

Review

A Critical Review of Water Resources and Their Management in Bhutan

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Abstract: Bhutan is a small yet water-abundant country. The country suffers from frequent flooding and is lately experiencing a growing risk of localized droughts due to inappropriate water resource management and climate change. Such a situation calls for much more efficient use and management of water in Bhutan. This paper undertakes an extensive analysis of the country's water resources for better planning and management of the available water resources. Bhutan can be divided into three zones, the Southern Foothills, the Central Inner Himalayas, and the Higher Himalayas. The top four leading industries of Bhutan are related to water, either directly or indirectly. The country at present is at a very early stage of development. The government has prioritized water resources management over recent years. Water for hydropower in Bhutan has been in focus as compared to that allocated for irrigation, industries, and environmental demand. The demand for water in Bhutan has also increased in the last decade due to population increase, changes in lifestyle, and economic advancements through tourism and hydropower projects. Climate variation, deteriorating water quality, frequent floods, and increasing urbanization threaten the sustainability of water resources. Water accessibility issues for settlements due to the country's harsh geographical landscape is leading towards localized water scarcity. Serious attention to rainwater harvesting and groundwater recharge is required to address localized water scarcity issues.

Keywords: Bhutan; water resources; scarcity; conflicts; governance; economy; glacial lake outburst flood



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1. Introduction

Bhutan is a small landlocked country with a 38,394 km² area that is located in between India and China [1]. The country is sparsely populated (20 persons/km²) with a total population of 771,608 according to United Nations (UN) data and out of which only 45.8% of the population is urban [2,3]. The country lies between longitudes 88° E and 93° E and latitudes 26° N and 29° N [4]. Figure 1 shows the location map of Bhutan along with its hydrological features. Bhutan remains 72.5% under forest cover. The country's constitution mandates that forest cover needs to be 60% at all times [1,4,5]. Bhutan has 2674 glacial lakes and more than 700 major glaciers [6,7]. In addition to that, there are also low-altitude wetland ecosystems. Bhutan also receives heavy rain in summer brought by the monsoon from the Indian Ocean and Bay of Bengal [6]. The concentration of rainfall in the monsoon season is so high that the country's development activities are planned considering these climatic conditions [8].

Freshwater in Bhutan is sourced mostly from glacial lakes, glaciers, wetlands, and monsoon rain. The steep mountains in the north reach elevations of up to 7500 m and the elevations are down to 100 m in the south of the country. This forms deep valleys that are divided by 4 major rivers: Amochhu, Wangchhu, Punatsangchhu, and Manas. These rivers carve and shape the country's topography and provide water for various purposes [5,9,10].

1.1. Previous Studies

Sufficient scientific literature is available about the different aspects of Bhutan's water resources. Different scientific studies cover water supply/sanitary, water quality, water balance, irrigation, institutional arrangements, glaciers, water availability, climate change, groundwater, hydro-economy, and the hydropower potential of Bhutan [11–20]. Kharat and Mundra [21] have covered Bhutan's internal and external water issues in detail. Two more studies carried out by Biswas and Bisht [22,23] have covered the transboundary water management issues of Bhutan under the umbrella of the larger south Asian region. In the same fashion, Gain and Giupponi [24] discussed the water scarcity issues of lower Brahmaputra and covered Bhutan's risk of water scarcity. Some interesting research has been carried out on different aspects of hydroclimatic features of Bhutan. Krusic et al. [25] analyzed more than 600 years of summer temperature variations in Bhutan and identified a correlation between solar variability and decadal-scale temperature variability.

Some water quality studies have been conducted using modern tools and techniques. Many studies have explored the monitoring mechanism of glacial lakes, glacial lake outburst floods, and water balance studies using remote-sensing and a Geographical Information System (GIS) [26–29]. Case studies to implement 'Participatory Water Resource Management' have been proposed by Saha et al. for Bhutan's river basins [30]. Gurung has implemented various modern techniques, including role playing, companion modelling, and multi-agent systems to address the irrigation issues of Bhutan [11,31–33]. Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) products have already been used to estimate the runoff characteristics of ungauged basins of the Wangchhu river [34]. Materna combined global navigation satellite systems (GNSS) with the Gravity Recovery and Climate Experiment (GRACE) to investigate the land deformation due to excessive hydrological loads [35].

In an experimental study to address the erratic rainfall patterns being predicted for Himalayan mountainous areas, Wangdi et al., conducted 100% throughfall exclusion and ambient control plots experiments to study the drought stresses on the ecology [36]. Chhetri used linear regression, multi-layer perceptron (MLP), convolutional neural network (CNN), long short-term memory (LSTM), gated recurrent unit (GRU), and bidirectional long short-term memory (BLSTM) to predict the monthly rainfall in Bhutan [37]. Using variable infiltration capacity (VIC) hydrological model, Sonessa et al. found that the temperature variation greatly affects the runoff in northern part the country where elevation is more than 5000 m above sea level [38]. Tenzin and Bhaskar [39] used hydrodynamic modelling to simulate flash flooding phenomena.

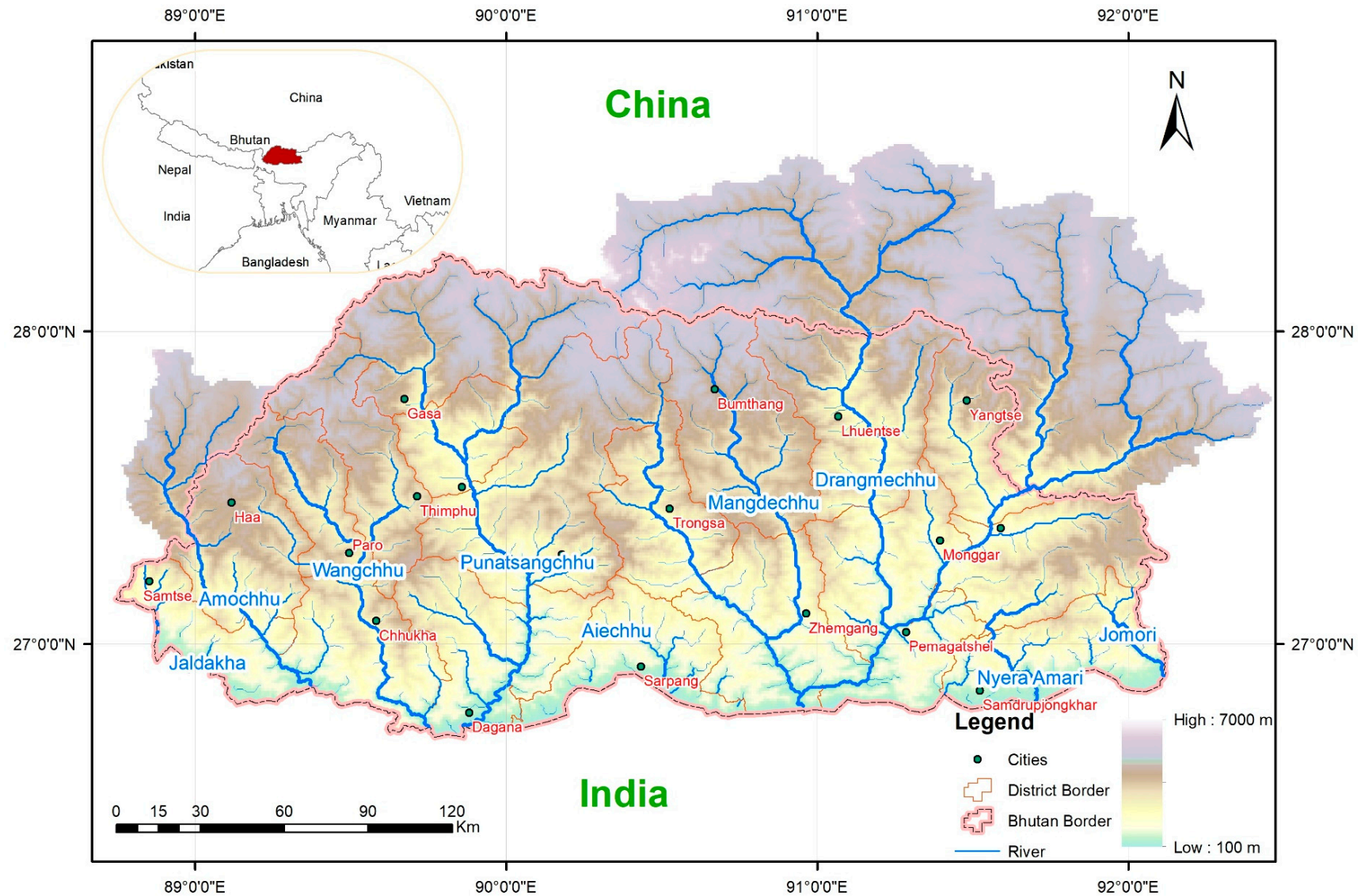


Figure 1. Map of Bhutan along with its geographical location and hydrological features (map developed from data of HydroShed [40]).

1.2. Research Aims and Objectives

Bhutan has one of the highest per capita water resource availability in the world with $94,500 \text{ m}^3/\text{capita}/\text{annum}$ [41–43]. However, it uses only 1% of its total generated annual freshwater due to poor water resource management and its peculiar terrain. In addition, there are increasing drought incidents all over the country. A study has forecasted different levels of water stresses in different districts, especially the capital, Thimphu, to expect absolute water scarcity by 2030. Moreover, due to its strategic geographical location as a small country located between China and India, the water resources and related economic activities deserve attention to investigate its future potential for the country. Despite several research studies focusing on multiple aspects of water resource management in Bhutan, a complete picture of the integrated resources, demands, climatic impacts, institutional setups and legislative developments, hydro-economic development, hydropolitics, and identification of forthcoming issues (that need prompt action) need to be taken into account. This paper covers all the aforementioned aspects along with a literature review of previous studies to identify the priority actions. Therefore, this research aims to investigate the water resource management in Bhutan to:

- (a) Assess and identify freshwater resources;
- (b) Identify the water-related issues;
- (c) Analyze the water resource management plans and practices.

To address the above research aims, the manuscript is structured in the following way:

1. Bhutan's water resource characteristics.
2. Water resource development, policies, and institutions.
3. Hydrology of the country.
4. Water management challenges.
5. Final conclusions.

An introduction to the country and relevant research carried out have already been discussed in Sections 1 and 1.1. The following sections will provide the remaining discussions about the aforementioned aims and objectives.

1.3. Climate and Rainfall

The climate in Bhutan is mainly influenced by altitude. Bhutan can be divided into three climatic zones and geographical regions as can be seen in Figure 2. These are the Southern Foothills, Central Inner Himalayas, and Higher Himalayas [1,41,44].

1.3.1. Southern Foothills Zone

Southern Foothills zone has a subtropical climate characterized by heavy rains and high humidity. The elevation of this zone ranges from 100 m to 1500 m with a temperature fluctuation of 15 to 30 °C, which means warm summers and mild winter. During the monsoon, which is from June to October, they receive plenty of rainfall with precipitation ranging from 2500 mm to 5550 mm per year [14,45–47].

1.3.2. Central Inner Himalayas Zone

Central Inner Himalayas zone is characterized by cold dry winter (−4 to 15 °C) and warm humid summer (5 to 24 °C). The altitude ranges between 1500–3000 m. The Central Inner Himalayas receive precipitation up to 1000 mm to 2500 mm per year [14,45,47].

1.3.3. Higher Himalayas Zone

Higher Himalayas, with an altitude of 3000 m to 7550 m, experiences heavy snow similar to Alpine climate. The temperature frequently drops below zero °C. The summer rains are very light with often foggy or cloudy weather. Mountain peaks are covered in heavy snow and lower parts of this region experience cold winters. This region receives annual precipitation of 400 mm [14,47,48].

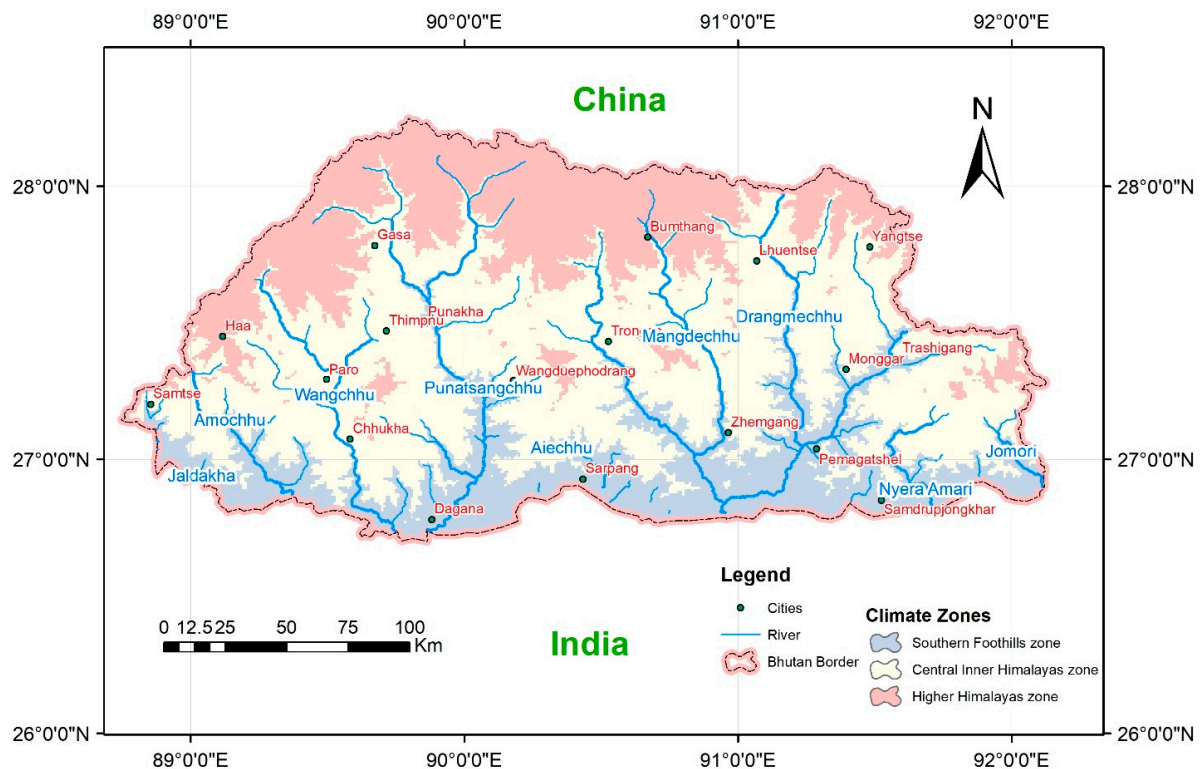


Figure 2. Map showing different climatic zones of Bhutan.

The annual average rainfall in Bhutan is 1825 mm (based on 2019 data). The temperature and precipitation of Bhutan vary significantly because of topographic variability. While the northern region of the country experiences cold freezing weather throughout the year, the southern parts remain warm throughout the year. Four seasons are experienced in Bhutan, namely spring from March till May, summer from June till September, autumn from October till November, and winter from December till February. Precipitation is at its peak with about 75% of the rainfall experienced during June–September and low precipitation during the winter season [49–51]. Figure 3 shows the average monthly temperature and precipitation data from 1901–2016.

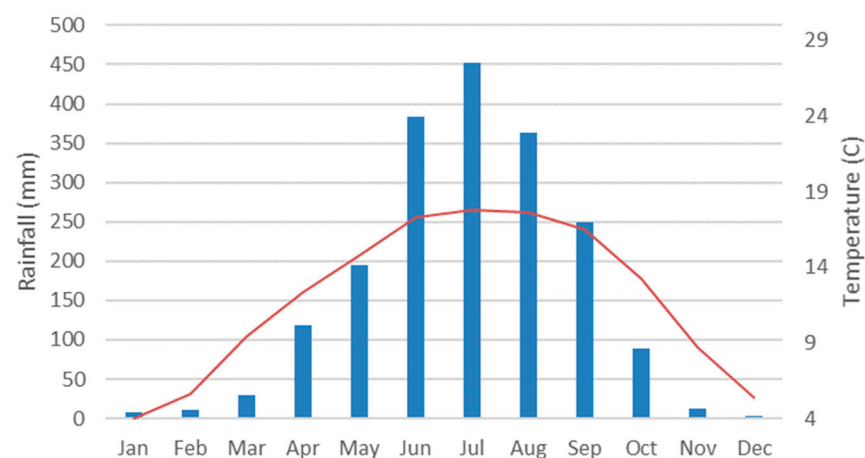


Figure 3. Average monthly temperature and rainfall of Bhutan (Data source: World Bank Group [52]).

1.4. Water Use in Bhutan

Bhutan generates 70,576 cubic hectometers (hm^3) of annual freshwater. Out of total generated freshwater, it consumes only 1% and drains 99% of water to India. 86% ($667 \text{ hm}^3/\text{yr}$) of water in Bhutan is used for agriculture, while the remaining 4.5% ($36 \text{ hm}^3/\text{yr}$)

is used for domestic and 9.5% (74 hm³/yr) for industrial purposes [41]. About 54% of the people of Bhutan reside in rural remote areas and farming is their main source of income and livelihoods [53]. Water from small rivers, streams, and springs are usually used for irrigation. Extraction of groundwater for irrigation is nearly impossible because of the rugged terrain and lack of shallow aquifers in most regions. Rural areas of the country still face seasonal shortages and a lack of accessibility to safe drinking water. Even in about 50% of the urban areas, water supply is not continuous ranging from 6 to 12 hours daily. Water quality does not meet the required quality standards [54–56].

With the country opening its border only a few decades ago, trade with neighboring countries has led to the opening of new factories, and construction of roads and other infrastructure has been increasing. Modernization has led new industries to open such as mechanized car washes, swimming pools, and water parks [57,58]. Water is also used for sanitation purposes and to keep the surroundings clean. Lack of proper sanitation could lead to contamination of water sources and landfills [54].

1.5. Water-Based Economy

Among the South Asian countries, Bhutan is one of the smallest yet fastest-growing economies in the world. From 2008–2017, the country's average GDP rate has grown at around 6.5% per year [59]. Water plays an important role in the economics of Bhutan. The top four major economic drivers, hydropower, agriculture, tourism, and small-scale industry are all related to water. Bhutan's strong trade relations and monetary links with India also play a huge role in its economy. Other key trading partners of Bhutan are Japan, Singapore, Bangladesh, and China.

1.5.1. Hydropower

Hydropower contributes to 25% of Bhutan's GDP. Revenues earned through hydropower exports to India starting from the 1960s are the main driver in Bhutan's development from a least developed country to a middle-income country. Water resources in Bhutan are known as 'white gold' as hydropower generated one of the highest revenues in Bhutan [57,60,61]. The country's hydropower projects are also structurally safe and economically cost-effective [15]. About 99% of the electricity used in Bhutan comes from power generated by hydropower plants. Bhutan's fast-flowing rivers along its steep terrain make it ideal for hydropower generation. It has been estimated that Bhutan's rivers and their tributaries have the potential to generate approximately about 30,000 MW of power [47,62]. Currently, only 1480 MW of power is being generated from the existing hydropower plants. About 94% of its hydropower potential is still unexploited. Table 1 below shows the existing hydropower plants and their installed capacities [43,63].

Table 1. Existing hydropower plants in Bhutan (source: Ministry of Economic Affairs (2018) [64]).

Hydropower Plant	Commission Date	Installed Capacity (MW)	River
Chhukha	1987–88	336	Wangchhu
Tala	2007	1020	Wangchhu
Basochhu 1	2001	24	Basochhu
Basochhu 2	2005	40	Basochhu-Rurichhu
Kurichhu	2002	60	Manas river (Kurichhu)

Bhutan plans to generate 10,000 MW capacity of power by installing 10 new projects. Three of the projects, Punatsangchhu-I (1200 MW), Punatsangchhu-II (990 MW), and Mangdechhu (720 MW) have been completed. Whereas Sunkosh Storage (Approx. 2040 MW), Kuri-Gongri (1800 MW), Amochhu storage (620 MW), Wangchhu (600 MW), Bunakha Storage (180 MW), Kholongchhu (650 MW), and Chamkharchhu-I (670 MW) feasibility studies are not ready and, with such delays, projects are scheduled for completion by 2025 [62].

For a few decades, India has been financing Bhutan's hydropower projects and importing electricity. Such cooperation between the two countries has helped both upstream and downstream communities for sustainable development [22].

1.5.2. Agriculture

Agriculture in Bhutan draws 86% of total water use in Bhutan. It is the source of income for almost 70% of the country's population who are directly or indirectly dependent on subsistence agriculture [65,66]. At the same time, the cultivation practices of the farmers are influenced by climatic factors on a large scale [67]. Agricultural products such as potatoes, cardamom, oranges, and apples are also exported to neighboring countries like India and Bangladesh. The agricultural sector also contributes 15% of total GDP [57,61].

Irrigation in Bhutan is as old as agriculture itself. The Irrigation Division was established under the Department of Agriculture (DoA) in 1967. The Division was mandated with the construction and renovation of irrigation channels/canals, protection of riverbanks from slides/erosion, and construction of feeder roads in the rural areas of Bhutan [68,69]. The farmers themselves managed most irrigation channels and the government provided support in the form of annual subsidies of Ngultrum (Bhutanese currency equal to 0.013 USD) 10,000–20,000 for operation and maintenance of such channels [12]. The subsidy was replaced in 1981 by the government providing full support on the cost of the construction of the irrigation channels. There are about 1200 community-managed irrigation systems in the country, of which 1000 are currently functionally irrigating about 26,000 ha of land [68].

1.5.3. Small-Scale Industries

Small-scale industries such as mining, cement industry, fishery, beverage industry, dairy farming, ferroalloys, poultry, hot stone bathhouse, and handicrafts all are mainly related to abundant availability of water to the country and contribute to the economy of the country. All these small-scale industries use water directly or indirectly for their production.

1.5.4. Tourism

Tourism in Bhutan is an important source of employment and the economy. Bhutan's pristine natural landscapes, which have been maintained in their rich and flourishing state due to abundant water availability, are gaining popularity from all over the world. National parks and nature reserves along the rivers add to the natural beauty of the land. Some of the major rivers flow through some of the tourism hotspot areas and also provide activities such as kayaking and rafting [57,61].

1.5.5. River Route Trade

In 2019, India opened the Brahmaputra river transport route to Bhutan and Bangladesh, which has made it easier and cheaper for Bhutan to export construction materials such as stone chips to Bangladesh. The Brahmaputra River in India is now used as a transit between the Bhutan and Bangladesh trade [70].

2. Water Governance Framework

Until the 1960s, Bhutan's water management focused mainly on single-purpose engineering works like hydropower projects and irrigation schemes to boost the economy of the country. During the 1970s and 1980s, water management planning considered multi-purpose water resource management by taking into account the environmental concerns and bringing the stakeholders onboard. After the establishment of the National Environmental Commission (NEC) in 1989, the vision for sustainable development made way to a comprehensive water management system. A system that focused on coordinated development and management of water, land, and environmental resources [48,57]. The current water resource management of Bhutan can be divided into three parts:

1. Water resource development.

2. Legal framework.
3. Institutional setup.

2.1. Water Resource Development

The first initiative to study water quality in Bhutan was carried out in 1997 by the NEC with support from the Asian Development Bank (ADB). A survey was performed to implement a water quality database for major water resources in Bhutan. The survey found that except for a few localized urban areas, water in Bhutan is safe on a large scale and Bhutan's waterways are exceptionally oxygenated, marginally basic with low conductivity, and have no hints of salinity [58]. As Bhutan focuses on enhancing water security and climate change adaptation, a National Adaption Plan was launched in 2019 with the United Nations Development Program (UNDP) and Green Climate Fund [71].

Negotiation has been used by the Ministry of Agriculture and Forest since 2003 as a mediation tool known as 'companion modeling' to help facilitate negotiations among the water users. The ministry also uses 'Serious Games' to identify the current disputes and proceeds with exchanging of ideas amongst farmers of the same or different village as well as with the local development researchers and authorities [72]. The Lingmteychhu watershed case located in the central west part of Bhutan is a successful implementation example. The approach is appreciated to solve the water conflict issues by Queste et al. [31].

Glacial lake outburst flood (GLOF) is an inherent threat in countries like Bhutan and GLOF prevention and adaptive measures started in 1998 when the Department of Geology and Mines with a research team from Japan made an initial assessment of these lakes by field observations only [73]. The Bhutan government initiated the GLOF Project with support from the Global Environment Facility and UNDP to prevent glacial outbursts and to prepare adaptive measures in 2008. Preventative measures included the installation of gauge monitoring and automated sensors and sirens to warn the authorities and people downstream.

2.2. Water Policies and Legal Framework

There were no separate water policies or formal established institutional framework for the management of water resources until 2003, when Bhutan's first water policy was developed. The issue has been addressed in the form of section clauses in other related policies like the initial editions of the Land Act 1979 and the Forest and Nature Conservation Act, 1995 [69]. Since then, many policies and laws have been developed and framed over the years, most of which broadly relate to water; there are still many that may not specifically have water as their central theme but in many ways are relevant to the protection and conservation of water resources, namely:

- Forest and Nature Conservation Act, 1995.
- Mines and Minerals Management Act, 1995.
- Seeds Act of Bhutan, 2000.
- Livestock Act of Bhutan, 2000.
- Pesticides Act of Bhutan, 2000.
- Environment Assessment Act, 2000.
- Electricity Act, 2001.
- Regulation on Environmental Clearance of Projects, 2002.
- Biodiversity Act, 2003.
- Forest and Nature Conservation Rules, 2006.
- Rules on Biological Corridor, 2006.
- The Constitution of Bhutan, 2008.
- Biodiversity Action Plan, 2009.
- Second National Communication to the UNFCCC, 2011.
- National Strategy and Action Plan for Low Carbon Development, 2012.

Some of the important contemporary policies and laws directly related to water are discussed briefly in the following sections:

2.2.1. Land Act 1979

Water has been principally used for irrigation in Bhutan and it was the prime water use sector by 1979. The Act was the first single piece of legislation, which had an entire chapter dedicated to irrigation. The provisions in the Act, however, were limited to water use and management in its most raw and simplest form. It laid down the responsibilities of water users, water-sharing rights in line with traditional practices [69]. The Land Act of Bhutan 2007 has similar provisions borrowed from the Land Act 1979 on the management of irrigation water including water allocation and maintenance of channels [74].

2.2.2. Bhutan Water Policy 2003

The Bhutan Water Policy 2003 recognizes and states that water is a valuable natural resource and a valuable characteristic asset that is essential to all social, financial, and natural prosperities. Accordingly, the water resources should be preserved and overseen productively, while guaranteeing manageability and without harming the uprightness of the environment. It also recognizes that every person has the right to clean, affordable, and adequate amount of water for individual utilization and sanitary purposes [43,48]. The policy provides a framework for water rights, water conservation, water user interest, water priorities, water-related issues, principles for water resources development and management, issues and resolutions related to trans-boundary water, and delineates institutional roles and strategies to improve institutional management [43,75].

2.2.3. The Water Act 2011

The Water Act 2011 is a significant achievement in the improvement of the legal structure for the water resources in Bhutan. Before this act, water management in Bhutan was divided, tended into various laws, and just centered on the operational level. The Act addresses the water resources in an incorporated way. It targets to propel a reasonable, coordinated, and transparent effort to deal with the various aspects of water resources sustainably. All water-related issues are addressed under this act [48,57,76].

2.2.4. National Irrigation Policy 2012

The National Irrigation Policy 2012 was developed mainly to advance development in the irrigation sector for achieving self-sufficiency and food security. The policy empowers the beneficiaries through a farmer-centered approach and enables effective participation at all levels right from the planning, implementation, operation, and management of the irrigation channels. Like all other policies, it focuses on new sustainable approaches to irrigation infrastructure development and maintenance. The policy also delineates institutional roles and strategizes to strengthen institutional capacity at all levels.

2.2.5. National Integrated Water Resource Management (IWRM) Plan 2016

The National Integrated Water Resource Management (IWRM) Plan 2016 focuses on coordination as a center administration rule and specifically expands on a strong Bhutanese custom of water sharing and coordinated management. This approach is again confronted with an imminent new challenge, climate change having important long-term implications for Bhutan [57]. IWRM serves as the guideline document in the planning and implementation of climate change adaptation to achieve sustainable water security. It provides a holistic approach in water management at the basin level incorporating both water and land resources. It optimizes water supply by assessing groundwater and surface water, incorporating reuse of wastewater, and also assessing the environmental impacts [48,57]. Figure 4 provides a timeline of water-related policies, acts, and regulations along with their connection with institutes and plans.

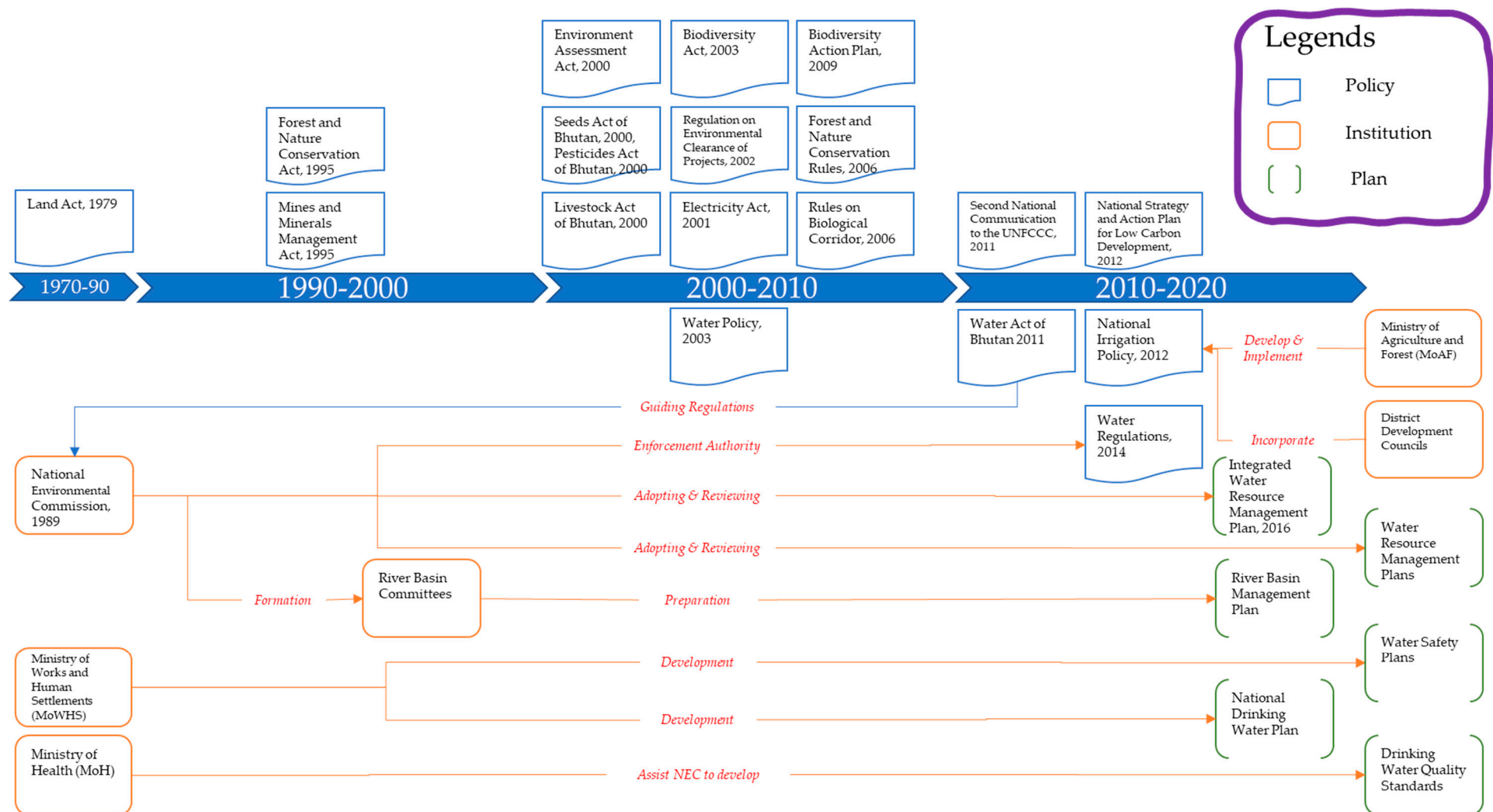


Figure 4. Timeline of policies, acts, and regulations and the connectivity between institutes, policies, and plans.

2.3. Institutional Setup

Water resources related tasks are well organized among the related ministries. The following section provides a brief of the roles and responsibilities of the stakeholders and institutions that are involved directly and indirectly in the water resource management of Bhutan.

2.3.1. National Environmental Commission (NEC)

The NEC is the main custodian of environmental and water resources management. The main role and purpose of the NEC are to develop policies, plan for water development, programs, and monitoring water resources management in Bhutan. The commission was established in 1989. The commission is also responsible for adopting, implementing, and reviewing the IWRM under national policies [48,69,77]. The functions of NEC are:

- Making sure the effective enforcement of water regulations by all authorities concerned;
- Adopting and reviewing the IWRM;
- Adopting and reviewing water resource management plan guidelines;
- Formation of river basin committees;
- Adopting and reviewing of water regulations.

2.3.2. Related Ministries

Ministry of Agriculture and Forests (MoAF)

The Ministry of Agriculture and Forests (MoAF) is responsible for the irrigation system, wetland, and watershed management in the country [77]. The ministry identifies watershed areas to conserve, protect, and manage them. They also develop, plan, and implement the National Irrigation Policy by the other stakeholders involved [48,69]. The ministry also develops the irrigational infrastructure and explores innovative irrigation technologies for the efficient use of water.

Ministry of Health (MoH)

The Ministry of Health (MoH) is responsible for the management of infrastructure, planning, monitoring, and implementation for drinking water and sewage in the rural regions of Bhutan in cooperation with local government and stakeholders [77]. The ministry also performs functions such as:

- Explore new sources such as rainwater harvesting in rural areas;
- Assist the NEC in revising the Drinking Water Quality Standards;
- Record, maintain, and update the physical, chemical, and biological status of drinking water in both urban and rural areas;
- Raise awareness of water-borne diseases.

Ministry of Education (MoE)

The Ministry of Education (MoE) raises awareness in urban and rural areas about the importance of water, water conservation, water-related issues and trains people with some simple water-conserving techniques and solutions for domestic purposes. The ministry also conducts activities and programs to raise awareness on the conservation of water, based on information collected from water resource departments and authorities.

Ministry of Works and Human Settlements (MoWHS)

The Ministry of Works and Human Settlements (MoWHS) is responsible for the management of infrastructure planning, monitoring, and implementation for drinking water supply and wastewater in the urban areas of Bhutan in cooperation with city corporations and local governments [48,76,77]. Some of the notable functions of the ministry include:

- Reviewing and maintaining the existing drinking water supply system in urban areas.
- Developing a National Drinking Water Plan and wastewater management system.

- Explore new drinking water sources such as rainwater harvesting.
- Developing, revising, and implementing Water Safety Plans.

Ministry of Economic Affairs (MoEA)

The Ministry of Economic Affairs (MoEA) through its department of hydropower and power systems ensures the hydropower projects in the country are sustainable, safe, and does not impact the environment or incur any loss to the country's economy [48,76,77]. The functions of the ministry include:

- Assisting the NEC in developing the IWRM with activities under hydropower;
- Collecting information on water resources with construction and planning of hydropower infrastructure;
- Develop safety measure guidelines for the plan, design, and construction of hydropower infrastructure;
- Plan and design hydropower projects for multiple purposes including irrigation and drinking water;
- Research on glacial lakes for threats like GLOFs.

Ministry of Home and Cultural Affairs (MoHCA)

The Ministry of Home and Cultural Affairs (MoHCA) develops public awareness by religious bodies about the water pollution caused by religious and cultural beliefs. The ministry through its Department of Disaster Management monitors and warns the public of any water-related natural disasters such as GLOFs and performs rescue and relief activities.

2.3.3. District Development Councils (Dzongkhag Tshogdu)

Dzongkhag Tshogdu are local government bodies. Each state has an elected leader and members on the council [48,77]. The committee plans and manages the drinking water and irrigation facilities at the district level in cooperation with the aforementioned ministries and represents the districts in the national assembly. The council shall perform the following functions:

- Develop a monitoring and evaluation system for drinking water and irrigation and report to concerned authorities.
- Incorporate the National Irrigation Plan into its activities related to water management.
- Provide technical data during investigations and feasibility studies on irrigation and drinking water abstraction proposals.
- Supervise works on construction of drinking and irrigation infrastructures.
- Conduct tenders and execute the contracts for the developments of irrigation and drinking water ventures.
- Encourage outsourcing of drinking water and irrigation design administrations to the private sector in the district.
- Keep track of water supply systems and submit reports to the competent authority.
- Make sure of regular maintenance of water supply system within its jurisdiction.

2.3.4. Civil Society Organizations (CSOs)

Civil society organizations (CSOs) comprise the Royal Society for the Protection of Nature (RSPN), the Tarayana Foundation, and the Bhutan Water partnership. These organizations spread awareness about the importance of water resources, conservation, water-related issues, water pollution, and misuse of water. They also promote solutions and alternate ways for the efficient use of water [77]. They also promote public–private partnership activities for conservation and sustainable use of water.

2.3.5. River Basin Committees

A river basin committee is responsible for planning and preparing the river basin management plan and monitoring water quality in the river. The committee then reports directly to the NEC [48]. The functions of the committees include:

- Preparing the River Basin Management Plan with the NEC;
- Monitoring and reporting to NEC on the effectiveness of policies and action in achieving sustainable management of water resources in its area of operation;
- Collecting, managing and sharing data as necessary to properly manage the basin in coordination with the NEC;
- Formulating rules and procedures for the establishment and operation of community-level Water Users Associations;
- Promoting community participation in the protection, use, development, conservation, management, and control of water resources in its area of operation through education and other relevant activities.

While the NEC has the central role for the planning, development, and implementation of water resource strategies, the country has recently developed its water policies, and supporting institutional support, to support water management plans. A strong will to secure environment and water resources can be seen as country's economy is purely water-based. However, the institutional setup can evolve to be stronger over the course of time.

3. Hydrological Characteristics

Water resources in Bhutan include rivers, glaciers, and wetlands, groundwater, and reservoirs. Water from the rivers and their tributaries serve as the main source for all sorts of water use, which are fed by annual rainfalls, glacial melt (estimated at 2–12%), and snowmelt (2%) [41]. There are numerous glaciers and glacial lakes to the north of the country, which serve as storage for freshwater. Other sources include wetlands, groundwater, and reservoirs. The seismic nature of the country has made it challenging for groundwater extraction and building large-scale reservoirs, making it a limiting factor in Bhutan.

3.1. The River System of Bhutan

All rivers in Bhutan eventually flow to the Brahmaputra River in India (Assam) and it flows to enter the Bay of Bengal through Bangladesh. The total drainage basin of the river is at an area of 580,000 km², out of which 50% lies in China, 34% in India, 8% in Bangladesh, and 8% in Bhutan [78,79]. The river is 2900 km long, out of which 1625 km flows in China, 918 km flows in India and 337 km flows in Bangladesh. Being a trans-boundary river, Brahmaputra exhibits remarkable flows across the borders, for example, 165 km³ from China to India, 78 km³ from Bhutan to India, and 537 km³ from India to Bangladesh.

Tributaries of the Brahmaputra are the main source of freshwater in Bhutan. The major rivers flow from the northern alpine region to the southern foothills and its tributaries flow from east and west directions as seen in Figure 1. These tributaries are mainly rainfed. The northern alpine region of the country has numerous lakes in remote places, which are formed due to increased glacial melt. The rivers in Bhutan usually flow from steep slopes and into narrow valleys with occasional wide valleys. Discharge of the river depends mostly on rainfall. Due to seasonal climatic variations, the rivers flow with a large amount of discharge and sediments during the wet season and very little flow during the winter season. There is a huge potential for hydropower plants due to the large river flow volumes and steep flowing rivers [49].

As mentioned earlier, the four major rivers of Bhutan are Amochhu, Wangchhu, Punatsangchhu, and Manas (also known as Drangmechhu) [69,80]. Other smaller rivers in Bhutan are Nyera Amari, Jaldakha, Aiechhu, Merak-Saktengchhu, and Jomori. These rivers flow from the alpine north of the country and flow to the south and eventually meet with the Brahmaputra River in India and flow to the Bay of Bengal. Bhutan's 4 major river

systems flow through the 20 districts of Bhutan and serve its population. Figure 5 shows the scheme of the rivers and their annual flows.

3.1.1. Manas River

Manas River is the largest and most extensive river in Bhutan. The river sources from the Arunachal Pradesh district of India and enters eastern Bhutan in the district of Trashigang. The river is 376 km long. Manas river consists of three large branches: Mangdechhu, Bumthangchhu, and Drangmechhu. The river flows through the eastern districts of Bhutan like Trongsa and the Bumthang valley. The river serves for irrigation, drinking, economic growth, tourism, and other purposes in the eastern region of Bhutan. The river also flows through the Royal Bhutan Manas National Park, which serves as an attractive tourism spot and provides water for the wildlife in the park [21,43,80,81].

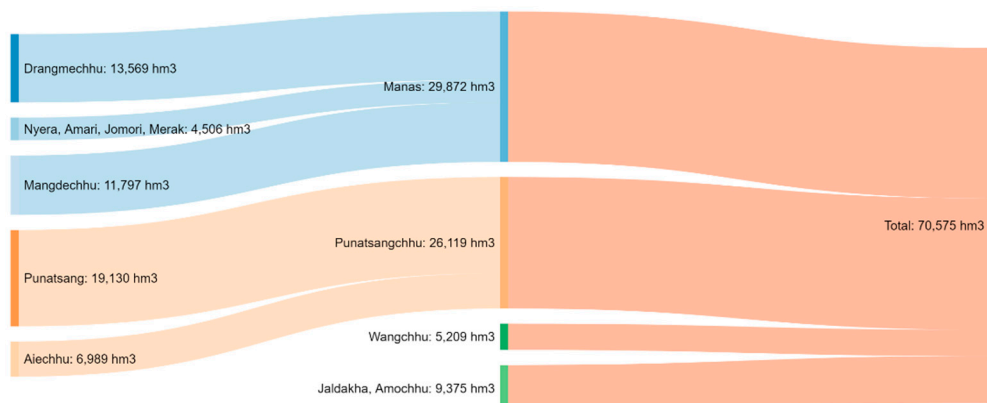


Figure 5. Annual flow of main rivers in Bhutan (Source: National Environment Commission and Katel, O. N. et al. [43,82]).

3.1.2. Wangchhu River

The Wangchhu River runs through the capital city Thimphu, where most of the country's population lives. The river originates from the Himalayan glaciers in the country. The river runs for 370 km. The river provides for various purposes like irrigation, drinking, and tourism [21,81].

3.1.3. Punatsangchhu River

The Punatsangchhu River has two main branches; Phochhu and Mochhu, which meet at Punakha district, and then the river is known as Punatsangchhu. The river sources from the great Himalayan range of the country and it runs for 320 km until it joins the Brahmaputra River in India. Currently, a hydropower plant to produce 1020 MW of power is being built on the Punatsangchhu River to boost the nation's GDP [21,80].

3.1.4. Amochhu River

The Amochhu River runs from China to India through Bhutan. The river is 358 km, out of which 145 km of the river runs in Bhutan. It runs through the southwestern parts of Bhutan. The river adds beauty to the natural landscape of the area and attracts tourists from all over the world [21,80,81].

The relationship between Bhutan and India has been quite smooth in terms of trans-boundary water relationships and managing the hydropower sector successfully together [83]. So far, there have been no trans-boundary water issues between China and Bhutan as well.

3.2. Glaciers

The exact number of glaciers in Bhutan varies as per data from different sources. However, according to the 'Bhutan glacier inventory' of 2018, 700 glaciers cover a total area

of 629.55 km², which covers 1.64% of the total land cover in Bhutan. There are 2674 glacial lakes with an area of about 107 km² [84]. However, the International Center for Integrated Mountain Development (ICIMOD) inventory of 2014 mapped 886 glaciers and the Glacier Area Mapping for Discharge in High Asia Mountains (GAMDAM) inventory of 2014 mapped 864 glaciers. This inconsistency or difference could be due to glacier depression over time, excluding glaciers located in shadow-covered regions during mapping, including seasonal snow in source data and the use of different technologies and methods during mapping [84].

Glaciers and glacial lakes serve as massive storage for freshwater. They also serve as the origin for some of the major rivers in Bhutan and provide for the people living downstream especially during the dry season, which is outside the Monsoon season [85,86]. Climate change and global warming have resulted in faster glacial melt and glacial lakes have become increasingly bigger. These glacial lakes have the potential to burst and could have serious impacts such as floods and erosion downstream of the river [21,86]. Loss of glaciers in Bhutan would mean loss of major freshwater sources as well. As mentioned in Section 1.2, a forecasted absolute water scarcity by 2030 is expected in Thimphu due to glacier melt and increased demographic load. These are melting at a higher rate due to climate change and are causing a potential risk of water security and floods.

3.3. Wetlands

Besides glacial lakes, wetlands are also an important water resource. Wetlands in Bhutan consist of water bodies such as high-altitude wetlands, marshes, bogs, lakes, swamps, paddy fields, springs, rivers, ponds, and streams, etc. A study conducted in 2010 by the Ugyen Wangchuck Institute for Conservation and Environmental Research (UWICER) funded by WWF, found 3027 high altitude wetlands in Bhutan, which covers about 0.26% of the total land cover in Bhutan [42]. Bhutan is part of 23 important bird areas and 8 ecoregions [87]. Bhutan joined the Ramsar convention in 2012. The Ramsar Convention is an intergovernmental treaty that aims at conservation, wise-use, and management of wetlands. It also provides a framework for international cooperation and national actions. Bhutan has designated three sites as wetlands of international importance (Ramsar sites), which has an area of about 1225 ha [88]. In Bhutanese culture, lakes are considered as sacred and holy sites and conservation is prioritized.

Lakes also provide for biodiversity and serve as a habitat for local and migratory animals. Birds such as the endangered Black-necked crane that migrate from Tibet to central Bhutan during winter. Tourists from all around the globe visit central Bhutan during the winter.

3.4. Groundwater and Reservoirs

The rough rugged geographical topography of Bhutan has made the existence of groundwater and aquifers limited. Groundwater resources in Bhutan are annually depleted by the surface water as the surface water and groundwater almost overlap while the river flows, being mainly rainfed, exhibit extreme seasonal variations. That is why groundwater in deep steep valleys of Bhutan is very hard to find. Marginal extraction is carried out only in some wider valleys such as in the districts of Thimphu, Paro, Phuntsholing, Punkaha, and Samtse, where the groundwater reserves are found and are being tapped at a household level only [21]. Extraction of groundwater is also a challenge because Bhutan lies in one of the most seismically active zones in the world and the bore failure rate is very high.

Unfortunately, no large reservoirs have been built in Bhutan. The building of large-scale reservoirs is a big challenge because of the seismic issues. Only small-scale reservoirs are built on rivers and river tributaries for hydropower plants to use as diversion dams [88].

4. Water-Related Issues and Challenges

Bhutan faces several challenges in water resource management due to its topography and seismic activity, and hence the country needs to explore various options under a

comprehensive planning approach. On top of that, climate change has brought in more water-related issues and threats such as floods, glacial lake outburst floods (GLOFs), and droughts simultaneously. Increasing water demand due to development and population increment has also contributed to issues related to conservation and protection of water resources.

4.1. Water Accessibility

Bhutan is a typical example of a country suffering from inadequate water resource management. Having water availability per capita among the highest in the world, Bhutan suffers floods and water scarcity at the same time. This management issue indicates the unavailability of water at the right time in the right place. In some rural parts of Bhutan, closest access to water means hours of walk to the nearest spring or river. This has led to strict water use. For domestic use, the priority of water use is given to drinking and cooking, followed by cleaning and other purposes [53]. Water for sanitation and hygiene is a priority.

Domestic water uses suffers mainly due to accessibility to water resources. The main issue of accessibility problems rises due to the scattered populations on mountain slopes in rural areas [89]. The supply of water to the scattered settlements becomes costly too. Most regions of the country have narrow valleys with settlements usually on the slopes of the mountain or hill while the river or its tributaries flow at the bottom of the valley. Therefore, accessibility becomes economically inefficient for domestic and irrigation activities on slopes. All activities, therefore, depend on mountain springs, streams, and lakes for all sorts of purposes like irrigation, drinking, washing, cooking, and industrial needs [21,89]. Consequently, lack of proper infrastructure and lack of investment in equipment such as pumps, storage tanks, reservoirs, and pipes has led to accessibility problems [63].

4.2. Water Quality

Water pollution is a growing issue in Bhutan. Due to a lack of wastewater infrastructure, settlements, and industries are not properly connected to sewage systems [13]. Privately owned small individual septic tanks are the main options for waste collection. These individual septic tanks have a higher risk as there could be sewage overflow and it could contaminate the river basins [54,90]. In rural areas, people use pit toilets and pour-flush toilets. The increasing population has become a major contributor to the pollution of water as more waste is generated. The rivers in Bhutan are also used for burial purposes because of Bhutanese tradition and religious belief. Infants who die are put inside a wooden casket and submersed in the river instead of cremation and ashes of the dead are also washed away on the rivers. While preserving culture and tradition is important to any nation and its people, river burial becomes an increasing concern as it pollutes the water [57]. The localized deterioration of water quality is limited to most urbanized areas; however, the issue is growing and getting worst in a few areas [91,92].

4.3. Catchments' Land Use

Modernization and anthropogenic activities have led to a lot of land use disasters or issues such as landslides and forest fires, which affect the surface runoff and damage properties and agricultural land. The green land cover (forest cover area, agricultural land, and scrubland) has decreased significantly in the last decade. It is estimated that forest cover is 43%, agriculture area is 6%, and scrubland is 30% as of 2009 [91].

4.3.1. Landslides

Recent infrastructure development has brought new road networks connecting the districts of the country. The construction of road networks in mountainous country and the intense rainfall has led to numerous landslides [93–95]. Cuts in the hill slopes and construction deposits during road construction make the area more prone to landslides.

Landslides affect surface runoffs and cause damages to infrastructure and loss of agricultural land [43,94,95].

4.3.2. Forest Fires

Forest fires are the leading cause of land degradation. Forest fires are regular phenomena, however, 6561 ha of forest reserves were lost to fire with 37 forest fire incidents in 12 districts of the country during 2017–18. Loss of trees and bushes affect the soil and can lead to increased runoff and even causing devastating landslides [93,96,97].

4.3.3. Overgrazing

Cattle grazing is commonly practiced in Bhutan and remains a major economic activity of the rural population. The grazing area covers 11% of the land area [66]. Overgrazing of pasture lands causes loss of plant or animal species, soil erosion, compaction of topsoil, and damage to roots of trees [97–99]. These may cause rapid runoff with higher peaks resulting in frequent flooding.

4.4. Floods

Unpredictable rainfall patterns and sudden heavy rainfalls during the monsoon due to climate change have increased the chances of flash floods in some of the river catchments of Bhutan [100]. Frequent flash floods and landslides were observed in the southern region of Bhutan in 2000 and 2004 when they received sudden heavy rainfall, which damaged properties, highways, agricultural lands, irrigation channels, and water supply schemes. Since 1999, the floods have been more frequent [101]. The direct and indirect impacts of flooding have resulted in an overall reduction of country's GDP by 0.36% [102]. Among the most severe floods during this period were the 2000 monsoon flooding, the 2004 monsoon flooding in eastern Bhutan, the 2009 flooding due to Aila Cyclone, and the 2016 monsoon flooding in southern Bhutan [103]. GLOFs are becoming an increasing threat. The Lugye GLOF in 1994 and Lemthang GLOF in 2015 are the most devastating recorded so far. Similar GLOFs are common in this area in neighboring countries as well. The GLOF from Guangxi Lake in Tibet 1988, the Dig Tsho GLOF 1985 Nepal, and Bhote Koshi GLOF 2016 Nepal are similar examples [28,104]. Further discussion on GLOFs in Bhutan is available in Section 4.6.1. Figure 6 shows areas, which are prone to flooding due to heavy rainfall.

4.5. Irrigation Water Allocation

Irrigation water distribution is based on old traditional rules that follow mutual understanding and fixed proportions among the users. Water allocation is governed by the first come first serve rule and new allocations are only granted to surplus water. Upstream settlements use the water with full rights without compromising the needs of downstream users. However, with increasing development and commercialization, water demand among users has increased. This inequitable sharing of water has become the main cause of conflict among users and demands the development of a systemic approach [32,33,72]. The National Irrigation Policy 2012 seems to be an effective solution for irrigation water allocation disputes and the Ministry of Agriculture and Forest is implementing the new policy with the institutional support of local governments using modern techniques of negotiations as mentioned in Sections 2.1, 2.2 and 2.3.2.

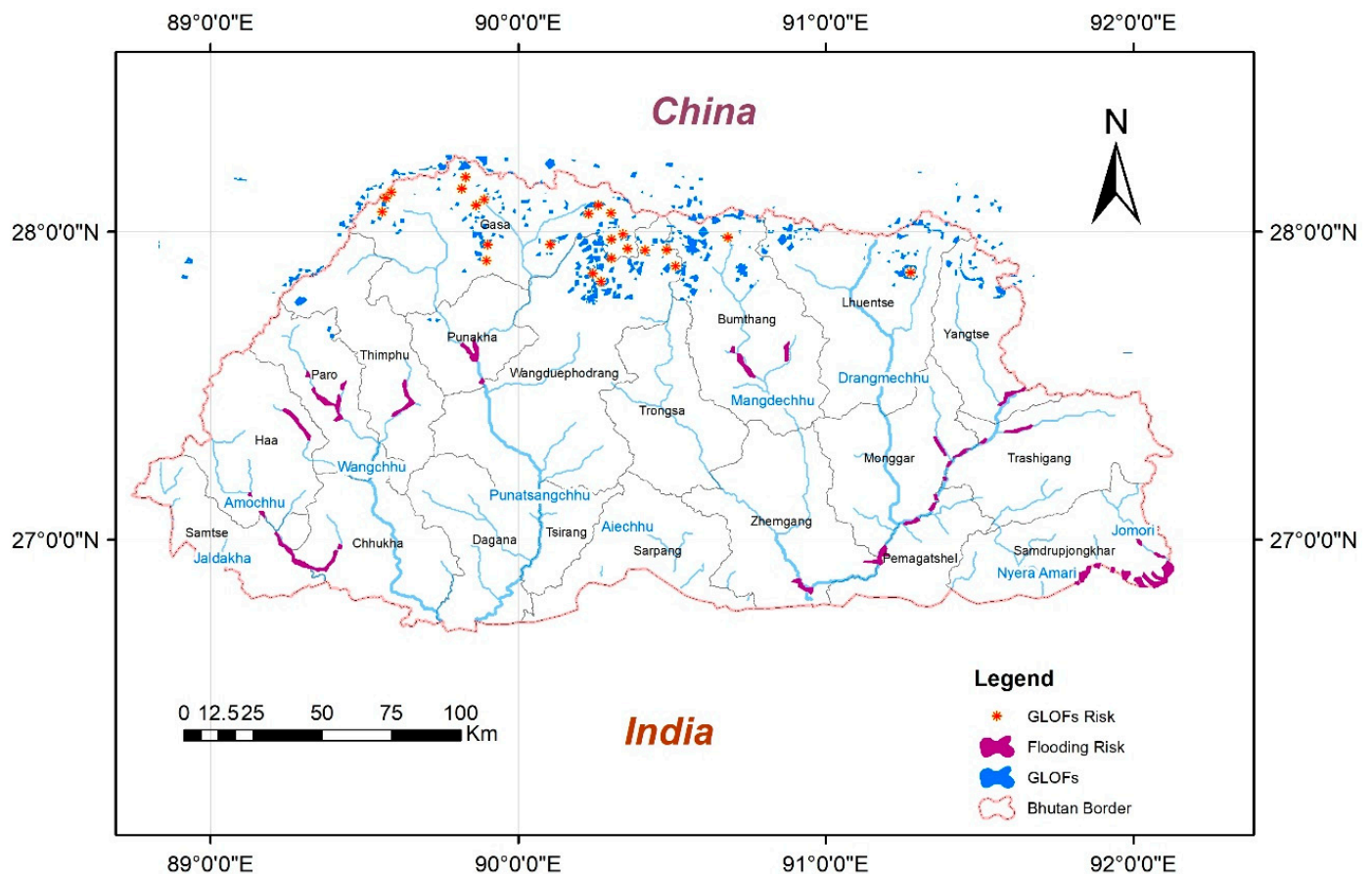


Figure 6. Map showing areas prone to flooding and potential glacial lake outburst flood (GLOF) lakes (Data source: National Environment Commission, Meenawat and Sovacool [7,48]).

4.6. Climate Variations

Climate change is expected to cause increased melting rates of glaciers due to global warming. The rivers, which already show extreme spatial variations in flows are expected to have increased flows in winter causing floods. Koutsoyiannis [105] suggested the phenomena can be termed as ‘climate fluctuations’ under the global hydrological cycle instead of climate change. However, either way, the dry winter season is expected to have more localized drought conditions, especially in urban areas [7,27,69,106]. Different regions in the country face different issues of water because of altitudinal variation over such small distances. In the same way, a large spatial and temporal temperature variability is observed along with increasing temperatures in recent decades [18]. Climatic variation has caused the drying up of water sources during the cold winter and causes water shortages in some regions of the country whereas in the monsoon, the climatic impact is reversed by demonstrating frequent rainfalls that raise the risks of floods and landslides. Unfortunately, the political response against climate change threats is not promising [107]. As 54% of the population living in rural areas depends on farming for their livelihoods, they rely on favorable climatic conditions for a good harvest [53]. During the winter season, people’s water needs are sufficed by snowfall but due to global warming, snowfall has been less frequent in the higher regions of the country. Glaciers in the alpine regions have been diminishing due to less snowfall. These glaciers are very important to Bhutan’s water source as they serve as storage of freshwater, which can be used in the future [43,86,106].

4.6.1. Glacial Lake Outburst Floods (GLOFs)

Increasing glacial melt due to climate change forms and expands the glacier lakes. These lakes have the potential to burst with rapidly increasing accumulation of sediments

and water. The resultant flood after the breach of the moraine dam is called a glacial lake outburst flood (GLOF) [108,109]. An outburst of these lakes possesses a great threat as most settlements are along the river and most valleys downstream are narrow. Across the Himalayas, GLOFs have caused severe damage including fatalities [26]. One such event occurred in the district of Punakha in 1994. The lake was located 100 km upstream of the Punakha valley. The results of the flood were catastrophic with damage to properties and infrastructure. The incident damaged more than 405 ha of agricultural land and 22 people lost their lives [73,109,110]. Bhutan at the moment has about 24 glacial lakes, which have the potential to burst and raising high risk and hazard potential to the regions lying downstream from the outburst [48,73,111]. Figure 6 shows the location of these lakes on the map. The country at present is focused on environmental sustainability, however, climate change-related threats are significant.

4.6.2. Droughts

Climate variation has brought spatiotemporally concentrated rainfalls with increasing temperatures. Changing rainfalls patterns and reduced snowfall along with the melting glaciers are the main causes of drought and drying of water sources in Bhutan [17,112,113]. Rural communities that rely on agriculture for their livelihoods are more vulnerable to droughts. Most Bhutanese farmers practice subsistence farming for which timely rainfall is very important. Cultivation of crops such as rice, which require more water, is affected by changing rainfall patterns [17,24,113]. Delayed rainfall and changing patterns of rainfall have become one of the major concerns for farmers. The southern districts of Bhutan experienced no rainfall for almost 4 months, which affected the livelihood of the farmers and the residents in the winter of 2012. Production of crops was significantly affected. Some districts even reported drying up of drinking water sources [114]. The increased water shortage is not only because of the reduction in water availability, but also due to increase in water demand. Collapse of the Maya civilization is an example of the most severe impact of reduction in precipitation [115,116]. Compared to neighboring countries, Bhutan experiences fewer and less severe droughts. Even though information and data on droughts is limited, there have been cases reported by individual municipalities and agencies [113].

5. Conclusions and Recommendations

The high availability of per capita water at the national level in Bhutan and the water scarcity at a local level has impeded development at various scales across all sectors. Among the main issues facing the country, the existing settlements on the rugged sloping terrains, inefficient water resource management, and lack of coordination between the institutions are prominent bottlenecks. The rapid socio-economic development and the growing population of the country have invariably increased the demand for water across all sectors, mainly in domestic, agricultural, industrial, and hydropower sectors. Water security is expected to worsen due to the impacts of climate change.

Currently, Bhutan's wastewater treatment plants are overwhelmed due to the rising population and most homes rely on individual septic tanks, which are sometimes not functional. Houses are not connected to a treatment plant properly and hence they pollute the water sources and the land. Bhutanese people have traditionally enjoyed abundant water for drinking and farming. It would be challenging to motivate the masses of people for undertaking remedial measures to overcome localized droughts. In such situations, government-backed projects appear to be the only workable and pragmatic options. It is anticipated that there may possibly be more severe regional water-sharing issues, but hardly any major trans-boundary issues are expected in the near future due to increasing population, urbanization, climate change, and increasing water needs.

The NEC is the apex authority for the overall leadership and coordination of efforts for the sustainable management of Bhutan's natural resources along with all other agencies with their clearly defined roles and responsibilities. Bhutan has invested a lot of resources in

setting up institutions, training people, and creating an enabling environment for effective policies and legal frameworks. Various acts and policies outline specific institutional arrangements and identify sector-specific agencies as functional nodal authorities to smoothly implement the provisions laid therein. Bhutan has developed adequate policies and a legal framework for coordinated water resources management to fulfill its socio-economic needs. The country also continues to improve its existing policies and management plans and has put in place a strong institutional system for good governance in the effective roll-out of the management plans.

Freshwater resources are a critical component of Bhutan's economy. Although, tourism is not directly related to water, indirectly it relies heavily on sustainable water management. Bhutan also has a big economic potential of hydropower, of which only a fraction is so far utilized, and the country has plans to explore it even further. While hydropower may have a significant advantage in terms of the economic growth of the country, it also impacts the environment and water resources. Community-managed irrigation systems are highly dependent on seasonal water availability, which is adversely impacted by floods, landslides, rainfall, and temperature variations. Due to the absence of the irrigation system's ability to resist climatic influences, the system is highly susceptible to climate change.

Bhutan has manageable water-related issues except for the localized water scarcity that is emerging due to climate change and growing water demands. Localized water scarcity is an issue that needs urgent attention. Based on the conclusions above, the following recommendations may help to further improve the water resource management in Bhutan:

- All relevant institutional agencies should promote sustainable water management practices to the public with events, campaigns and advertisements held more often.
- Investing in more treatment plants to meet the current requirements, which would help reduce the risk of water pollution.
- While further developing hydropower projects is good, its harmful environmental and ecological impacts should not be overseen. These considerations also contribute to promoting the 'tourism industry' because adopting sustainable environmental and ecological management practices attract tourists.

Due to climatic variation, rainfall is becoming unpredictable and water sources are drying up. At the same time, water demand has grown due to increasing population, lifestyle changes and increased industrial demands. Many urban areas prone to localized water scarcity need the introduction and promotion of water storage techniques such as rainwater harvesting and groundwater storage. Localized storage of water for drinking and irrigation of small fields would be enough for use during dry seasons. Although groundwater extraction and building of large-scale reservoirs are challenging in Bhutan due to its topography and seismic activity, these could still be constructed in some wider valleys or other suitable locations. Bhutan must also invest in and construct large seismic-resistant reservoirs, which will augment the water supply system during the dry periods and help meet the water needs of the future.

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