. 1.2 shows the observed changes in the global average temperatures (anomaly) in 1850–2020 (Jones and Palutikof 2006).

The effect of climate change on precipitation by examining the past statistics shows that precipitation increased in most areas in the world, especially in parts of South and North America, Northern Europe, and Central Asia from 1900 to 2005. Drought intensities also increased in parts of South Africa and parts of South Asia (IPCC 2007b).

1.6 IPCC Reports and Steps for the Forecast

The World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established IPCC in 1988, which consisted of thousands of scientists from all around the world. Its main task is to research scientific and technical issues and the potential risks following climate change, as well as its impact on the world and set policies to deal with it. Three main working groups were formed by IPCC. The first working group evaluates the scientific, economic, social, and technical information to understand the phenomenon of climate change; the second working group examines the potential effects of climate change, adaptation to this phenomenon, and the vulnerability of various systems affected by it; and the third working group investigates the reduction of the effects of this phenomenon (IPCC 2001).

One of the main goals of this study is to predict the Earth's climate. Today, with the advancement of computers and the high speed and accuracy of their calculations, it is easier to make climatic predictions. In general, there are three significant steps to perform a climate forecast. However, it is worth noting that each of these steps has a very high diversity. The first step is to select a scenario for the Earth's forward state. In other words, at this stage, assumptions about the expected conditions for the Earth are considered, which take into account various topics such as the growth rate of the future population, the technological progress, and the emission of greenhouse gases. The second step, after selecting the scenario, is to simulate the Earth's climate. At this stage, the Earth's climatic behavior is defined in the form of a model and simulated according to the selected scenario in the first step as the initial conditions in the model. While the Earth's future climate can be predicted after these two steps, the results of these predictions, which are done at large scales in the atmospheric general circulation models, cannot be generalized to smaller scales (e.g., a basin scale). To solve this problem, it is necessary to take another step which is known as downscaling. In addition, it is essential to use precipitation-runoff models to estimate runoff in the study of climate change impacts on water resources. In the following section, after reviewing the IPCC reports, the scientific logic of each of these steps is examined, and some of the conventional methods and models for each step are described.

The IPCC has so far published five series of its reports: First Assessment Report (FAR), Second Assessment Report (SAR), Third Assessment Report (TAR), Fourth Report (AR4), and Fifth Report (AR5). The FAR was completed in 1990. One of the most important achievements of this report was its overall forecast for the average global temperature changing pattern up to 2005. In addition, the report emphasizes that greenhouse gas emissions are growing, and human activities increase the gases such as CO2, CH4, Nitrous Oxide (NO and NO2), and Chlorofluorocarbons (CFCs). This increase can cause the rise of temperature on a global scale. The SAR published in 1995 was a report on the socio-economic information at the time and its relationship to climate change. The report used a set of scenarios called IS92 for climate forecasting (IPCC 2013, 2014).

The final version of the TAR was prepared and published in 2001. It was commonly used as a reference to demonstrate a scientific agreement on global warming. The highlight of this report was the definitions of a total of 40 scenarios as a special report on SRES scenarios. This series of scenarios with slight changes have been used by climate researchers for nearly 13 years as the best and most complete scenarios.

The AR4 was a complete climatic report that had been published by that time. It has a scientific basis similar to that of the TAR. The biggest advance in the AR4 in comparison with the TAR and older versions is the better conception related to interpretations of past and present climate changes and consequently the better simulation of the future climate change relying more on the uncertainty in the models.

The decision to prepare the AR5 was made by IPCC members at its 28th meeting in Budapest, Hungary, on 9 and 10 April 2008. IPCC introduced a new procedure for preparing scenarios called Representative Concentration Pathways (RCPs), with the help of the scientific community in the climate change field. Thus, four concentration pathways of greenhouse gases (rather than emissions) were proposed. The difference between these four hypothetical pathways was the imaginal amount of the Radiative Forcing (RF) for them. A brief overview of the concept of RF is provided in the section regarding the concepts and theories used in the IPCC scenarios.

1.6.1 IPCC Scenarios (from SERS to RCPs)

1.6.1.1 SERS

Undoubtedly, in the coming years, humans will face more changes in climate variables due to the increase in greenhouse gas emissions. As noted, any changes in the concentration of greenhouse gases in the Earth's atmosphere will change the balance between the elements of the Earth's climate system (Mandal 2017). However, it is not clear how much gases will enter the Earth's atmosphere by human societies in the future and what will happen to the Earth's climate system. Therefore, they are presented in a completely uncertain way and under different emission scenarios (Ashofteh 2014). These scenarios are divided into Non-Climatic Scenarios and Climatic Scenarios, as detailed below.

- **Non-climatic Scenarios**

The information on greenhouse gas emissions, population growth, economic and social status, as well as technological and agricultural issues is the basis of non-climatic scenarios. A number of emission scenarios were introduced by IPCC in 1996 in the Special Report on Emission Scenario (SRES).

SRES defined four main titles, including A1, A2, B1, and B2, as families of emission scenarios to describe the relationship between greenhouse gas emissions and airborne particles and their outcomes in different parts of the world. Figure 1.3 shows these four titles (Nakicenovic et al. 2000).

Figure 1.3 reflects the emphasis of each scenario group on the global, regional, environmental, and economic perspectives. In summary, scenarios A1 and A2 consider more economic issues, while scenarios B1 and B2 focus on environmental issues. Scenarios A2 and B2 consider regional solutions, and scenarios A1 and B1 target global solutions (IPCC 2007c). Each family of the scenarios offers different conditions (e.g., environmental, social, and industrial conditions) and consists of different groups. Three different groups for the family of A1 are considered based on the types of industry used in the twenty-first century:

A1F1: Intensify the use of fossil fuels.
A1T: Use non-fossil energy sources.
A1B: Use fossil and non-fossil resources in a balanced way.

In total, these scenarios are divided into six groups: A1F1, A1T, A1B, A2, B1, and B2, each of which is further divided into several sub-branches. They form 40 different scenarios. It should be noted that based on the production of radiative forcing, the status of the scenarios is A1F1, A2, A1B, B2, A1T, and B1 (IPCC 2000).

- **Climatic Scenarios**

In general, climatic scenarios can be defined as the detection of the extent and manner of the change in climatic variables which will happen in the future periods and on a regional scale (Ashofteh 2014).

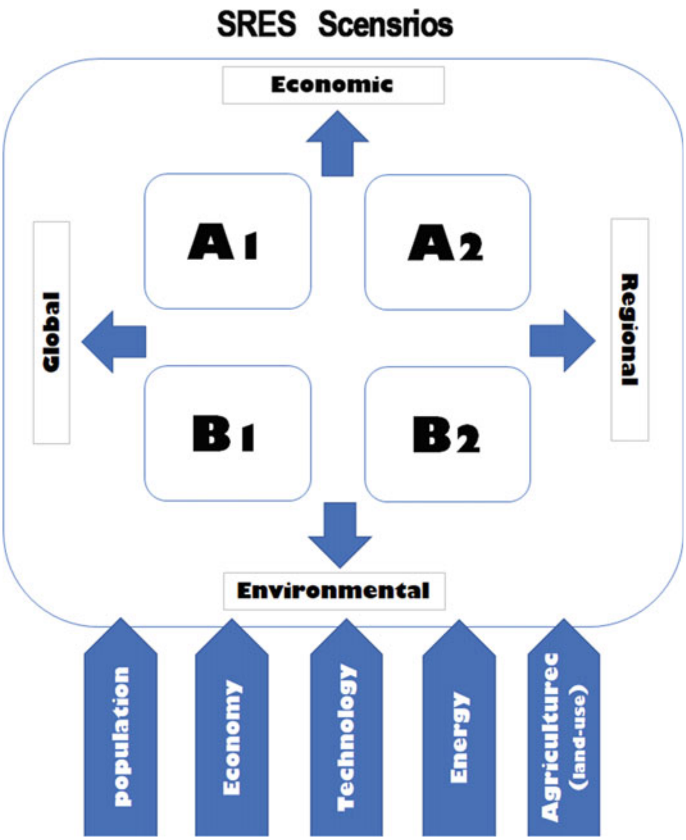

Fig. 1.3 Four families of emission scenarios and their triggers (Based on Nakicenovic et al. 2000)

1.6.1.2 RCP

In 2014, the scientific community decided to design a set of scenarios to consider not only the greenhouse gas concentration but also other parameters such as land use in these new scenarios. The goal is to use advanced models in parallel for various scenarios that could justify the set of climate stimuli, which help the development and definition of possible routes for the future of the Earth's climate. This is exactly the opposite of the process that was used to define the older IPCC climate scenarios previously (Zolghadr-asli 2017).

In these scenarios, a set of RF components are used and applied in chain processes in climate forecasting. In fact, the deliberate use of the term of "concentration", instead of "emission", suggests that emission is just one of the outputs of these scenarios. Finally, four general pathways are expressed for the rates of RF: 8.5, 6.0, 4.5, and 2.6 w/m^2, represented by RCP 8.5, RCP 6, RCP 4.5, and RCP 2.6, respectively (Mandal 2017). In fact, the simulation has been performed for each case

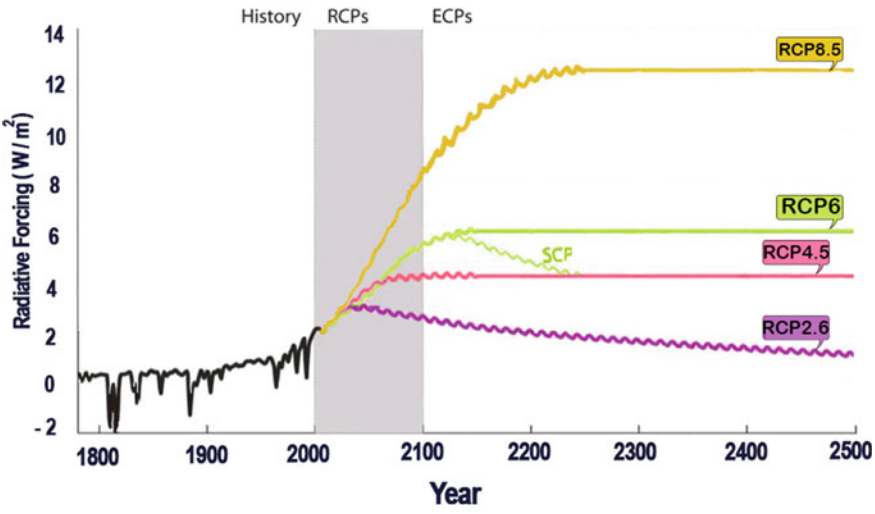

Fig. 1.4 Illustrated paths for RCP scenarios (Based on Clarke et al. 2014)

by the end of the present century. The higher RF number a scenario has, the more energy the Earth absorbs from the Sun, and therefore the higher average temperature the Earth has under the scenario. Figure 1.4 shows the average behaviour of the Earth's temperature under the four scenarios (Clarke et al. 2014).

- **RF**

The concept of RF, first proposed in the TAR, was calculated on a global scale with acceptable accuracy in AR4 and used in AR5 as a tool for the definition of climatic forecasting scenarios. In climatic sciences, radiative forcing or climate forcing is defined as the difference between insolation (sunlight) absorbed by the Earth and energy radiated back to space. Typically, the unit of RF in the Tropopause space is watts per square meter (w/m^2) which itself indicates the amount of energy absorbed per unit area of the planet. Positive values of RF mean that the system is warmer and negative values indicate a decrease in the system temperature. The reasons for the change in the amount of RF include the changes in the concentration of greenhouse gases and the amount of dust in the air. It should be noted that all greenhouse gases have a positive RF value, which means that by increasing their concentrations in the atmosphere, these gases will be able to increase the energy absorbed by the Earth.

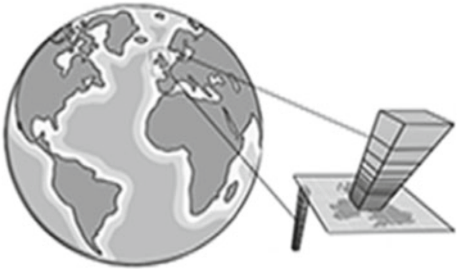

Fig. 1.5 An overview of the General Atmospheric Circulation Model (Based on Viner and Hulme 1997)

1.6.2 *Climatic Models*

After defining the behavioral pattern of climate stimuli, it is necessary to simulate how they affect the planet's climate. The solution lies in the AGCMs[8] that are designed to model the Earth's existing climate and can predict changes in the Earth's climate in the future (Xu 1999). Computer modelling based on the knowledge of the global atmospheric and oceanic thermodynamics is an acceptable method and has been widely used for estimating future climate change. IPCC has examined several GCMs (Mendoza-Ponce et al. 2021), which have been employed to simulate climatic variables such as temperature and precipitation during a period (IPCC 2011). These models are developed based on the physics rules described by mathematical equations that are solved on a three-dimensional network on Earth. To simulate the Earth's climate, the key climatic processes are simulated in separate sub-models, and then all sub-models related to the atmosphere and ocean are integrated to form the AOGCMs—the most reputable tools for predicting climatic variables (Lane et al. 1999; Mitchell 2003; Wilby and Harris 2006).

In general, spatial GCM models typically simulate the atmospheric space in the form of a vertical column and a grid of 5 to 20 unequal layers. To improve the simulation performance of these models, the layers located near the Earth's surface are closer to each other. Obviously, a larger number of layers used in the model lead to a smaller size of the defined cells and a shorter time interval in the model. As a result, the modelling of higher accuracy requires more computing resources and a longer running time (Fig. 1.5).

In the third assessment report, IPCC cited seven AOGCMs including HadCM3 from the Hadley Climate Research and Forecasting Center in the United Kingdom, CGCM2 from the Canadian Climate Modeling Center, CCSR-NIES from the Japan Research Center, ECHAM4 from the German Research Center, GFDL-R30 from the AGFDL,[9] CSIRO-MK2 from the Australian Scientific and Industrial Center, and the NCAR-DOE PCM from the American Atmospheric Research Center (Ashofteh 2014).

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[8] Atmospheric General Circulation Model.

[9] American Geophysical Fluid Dynamics Laboratory.

In 1995, in order to integrate the results of the models, the WMO created the Climatic Models Working Groups (WGCM) responsible for creating an overall modelling framework of GCMs. The relevant result was presented in the form of a project called Coupled Model Inter-comparison Project (CMIP). Finally, in 2014, the fifth phase of this project (CMIP5) began to work on the results of AR5.

1.6.3 Downscaling

One of the main limitations in the use of GCMs is that their spatial and temporal resolutions do not meet the required accuracy of regional hydrological models. The spatial resolution of the GCMs is about 200 km, which is not particularly suitable for the study of mountainous areas and climatic variables such as precipitation and temperature (Wilby and Dettinger 2000). The output of these models can be converted from large-scale to local-scale variables over the study basin using certain downscaling methods. Commonly used downscaling methods include Proportional Downscaling, Dynamical Downscaling, and Statistical Downscaling (Wilby and Harris 2006).

1.6.3.1 Proportional Downscaling

The Proportional Downscaling method is one of the simplest methods for retrieving large-scale data, in which climate variables simulated by AOGCM are derived from the information about the cells of the study area. In this method, the difference between the basic and future AOGCM data is added or multiplied to the observed values by the Change Factor method (Hay et al 2000; Diaz-Nieto and Wibly 2005; Ashofteh et al. 2013a).

In this method, it is necessary to model the climatic conditions in the intended base period by GCMs. The model then produces temperature and rainfall climate change scenarios. Finally, it is necessary to calculate the average changes observed each month for the selected variables between the simulations for the basic and future periods, as follows (Ashofteh 2014):

$$\Delta T_i = \overline{T}_{GCM,fut,i} - \overline{T}_{GCM,base,i} \tag{1.1}$$

$$\Delta P_i = \frac{\overline{P}_{GCM,fut,i}}{\overline{P}_{GCM,base,i}} \tag{1.2}$$

in which i ($1 \le i < 12$) = month i; $\overline{T}_{GCM,fut,i}$ and $\overline{P}_{GCM,fut,i}$ = average temperature and precipitation simulated by GCMs in the future period for month i; and $\overline{T}_{GCM,base,i}$ and $\overline{P}_{GCM,base,i}$ = average temperature and precipitation simulated by AOGCMs in the baseline period for month i.

$$T_i = T_{obs,i} + \Delta T_i \tag{1.3}$$

$$P_i = P_{obs,i} \times \Delta P_i \tag{1.4}$$

in which $T_{obs,i}$ and $P_{obs,i}$ = time series of temperature and precipitation observed in month i of the baseline period, respectively; and T_i and P_i = time series of predicted temperature and precipitation for month i, respectively (Ashofteh 2015). Although this method presents acceptable results in some cases, especially in short-term climatic forecasts, in many cases, it may not be able to provide the best solution for climate forecasting because it does not account for a variety of variables in the climatic prediction.

1.6.3.2 Statistical Downscaling

Various statistical downscaling methods have been developed to convert the large-scale GCM output to smaller-scale data. The basis of statistical methods is to establish a favorable relationship, import large-scale climatic variables from AOGCM as the input and obtain the regional-scale climatic variables (Qian et al. 2005; Fowler et al. 2007). In statistical methods, the production of weather conditions is mainly based on the modification of the patterns provided by conventional meteorological data generators, such as WGEN, LARS-WG, and EARWIG. These methods enable users to use multiple chains of scenarios, which are ideal for risk analysis, instead of using just one time series. On the other hand, the inability of these methods to investigate decadal climate variability, which stems mainly from the weakness of the inter-annual data series produced by these models, in some cases, may lead to irrational responses.

1.6.3.3 Dynamical Downscaling

In the dynamical downscaling method, a high-resolution Regional Circulation Model (RCM) is commonly used. In such a way, the GCM outputs are used as the boundary conditions of the RCM. Due to the time and cost constraints of these models, the physical scales of these methods range from 20 to 50 km^2. The greatest advantage of these methods is their accuracy. Since the RCM is coupled with a GCM, the overall quality of dynamically downscaled RCM output is tied to the accuracy of the large-scale forcing of the GCM and its biases (Seaby et al. 2013). The fact that these models depend on the output from GCMs has led to some limitations for users and climate researchers, such as the size of the domain covered by them, the number of experiments, and ultimately the duration of the simulation.

1.6.4 Precipitation-Runoff Models

Runoff estimation has always been a challenge. This is important because it determines how much water from a rainfall event can be expected, as well as to what extent a flood event may have a destructive risk. The first attempt associated with this matter was made about a century and a half ago, when an Irish engineer, Thomas James Mulvaney (1822–1892), tried to estimate the peak discharge of a flood in 1851. This way of thinking has shown remarkable progress over time, but it is still one of the most important issues in water science (Beven 2011). Finally, according to the methodology section, Fig. 1.6 shows the flowchart related to the basic principles of studying and examining the effects of climate change on water resources planning and management at the basin level.

1.7 Practical Examples

The influences of climate change on various parts have been studied by many researchers in the water resources field. In this section, climate change studies are illustrated with three examples in the context of water resources development and management.

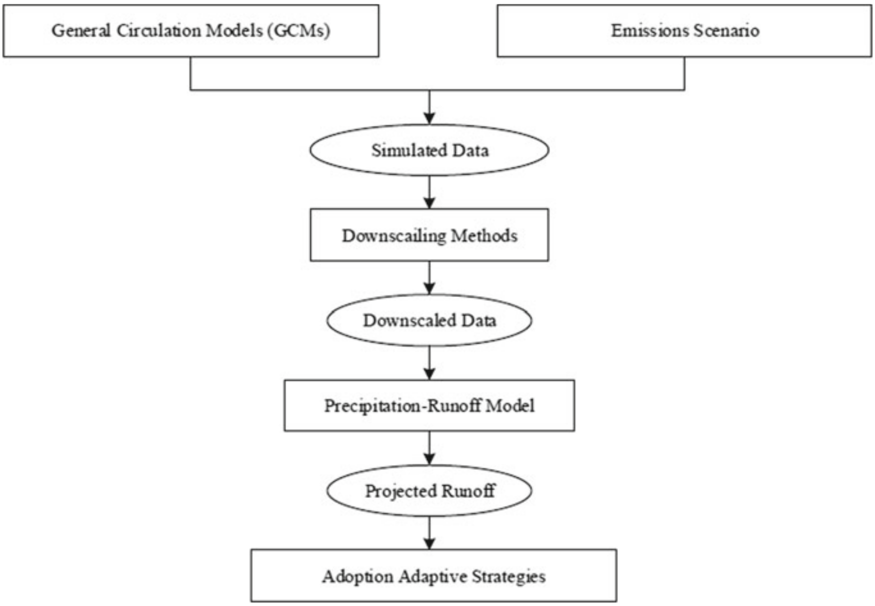

Fig. 1.6 Flowchart of assessment of climate change effect on water resources

Table 1.1 Computed Nonparametric Test Statistics (Confidence Level of 99%) of Hydroclimatic Variables (Ashofteh et al. 2017; Mandal et al. 2019a, b)

	Mann–Kendall trend tests	Spearman trend tests
Variable	(Z_M)	(Z_S)
Temperature	0.25	0.26
Rainfall	−0.20	−0.23
Runoff	−0.07	−0.10

1.7.1 Example I

Influences of "Climate Change on the Conflict between Water Resources and Agricultural Water Use" (Mandal et al. 2019a, b; Ashofteh et al. 2017).

Increasing CO_2 emissions will affect the climate and lead to adverse human and environmental effects. Water resources can be particularly vulnerable to this phenomenon. Since agricultural water use accounts for about 70% of the total, it is necessary to study the impacts of climate change on water resources and analyze the future of agriculture.

This sample is related to the research by Ashofteh et al. (2017). The Aidoghmoush irrigation network in Iran was assessed as a case study of the conflict between water resources and water consumption under climate change conditions" (Mandal et al. 2019a, b). In the study, the trend of climatic variables was determined by the Mann–Kendall (Z_M) and Spearman (Z_S) tests (Table 1.1). The statistics in Table 1.1 indicate that temperature increased while rainfall and runoff decreased due to the climate change in the observation period.

Seven AOGCMs (including HadCM3, CCSR-NIES, CSIRO MK2, CGCM2, GFDL R30, NCAR DOE PCM, and ECHAM4) (Mandal et al. 2019a, b) were used to examine the future changes under emission scenario A2. Emission scenario A2 was selected since it produced a high amount of CO2 (Mandal et al. 2019a, b). The input data of GCMs (i.e., monthly climatic data) were obtained from the IPCC's site (IPCC-DDC 1988) for the baseline period (1971–2000), first (2010–2039), second (2040–2069), and third (2070–2099) future periods (Mandal et al. 2019a, b). In addition, the technique of proportional downscaling with the GCM-Retrieve Data Program was used (Mandal et al. 2019a, b). The differences of the long-term AMT[10] and rainfall in the future and in the baseline period were calculated with the seven AOGCMs (Mandal et al. 2019a, b).

Results showed that the temperature in the future third period was greater than those in the first and second future periods (Mandal et al. 2019a, b). The changes in rainfall in winter, spring, summer, and autumn ranged from −27% to 27%, from −52% to 37%, from −94% to 140%, and from −19% to 119%, respectively, in the first future period; from −41% to 51%, from −81% to 20%, from −59% to 108%,

[10] average monthly temperature.

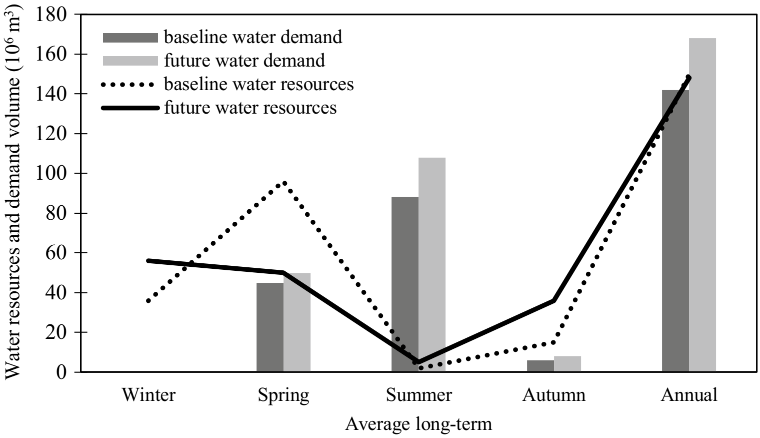

Fig. 1.7 Comparison of the long-term average water resources and water demands (Based on Ashofteh et al. 2017)

and from −35% to 94%, respectively, in the second future period; and from −51% to 38%, from − 74% to 118%, from −98% to 464%, and from −35% to 254%, respectively, in the future third period (Mandal et al. 2019a, b).

The irrigation requirement in the coming periods under changing climatic conditions will put more pressure on the agricultural water supply system and worsen food security (Mandal et al. 2019a, b). The annual increase in the irrigation required for walnuts, alfalfa, and potatoes will be approximately 20%, 16%, and 19%, respectively, in the first future period compared to the baseline period (Mandal et al. 2019a, b). All in all, water availability for agriculture would decline in the future. Figure 1.7 shows the emerging conflict from the effect of climate change on the temporal distribution of water resources and water consumption.

Figure 1.7 indicates that the future water resources in spring (wet season) will be drastically reduced (around 46%) due to a significant decrease in rainfall compared to the baseline rainfall (about 25%) in comparison with other seasons (Mandal et al. 2019a, b). However, there would be an increase of about 53 and 35% in the volume of water resources in the future periods in autumn and winter, respectively, due to the lower water demands in these seasons (Mandal et al. 2019a, b). Finally, the summer water demand is high, while the water availability is limited. Therefore, summer will be the most important season of the water crisis in this case study.

In conclusion, there would be a growing discrepancy between available water resources and agricultural water demand under the future climate change (Mandal et al. 2019a, b). So, awareness of this crisis can encourage decision-makers to adopt various strategies such as improving the irrigation efficiency (Mandal et al. 2019a, b), delaying planting dates, changing the system management methods, and/or implementing other adaptive methods.

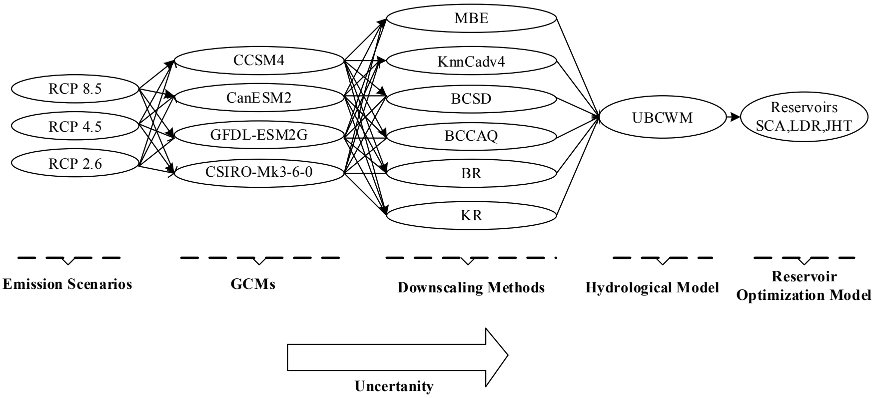

Fig. 1.8 Framework for assessing climate change impacts on reservoir operations (Based on Mandal et al. 2019a, b)

1.7.2 Example II

"Reservoir Operations under Changing Climate Conditions: Hydropower-Production Perspective" (Mandal et al. 2019a, b).

The second sample is associated with the study by Mandal et al. (2019a, b). The purpose of this study was to examine the impacts of climate change on reservoir system operations in the Campbell River basin in British Columbia, Canada that consisted of three reservoirs: Strathcona, Ladore, and John Hart (Mandal 2017). Three GHGES,[11] four GCMs, six downscaling methods, one hydrologic model, and an SDM[12] were integrated and used for the assessment. The modelling was performed for a future time period (2036–2065) and compared with the historical time period (1984–2013) (Mandal et al. 2019a, b). The models for the historical and future time periods were respectively used for validation and planning purposes (Mandal et al. 2019a, b).

The uncertainty analysis of the climate change process and the modelling involved: (I) different processes in GCMs, (II) choice of GCMs, (III) selection of emission scenarios, (IV) selection of downscaling models, (V) uncertainty analysis of hydrologic model parameters, and (VI) different hydrologic model structures. As shown in Fig. 1.8, 72 different scenarios, which consisted of three RCPs, four GCMs, and six downscaling models, were analyzed.

Additionally, the GCMs used in this study are from the CMIP5. The six downscaling models were BCSD, bias-corrected constructed analogues with quantile mapping reordering (BCCAQ), delta change method coupled with a nonparametric k-nearest neighbor weather generator, delta change method coupled with a maximum

[11] Greenhouse Gas Emission Scenarios.

[12] System Dynamics Model.

entropy-based weather generator, nonparametric statistical downscaling model based on the kernel regression (KR), and beta regression (BR) based statistical downscaling model (Mandal et al. 2019a, b).

At the first stage, climate variables were extracted for GCMs and different emission scenarios (RCPs). These variables included maximum temperature (Tmax), minimum temperature (Tmin), precipitation (Pr), mean sea level pressure (mslp), specific humidity (hus) at 500 hPa, zonal wind (u-wind), and meridional wind (v-wind) (Mandal et al. 2019a, b). Then, the climate variables were spatially interpolated at 10 downscaling locations in the basin and used as the input of the four downscaling models (MEB, KR, BR, and KnnCAD V4) (Mandal et al. 2019a, b). The downscaled climate variables (Tmax, Tmin, and Pr) (Mandal et al. 2019a, b) were directly derived from the IPCC databases (BCCAQ and BCSD) (IPCC 2014). At the last step, the downscaled climate variables were inputted to the UBC Watershed Model to generate daily runoff. BC Hydro was used for calibrating and validating the UBCWM. Note that an SDM was used to simulate the operation of multiple reservoirs in the Campbell River basin. Using the streamflow data from the UBCWM, the SDM simulated water inflow, storage, and release of all reservoirs. The power generated by this system was estimated by using the storage and release data.

The modelling results indicated that power generation was reduced due to the decrease of inflow of all three reservoirs over summer and autumn. The results also showed that the highest level of uncertainty was associated with the downscaling models, and the hydropower reliability declined more than 50% for all three reservoirs under climate change conditions (Mandal et al. 2019a, b). Table 1.2, 1.3and 1.4 show the comparisons of the predicted and historical hydropower generated by the Campbell River system for varying RCPs, GCMs, and downscaling methods.

1.7.3 Example III

"Reservoir water-quality projections under climate-change conditions" (Azadi et al. 2019).

Azadi et al. (2019) assessed water quality variations in the Aidoghmoush reservoir located in East Azerbaijan in Iran under climate change conditions in 2026–2039 (Azadi et al. 2018). The HadCM3 model was applied to calculate the temperature and rainfall under emission scenario A2 in the baseline period (1987–2000), and these two climate variables were then predicted over a future study period (2026–2039). In addition, the IHACRES model was used to simulate the average annual runoff, and the CE-QUAL-W2 model was used to simulate the reservoir water quality under climate change conditions. The streamflow velocity decreased as entering the reservoir, which led to thermal stratification because of uneven mixing and the induced changes in the density of water with depth (Azadi et al. 2018). The water quality of incoming streamflow was affected by reservoirs. Such changes can be harmful to the downstream ecosystem. Thus, it is necessary to predict water quality variations under climate change and also determine the related water withdrawal

Table 1.2 Comparison of the historical and future mean seasonal power production (MW) for different emission scenarios for Strathcona, Ladore, and John Hart reservoirs in the Campbell River System, British Columbia, Canada (Mandal et al. 2019a, b)

2036–2065

			RCP 2.6		RCP 4.5		RCP 8.5	
Reservoir	Season	Historical (1984–20,013)	Mean	Change in mean value (%)	Mean	Change in mean value (%)	Mean	Change in mean value (%)
Strathcona	Winter	29.4	26.8	−9	27.3	−7	27.0	−8
	Spring	24.5	22.4	−8	22.5	−8	22.1	−9
	Summer	22.6	8.5	−61	7.8	−65	7.1	−67
	Fall	25.9	18.2	−27	18.3	−27	17.7	−30
Ladore	Winter	31.5	20.9	−33	21.4	−32	21.3	−32
	Spring	27.0	19.7	−26	19.9	−26	19.6	−27
	Summer	20.7	7.0	−65	6.5	−68	5.9	−70
	Fall	25.1	15.2	−38	15.3	−37	14.9	−40
John Hart	Winter	106.4	87.8	−17	88.6	−16	87.9	−17
	Spring	92.0	80.9	−12	81.5	−11	80.5	−12
	Summer	68.7	30.5	−54	28.3	−58	25.9	−60
	Fall	84.5	59.3	−28	59.5	−28	57.4	−31

policies. Figure 1.9 shows the modelling components and framework for simulation of climatic variables, estimation of reservoir inflows, and assessment of reservoir water quality (Azadi et al. 2018).

TDS was selected as the water quality indicator in this area associated with an arid climate and relatively high suspended solids. The raw data were obtained from the meteorological administrations in Iran. The climate data such as temperature and rainfall were obtained from the IPCC website by applying the HadCM3 model under the scenario of A2 for both base time period and climate change period. Using the downscaled climatic data, the IHACRES model was used to simulate future runoff. Then, reservoir inflow and water demand for the future period were calculated. Finally, the water quality of the reservoir was simulated by CE-QUAL-W2. The input data of CE-QUAL-W2 included geometric and meteorological data, as well as initial and boundary conditions such as initial water depths and temperatures, inlet and outlet data, and inlet water temperatures (Azadi et al. 2018).

The results illustrated that the future mean annual runoff would decline by around 1%, while the agricultural water demand would rise by 16%. The surface air temperature would increase by 1.3 °C in comparison with the base time period. The bottom and surface water temperatures of the reservoir increased by 1.19 °C and 1.24 °C, respectively. Moreover, climate change would also affect the total dissolved solids of the reservoir, especially for the options with irrigation. Compared to the TDS in the base time period, the average TDS near the reservoir water surface for the climate