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A Review and Analysis of Water Research, Development, and Management in Bangladesh

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Abstract: This paper presents a review of water research, development, and management in Bangladesh, with examples drawn from the past and present. A bibliometric analysis is adopted here to analyze the water-related publication data of Bangladesh. Water-quality-related research is the dominating research field in Bangladesh as compared to water-quantity (floods and droughts)-related ones. The most productive author was found to be Ahmed KM for water-related publication in Bangladesh. The arsenic contamination in Bangladesh has received the highest attention (13 out of the top 15 highly cited papers are related to arsenic contamination). Climate-change-related topics have been showing an increasing trend in research publications over the last 5 years. Bangladesh Delta Plan 2100, prepared recently, is a visionary master plan that is expected to shape water management in Bangladesh in the coming decades to adapt to climate change. A set of recommendations is made here to achieve sustainable water management in Bangladesh.

Keywords: Bangladesh; hydrology; floods; groundwater; arsenic; rainwater harvesting; water sharing; climate change; Bangladesh Delta Plan; BDP 2100

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1. Introduction

The importance of water as a precious resource for human sustenance and development has been well recognized since the advent of the ancient civilizations, which flourished along with the major river systems across many countries such as Egypt, India, and China [1]. There is a common saying that "water is the oil of the 21st century" [2]; however, this misses out on the most crucial fact that water, unlike oil, has no substitute for living beings. It is well-known that accelerated population growth and the increasing demand for resources have significant impacts on hydrological cycles and ecosystems [3]. Rapid land-use change, such as urbanization, alters flow regimes and deteriorates water quality [4,5]. Besides drinking water needs, water also has an indispensable role in food and energy production, ecosystems, and climate systems [3,6,7]. Furthermore, socio-economic development is resulting in increased water demand. Moreover, environmental and ecological water demands are increasing due to greater environmental awareness.

Bangladesh is one of the largest and most active deltas formed by the complex Ganges–Brahmaputra–Meghna River systems. It has an area of 148,000 km^2 and about 24,000 km of rivers and their tributaries and distributaries, freshwater marshes, mountain streams, brackish water impoundments, and winding seasonal creeks and canals [8,9]. There are 405 prominent rivers, including 57 transboundary rivers with India, Nepal, Myanmar, and China [10]. The Ganges, Brahmaputra, and Meghna, the three major rivers of Bangladesh are characterized by active erosion and sedimentation processes. These river systems have a total catchment area of 1.72 million km^2, only 7% of which lies in Bangladesh [11,12]. Bangladesh is a tropical monsoon country characterized by warm, humid summers, relatively cold, dry winters, and heavy monsoonal rainfall. About 80% of the total rainfall occurs in the five monsoon months [8]. The topography of Bangladesh is mainly low-lying, flat floodplain, which experiences frequent floods. The main water problems in Bangladesh are related to high flow (flooding) during monsoons and a prolonged dry period in winter (lasting about six months).

In Bangladesh, about 80% of the water is used for agricultural purposes. About 97% of the total population of Bangladesh has access to water; however, the quality of water is a major concern [13]. Drinking water is often contaminated, and hence, water-borne diseases are common in Bangladesh. None of its city water supplies are reliable, and hardly any person would like to drink mains water without further in-house treatment such as filtering or boiling. Parvez [14] tested 53 tube-well water samples across the country and found that 81.2% of the samples contained coliforms. Acharjee et al. [15] detected a high concentration of pathogenic bacteria in the water samples of the Dhaka Water and Sewerage Authority (WASA).

Surface water is generally highly contaminated by numerous sources such as untreated industrial effluents, domestic waste, and agricultural runoff. Groundwater, used for drinking by rural people, has been contaminated with a high level of arsenic, affecting about 30 million people [16]. Water and sanitation problems are attributed to about 8.5% of the total deaths in Bangladesh [17]. The salinity level in the soil and water has been increasing due to high water abstraction by India from the international rivers and due to climate change. Bangladesh is ranked sixth on the Global Climate Risk Index, and the vast majority of Bangladesh could be under water due to sea-level rise within the next few hundred years. Major water issues in Bangladesh are illustrated in Figure 1, which shows that Bangladesh water research and developments are dominated by floods, climate change, water contamination, water sharing, and transparency.

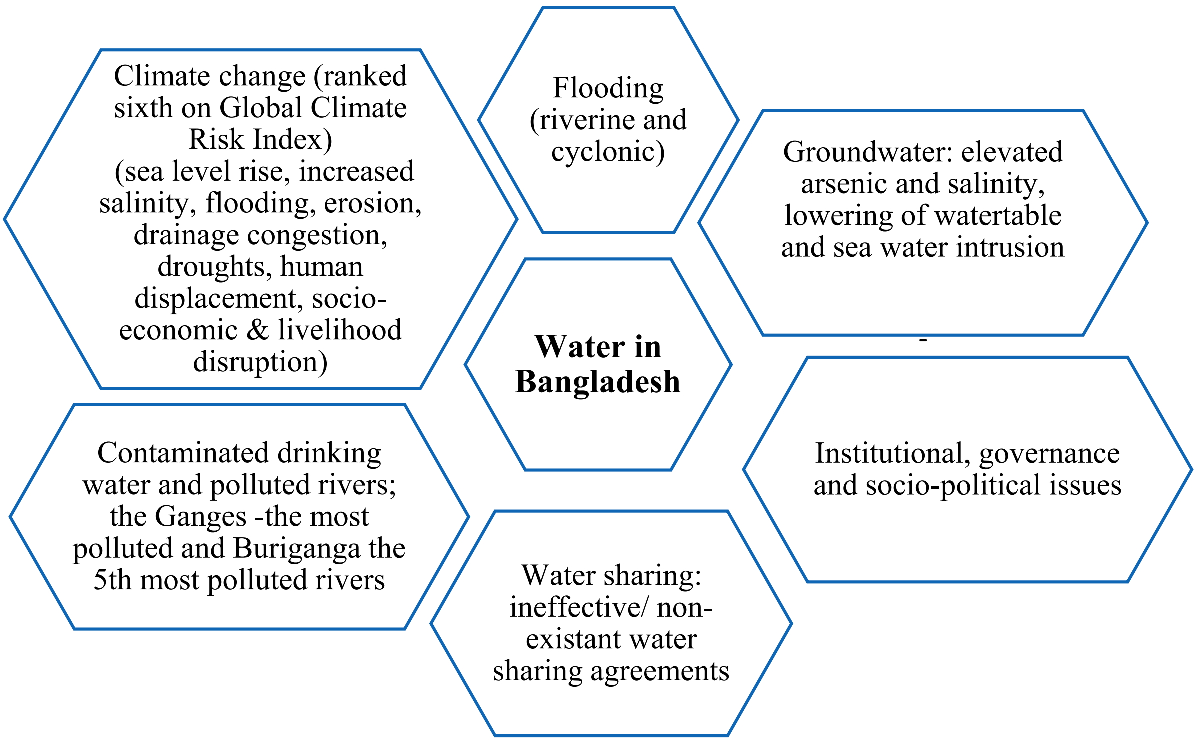

Figure 1. Illustration of major water issues in Bangladesh.

Barbour et al. [18] stated that over 35 million people living in the coastal zone of Bangladesh are being affected by increased flood risk, salinization, and waterlogging. By a modeling exercise, they demonstrated that improved drainage is more effective than embankment rehabilitation in improving agricultural production in Bangladesh. Rahman et al. [19] noted that increased salinity in the coastal areas of south-western Bangladesh has caused a crisis in drinking water. As per this study, the development of a community-based model is needed to solve drinking water problems, which should incorporate all levels of governments, non-government organizations (NGOs), and community people. Roman et al. [20] investigated investment scenarios to provide safe drinking water in coastal areas of Bangladesh, which have been badly affected by a high level of salinity. They compared several options, including deep tube wells, desalination plants, and piped systems, and the results of this study can inform investment in the water supply in the coastal region of Bangladesh. Fisher et al. [21] noted that in 2018 there were USD 253 million private investments in tube wells, accounting for about 65% of the total water and sanitation sector's household-level investment. This indicates that a 'private–public blended financial model' could potentially solve the drinking water crisis in coastal Bangladesh.

Islam et al. [22] noted that 20.1% of the shoreline in Bangladesh is highly vulnerable to sea-level rise, while 21.5% is moderately vulnerable. Hoque and Hope [23] noted that poor people in the coastal areas of Bangladesh often use multiple sources of drinking water to reduce expenses and travel distances. They identified five water expenditure types—all of these are based on poor water quality sources (shallow tube wells, pond sand filters, and rainwater); however, about a small percentage of wealthy people use vended water for drinking and cooking, accounting for about 3–7% of total household expenditure. Hossain et al. [24] found that risk-averse farmers are willing to take up flood insurance to minimize crop loss due to flooding. In developing such a flood insurance scheme in Bangladesh, the flood risk level and farmers perceptions should be considered. Hoq et al. [25] noted that floods affect haor areas badly, in particular Sunamganj district. Mehryar and Surminski [26] stated that climate change is resulting in increased flood risk. They also argued that flood-related regulations are formulated after a major flood event and the majority of these are based on a reactive approach, which should be changed to proactive approaches such as risk reduction and nature-based solutions.

There have been numerous studies on water research in Bangladesh; however, there is hardly any bibliometric analysis available in the literature to map these research studies. To fill this current knowledge gap, the objective of this paper is to present a brief overview of water development and research in Bangladesh and present a bibliometric analysis to map the previous studies on water research and to identify current trends and future challenges.

2. Methodology

In this study, a systematic literature review is conducted to evaluate the water management status in Bangladesh. At the beginning, water resource management in Bangladesh is reviewed to provide a historical perspective, which is followed by a bibliometric analysis, which was conducted in three main stages: (i) defining the keywords; (ii) searching relevant articles, analyzing data, and refining of scope; and (iii) science mapping and data visualization. Peer-reviewed publications were searched through the Scopus database covering the period 1972–2021. The search was performed in the title (TITLE) and keywords (KEY) of the publications on 5 October 2021. Key terms for the query were selected carefully, and the query was refined by limit to language (English), source types (e.g., journals, conference proceedings papers, and book chapters), document type (e.g., article, conference paper, book chapter, book, and review), which were related to water research in Bangladesh. The bibliometric analysis was conducted using the bibliometrix R-package version 3.1.4 (https://www.bibliometrix.org/home/, accessed on 24 October 2021) in the Rstudio environment (https://www.rstudio.com/, accessed on 24 October 2021) and VOSviewer version 1.6.17 (https://www.vosviewer.com/, accessed on 24 October 2021).

3. An Overview of Water Management in Bangladesh

Water governance in Bangladesh has seen notable changes and shifts since 1947, in particular in the last 30 years. The government of Bangladesh has shown a keen interest and has taken a proactive approach to forming water governance bodies in line with the advice of development partners, as summarized in Table 1 and Figure 2. In water governance, several agencies have taken the leading role, such as the Bangladesh Water Development Board and the Bangladesh Agricultural Development Corporation. In terms of water research, universities and development partners have taken the leading role.

Table 1. Five eras of the evolution of water policies in Bangladesh [27–31].

Era	Ancient Time to 1947	Foundation of Water Institution (1947–1988)	Establishing the Flood Action Plan (1989–1994)	Restructuring the Water Sector (1995–1998)	Evolution of Water Governance (1999 to Date)
Main Concerns/Goals	Open-lined and unlined wells, overflow irrigation, manual bucket irrigation	Establishment of key institutions (e.g., Irrigation Department, EPWAPDA, BWDB) of water management	Flood controlling and managing strategy formulation	Reformation of water management systems, particularly in decision-making process	Developing standardized policy instruments to tackle water challenges
Major Challenges	Increase agricultural production and flood control	Increase agricultural production and flood control	Controlling floods, particularly saving agricultural production	Integrated approaches of water resource management	Managing water demand and crisis by leveraging science, technology, and sociology
Main Projects	Construction of embankments along flood-prone rivers	A 25-year Water Master Plan (WMP)	The Flood Action Plan (FAP)	The Guidelines for People's Participation (GPP) for water development projects	The National Water Policy, Guidelines for Participatory Water Management (GPWM) and National Water Management Plan (NWMP)
Key Features	Construction of open-lined and unlined wells for domestic and supplement irrigation water needs. Some large-scale canals were constructed in Mughal period for irrigation purposes. Moreover, the construction of embankments along the major rivers was also used for irrigation as well as flood control measures. Overflow irrigation was another popular method for diverting water from rivers to agricultural lands.	Preparing WMP was the initial step of water management. It focused only on the surface water management and overlooked groundwater management. Water management focused mainly on "sectoral approaches" and "structural engineering solutions" that raised many criticisms. Broadly, water management approaches covered flood control, drainage, and irrigation management, and decision making was solely BWDB-centric.	Flood control received international attention and donors' support to prepare FAP. However, FAP was criticized by civil societies and NGOs as it dissuaded decentralized decision making. Small irrigation was privatized because of the flourishment of shallow tube wells at this time, which resulted in substantial tax reduction.	The focus of water management was flood control and drainage, though water crisis remained a major problem in the dry season. Enacting Upazila (Sub-district) Parishad Act 1998. Establishing Local Government Engineering Department (LGED) and preparing LGED to involve local people in water projects. Reinforcing local government organizations and implementing Environmental Impact Assessment (EIA) practice	Several strategic initiatives were taken, such as facilitating partnerships and devolutions of power. The government had approved a 25-years NWMP and developed other instruments, namely BWDB Strategic Plan 2009–2014, National Water Act 2013, and Haor (flooded tectonic depressions) Master Plan 2012–2032. However, the challenges lie in the implementation of these instruments, as the country has a shortage of resources and political will.

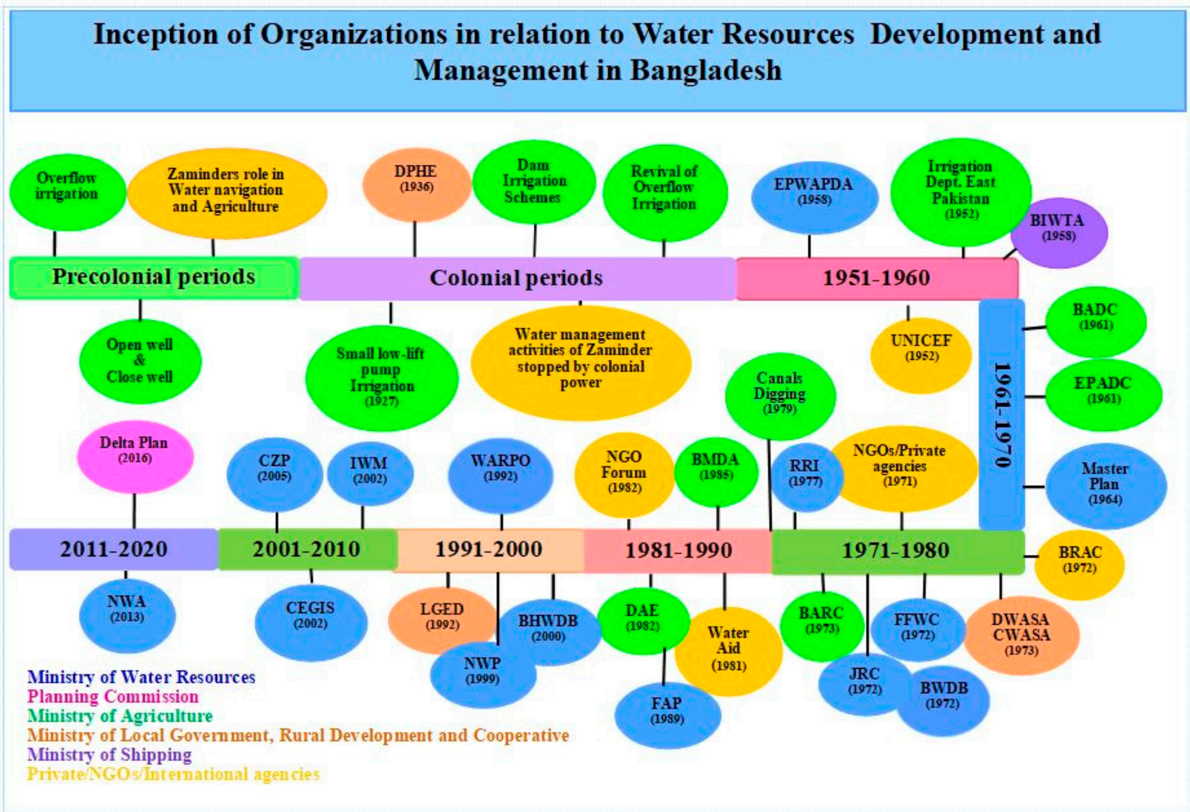

Figure 2. Water sector institutional framework in Bangladesh [32].

4. Groundwater Management

Surface water is abundant during the monsoon, resulting in seasonal floods; however, there is a deficiency of water during the dry season to meet irrigation, industrial, and other water demands. As a result, the dependency on groundwater in Bangladesh has increased profoundly since the 1960s with the introduction of high yield variety (HYV) rice, which require a timely and assured water supply [33]. The unsustainable extraction of groundwater leads many rural and urban areas of Bangladesh facing water problems, including the drying up of wells during the peak irrigation period and the lowering of the groundwater table. Currently, about 80% of the dry season irrigation water supply is derived from groundwater, which plays a vital role in meeting the growing demand for food production, and nearly 98% of drinking water comes from groundwater [8]. The Dhaka Water Supply and Sewerage Authority (DWASA) sources 78% of its water supplies from groundwater through a network of about 887 production wells, and in several parts of the city ground level has now dropped 60–70 m below the ground surface due to over-exploitation [34].

Regardless of hydrogeological complexity and an inappropriate understanding of aquifer responses to stresses, groundwater management started from a fragile institutional arrangement like in other developing countries. Scientific and institutional governing approaches are slow to ensure the effective use of groundwater. With the frequent occurrence of water-related conflicts, mainly due to water scarcity, the institutional development to govern the use of water resources, its allocation, and management are not receiving adequate policy attention. Good governance needs a proper matching between the scale of ecological processes and the institutions that deal with groundwater resources [35].

Besides unplanned exploitation, groundwater resources are increasingly facing quality problems that are both anthropogenic, i.e., pollution from urban, industrial, and agricultural activities, as well as geogenic, i.e., arsenic contamination in floodplains and salinity in coastal areas make the water unacceptable for human consumption for many areas. The arsenic contamination of groundwater caused an unprecedented impact on human health in rural areas of Bangladesh for decades [36–40]. This section collates the information on the history of the identification of arsenic in groundwater in Bangladesh. The section also discusses the water table lowering, which is also a burning issue in Bangladesh, even though it enjoys the benefits of the frequent recharge of groundwater due to rainfall.

4.1. Arsenic Contamination

Rural people in Bangladesh use a hand pump called a tube well to extract groundwater for drinking and other household purposes. The tube well consists of a tube (usually 5 cm in diameter), which is inserted into the ground (at a depth of <200 m) to tap the aquifer and is capped with a steel casing [41]. People in Bangladesh rely on tube wells as a safe source of drinking water compared to river/pond water [42]. This is generally the only source of drinking water in rural areas and was endorsed by the government and aid agencies, such as UNICEF (The United Nations Children's Fund), since the 1970s [41].

The presence of arsenic in groundwater and its impact on human health was first identified in the 1980s in the neighboring West Bengal, India, [43,44]. Skin diseases, including changes in pigmentation on the chest, arms, and legs and keratoses on the palms and feet were observed. Some of the patients examined by Guha Mazumder et al. [43] were from Bangladesh, which raised the alarm that similar arsenic contamination may already have occurred in Bangladesh. In Bangladesh, the presence of arsenic in groundwater was first identified in 1993 in Chapai Nawabganj district, in the north-western part of Bangladesh [41,45,46]. However, no scientific communication was made by the government of Bangladesh in that year. In 1995, a group of researchers from the School of Environmental Studies, Jadavpur University, Calcutta, India, organized a conference to raise awareness of arsenic contamination in West Bengal and Bangladesh [47]. The conference paved the way to alert the aid agencies working in Bangladesh as well as the government of Bangladesh to check the quality of the drinking water for arsenic contamination. In 1996–1997, different research teams from Jadavpur University, India; Dhaka Community Hospital, Bangladesh; and the National Institute of Preventive and Social Medicine (NIPSOM), Bangladesh, surveyed to analyze water samples from tube wells for arsenic contamination in different parts of Bangladesh [41,48].

Samples of hair, nails, and skin were also collected to check for arsenic. In all of the samples, a high level of arsenic was found [41,48]. In 1998, the British Geological Survey (BGS) conducted an extensive survey in 41 districts of Bangladesh and found arsenic in the water samples in the range of 50–300 μg/L, which was far above the WHO-approved standard of 10 μg/L [49]. In the same year (1988), the scientific community was informed about the severity of the arsenic contamination problem at a conference organized in Dhaka, Bangladesh [50,51]. The conference was able to attract the attention of major international aid agencies, such as the World Bank, UNICEF, DANIDA, and BGS. The aid agencies then started to actively collaborate with the government of Bangladesh in the further identification of arsenic contamination and the mitigation measures [47].

Currently, tube wells in 61 districts out of 64 districts are arsenic-affected [44,49,52]. Tube wells are marked according to the Bangladesh standard arsenic threshold level of 50 μg/L; the tube wells are marked green if the arsenic level in the tube well water is less than the threshold level and are otherwise marked red [47]. Different mitigation measures are implemented to fight arsenic contamination, which includes public awareness and alternative sources of water, such as arsenic removal plants, deep tube wells, ring wells, filters, rainwater harvesting, and pipe-line water supplies [53–56]. Although the mitigation programs are improving the situation [56] and the percentage of the rural population with access to safe water has increased by around 87% as reported by DPHE [57], 13% of the water source is still under threat, with arsenic concentrations higher than the government of Bangladesh's defined threshold level.

4.2. Water Table Lowering

The geomorphology of Bangladesh can be divided into four regions, namely, tableland (consisting of Pleistocene plain and Pleistocene upland), flood plain, deltaic, and hill tract [48]. While flood plains dominate in most of the northwest, northeast, north-central, and south-eastern part, tableland is observed in some parts of the northwest and north-central region. The south-western part is under deltaic plains with some exceptions for the presence of coastal plains in the coastal areas of Bangladesh [48,58–60]. The thickness of aquifers differs depending on the type of aquifer and location. For example, the thickness of shallow aquifers ranges from a few meters in the northwest to 60–75 m in the south, and the deeper aquifers range from 190–960 m in the northwest to 250–1500 m in the south [60]. The Pleistocene aquifers are observed in terrace areas, including the north-central (i.e., greater Dhaka) region and the Barind Tract in the northwest part of Bangladesh [59,60].

According to Harvey et al. [61], the recharging of aquifers in Bangladesh occurs by surface water during the dry season (November–March) and by rainfall during March–June. Typically, 40% of the yearly recharge is contributed by surface water and 60% by rainfall. The groundwater is rarely recharged during a flood due to the absence of a hydraulic gradient. The extraction of groundwater has increased vastly in the last three decades. According to Zahid and Ahmed [60], between 1985 and 2004 throughout the country, the number of shallow tube wells increased from 133,800 to 925,152, and the number of deep tube wells increased from 15,300 to 24,718. The lowering of the water table occurs when the extraction is higher than the recharge over a period. It is particularly evident in vast agricultural areas that rely on groundwater for irrigation. One such agricultural area is the Barind tract, a major rice-producing area situated in the northwest part of the country. Starting in 1986, an estimated 62% of the 767,900 ha in the Barind tract are irrigated with groundwater [60]. The groundwater is extracted using shallow and deep tube wells. Mojid et al. [33] reported a falling trend in the water table after analyzing the water table trend in 350 monitoring wells between 1985 and 2016; in about 60% of these wells, the water table was below the suction limit for three to six months of the year. A similar lowering trend in the water table was also observed by other researchers [33,62–65]. According to Kirby et al. [59] the groundwater level in this area in the pre-monsoon months shows a declining trend (due to continuous withdrawal of water for irrigation), but, in post-monsoon months, the level of the water table regains some extent. The regain of the water table depends on the recharge and is affected by the variability in the rainfall and, thus, climate change [59]. Apart from climate change, other significant reasons for less groundwater recharge are due to changes in the courses of major rivers (i.e., Ganges, Teesta, and Kosi), unsustainable irrigation practices (by the overexploitation of groundwater), and drainage characteristics [64]. The construction of the Farakka barrage upstream of the Ganges River in 1975 by India, which restricts water flowing downstream during the dry season, is also responsible for water scarcity in this area [66].

The lowering of the water table is also observed in metropolitan cities, such as Dhaka, the capital city of Bangladesh and one of the largest of 22 growing megacities in the world [67]. Unplanned groundwater extraction, rapid urbanization, land transformation, and growth of the urban population are some of the reasons for the water table lowering in Dhaka [60,68]. In four decades (1970–2013), groundwater extraction in Dhaka city and its surroundings has increased from 0.5 million m^3/day to 5.9 million m^3/day to meet the domestic, commercial, industrial, and irrigation demand [67]. After analyzing a long-term (2000–2018) groundwater table dataset in the wells in metropolitan Dhaka city and surrounding areas, Roy and Zahid [69] concluded that the groundwater table is lowering by 1.5–2.1 m/year in Dhaka city and around 1 m/year in the surrounding areas. The decline in the water table is continuous, with little or no fluctuation, meaning the aquifer is not recharged much. A similar observation of the decline of the water table was also made by other researchers [67]. The lowering of the water table also risks the quality of the groundwater. Harvey et al. [61] suspect that the lowering of the water table in greater Dhaka may reach the level of the aquifer where the dissolved arsenic level is very high, causing an increase in the arsenic level in the groundwater. Some of the steps that may reduce the decline of the water table, as suggested by Roy and Zahid [69], are: (i) to regulate unplanned over-pumping; (ii) to find alternative sources of groundwater; (iii) to implement managed groundwater recharge; and (iv) to incorporate research-based knowledge in groundwater management, modeling, and prediction [68].

5. Social Aspects

For centuries, the people of Bangladesh have adapted their lifestyle to live with water, which has been embroidered in the poetry, literature, arts, history, and socio-culture of Bangladesh [70]. This delta is the home of very old civilizations, which symbolize the art of using water bodies in shaping their social, cultural, and economic lives [71]. The people of Bangladesh have diverse religious and cultural backgrounds. This country is a melting pot of different religions, cultures, ethnicities, and dynasties where people from different backgrounds coexist harmoniously and have shared their cultures and traditions over the centuries. Since ancient times, different cultures, religions, and their practices have influenced the people's way of understanding and habit of using water resources [72]. Therefore, relations between the society and water here are mostly embedded in religious and cultural traditions, which are strongly interlinked [73]. Water is a vital resource of life, and culture determines its way of utilization in life. All religious scriptures have highlighted the importance of water in nature and human life. Water acts as a key building block of life, a cleanser of pollutants, and a carrier of land nutrients and plays a crucial role in the religious beliefs and rituals in pluralistic Bangladesh. The Muslims believe that water is a special gift from God, and the Hindus believe that the Ganges water has the power of cleaning sins. However, it is disappointing that, despite religious instructions on water preservation, Bangladesh has some of the most polluted rivers in the world.

Water is critical for many professions in Bangladesh, such as fishermen, boatmen, and farmers. Too much water, inadequate water, and polluted water are 'life and death' issues for many of these people. Some people lose their homes due to river erosion and become homeless. Due to increased salinity, many people in coastal areas are compelled to in-country migration towards the cities, which is increasing the density of slum mass in Bangladeshi cities.

6. Water Sharing

The Ganges–Brahmaputra–Meghna River system is one of the most extensive freshwater river systems in the world. Hundreds of millions of people from Bangladesh, Nepal, India, China, and Bhutan live in the basins of this transboundary river system [74]. However, the sharing of water among the user countries causes socio-political tensions among them, especially between India and Bangladesh [75].

Bangladesh and India share 4096 km of land borders and 54 rivers that flow from India to Bangladesh [76]. Bangladesh is highly dependent on India for its fresh water and, as a lower riparian country, it has no control over them [77]. Despite having a close relationship in many cases, trans-boundary water sharing between these countries has been a matter of discord for over half a century [78]. Increased water demand and climate change associated with irregular rainfall patterns led to water scarcity in these areas, which made the water resource management and sharing issues an unsolvable matter [79]. Therefore, the conflict between the two countries dates to the early 1960s [75,80,81]. According to Abbas [82], who was one of the pioneer experts in trans-boundary water management, the water sharing problem between Bangladesh and India is a socio-political issue rather than a socio-economic issue, which made it more complex to solve.

Since 1972, Bangladesh and India have been working for equitable water sharing of all rivers common between Bangladesh and India, pursuant to the establishment of the Indo-Bangladesh Joint Rivers Commission through the joint declaration of the Prime Ministers of Bangladesh and India on 19 March 1972 and the subsequent signing of the 'statute of the Joint Rivers Commission' on 24 November 1972. However, the Joint Rivers

Commission did not work well due to the lack of proper cooperation from India [80]. The primary disagreements between Pakistan (East Pakistan) and India started in 1951 when the Indian plan for the construction of Farakka Barrage for diverting Ganges waters to improve the navigability of the Kolkata port was released (published in an Indian newspaper in 1951). Due to the construction of the Farakka barrage on the Ganges River to maintain the navigability of Calcutta port, about 17 km upstream of Bangladesh, by redirecting water from the Ganges to the Hooghly River [83,84], water flow in the Bangladesh part significantly reduced since the barrage began its operation in 1975 and resulted in a severe drought and salinity problems in the southwestern part of Bangladesh [85].

Water experts from the Bangladesh side often claimed that the dry season flow in Bangladesh was considerably reduced when India started the diversion of the Ganges water at Farakka in 1975 [80,86–90]. The diversion of water by India using the Farakka Barrage caused dissatisfaction among Bangladeshi people. The first popular anti-Farakka movement 'the Farakka Long March' was led by popular political leader Maulana Abdul Hamid Khan Bhashani in May 1976, demanding the demolition of the Farakka Barrage and the rightful distribution of Ganges water to protect Padma River from drying up and the desertification of Bangladesh [91,92]. In 1951, when Bangladesh was a part of Pakistan, concern was raised about the proposed construction of the Farakka Barrage on the Ganges River. Its constriction was started in 1964. The first Ganges water agreement between Bangladesh and India was signed in 1977, and two memorandums of understanding (MoUs) were signed in 1982. Bangladesh and India have shared the available water at Farakka from 1 January to 31 May every year since 1997 as per GWT, 1996, based on a given formula as well as ensuring 35,000 guaranteed cusec to each country in three alternate ten-day periods starting from 11 March to 10 May.

India also planned to divert water from the Brahmaputra River to the Ganges River, which was objected by Bangladesh, considering the harmful impacts of the plan, and the negotiation continued without any fruitful result [93]. India commenced a test run of the feeder canal of the Farakka Barrage on 21 April 1975 that continued up to 31 May 1975 following a decision between the Indian Minister of Agriculture and Irrigation and the Bangladesh Minister for Flood Control, Water Resources, and Power who met in Dhaka from 16 to 18 April 1975. The test run was carried out with varying flows of 11,000 cusecs to 16,000 cusecs. However, after the brutal killing of the then President of Bangladesh Sheikh Mujibur Rahman, India started unilaterally diverting the water of the Ganges at the full capacity of the feeder canal (40,000 cusecs), causing devastating impacts in the southwestern region of Bangladesh, including the Sundarbans. Hence, in 1976 the issue was raised in the UN General assembly. Therefore, without any treaty/agreement with Bangladesh, India began to build several barrages/regulators across many trans-boundary rivers, such as the Teesta, Gumti, Khowai, Monu, and Muhuri.

Trans-boundary freshwater resource disputes among the user countries are mostly being discussed as a socio-political issue, which often overlooks the ecological and environmental issues [76,93]. Consequently, Bangladesh has been experiencing severe ecological damages in the wetland ecosystems. The wetland ecosystem of Bangladesh depends on about 1200 billion m^3 of river discharges from the Ganges, the Brahmaputra, and the Meghna River systems, and about one-third of the ecosystem is nourished by the Ganges River ecosystem. The Ganges River is very rich in biodiversity and acts as a natural breeding and raising ground for many freshwater fish species. However, the Ganges basin ecosystem in Bangladesh is experiencing ecocide due to the changes in its regular seasonal water flow by the Farakka Barrage. The ecosystem has lost its regular flow pattern and navigation routes. Therefore, the diversity and distributional patterns of more than 100 species of Gangetic fish and plankton have changed [66,94].

Moreover, different aspects of water diversion at the upstream rivers significantly reduced the reduction of the freshwater supply in downstream Bangladesh, which ultimately increased the river salinity in southwestern coastal Bangladesh. Increased salinity has a significant implication for the reduction of agricultural production, the fish population and diversity, and the regeneration and survival of major mangrove plants (e.g., Heritiera fomes) in the coastal region of Bangladesh [95,96]. The floral composition of the largest mangrove forest, Sundarbans, has also been significantly reduced, which ultimately threatens economic livelihoods [66,89]. The Ganges–Kobadak (GK) Irrigation Project, which was started in the 1960s remarkably improved the economic solvency and quality of life of the people of southwest Bangladesh. However, the operation of the Farakka Dam caused a drastic fall in surface and groundwater availability in this region [97]. Hence, the halt of the irrigation project in 1994 badly affected 350,000 acres of agricultural lands, which had a negative impact on the food security and livelihood opportunities of 10 million subsistence farmers, particularly in the dry season [98,99]. Furthermore, irregular rainfall patterns with increased numbers of warmer summer days and colder winter days have turned the climate extreme. Increased coastal erosion, widespread inland salinity, and water quality deterioration may be the additional effects of the water diversion of the Ganges River [87,100–102]. The impacts of the Farakka barrage on Bangladesh are illustrated in Figure 3.

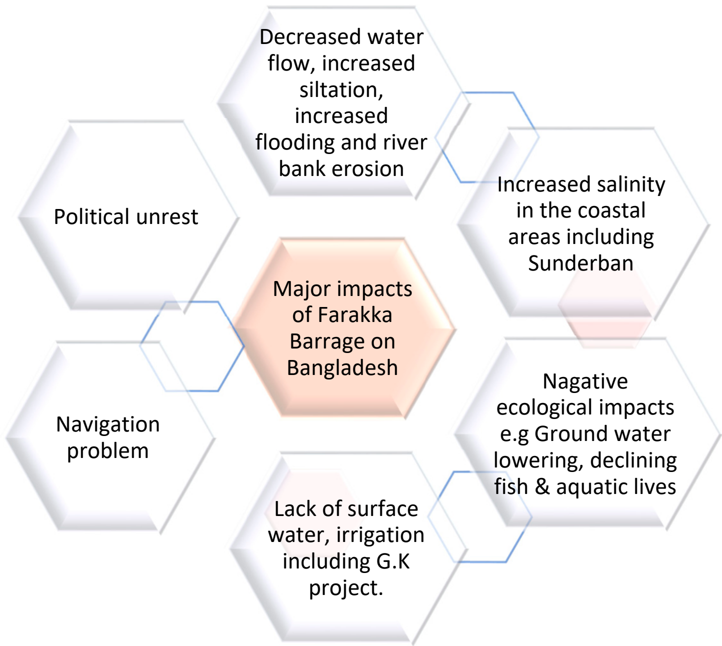

Figure 3. Impacts of Farakka Barrage on Bangladesh hydrology.

It is worth mentioning that Bangladesh and India started discussing the sharing of transboundary rivers considering not only the two countries but also sharing the river and ecological requirements after the signing of the Ganges Water Treaty in 1996.

7. Climate Change and Adaptability

Climate change issues are extremely prominent in Bangladesh, and it is known as one of the most vulnerable counties in the world to climate change. As water resources are highly connected to climatic factors, the water sector is the most critical one in Bangladesh under changing climatic conditions. According to the National Adaptation Program of Action (NAPA) of Bangladesh (MoEF 2005), "Water-related impacts of climate change will likely be the most critical for Bangladesh—largely related to coastal and riverine flooding, but also enhanced possibility of winter (dry season) drought in certain areas. The effects of increased flooding resulting from climate change will be the greatest problem faced by Bangladesh. Both coastal flooding (from sea and river water), and inland flooding (river/rainwater) are expected to increase" [103].

Clear signs of climate change and climate variability have been found across Bangladesh [104]. This data analysis since 1975 has indicated the rising trends in temperature and the increasing trend of extreme rainfall events across the country. Since the hydrological cycle is closely connected to climatic factors, the impact of climate change and climate variability will have critical impacts on water resources in Bangladesh. Eventually, the impact on water resources will affect all aspects of livelihood and the overall growth and development of the country's economy. The World Bank (2010) estimated a loss of around 0.5 to 1 percent of GDP in Bangladesh due to the damage to infrastructure, loss of lives, livelihoods, and agricultural productions caused by natural disasters during the previous decade. This report also forecasted losses of about 3.1% in agricultural GDP and even larger economical losses through 2050 due to climate change [105].

Bangladesh is already suffering from climate-related extreme events in recent decades. For example, several cyclonic storms, namely Mohashen/Viyaru (May 2013), Roanu (May 2016), Mora (May 2017), Fani (May 2019), Bulbul (Nov 2019), Amphan (May 2020), and Yaas (May 2021), with maximum wind speeds of 100 to 260 km/h hit the Bangladesh coast in recent times, which caused many deaths and massive damage to agricultural production, coastal embankments, and infrastructure. Furthermore, flooding is the most common and devasting natural disaster in Bangladesh. The country has been experiencing back-to-back flooding in recent times. For example, around 21%, 28%, 33%, and 23% of the country were inundated by the 2013, 2014, 2016, and 2018 flood events, respectively (Flood Forecasting and Warning Centre, Dhaka, Bangladesh). In 2017, around 42% of the country was inundated by an extensively long period of flooding, impacting around 6.1 million people [106]. Again in 2020, around 24% of the county was affected by floods impacting around 3.3 million people.

According to Roy et al. [107], the agricultural activities in the coastal areas of Bangladesh are being badly affected, such as reduced crop yield due to reduced soil fertility and increased levels of salinity. Furthermore, shrinkage of agricultural land, increased water logging, and damage to farm infrastructure are seen due to more frequent cyclones.

In summary, there are numerous negative impacts of climate change on Bangladesh, including an increased frequency and severity of floods, increased drainage congestions, a rise in sea level and salinity level, increased sedimentation in flood plains, increased pressure on freshwater availability, increased drought conditions, increased river erosion, and increased intensity and frequency of cyclones and storms [108]. Bangladesh is the country that is seventh most affected by extreme weather events and saw around 191 extreme events during the 20 years from 1999 to 2018 [109]. Bangladesh is ranked 6th when considering climate change vulnerability or facing the worst impact of climate change. Hence, adaptive water management capacity in Bangladesh is crucial to tackling these climate change impacts.

Adaptive capacity has been defined by the Intergovernmental Panel on Climate Change (IPCC) in their 5th assessment report as "The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequence" [110]. If a country has a greater adaptive capacity, that ensures a higher possibility of resilience to climate variability and extremes. The adaptive capacity allows for changing the current state/practices to a resilient state to face the impacts of climate-related hazards when they are unavoidable.

For a long time, the people of Bangladesh have adapted to the risk of floods, droughts, and cyclones with their indigenous knowledge and experience and with recent/updated knowledge as well. In recent decades, there have been some notable improvements in increasing the adaptive capacity of water resource management. Water resource management systems have implemented several adaptive measures to reduce the impact of climate hazards, such as the improvement and use of modern technology in the regulation and distribution of water for irrigation, food production, and water supply and irrigation schemes to enable farmers to grow crops in the areas affected by the floods and droughts. Many flood defense and drainage measures have also been adopted to reduce flooding and the impacts of flooding, such as polders, embankments, cyclone shelters, and cyclone-resistant housing. In addition to structural measures, some non-structural measures have also been introduced, such as early warnings about climatic events, including heavy rainfall, high temperatures, hailstorms, and floods, improved access to digital information and knowledge, training and knowledge on advanced technology to cultivate, awareness-raising programs, and the conjunctive use of water supply sources.

Funding/financial support is crucial in implementing effective and appropriate adaptation programs. The Bangladesh government has invested in a diverse portfolio of water development and disaster management schemes since the 1960s, which have significantly reduced the damages and losses from extreme weather events over time. The World Bank (2010) has estimated that these investments are around USD 10 billion. However, the noteworthy national-level adaptation strategies, programs, and plans include the National Adaptation Program of Action (NAPA)-2005 (updated 2009) and the Bangladesh Climate Change Strategy and Action Plan (BCCSAP)-2009. The general objectives of these national documents are to incorporate potential adaptation measures into the overall development planning processes, make development resilient to climate change, and promote sustainable development in Bangladesh. These documents have identified that, even with this infrastructure in place, around 500 million programs are needed for priority actions/measures, such as improving disaster management, research and information management, capacity building and public awareness programs, and urgent infrastructure development, such as increasing the number of cyclone shelters and the improvement of drainage systems [105].

8. Recent National Legal and Institutional Framework on Water Management

The first comprehensive national policy related to climate change and water in Bangladesh was The National Water Policy (NWP), which was announced in 1999 and covered the short-, medium-, and long-term perspectives for water resources. As a follow-up to this NWP, the National Water Management Plan (NWMP) was developed in 2001 to look at the implementation and investment sides to address the priorities identified in the NWP. The NWP was developed to guide both the public and private sectors to ensure optimal water sector development and management. The NWP does not explicitly mention climate change in the document. However, many actions/measures identified in the NWP are harmonious with climate change adaptation, such as the early warning and flood proofing systems are recommended in the NWP. In addition, the NWP also classifies several challenges, including salinity intrusion in fresh water. It also identifies the loss of coastal zone habitat, droughts, and flood stress.

Importantly, the NWMP has taken climate change as one of the critical factors in determining future water supply, including the sea-level rise impacts, which guide the implementation of the NWP. The NWMP covers effective planning and preparations for managing risks in water sectors under flood and drought conditions, highlighting both structural and non-structural measures. In addition, different climate change scenarios in the future, criteria for assessing vulnerability, and potential measures to reduce the vulnerability under climate change are discussed in the NWMP. In 2004, the NWMP identified eight major programs to be implemented to address climate change issues in the short-term (2000–2005), medium-term (2006–2010), and long-term (2011–2025) periods.

In addition to this NWP and NWMP, the Coastal Zone Policy was prepared in 2005 to guide the management and development of the coastal zone in Bangladesh, which includes the most vulnerable locations in Bangladesh in terms of climate change impacts. This coastal zone in Bangladesh is being continually confronted by cyclones, storm surge, localized storms, and sea-level rise, which have caused devasting impacts on these low-lying coastal areas.

In response to climate change adaptation and mitigation, a great initiative was taken in 2005 to formulate the National Adaptation Program of Action (NAPA). The NAPA identifies flood, drought, cyclone and storm surge, sea-level rise, and salinity intrusion as some of the climate-related hazards. However, it has not adequately covered riverbank erosion, which is one of the major hazards in river management under changing climatic conditions in Bangladesh. Like the CZP, the NAPA also suggested an enhancement in providing safe drinking water to coastal communities to address the increasing salinity issues in water because of sea-level rise.

NAPA helped to initiate a ten-year-long program called the Bangladesh Climate Change Strategy and Action Plan (BCCSAP). The BCCSAP was launched by the Bangladesh Government to identify the immediate needs for adaptation and to address the issues of climate change. This plan has focused on six principles to identify potential measures to adapt to climate change issues, which are food security, social protection and health, comprehensive disaster management, infrastructure, research and knowledge management, mitigation and low carbon development, capacity building, and institutional development [111]. BCCSAP identifies several climate-change-related issues and impacts, including flood, drought, sea-level rise, salinity intrusion, cyclone, storm surge, river erosion, water supply, and sanitation issues.

Some of the other relevant policies addressing climate change impact to some extent include the National Sanitation Strategy (2005), the Poverty Reduction Strategy Paper (PRSP), and the National Conservation Strategy (NCS). The National Sanitation Strategy considered the emergencies (e.g., floods and cyclones) in its document when providing guidelines for the improvement of sanitation programs. However, this does not explicitly mention climate-proof sanitation systems in Bangladesh [112]. The Revised Poverty Reduction Strategy Paper (PRSP II, 2010) also recognized climate change (e.g., increasing rainfall extremes, increasing temperature, frequent floods, riverbank erosion, drought, sea-level rise, and salinity increase in the soil and water) as critical threats for the development of the country. It specifically mentioned the negative impacts of climate change on surface water availability in Bangladesh and suggested several adaptation measures in this regard.

In general, most of the policy documents mentioned above recognized the need for capacity building at the state level as well as local levels to address the climate change impacts in Bangladesh. However, specific programs need to be identified and implemented on water resource management aspects to adapt to the climate change challenges. Adaptation to climate change in water resource management is a complex policy issue that requires collaboration and coordination among all government organizations, non-government organizations (NGOs), and the community and individual levels. Integrated planning with community participation, including NGOs and civil society organizations at different levels, is also important to ensure the successful implementation of institutional response frameworks and national policies.

At the state level, the Bangladesh government develops the policies and identifies and implements measures to address the climate change issues. Many times, these measures lack logical/sequential implementation strategies due to the lack of coordination among government agencies. However, the formal involvement of civil society can play a significant role to handle these situations. A salient feature of civil society is that these non-state players can influence public policy from outside the formal governmental structure [113]. They can explore and investigate government policies/measures by providing persistent advocacy and by acting as informal regulators.

Bangladesh is a well-known country for the active involvement of civil societies in many areas, such as microcredit and the empowerment of marginalized communities, the protection of environmental health, and poverty mitigation. Hence, civil societies, mainly NGOs, have become major partners of the Bangladesh government enabling them to exercise an increasing influence on government policies and actions. The Water Act of 2013, developed by the Ministry of Water Resources in Bangladesh, mentioned that government agencies should work in partnership with NGOs in policy development and implementation. However, NGO involvement in the national water policy formation process is still quite low. For example, Section 4 of the Water Act of 2013 established the National Water Resources Council, which is the highest decision-making body about water resources. The council is comprised of 34 members, where 33 of them are either ministers or members of a ministry, and the only remaining person would be from NGOs as a water resource expert. However, this can be improved by engaging more civil society organizations and NGOs for any effective adoption measures to be implemented to tackle climate change issues.

9. International vs. Bangladesh Development in the Water Sector

Flood plain management, irrigation, and the supply of drinking water are three important issues in the water sector of Bangladesh. Being a flood-prone country, the Government of Bangladesh (GoB), with the help of international aid agencies, has taken different initiatives for building flood control structures as well as devising policies and strategies for flood plain management [114,115]. However, when compared to the policies and strategies related to flood control and flood plain management in the Netherlands, which is a similar delta country situated in northwest Europe, Bangladesh was found to be far behind [116]. For example, from 1960–2000 the Bangladesh government invested around USD 4 billion in building embankment and drainage channels, drainage structures, dikes, dams, barrages, pump houses, and river closures in different parts of the country compared to USD 444 million that was spent in only one year (1998) for the flood protection in the Netherlands [116,117]. Moreover, the Dutch Delta Program, which was devised in 2010, was developed based on an adaptive approach to tackle difficulties for flood management, which may occur due to climate change and other social and economic development [118]. Such a delta plan in Bangladesh was only devised recently by the Bangladesh Government, which is called the Bangladesh Delta Plan 2100 (BDP 2100) [119]. In its short-term target (i.e., by 2030), the BDP 2100 plans to implement eighty projects at an estimated cost of USD 38 billion, and in the long term (i.e., beyond 2041), it plans to make Bangladesh a prosperous country by implementing six goals mentioned in the BDP 2100 [120].

Another vital water sector in Bangladesh is the drinking water sector. The development of this sector can be measured by indicators including the access to safe drinking water supply and the level of services. According to the WHO (2017), the level of services can be divided into five categories, i.e., "safely managed", "basic", "limited", "unimproved", and "no service or surface water" [13]. In 2020, on average 62% of the population had access to safely managed drinking water services in central and southern Asia, which is below the world average (74%), Europe and North America (96%), North Africa and Western Asia (79%), and Latin America (75%) but higher than sub-Saharan Africa (30%) [121]. In Bangladesh, 59% of the population had access to safely managed drinking water services in 2021. This access rate is higher than Nepal, Afghanistan, Pakistan, Bhutan, and Tajikistan but lower than Kazakhstan, Iran, and Turkmenistan in the central and southern Asia region. Table 2 shows a comparison of the level of services for drinking water in Bangladesh with the rest of the world.

Table 2. Comparison of drinking water service level between Bangladesh and the rest of the world [121,122].

Access to the Level of Services of Drinking Water	2000		2015		2017		2020	
	World	Bangladesh	World	Bangladesh	World	Bangladesh	World	Bangladesh
[a] Safely managed service (%)	61	56	70	56	71	55	74	59
[b] At least basic service (%)	81	95	88	97	90	97	90	98
[c] Limited service (%)	3	<1	3	<1	3	2	4	<1
[d] Unimproved service (%)	12	2	6	<1	6	<1	5	<1
[e] No service (%)	4	2	2	1	2	<1	2	<1

[a] Improved source of water located on-premises, available as needed and free of contamination; [b] Improved source where collection time <30 min; [c] Improved source where collection time >30 min; [d] Water source is unprotected well or spring; [e] Water collected from surface water (lake, river, pond, canal).

In Bangladesh, 83% of the population is served by a non-piped source of improved water, while 15% is piped water [121]. In the metropolitan Dhaka city, piped water is supplied by the Dhaka Water Supply and Sewerage Authority (DWASA). Some of the slum areas are also supplied with piped water by the DWASA [123]. In many areas of Dhaka city, the piped drinking water supply network is contaminated due to leakage and faulty connections. It is a common practice to boil the water or use chlorine tablets before the consumption of the piped water to avoid diseases such as diarrhea [124]; such practice is very uncommon in developed countries such as Australia.

10. Bibliometric Analysis of Water-Related Research in Bangladesh

Table 3 presents the main information about the bibliometric analysis used in this paper. A total of 4177 documents from 1311 sources covering 1972–2021 were found in water research in Bangladesh. This shows that there has been a significant number of research publications on water-related issues in Bangladesh during 1972–2021. Trends of publications over time and documents by subject area are provided in Figures S1 and S2, respectively (in the Supplementary Materials).

Table 3. Main information and statistics on bibliometric data used in this study (1972–2021).

Description	Results	Description	Results
Main Information		Document Contents	
Timespan	1972:2021	Keywords Plus (ID)	17,075
Sources (Journals, Books, etc.)	1311	Author's Keywords (DE)	7886
Documents	4177	Authors	
Average years from publication	8.91	Authors	8879
Average citations per document	28.89	Author Appearances	19,930
Average citations per year per doc	3.089	Authors of single-authored documents	393
References	168,106	Authors of multi-authored documents	8486
Document Types		Authors Collaboration	
Article	3486	Single-authored documents	527
Book	5	Documents per Author	0.47
Book chapter	175	Authors per Document	2.13
Conference paper	319	Co-Authors per Document	4.77
Review	191	Collaboration Index	2.32

Table 4 shows the top 15 most productive countries (involved with the water research in Bangladesh) with their total citations, single-country publications (SCP), multiple-country publications (MCP), frequency of publications, and average article citation. It has been found that Bangladesh, the USA, and the UK were the top three countries in terms of several articles, total citation, frequency, SCP, and MCP out of 62 countries that were involved with water-related research publications in Bangladesh. The USA was the first ranked country in terms of total citations (35069), whereas Bangladesh was the top country based on the number of publications (1085) about water research in Bangladesh. Bangladesh was also a leading country in terms of SCP and MCP. Furthermore, it has been found that the most productive institutions were located in Bangladesh (Table S1).

The most productive publications on Bangladesh water research based on the number of articles, H-index, g-index, and total citations are given in Table 5. *Science of the Total Environment*, which started in 2003 was found to be the leading journal publishing water-related research in Bangladesh (91 articles out of 1311, which received 4286 citations). Although the *Environmental Science and Technology* journal was ranked in second place, it had the highest total citations (7573), highest H-index (47), and highest g-index (78). *Natural Hazard*, the oldest journal (first publication in 1990), was in 4th place, whereas *Groundwater for Sustainable Development*, the youngest journal (first publication in 2017) placed in 11th, with 47 and 36 articles, respectively. Figure S3 illustrates the most productive sources' cite score in the last 10 years.

The most globally cited and influential articles on water issues in Bangladesh are presented in Table 6. This clearly shows that arsenic contamination in Bangladesh has received the highest attention (13 out of the top 15 papers are related to arsenic contamination). Under arsenic research, groundwater, drinking water, food, and human health were the main areas of interest. Mohan and Pittman Jr. [125] published the most cited article on arsenic contamination in the *Journal of Hazardous Materials*, with 2556 citations (170.4 citations per year). Although this article is not related to Bangladesh arsenic contamination alone, it has discussed the Bangladesh arsenic issue with high importance. The article by Smith et al. (2000), discussed arsenic contamination in Bangladesh and is the second most cited article, which was published in *Bulletin of the World Health Organization*, with 1429 citations and 64.96 citations per year [126]. Flooding is a major problem in Bangladesh, and an article on coastal flooding by Neumann et al. (2015) (included Bangladeshi flooding) is listed sixth in terms of total citations; however, it has received the second-highest total citations per year [127]. The most local cited documents can be seen in Table S2. Local citations present citations within the 4177 documents whereas global citations show actual Scopus citations.

Table 7 lists the top 15 authors with their affiliation, country, number of articles, H-index, g-index, total citations, and citations per paper in the water-related studies in Bangladesh. Twelve of these authors were from Bangladesh and the USA. The other three authors were from Sweden, Malaysia, and China. The most productive author was Ahmed KM (University of Dhaka) from Bangladesh who has published 151 articles on Bangladesh water issues. van Geen A from the USA has the highest total number of citations as an author: he has published 109 articles on water issues in Bangladesh (with 8637 total citations). Zheng Y, who is from China, has the highest citations per paper; every paper on Bangladesh water research is cited nearly 100 times.

Figure 4 illustrates the most frequently used keywords in water-related studies in Bangladesh. The bigger size of a keyword and a bold font emphasize the frequency and strength of the keyword on the water field in Bangladesh. The word cloud visually represents the most frequent words used in relevant studies and helps to identify the more (or less) important ones. The most dominant keywords in water-related research publications for Bangladesh were found to be Bangladesh (n = 5355), arsenic (n = 2372), drinking water (n = 1240), water supply (n = 1191), climate change (n = 1082), human (n = 997), female (n = 936), male (n = 795), humans (n = 785), and groundwater (n = 767). The most used keywords dynamics (based on annual occurrences and cumulative occurrences) show that 'climate change' has the steepest trend after 2010 (Figures S4 and S5).

Table 4. Top 15 productive countries concerning Bangladesh water-research-related publications (R is the rank based on the number of articles. SCP and MCP refer to single- and multiple-country publications, respectively. AAC is the average article citation).

Corresponding Author's Countries						Most Cited Countries			
R	**Country**	**Articles**	**Freq (%)**	**SCP**	**MCP**	**R**	**Country**	**TC**	**AAC**
1	Bangladesh	1085	31.00	619	466	1	USA	35,069	51.57
2	USA	680	19.43	248	432	2	Bangladesh	16,808	15.49
3	UK	287	8.20	111	176	3	UK	13,611	47.43
4	Australia	245	7.00	79	166	4	India	7556	48.75
5	Japan	243	6.94	105	138	5	Japan	6871	28.28
6	India	155	4.43	110	45	6	Australia	6020	24.57
7	China	95	2.71	27	68	7	Sweden	3900	56.52
8	The Netherlands	89	2.54	23	66	8	Switzerland	2989	106.75
9	Germany	84	2.40	32	52	9	Canada	2687	35.83
10	Canada	75	2.14	33	42	10	Germany	2166	25.79
11	Sweden	69	1.97	11	58	11	The Netherlands	1907	21.43
12	Malaysia	62	1.77	25	37	12	China	1888	19.87
13	Belgium	28	0.80	8	20	13	Malaysia	1244	20.06
14	Switzerland	28	0.80	10	18	14	Belgium	370	13.21
15	Thailand	25	0.71	8	17	15	Thailand	360	14.4

Table 5. Top 15 productive journals in Bangladesh water-research-related publications (Note: R is the rank based on the number of publications. TC is total citations. PY start is the year of first publication).

R	Sources	Articles	H-Index	g-Index	TC	Publisher	PY Start
1	Science of the Total Environment	91	33	64	4286	Elsevier	2003
2	Environmental Science and Technology	80	47	78	7573	ACS	2001
3	Environmental Health Perspectives	55	39	55	5574	NIEHS	1999
4	Natural Hazards	47	22	37	1445	Springer	1990
5	PlOS One	47	20	43	1910	PLOS	2010
6	Sustainability (Switzerland)	47	10	18	386	MDPI	2013
7	Environmental Monitoring and Assessment	46	18	36	1358	Springer Netherlands	2001
8	Water (Switzerland)	42	11	18	386	MDPI	2011
9	International Journal of Environmental Research and Public Health	39	13	23	577	MDPI	2005
10	Journal of Environmental Science and Health—Part A Toxic/Hazardous Substances and Environmental Engineering	37	20	37	1482	Taylor and Francis Ltd.	2000
11	Groundwater for Sustainable Development	36	14	18	404	Elsevier	2017
12	American Journal of Tropical Medicine and Hygiene	31	14	28	806	ASTMH	2006
13	Environment Development and Sustainability	31	11	18	361	Springer Netherlands	2007
14	Climate and Development	30	13	26	706	Routledge Taylor and Francis	2009
15	Environmental Earth Sciences	29	10	22	494	Springer	2010

Table 6. Top 15 most globally cited articles in Bangladesh water-research-related publications (Note: TC and NTC represent total citations and normalized total citations, respectively).

R	Author and Year	Article Title	Journals	TC	TC/Year	NTC
1	Mohan D, 2007	Arsenic removal from water/wastewater using adsorbents—A critical review	Journal of Hazardous Materials	2556	170.40	33.97
2	Smith AH, 2000	Contamination of drinking-water by arsenic in Bangladesh: A public health emergency	Bulletin of the World Health Organization	1429	64.96	12.53
3	Nickson RT, 2000	Mechanism of arsenic release to groundwater, Bangladesh and West Bengal	Applied Geochemistry	999	45.41	8.76
4	Islam FS, 2004	Role of metal-reducing bacteria in arsenic release from Bengal delta sediments	Nature	941	52.23	8.67
5	Harvey CF, 2002	Arsenic Mobility and Groundwater Extraction in Bangladesh	Science	913	45.65	7.82
6	Neumann B, 2015	Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment	PLOS ONE	887	126.71	28.61
7	Meharg AA, 2003	Arsenic Contamination of Bangladesh Paddy Field Soils: Implications for Rice Contribution to Arsenic Consumption	Environmental Science & Technology	747	39.32	12.31
8	Mcarthur JM, 2001	Arsenic in groundwater: Testing pollution mechanisms for sedimentary aquifers in Bangladesh	Water Resources Research	660	31.43	9.92
9	Chowdhury UK, 2000	Groundwater arsenic contamination in Bangladesh and West Bengal, India	Environmental Health Perspectives	660	30.00	5.79
10	Williams PN, 2005	Variation in arsenic speciation and concentration in paddy rice related to dietary exposure	Environmental Science & Technology	595	35.00	10.72
11	Singh R, 2015	Arsenic contamination, consequences, and remediation techniques: A review	Ecotoxicology and Environmental Safety	579	82.71	18.68
12	Wasserman GA, 2004	Water Arsenic Exposure and Children's Intellectual Function in Araihazar, Bangladesh	Environmental Health Perspectives	509	28.28	4.69
13	Abedin J, 2002	Arsenic Accumulation and Metabolism in Rice (*Oryza sativa* L.)	Environmental Science & Technology	481	24.05	4.12
14	Ahmed KM, 2004	Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview	Applied Geochemistry	475	26.39	4.38
15	Wasserman GA, 2006	Water Manganese Exposure and Children's Intellectual Function in Araihazar, Bangladesh	Environmental Health Perspectives	448	28.00	7.47

Table 7. Top 15 productive authors concerning Bangladesh water-research-related publications (Note: R is ranking of authors based on number of articles. TC is total citations. CPP is citations per publication).

R	Author	Affiliation	Country	Articles	H-Index	g-Index	TC	CPP
1	Ahmed, K.M.	University of Dhaka	Bangladesh	151	48	86	7863	52.07
2	van Geen, A.	Lamont-Doherty Earth Observatory	USA	109	68	92	8637	79.24
3	Ahsan, H.	The University of Chicago	USA	75	79	74	5953	79.37
4	Luby, S.P.	Stanford University	USA	75	65	45	2150	28.67
5	Graziano, J.H.	Mailman School of Public Health	USA	73	66	72	5247	71.88
6	Parvez, F.	Columbia University Arsenic Project in Bangladesh	Bangladesh	72	48	71	5487	76.21
7	Yunus, M.	International Centre for Diarrhoeal Disease Research Bangladesh	Bangladesh	62	59	57	3323	53.60
8	Unicomb, L.	International Centre for Diarrhoeal Disease Research Bangladesh	Bangladesh	58	38	39	1616	27.86
9	Slavkovich, V.	Columbia University	USA	56	48	55	4758	84.96
10	Bhattacharya, P.	The Royal Institute of Technology (KTH)	Sweden	49	47	40	1998	40.78
11	Chen, Y.	NYU Grossman School of Medicine	USA	48	59	47	3416	71.17
12	Islam, T.	Noakhali Science and Technology University	Bangladesh	45	29	48	2369	52.64
13	Quamruzzaman, Q.	Dhaka Community Hospital	Bangladesh	45	30	45	2962	65.82
14	Shahid, S.	Universiti Teknologi Malaysia	Malaysia	44	44	39	1586	36.05
15	Zheng, Y.	Southern University of Science and Technology	China	42	43	40	4190	99.76

Figure 4. Word cloud in terms of keywords plus on Bangladesh water-research-related publications.

We prepared a thematic map (Figure 5) of author-nominated keywords by determining research themes in six clusters. We used the parameters to create the thematic map (Figure 5) as follows: the top 250 keywords, but the items placed in the clusters are set to the minimum cluster frequency of 5 with three representative labels for each cluster. The centrality (x-axis) and the density (y-axis) measure the importance of the selected theme and the development of the chosen theme, respectively [128,129]. Figure 5 shows that 'arsenic', 'groundwater', and 'drinking water' are placed in motor themes, which means they are well-developed and important for the structuring of a research field. This result shows that the cluster that includes 'Bangladesh', 'climate change', and 'adaptation' is an important research field but it is not yet well-developed. Similarly, the cluster that includes 'water quality', 'water', and 'heavy metals' is important but needs more research. The niche theme has one cluster consisting of 'irrigation', 'India', and 'Asia'. This theme is well-developed but isolated and is of only marginal importance in the field. Two clusters are placed in emerging themes, which include 'coastal Bangladesh' and 'GIS', which have low centrality and density and, hence, are weakly developed.

Figure 6 illustrates the occurrence network of index keywords in water-related publications in Bangladesh. We selected a minimum number of occurrences of a keyword of 50 times, and 273 keywords met the threshold out of 17,115 keywords. Figure 6 was prepared based on the top 100 out of the 273 keywords. Each keyword is represented by a circle. A bigger circle represents a more frequent occurrence of a keyword, a line shows the connection between keywords, and the color represents the average publication year. As seen in Figure 6, keywords such as 'Bangladesh', 'arsenic', 'drinking water', and 'water supply' have higher total link strength and greater frequency. Besides, the most cited keywords were 'concentration (parameters)', 'food contamination', 'Eurasia', 'groundwater', and 'health hazard' with 96.74, 89.29, 80.94, 80.60, and 79.21 average citations, respectively. The evolution of interest in the water research field has been changing over time, and the average publication year of keywords allows us to see how research focus is changing over time. For instance, the blue color represents the average publication years before 2010, which were associated with keywords such as 'water supply', 'irrigation', 'water contamination', 'arsenic poisoning', and 'diarrhea'. This finding also supports the most cited articles related to arsenic, water contamination, and health have publishing years before 2010 (see Table 4). On the other hand, we see that the authors' interest has changed to 'procedures', 'salinity', 'climate change', 'cross-sectional study', 'concentration (composition)', and 'cohort analysis', which were the most common keywords after 2015.

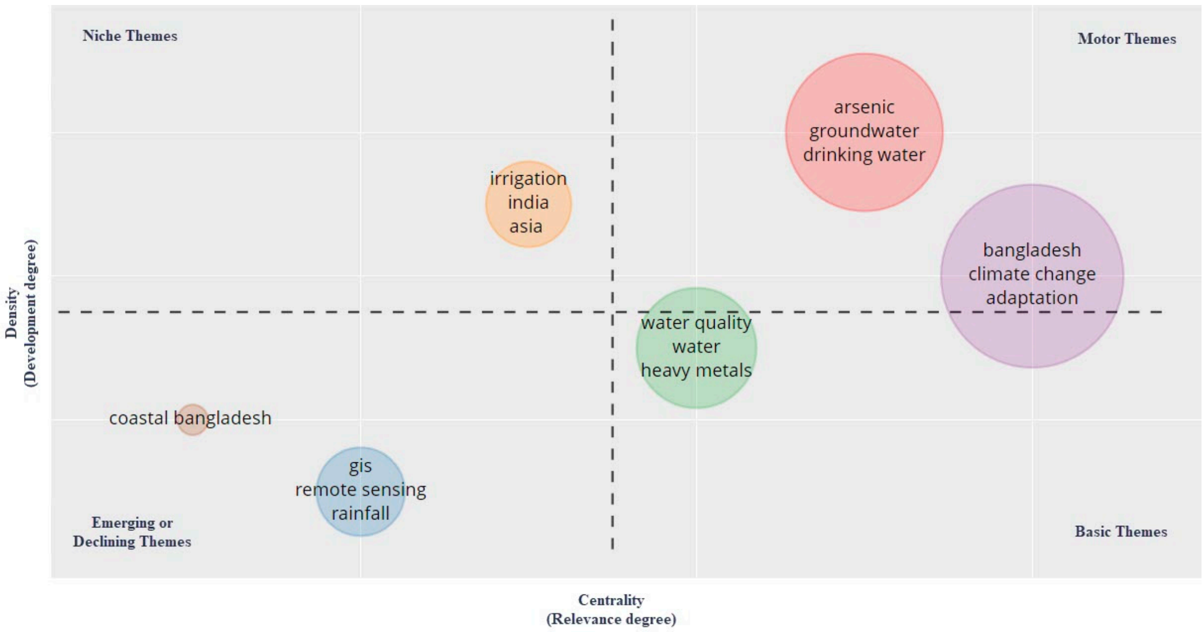

Figure 5. Thematic map of Bangladesh water-research-related publications.

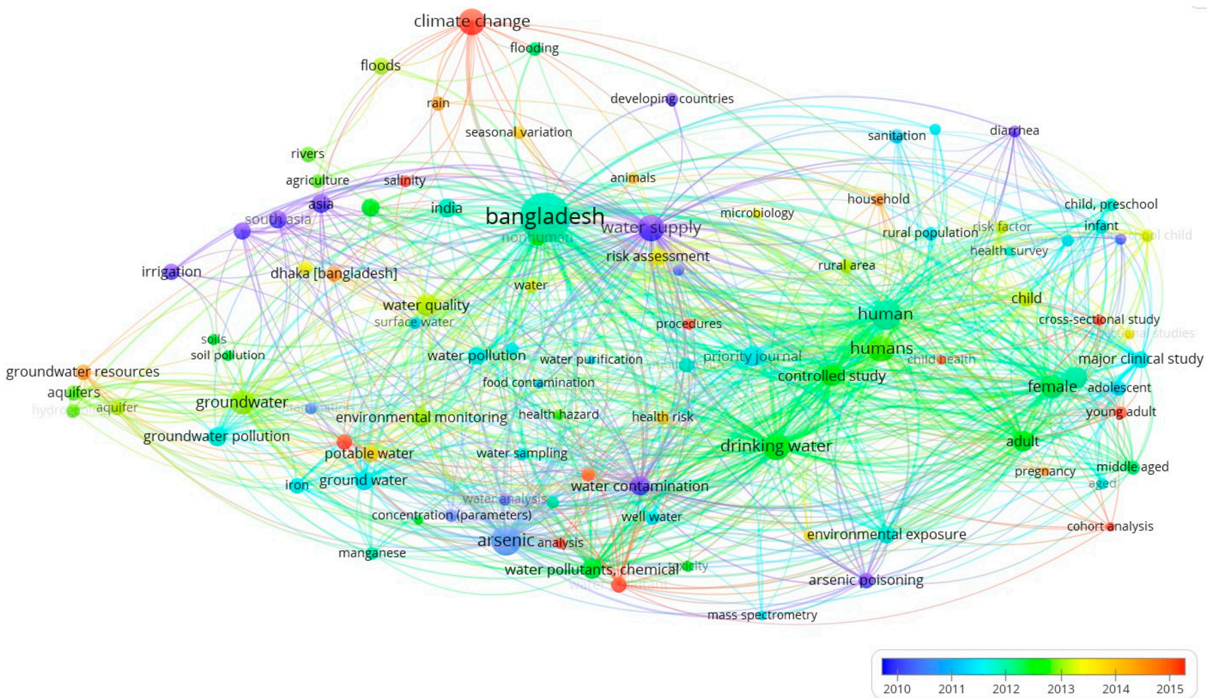

Figure 6. Occurrence network map of index keywords from Bangladesh water-research-related publications.

As a measure of collaborative research on water in Bangladesh, Figure 7 illustrates 530 links between 51 out of 133 countries in seven clusters. Strong collaborations are found among the countries: Bangladesh–USA (link strength = 605), Bangladesh–Australia (link strength = 278), Bangladesh–UK (link strength = 281), and Bangladesh–Japan (link strength = 262). The results show that even though India is in the top five in terms of total link strength, a strong collaboration is not detected between Bangladesh and India (link strength = 98) for joint water research.

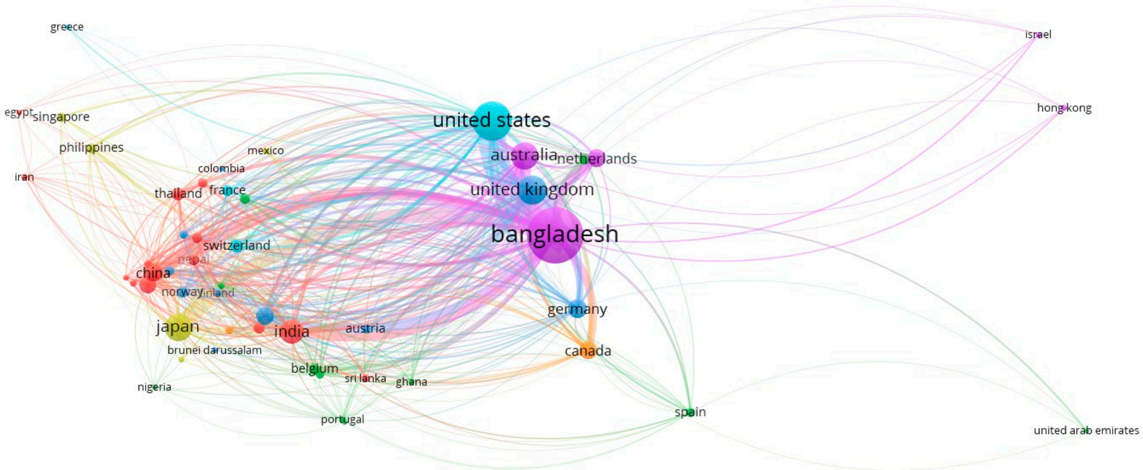

Figure 7. Network map of country co-authorship for Bangladesh water-research-related publications. Countries with a minimum of 10 published and cited articles are included. The map includes 51 countries out of 133 countries in seven clusters. Total link strength of top five countries was as follow: Bangladesh = 2611, USA = 1160, UK = 699, Australia = 583, India = 413.

Trending topics in water-related publications in Bangladesh between 1999 and 2021 are presented in Figure 8. Trending topics were generated based on the most frequent author-nominated keywords. The trending topics reveal the most frequent keywords with their occurrence by time. The size of dots represents the frequency of words, whereas the horizontal line depicts the time frame of the frequency of occurrence. As an illustration, 'machine learning' and 'northern Bangladesh' are currently (in 2021) trending topics with frequencies of 11 and 6, respectively. Furthermore, it is clear that adaptation and climate change have been trending for the last 5 years: 'adaptation' (n = 145, 2017), 'climate change' (n = 483, 2017), 'climate change adaptation' (n = 46, 2018), and 'adaptation strategies' (n = 12, 2020). Similarly, other trending topics allow researchers to interpret how studies have evolved over time and what trends they have.

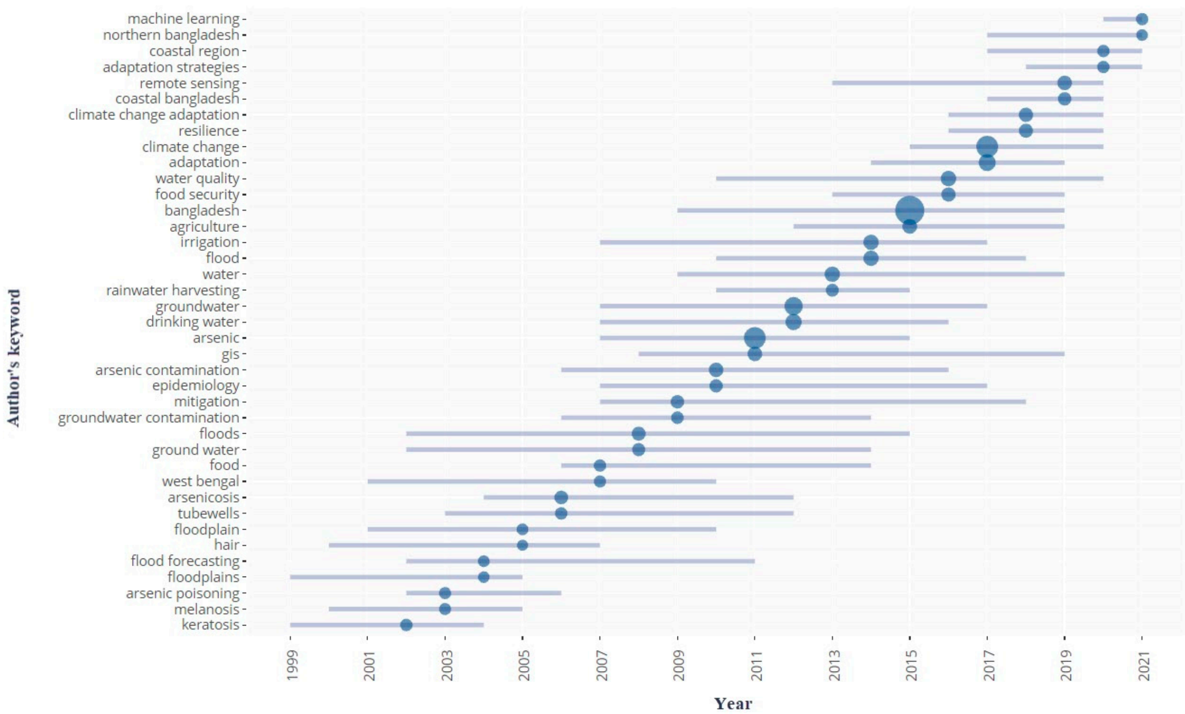

Figure 8. Trending topics in water-research-related publications in Bangladesh.

11. Future Goals and Challenges

It is encouraging to witness the economic growth of Bangladesh in recent years and the general improvement of the livelihoods of millions of people despite a significant inequality among rich and poor people. It is encouraging that Bangladesh has formulated many sound policies for sustainable water resource management. A few of the challenges that need to be tackled in attaining sustainable water management in Bangladesh are listed below:

Climate change impacts: increased flooding, more severe droughts, increased water, and land salinity in the coastal areas, sea-level rise, internal migration of people, loss of productive lands, and unplanned urbanization.

Water sharing: inadequate water-sharing treaties/agreements between Bangladesh, India and other neighboring countries will increase salinity in the coastal areas, groundwater lowering, and the lack of surface water irrigation in dry seasons.

Drinking water: unsafe drinking water to most people due to water pollution (arsenic and pathogens), groundwater lowering, a lack of proper maintenance, and a lack of investment.

Agricultural water: unsustainable groundwater use due to increased demand for irrigation in the dry periods, a lack of surface water irrigation projects, waterlogging, salinity, and inefficient irrigation systems.

Quality fish production: Poor water quality can contaminate fish with heavy metals and micro-pollutants, including plastics, which can affect the human food chain. In this regard, the "good water means good fish" principle should be promoted in Bangladesh, as fish is the main source of protein for the majority of Bangladeshi people.

Institutional and socio-political issues: Lack of coordination and transparency occasionally lead to poor construction practice.

Recreational water: most urban rivers are highly polluted due to unregulated effluent discharge from industries and indiscriminate solid waste disposal by the general public, municipalities, and industries, preventing the use of water for water parks, water fountains, boating, fishing and high-profile water-front housing projects.

Social issues: population displacement from coastal areas in the short term; however, in the long-term a significant part of Bangladesh will be underwater, which will need mass migration (in the form of water-refugees) within the country and from Bangladesh to other countries.

Sustainable water resources: rainwater harvesting, solar distillation, greywater reuse, artificial recharge, water-sensitive urban design, water-efficient irrigation systems, artificial-intelligence-based urban irrigation to generate cooling effects, the use of remote sensing data to manage the urban canopy and green space using stormwater and greywater, the circular economy, and public participation are important components in sustainable water resource management for Bangladesh.

12. Conclusions

Water is very much connected to the livelihood of Bangladeshi people. Although it receives a high volume of rainfall during the monsoon, it receives little rainfall in the winter and spring, making it very much water-limited during 50% of the year. Since it has a huge population compared to its size, the need for water is too high to sustain its agricultural productivity and other water requirements. The majority of its rivers are transboundary in nature, and hence, it has little control over its quantity and quality management. Water withdrawal by upstream countries due to non-existent and ineffective water-sharing treaties/agreements is putting Bangladesh in a critical condition in terms of flood control, surface water irrigation, salinity, and navigation.

The state of water quality is too low in both surface water and groundwater. Safe drinking water is not accessible to millions of its people. Water from its piped water supply systems is hardly consumed without in-house treatment. Climate change is posing a significant threat to Bangladesh in the form of increased salinity, waterlogging, sea-level rise and population displacement, and possible water refugees. Furthermore, a lack of transparency is affecting water sectors like many other sectors in Bangladesh. It is found that water-related publications in Bangladesh are dominated by water quality rather than water quantity.

The Government of Bangladesh has formulated several comprehensive water policies, which could pave the way for sustainable water resource development in Bangladesh. Among these, the Bangladesh Delta Plan 2100 (BDP 2100), a water-centric comprehensive plan, is likely to guide the water management in Bangladesh for the next 50 years or so.

It has been found that water-arsenic-related research has been dominant in the literature, as groundwater is the major source of drinking water in Bangladesh; however, more recently, climate-change-related research is receiving attention. Private–public partnership and flood insurance could be the possible pathways among other strategies in water resource management in Bangladesh. Bangladesh does not have a standard water design guideline like Australian Rainfall and Runoff, which should be prepared as soon as possible. For this, a national and international collaborations should be established [130].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14121834/s1, Table S1: The most productive institutions, 1972–2021, Table S2: The most local cited documents, Figure S1: Trending of publications over time, 1972–2021, Figure S2: Distributions of documents by subject area, 1972–2021, Figure S3: The most productive sources and their cite scores in last 10 years, Figure S4 The most used keywords dynamics over time based on annual occurrences, Figure S5: The most used keywords dynamics over time based on cumulative occurrences.

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