

Review

Water Quality Assessment and Monitoring in Pakistan: A Comprehensive Review

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Abstract: Water quality has been a major problem in Pakistan owing to a mix of factors such as population expansion, industrial units in urban areas, and agricultural activities. The purpose of this research is to conduct a comprehensive evaluation of water quality monitoring and assessment in Pakistan. The article begins by examining the water sources of Pakistan (i.e., surface water, groundwater, and rainwater). The paper then discusses the methods used by researchers in Pakistan for water quality monitoring and assessment, including chemical, physical, and biological methods. It has been determined that in certain regions in Pakistan, the concentration of arsenic present in the groundwater exceeds the national and international prescribed maximum limits. The range of arsenic concentrations in the Punjab province can vary from 10 to 200 µg/L, while higher concentrations of up to 1400 µg/L have been recorded in Sindh. In the Punjab province, fluoride concentrations vary from 0.5 to 30 mg/L, while in Sindh, the levels can reach up to 18 mg/L. In addition, some of the research has talked about bacteria. A 2017 study found that the fecal coliform concentrations in certain water in different cities of Pakistan surpassed limits and were as high as 1100 CFU/100 mL. Additionally, natural factors such as geological formations and high salinity in some areas contribute to the contamination of water. The effect of water pollution on public health has the potential to cause harm. It is critical to investigate creative strategies for improving water quality, and it is necessary to make investments in research and development, which could include the implementation of sophisticated technologies and the conception of new treatment processes. The review performed in this paper facilitates an understanding of the current water quality in Pakistan, including the types and magnitudes of contaminants present in the water sources. Subsequently, the assessment emphasizes deficiencies and challenges in the existing water quality monitoring frameworks and provides suggestions for improving them. This review is also of significant benefit to all the stakeholders involved in ensuring clean and safe water for human consumption and other purposes in Pakistan, such as policymakers, water managers, researchers, and other stakeholders.

Keywords: water quality; pollutant; surface water; monitoring; Pakistan; drinking water



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1. Introduction

Pakistan experiences severe shortages of water and water contamination, just like other developing nations throughout the world. The country is regarded as water-stressed and is expected to experience a water shortage in the coming years since its existing water resources have practically depleted [1,2]. The government and officials are in charge of providing inhabitants with access to potable drinking water, but unfortunately, in Pakistan, water shortages and pollution brought on by ineffective water management by the nation's government agencies are posing a threat to human existence [3]. According to community

health surveys and statistics, drinking water of inadequate quality causes 40% of deaths and 50% of waterborne infections in Pakistan [4]. The presence of arsenic in high concentrations in Pakistan's drinking water may affect up to 60 million people [5]. In the last 4 years, roughly 1832 children lost their lives to waterborne illnesses and drought [6]. Currently, only a fifth of the population has access to safe drinking water, while the rest are forced to rely on water that is contaminated by various pollutants such as chemicals, fertilizer, industrial waste, and sewage [7]. The availability of insufficient and substandard drinking water is a serious human health issue. The release of hazardous industrial chemicals and contaminated trash into water bodies lowers the water quality and has detrimental effects on individual health. Lack of knowledge, outdated treatment methods and apparatuses, unskilled laborers, and insufficient inspection all play a role. It is likely that a war on water will begin both domestically and globally if the current scenario worsens [8]. Issues of sanitation, water, and hygiene have also caused a number of dangers to population health since the probability of contracting waterborne diseases is increasing fast. In Pakistan, 2.5 million cases of diarrheal disease-related fatalities were recorded in 2017; 40% of these deaths and 50% of the country's disorders are brought on by drinking polluted water [4].

Numerous contaminants, including pathogens and microorganisms, metal poisons, household and industrial waste, pharmaceuticals, and other dangerous medications, are present in the water [9] and need to be monitored [10] and managed [11–13]. Changes in climate that affect the annual precipitation, the inadequate construction of water storage structures, and governmental pressures are some of the causes of current water issues in Pakistan [4]. Other factors include a rise in demand brought on by a significant expansion of industry and population [14]. Due to insufficient water sanitization, Pakistan faced major economic difficulties in 2019 [15], costing around PKR 343.7 billion (USD 1.5 billion). Additionally, from 2016 to 2017, albeit with UNICEF's assistance, the cost of distributing facilities for cleaner water grew from PKR 48 billion to PKR 72 billion [15]. It might be claimed that the provision of clean water in Pakistan will need financing because poor facilities are offered to the entire country. Many of the existing problems, including unemployment, the incidence of sickness, and economic instability, are expected to become significantly worse in the near future if things do not change [16].

This paper intends to provide a comprehensive review of the published scientific studies on monitoring, determining, and methodologies related to water quality. Surface water, drinking water, and groundwater sources are the focus of much of this study. Study results on water quality assessment and monitoring in Pakistan during the period of 2012 to 2022 are reviewed in-depth and methodically in this study. Surface water, groundwater, and rainwater are the three categories of water sources in both urban and rural Pakistan, and these categories were used to separate the subject in this paper.

Geography and Water Resources of Study Area

This section provides information about the topography and water resources of the study area. These are the critical characteristics of surface water, groundwater, and rainfall supplies and their present state. The weather data set the tone for readers to better understand the debates on surface and groundwater in Pakistan. The hydrological and geological knowledge is particularly significant since it will assist readers in understanding how hydrogeochemical processes impact the country's water quality.

Pakistan is a country in southern Asia that has borders with Afghanistan, India, and China (Figure 1). The Himalayas and the Karakoram are located in eastern Pakistan. There are mountain ranges in the north (Hindukush), hills in the northwest, and a highland plateau in Baluchistan. There is a wide range in the average rainfall, from arid to semiarid, across Pakistan [17]. The Indus River is Pakistan's most important waterway; it originates in the northern Karakorum Mountains, meanders its way south, and empties into the Arabian Sea. Pakistan's agricultural sector is vital to the nation's economy. Wheat, maize, rice, cotton, and sugarcane are the most common agricultural products, and they are grown in 27% of the total area. Increasing the agricultural yield is a common practice to meet

the needs of a growing population. Industrial powerhouses such as the textile, pesticide, and fertilizer sectors may be found in the urban hubs of Pakistan [4]. Pakistan has two major river systems: those that flow into the Arabian Sea and those that flow into the Endorheic River basin. The former includes the Indus River basin, the Lyari river, and the Hingol and Hub rivers. The latter includes Mashkal, the Siastan Basin, and the Indus Plain [17]. The Indus Basin, the Kharan Desert system, and Makran coastal drainage make up Pakistan's three hydrological groups. The Indus Basin is where the majority of surface and groundwater resources are found. Few inter-basin diversions are technically or economically viable due to Pakistan's topography [18]. The overall water resource quantity is relatively unclear due to a lack of water data (particularly in Balochistan, where the hydrology is very unpredictable) and a lack of solid water accountancy, resulting in only estimated resources. Furthermore, surface groundwater fluxes are poorly measured [18].

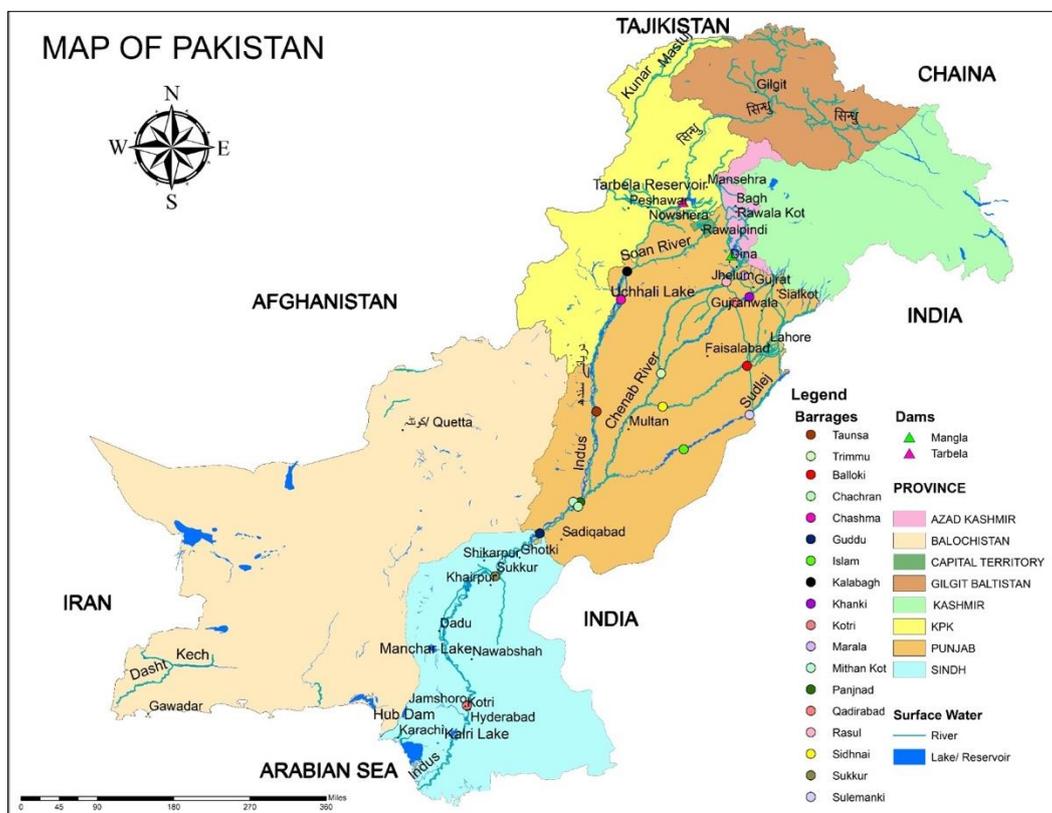


Figure 1. Geography and water resource map of the study area.

Approximately 70% of the yearly precipitation falls between June and September. This results in the majority of rainwater from the lower Indus valleys being drained into the sea. The pattern of mean annual precipitation in Pakistan exhibits substantial geographical variation. It varies from 125 mm in Balochistan (southeast) to 750 mm in the northwest [19,20]. In the lowlands of Sindh, heavy precipitation falls in July and August, and its strength decreases from the coast to the center of the province. The yearly precipitation in southern Punjab and northern Sindh is less than 152 mm. The regions above the Salt Range, such as some districts of Punjab and Sindh, receive a mean of more than 635 mm of precipitation annually [21]. Winter precipitation is often widespread. During the wintertime, the northern and northwestern regions of NWFP and the northern regions of Balochistan receive a relatively large amount of precipitation. Yearly rainfall over almost 21 million hectares (Mha) of the Indus Plains and Peshawar Basin averages 26 million acre-feet (MAF) (Figure 2). The rainfall yield to crops in irrigated areas is expected to be around 6 MAF [22].

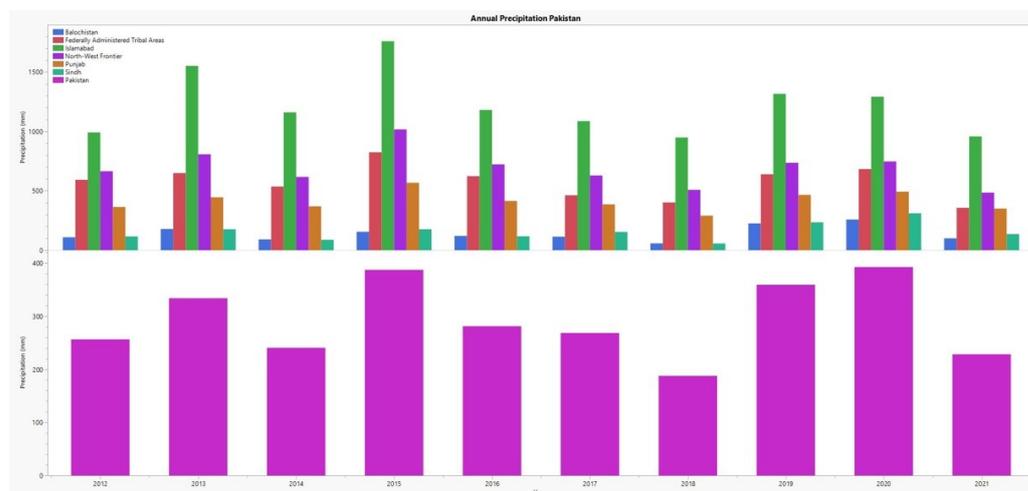


Figure 2. Annual precipitation in Pakistan and its provinces (source: World Bank Climate change knowledge portal, downloaded on 20 March 2023).

Surface water resources are mostly conditional on the tributaries of the Indus River. The total distance of the Indus River is 2900 km, and its basin is around 966,00 square km. Five main streams join its eastern side: the Jhelum, Chenab, Ravi, Beas, and Sutlej [23]. Additionally, three smaller rivers flow from hilly regions: the Soan, Harow, and Siran. In addition, a number of little streams enter the Indus on its west side. The largest of these is the Kabul River. Rivers in Pakistan have distinct charge characteristics, but all of them begin to increase in the spring and early summer due to the rainy season and snowmelt from the mountains, and they reach their stream flow in July and August. During the months of November through February, the average monthly flows are around one-eighth of those that occur during summertime. In addition to the larger rivers, there are countless tiny rivers and streams whose flow is only seasonal and dependent on precipitation; they carry little flow throughout the winter [24]. Furthermore, the majority of Pakistani groundwater resources are located on the Indus Plain, which stretches from the foothills of the Himalayas to the Arabian Sea and are kept in alluvial layers [25]. The Indus Plain is blessed with a huge aquifer system, which is quickly replacing it as a secondary supply of water for agriculture. It is around 1600 km wide and spans a region of 21 Mha. The aquifer was built over the course of the previous 90 years as a result of direct recharge from rainfall, river flow, and ongoing seepage from a conveyance network of canals, irrigation canals, waterways, and application losses in the irrigated regions [26].

Pakistan is usually regarded as both water-scarce (limited per capita water availability) and water-stressed. Despite this, crucial facets of Pakistan's water issues are frequently disregarded. Most evaluations of the water shortage exclude 24 percent of the total supply that is created locally (including the recharging of groundwater by precipitation) [27]. Decades-long population growth has led to a decline in mean availability, which also changes yearly with climatic changes [18]. The present water supply is around 79%. Public health is very at risk when drinking water is supplied improperly or poorly. The release of hazardous chemicals from urban areas and industries into bodies of water without proper treatment causes water pollution and has detrimental effects on human health. Due to rising demand, Pakistan's water and sanitation administration has been emphasizing the quantity of water over water quality [4]. This is all the result of a lack of knowledge, treatment technology, tools, trained staff, and quality control. One of the main factors in community health in Pakistan is highly polluted water. In this review, we have discussed water quality and the methods used to measure it from 2012 to 2022.

2. Water Quality Parameters and Limits in Pakistan

According to the World Health Organization, “safe drinking water” is any water that does not pose a significant threat to health during use, taking into account any variations in sensitivity between different life stages. Since water is the most frequently consumed liquid, it is thought to be the main means of disease transmission [28]. Bacterial pollution in water causes 80% of all human illnesses in developing countries. Access to potable water is one of Pakistan’s key public health challenges, since the country faces water quality and quantity problems, as recorded in much research. The majority of the water supply, over 70%, is derived from groundwater aquifers throughout the nation [29]. Pakistan is a rich country with many policies. Several policies are directly and indirectly linked to maintaining the standards of water quality, but concerns about drinking water quality in the nation receive less attention since water system organizations prioritize volume over the quality of drinking water. Additionally, the lack of a legislative framework for drinking water quality concerns, poor institutional arrangements, a lack of well-equipped facilities, a lack of routine water quality monitoring, and inadequate institutional arrangements have made the situation worse [30]. In order to solve the major challenges and difficulties in the supply of clean drinking water, the Federal Cabinet of Pakistan passed the National Drinking Water Policy (NDWP) in September 2009. The overarching objective of the policy is to provide cheap, accessible, sustainable, and adequate access to potable water for the entire population and decrease the rate of waterborne disease-related morbidity and mortality. According to the policy, the federal government is in charge of creating special plans of action for underserved and poorly served regions; saline water regions; places vulnerable to natural disasters such as earthquakes, floods, and drought; and areas where women must travel more than 0.5 km to access clean drinking water. A study on Pakistani water quality was published in 2004 by the Pakistan Council of Research in Water Resources (PCRWR) and included suggestions for creating national drinking water quality standards. The World Health Organization (WHO), the Pakistani government, and the Ministry of Health examined the drinking water standards in place for quality assurance, revised them to reflect WHO drinking water quality requirements, and then finalized them (Pak-EPA 2008). The first safe drinking water legislation in Pakistan would be drafted and passed in accordance with the 2009 National Drinking Water Strategy. The policy also proclaimed access to clean water as a basic human right. In order to make the most of the resources available to the local government, cost-effective solutions will be used. The communication of information to all stakeholders regarding the Pakistan National Standards for Drinking Water was held to be the responsibility of the Ministry of Environment (currently the Ministry of Climate Change), the PCRWR, and the Pakistan Standards and Quality Control Authority (PSQCA) [31].

After Pakistan’s 18th amendment to the constitution [32], province EPAs/EPDs were tasked with creating and executing environmental policies within their particular jurisdictions under the Provincial Environmental Protection Act and Policies. Additionally, the law divides up governing duties between the federation and the provinces. Following the passage of the Constitution (Eighteenth Amendment) Act of 2010 (the “18th Amendment”), Parliament is now able to pass laws, exercise executive power over the matters included in the Federal Legislative List in the Fourth Schedule to the Constitution and create extraterritorial legislation. On the other hand, regional assemblies have the authority to enact laws and exercise executive authority over any matter not included in the Federal Legislative List. Furthermore, the Constitution also gives the provinces the freedom to ask Parliament to pass legislation on any issue falling under their purview. The water quality standards of all four provinces and the Pakistan EPA can be found in the following list of websites (Table 1).

Table 1. Water quality standards.

Agency/Department Name	Website
Pakistan Environmental Protection Agency (PEPA)	https://www.elaw.org/system/files/Law-PEPA-1997.pdf , accessed on 20 March 2023
Sindh Environmental Protection Agency (SEPA)	https://hseforum.pk/forums/discussion/sindh-environmental-quality-standards/ , accessed on 20 March 2023
Punjab Environment Protection Department (PEPA)	https://epd.punjab.gov.pk/system/files/Punjab%20Environmental%20Quality%20Standards%20for%20%20Drinking%20Water.pdf , accessed on 20 March 2023
KPK Environmental Protection Agency	https://epakp.gov.pk/ , accessed on 20 March 2023
Baluchistan Environmental Protection Agency	https://bepa.gob.pk/ , accessed on 20 March 2023

Samples are typically obtained, categorized for various contaminants and characteristics, compared to all these standards, and highlighted when the findings depart from the benchmarks. In Pakistan, this strategy is used for all sources of drinking water (surface water, groundwater, and rainwater) [33]. Various indicators (such as pH, TDS, heavy metals, and fecal coliforms) have also been used in other research to track water contamination. Studying the macroinvertebrate community, as well as other groups of microorganisms, is part of this. The number and variety of macroinvertebrates and microorganisms are utilized to inductively assess the water quality source even though they are not specifically employed as an indicator [34].

The establishment of the above water quality standards is regarded as a positive move that might serve as a model in addressing Pakistan's water security issue [35]. Regardless of having extensive national laws and regulations for groundwater resources and control of pollution and a policy structure for the protection of the environment, Pakistan's organizational and implementation capacity is severely deficient [36]. Local authorities in Pakistan are accountable for water supply and sanitation (WSS); solid waste disposal; and the disposal, treatment, and management of wastewater. The municipal administrations of Tehsil, as well as water and sanitation organizations, are in charge of implementation. Their effectiveness, unfortunately, is generally unregulated. Various national regulations control the water, sanitation, and hygiene (WASH) system; however, because water is a provincial issue, the influence of national organizations is limited. The NSP 2006 was created to encourage public participation, ownership, and management while also freeing up resources to spend on closing the clean water deficit [37]. The Pakistani government established the National Drinking Water Policy (NDWP) in September 2009 with the goal of supplying safe drinking water to all by 2025, with a focus on the poor and vulnerable [31]. The major goal is to distinguish between service provision and control. The right to drink water has priority over all other activities, such as agricultural or industrial water usage. In order to address the issue of water security, Pakistan established the new National Water Policy of Pakistan (NWPP) in 2018. The strategy highlights the need for Pakistan to address present and future challenges to its energy, water, and food security. It addresses a wide range of water-related issues in Pakistan, including the distribution and usage of water based on economic priorities, the sustainability of water basins, agriculture, changing climate impacts, drinking water and sanitation, groundwater, water rights and obligations, hydropower, conservation, sustainable water infrastructure, water-related risks, and regulatory frameworks [38]. Still, there is a lack of a clear framework and a sufficient implementation plan to address the problem, especially in organizational governance systems. However, due to insufficient law enforcement, none of the government's various projects to address water shortages and pollution in Pakistan have been successfully carried out, and the problems continue to exist. Along with legislation, public awareness is necessary to

combat community indifference toward water contamination. Furthermore, official support is presently weak regarding laws, management efforts, and law enforcement, all of which are necessary for citizen education.

3. Methodology

In order to enable future research, recognize gaps in knowledge, and effectively specify study focuses, the goal of this review is to consolidate and categorize research results. This study consistently highlights the future prognosis for water quality monitoring and evaluation, and it goes on to concentrate on the importance of water quality in the environmental sustainability of Pakistan. The literature published on the topic over the previous 10 years was thoroughly searched on Google Scholar and Scopus to find data for this study. The relevant methods have been used in other research, as per Mosley, 2015 and Razali et al., 2018 [39,40]. The search terms used were “water,” “quality,” and “Pakistan”; the country name (Pakistan) was included for this purpose. After that, we narrowed it down to domestic articles in English, along with some other criteria such as the location, origin, document type, and publication year (2012–2022). This was successful in removing any important papers without omitting the pertinent ones. In the context of Pakistan, there are no such contemporary evaluations of this topic, nor are there any with the present breadth of coverage. This supports the originality and importance of such a complex strategy and emphasizes its applicability to a broad variety of Pakistani demographics, including academics, students, authorities, entrepreneurs, and common citizens.

4. Water Quality Assessment in Pakistan

4.1. Surface Water Quality Assessment

The examination and monitoring of the quality of surface waters in Pakistan have been discussed in light of the reported source of contamination, sample location, pollutant parameters, and relevant health issues. Table 2 includes, in reverse chronological order, complete information on the various water sources analyzed in the nation over the last decade (2022–2012), as well as the discovered contaminants. According to an older study by Sial et al. (2006), 1228 of Pakistan’s 6634 recognized enterprises are classified as severely hazardous [2,41]. Industries became a major cause of water pollution in Pakistan because of the high load of organic and poisonous compounds in their wastewater effluents [42]. Textiles, leather, paper, pharmaceuticals, ceramics, petrochemicals, food, steel, oil mills, the sugar industry, and fertilizer plants are the main sectors causing water pollution [43]. These industries generate hundreds of thousands of tons of wastewater loaded with heavy substances such as mercury, magnesium, lead, cadmium, nitrites, chromium, and many more [44]. The majority of companies in Pakistan are concentrated in or near large cities. They directly discharge their waste effluents into surrounding sewers, streams, creeks, lakes, canals, and open or agricultural land. According to Fida et al. (2022) [44], waterborne diseases are caused by bacterial pollutants, including coliforms; toxic components such as Fe, Ni, As, Cl, Hg, and F; and pesticides, which have been identified in surface water and groundwater. Forty-one locations all along the Indus River and its tributaries were sampled by Ahmad et al. (2021) [45] to determine the surface quality of the water in Sindh. Only four of the ten physiochemical properties tested (average values of 857 S/cm, 378 mg/L, 8.5 mg/L, and 220 mg/L for EC, TDS, pH, and COD, respectively) fulfilled the standards set by the WHO and the NSDWQ. Contrarily, the levels of TA (1400 mg/L), TH (584 mg/L), DO (6.40 mg/L), and NTU (219) were all above the recommended limits set by the WHO.

Table 2. Research on surface water quality in Pakistan.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2022	Basho Valley, Gilgit Baltistan	23	Incoming pollution load from upstream channels	Cu, Zn, Mn, Mo, TCC, TFC, and TFS	Lab analysis, WQI, and statical analysis	x	[46]
	Kallar Kahar wetland, Punjab	5	Tourism, fishing, urban discharge, and open littering	Microplastics	Lab analysis and comparison	-	[47]
	Indus Drainage System	26	Anthropogenic	Mn, Co, Cu, Zn, Cr Ni, Cd, Hg, and Pb	Lab analysis, risk assessment	x	[48]
	Punjad Headworks	27	Anthropogenic	Pb, As, Al, and Ba	Lab and statistical analyses, and risk assessment	x	[49]
	Tehsil Swabi	15	Flood runoff, biological contamination, and anthropogenic activities	Mg and HMs	Lab, statistical analysis, and risk assessment	x	[50]
	Chu Tran Valley	24	Agricultural activities, erosion, and domestic discharge	Heavy metals	WQI, PCA, and IDW	x	[51]
	Malakand	27	Anthropogenic	Cu, Fe, K, Mg, Al, Ca, Cr, Mn, Ni, P, and Zn	Lab and statistical analyses, and risk assessment	x	[52]
	Sutlej River	400	Livestock and human sources	Fecal coliform bacteria	Lab analysis, SWAT, and SSPs	x	[53]
	Eastern Peshawar basin	34	Industrial outlets	Heavy metals	Lab and statistical analyses	-	[54]
	Khyber Pakhtunkhwa	120	Not specified	Cu, Zn, Pb, Zn, Pb, Cu, Cr, Co, Ni, Hg, Cr, Co, Ni, Hg, Zn, Cu, Cr, Pb, Co, Ni, and Hg	Lab experiments and risk assessment	x	[55]
	Phuleli Canal	8	Industrial outlets	pH, EC, TDS, COD, CA, Mg, Na, K, BOD, COD, and fecal coliforms	Lab experiments	x	[56]
	Mirpurkhas	8	-	Salinity	Lab experiments	-	[57]
	Faisalabad	2	Industrial outlets	Sulfate ions, TDS, and barium ions	Lab analysis	x	[58]
	2021	Kot Addu, Punjab	90	Not specified	As, Cd, and Pb	Lab analysis and multivariate statistical analysis	x
Bajaur		75	Geogenic and anthropogenic activities	Cd, Pb, and Mn	Lab analysis, risk assessment, and questionnaire Survey	x	[34]
Swat		9	Sewer waters	Escherichia coli	Lab analysis, statistical analysis, and questionnaire Survey	x	[60]
Skardu		45	Not specified	Cd	Lab analysis, spatial analysis, and statistical analysis	-	[61]

Table 2. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
	Rawal Dam	148	Tourist	pH, EC, TDS, alkalinity, hardness, Cl, DO, SO ₄ , Ca, Mg, Fe, Cd, Ni, Cu, As, and F	Lab analysis, machine learning techniques, and WQI	-	[62]
	Ravi River	15	Industrial, domestic, and natural	TDS, COD, BOD, DO, TN, Cu, Pb, As, Cr, Mn, Zn, and Cd	Lab analysis, GIS, and statistical analysis	x	[63]
	Upper Indus River	642	Minerals, natural and anthropogenic	Bicarbonate	Gene expression programming, artificial neural networks, and linear and non-linear regression models	-	[64]
	RightBank Outfall Drain and Manchar Lake	14	Irrigation	EC, TDS, TH, SO ₄ , Cl, BOD, COD, Na, K, Ca, Mg, Cr, Ni, and Al, Pb, Cd, and fecal coliform	Lab analysis, WQI, and statistical analysis	-	[65]
	Sutlej River	97	Anthropogenic	Ca ⁺ , Mg ⁺ , HCO ₃ ⁻ , Ca ⁻ , Mg ⁻ , Cl ⁻ , and SO ₄	Lab analysis, WQI, and statistical analysis	x	[66]
	Nawabshah	18	Agro-industrial and sewage	pH, TDS, EC, total hardness, and calcium	Lab analysis	-	[67]
2020	Harnai, Balochistan	24	Not specified	Nitrate	Lab analysis	x	[68]
	Abbottabad	100	Not specified	Turbidity, EC, and pH	Lab analysis	x	[69]
	Hattar Industrial Estate	60	Industries	Cd, Cr, Ni, Pb, and Zn	Lab analysis, risk assessment, and statistical analysis	x	[70]
	Lower Jhelum Canal	20	Industrial pollution	<i>E. coli</i>	Lab analysis, WQI, and GIS	x	[71]
	Swat River	30	Natural and anthropogenic	Cu, Ni, and Pb	Lab analysis, risk assessment, and statistical analysis	x	[72]
	Central Indus Basin	12	Mining activities	Fe, Mn, Ni, Cd, and Se	Lab analysis	x	[73]
	KhyberPakhtunkhwa and Gilgit-Baltistan	181	Anthropogenic	EC, turbidity, and As	Lab analysis risk assessment, and statistical analysis	x	[74]
2019	Faisalabad	37	Textiles, ice, pharmaceuticals, flour, cotton, sugar, and food	Cu, Fe, Pb, Al, As, Ba, Cd, Cr, Ni, and Zn	Lab analysis and health risk assessment	x	[75]
	Lower Sindh	8	Industry and agriculture	Cu, Mn, Ni, and Zn	Lab analysis and health risk assessment	x	[76]
	Lower Indus Plain	360	Irrigation	As	Lab analysis	x	[77]
	Industrial Hub of Pakistan	13	Industries	Cr	Lab analysis	x	[78]

Table 2. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2018	Mangla Lake, Rawal Lake, and Simly Lake	6	Anthropogenic	Cr, Cd, Co, Pb, and Ni	Lab analysis, risk assessment, and statistical analysis	x	[79]
	Swat	58	Human and animal fecal material	Coliform bacteria	Lab analysis, questionnaire survey, and statistical analysis	x	[80]
	Jaffarabad	25	Natural disasters, residues from pesticides, fertilizers, and other domestic and industrial wastes	Turbidity, hardness, TDS, Cl, SO ₄ ⁻² , and Fe	Lab analysis and risk assessment	x	[81]
	Indus Delta	50	Industrial sewage and agricultural and industrial wastes	As	Lab analysis, statistical analysis, WQL, and SPI	-	[82]
	Indus River Basin	84	Geogenic and anthropogenic	TDS, pH	Lab analysis	-	[83]
	Lahore	15	Domestic and industrial	BOD ₅ , COD, Cu, Zn, Fe, Pb, Co, Ni, and Cd	Lab and statistical analyses	-	[84]
	Lower Indus Plain	48	Domestic and industrial	EC, TDS, hardness, cations, and anions	Lab analysis	x	[85]
2017	Rasul Barrage, River Jhelum	18	Not specified	TDS, turbidity, Fe, Cr, and Ni	Lab and statistical analyses	x	[86]
	Mansehra	24	Human	NO ₃ ⁻ , PO ₄ ⁻ , Fe, Pb, and Cd	Lab and statistical analyses	x	[87]
	Jhelum	292	Natural and anthropogenic	TDS	Lab and Statistical analysis	-	[88]
	Faisalabad	92	Textile industries	Pb, Cd, COD, and COD	GIS, lab analysis, and statistical analysis	x	[89]
2016	Coastal Areas of Sindh	34	Industrial waste	As, Mg, Mn, Cr, Cu, Fe, Pb, and Ni	Lab and statistical analyses	x	[90]
	Mangla Dam	120	Anthropogenic	Cd, Cu, Zn, Co, Pb, Ni, As, Fe, Cd, Co, Pb, Ni, As, Fe, Zn, Cu, and Mn	Lab and statistical analyses	-	[91]
	Peshawar	50	Natural	TDS, Cu, Pb, Cr, Cl, and Nitrites	Lab analysis	x	[92]
	Faisalabad	225	Not specified	TDS	Lab analysis	-	[93]
	Jamshoro	67	Irrigation	TDS, EC, salinity, turbidity, and pH	Lab and statistical analyses	x	[94]
	Gulshan-e-Iqbal Karachi	6	Industrial and domestic	pH, EC, and TDS	Lab analysis	x	[95]
	Punjab	1600	Domestic	TDS, F, and Fe	Lab and statistical analyses	-	[96]
2015	Pakistan	753	Natural and anthropogenic	As and c	Lab and statistical analyses and risk prediction	x	[97]
	Northern Pakistan	33	Natural and anthropogenic	Mn, Fe, Ni, Cr, and Co	Lab and statistical analyses and risk prediction	x	[98]

Table 2. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
	Rawalpindi and Islamabad	30	Not specified	TTHMs and chloroform	Lab analysis and risk assessment	x	[99]
	Lahore	9	Not specified	Cr, Fe, and Cu	Lab analysis	-	[100]
	Nawabshah	60	Point and nonpoint sources	TDS, pH, bicarbonates, Hardness, Cl, and SO ₄ .	Lab analysis	x	[101]
	Nowshera	39	Domestic	Cr, Ni, Pb, Cd, and As	Lab analysis and risk assessment	x	[102]
	Quetta City	16	Agriculture and domestic	TDS and EC	Lab analysis	x	[103]
	Panjhora River, Lower Dir	6	Not specified	ZN, Ir, and Mg	Lab analysis	x	[104]
	Haripur Basin	32	Natural and anthropogenic	Pb, Co, Cr, Cu, Cd, As, Hg Fe, Mn, Zn, Ni, and Zn	Lab and statistical analyses and risk assessment	x	[105]
2014	Tando Muhammad Khan	14	Not specified	TDS, Cl, SO ₄ , Ca, Na, hardness, and As.	Lab analysis	-	[106]
	Manchar Lake	10	Anthropogenic	pH, EC, salinity, TDS, Alkalinity, nitrates, Cl, and total hardness	Lab analysis	-	[107]
	Hingol River, Balochistan,	22	Natural and anthropogenic	Pb, Ni, Zn, Mn, Fe, As, Cr, and Cu	Lab analysis	-	[108]
	Mianwali	28	Anthropogenic	BOD, COD, TDS, EC, pH, and heavy metals	Lab analysis	-	[109]
2013	Pakistan	747	Natural and anthropogenic	Fluoride	Lab analysis	x	[110]
	Bahawalpur	20	Natural and anthropogenic	EC, TDS, hardness, pH, Ni, Na, and K	Lab analysis	x	[111]
	Badin	18	Anthropogenic	pH, EC, and TDS	Lab and statistical analyses	x	[112]
2012	Jamshoro	57	Natural and anthropogenic	As	Lab analysis	-	[113]
	Indus River	27	Natural and anthropogenic	Cd, Pb, Hg, and Cu	Lab and statistical analyses	-	[114]
Total	73	7452				48	

x—included health issues in paper. —did not include health issues.

Major Pollutants and Their Sources in the Surface Water of Pakistan

Effective water contaminants may be responsible for the pollution and transmission of infection [115]. Bacteria (microorganisms and infections), chemical contaminants (toxic and heavy metals, salts, and acids), and cations and anions are the most prevalent contaminants [44]. These compounds are toxic if they exceed limits and represent significant physical concerns to individuals and other species in the environment if they exceed certain values [116]. Microbiological contamination; heavy metals, including Pb, As, Hg, and Cd; pesticides; and other anions such as NO₃ and F impact the environment and human health throughout Pakistan [8]. Table 2 depicts the primary pollutants discovered in several cities and provinces, as well as the ratios of samples that exceeded the requirements.

The most likely source of drinking water contamination in Pakistan has been identified as coliform pollution [117]. According to numerous studies, the country's drinking water is heavily contaminated by bacteria [71]; many of the documented bacterial species can have serious health consequences (Table 2). Most parts of the country's sources of water, including streams, waterways, rivers, and lakes, are heavily contaminated with bacteria. Out of 73 reviewed papers in this study, the authors found 12 studies that found bacterial contamination in their samples (Table 2). These studies also talked about health issues due to this [118]. Ref [2] studied bacteria contamination in the Sutlej River. In their research, they collected 400 samples from 13 different locations around the river. Their model found that *E. coli* levels in a more polluted environment will show 108% and 173% increases in the near- and mid-future, respectively, and a 251% rise in the distant future compared with the reference time (baseline) levels. In Phuleli Canal, Sindh Province, out of eight water samples, most were found to contain fecal coliforms [56]. Another study in Khairpur found fecal coliform and coliform bacteria in 100% of water samples taken from the water channel, the distribution system, and household taps [119]. The scenario is similar to all other major cities across the country, including Islamabad, Quetta, and Hyderabad. All of these cities' drinking water was determined to be polluted with bacteria. The major sources of these contaminants were domestic anthropogenic activities and old, open water supply lines [119]. Furthermore, several studies have found health issues due to using bacteria-contaminated water, such as asthma and infections related to the urinary tract, circulation, and other organs. An invasive pathogen creates a range of bloodstream pathogens in patients' urinary tracts, respiratory tracts, blood, and other ordinarily sterile areas [33].

The physical and chemical characteristics of water, such as pH, EC, DO, and BOD, and the presence of things such as TDS and TSS are used to establish standards and evaluate the physical and chemical water quality. Pesticides and fertilizers are examples of toxic elements that come from factories, ground sediments, and fertilizer waste and end up in water supplies nearby [4]. These water sources have trace-metal contaminants because, as water moves downhill in a hydrological cycle, it dissolves these things [120]. In addition, these metals enter both surface water and groundwater due to human actions such as dumping untreated municipal and industrial waste and using a lot of chemicals in farming. Many of these elements are important for individual health, but too many of them can pollute water and make people and other living things sick [121]. Table 2 is a summary of the different studies that have been conducted from 2012 to 2022 in Pakistan on water pollution caused by physicochemical pollution, such as EC, pH, TDS, TH, and TA. A study by Jabeen et al. (2014) [105] of the Haripur Basin on physicochemical parameters found that a stream sample from the Hattar Industrial Park region had the lowest pH (5.4), whereas a river sample from next to a marble industry area had the highest pH (9.20). Moreover, the surface water had an electrical conductivity range of 0.180 to 1.182 mS/cm. Surface samples from areas near industrial areas often have higher EC values. TDS concentrations in surface water can vary from 116 to 956 mg/L (mean, 322). Mean pH, EC, and TDS values in surface water have been reported to be below the WHO (2008) recommendations. The surface water quality of the Indus River in Sindh was studied by sampling 41 locations all along the river and its tributaries. Only four physicochemical characteristics, namely, EC, TDS, pH, and COD, with average values of 857 S/cm, 378 mg/L, 8.5 mg/L, and 220 mg/L, respectively, were within the WHO-permitted standards. TA (1400 mg/L), TH (584 mg/L), DO (6.40 mg/L), and NTU (219) values, on the other hand, were above the WHO-permitted criteria [45]. Arshad and Imran (2017) [122] found significant As concentrations in two villages in the central Punjab region. Out of 73, most of the studies found low-to-high concentrations of As, COD, BOD, TDS, and other chemicals (Table 2). Furthermore, the sources of these contaminations were industrial and anthropogenic activities and, in some areas, natural inputs [123].

The accumulation of harmful compounds in surface water, particularly harmful heavy metals, is a major environmental and social problem across the world [44]. Heavy metal traces, such as Pb, Mn, Cu, Ni, Fe, and Cr, are substantial environmental contaminants,

especially in regions subjected to intense anthropogenic pressure [124]. These pollutants are capable of causing several negative health consequences in humans through the use of heavy-metal-contaminated water [125]. Although certain toxic substances are required for life in low quantities, others, such as Cd, Ni, Hg, and Pb, are physiologically nonessential and extremely dangerous to living creatures [126]. Recent research has found heavy metal pollution in the drinking water of Pakistan, as detailed in Table 2. In the majority of Barandu River samples, heavy metal concentrations of Fe, Pb, Ni, Cr, Mn, and Cd were found to be higher than the WHO-permitted levels for drinking water. People and other living things may have issues as a result of this high concentration of polluted water. Fe is one of the required elements, but if it is present in excess, it can have a negative impact on aquatic life and human health. High levels of Fe harm gastrointestinal tract cells and prevent them from controlling Fe absorption, which results in an unwarranted increase in blood's Fe concentration [127]. Another study on the Indus Drainage System found that the concentrations of most metals in riverine surface water were well below (Table 2) the guidelines established by the WHO and national agencies, but they showed wide interannual variation when compared with the other river systems. Along with the Indus Drainage System, the general riverine water contamination was higher than that observed in the surface water of the Shatt Al-Arab River [128], the South China Pearl River [129], and Argentine rivers [130] but smaller than those of the stream water of the Ganga River, India [131], and Gadea, Spain [132]. Since the Indus River primarily flows through the populated industrial zones of Faisalabad, Jhang, Sialkot, and Kabul, the heavy metal contamination level of the Chenab River was found to be lower than that of the Indus River [118]. Heavy metals in drinking water can pose significant health risks, including damage to the nervous system, kidney and liver damage, and cancer. In Pakistan, studies conducted between 2012 and 2022 found that high levels of heavy metals, such as lead, chromium, and arsenic, have been detected in drinking water sources (Table 2). It is crucial for Pakistan to tackle heavy metal contamination in drinking water in order to safeguard public health.

4.2. Groundwater Quality Assessment

Pakistan is one of the world's driest regions, and the majority of the people rely on groundwater to meet their water needs for drinking and other household reasons [133]. Groundwater is a vital resource in Pakistan, providing drinking water and irrigation for agriculture; however, the overuse and overexploitation of this resource have led to a decline in both water quantity and quality in the country [134]. Research on groundwater has largely been studied by authors in Pakistan. We found 97 studies conducted from 2012 to 2022 (using the above method), and 18,220 water samples were collected for water quality analysis (Table 3). Furthermore, these studies were important because groundwater levels in Pakistan have been declining at an average rate of 0.5 m per year over the past decade [135]. This decline is due to the overuse of groundwater resources for irrigation, as well as a lack of effective management and regulation in the groundwater sector [66]. Several studies have also warned that the depletion of groundwater resources could have severe consequences for food security and economic development [136,137]. Groundwater in Pakistan is also being contaminated by a variety of pollutants, including agricultural chemicals, industrial effluents, and sewage (Table 3). Our comprehensive review found that these pollutants are affecting both the quality and the quantity of the groundwater, making it unsuitable for use. Furthermore, studies over the last decade have reported high levels of nitrates, arsenic, and fluoride in groundwater, making it unsafe for drinking and irrigation [138]. To address these issues, researchers have studied the implementation of sustainable groundwater management strategies in Pakistan. This includes the development of water quality assessment methods, policies, and regulations to better manage and conserve groundwater resources, as well as the use of new technologies and practices to reduce water loss and improve water quality. All the information on

the many places examined throughout the country over the last decade, as well as the discovered contaminants, can be found in Table 3, listed in reverse chronological order.

Table 3. Research on groundwater quality in Pakistan.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
	Tehsil Swabi	26	Flood runoff, biological contamination, and anthropogenic activities	Mg and HMs	Lab and statistical analyses	x	[50]
	Eastern Peshawar Basin	36	Industrial outlets	Heavy metals	Lab and statistical analyses	-	[54]
	Industrial Zone of Faisalabad	60	Madhuana drain's recharge	pH, EC, Fe, Mn, Cu, and Cr	Lab experiments and GIS	x	[139]
	Khyber Pakhtunkhwa	120	Not specified	Co, Ni, Cu, Cr, Pb, Hg, Cu, Zn, Pb, Cu, Cr, Zn, Pb, C, Co, Ni, Hg, Zn, Co, Ni, and Hg	Lab experiments and risk assessment	x	[55]
	Taluka Ratodero	25	Agricultural fertilizers, industrial waste, and drainage	EC, TDS, Cl, Fu, Pb, Ni, and Cd	Lab experiments and WQI	x	[140]
	Gujranwala	200	Not specified	pH, EC, TH, Ca, Mg, Cl, and heavy metals	Lab experiments, risk assessment, and statistical and spatial data analyses	x	[141]
2022	Tharparkar	25	Natural and anthropogenic	EC, TDS, F, and As	Lab experiments, risk assessment, and statistical and spatial data analyses	x	[2]
	Rajanpur	200	Not specified	Ca, Na, HCO ₃ , Cl, Mn, and SO ₄	Lab experiments and statistical and spatial data analyses	x	[142]
	Badin	1	Not specified	-	VES	-	[143]
	Larkana	43	Anthropogenic	EC, Cl, Ca, Mg, and hardness	Lab experiments, WQI, and SPI	-	[144]
	Nowshera KPK	48	Not specified	TDS and Cl	Lab experiments and map	x	[145]
	Kamber-Shahdadkot	46	Industrialization and urbanization	pH, TDS	Lab experiments, WQI, and GIS	x	[146]
	Batkhela	60	Anthropogenic and natural	CaHCO ₃ , NaHCO ₃ , and NaCl	Geostatistical analysis and risk assessment	x	[147]
	Bahawalnagar	40	Natural	As	Lab and statistical analyses	x	[148]
	Pakistan	2160	Natural and anthropogenic	F ⁻	Lab analysis and modeling	x	[135]
	Jhelum	82	Natural	F ⁻ , As, nitrate, and bacteriological	Lab experiments, WQI, and risk assessment	x	[118]
	Mardan	13	Landfilling	(TDS), pH, EC, TH, NO ₃ ⁻ , TC, Cr, Ni, Zn, Cd, TC SO ₄ ⁻² , NO ₂ ⁻ , Ca ⁺² , and Na ⁺ ,	Questionnaire survey and lab and statistical analyses	-	[149]

Table 3. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2021	Kot Addu, Punjab	90	Not specified	As, Cd, and Pb	Lab analysis and multivariate statistical analysis	x	[59]
	Peshawar	217	Agricultural activities, sewerage lines, toilets, seepage, and percolation of polluted water	Nitrate and Ca	Lab analysis, spatial analysis, and risk assessment	x	[150]
	Bajaur	88	Geogenic and anthropogenic activities	Cd, Pb, and Mn	Lab analysis, risk assessment, and questionnaire Survey	x	[34]
	Central Punjab	20	Leaching	Zn, Fe, Cu, Cr, Ni, Cd, Co, and Pb	Lab analysis	x	[151]
	Swat	32	Sewer water	<i>Escherichia coli</i>	Lab analysis, statistical analysis, and questionnaire survey	x	[60]
	Rawal Dam	30	Tourist	pH, EC, TDS, Tur, alkalinity, hardness, Cl, DO, Fe, F, SO ₄ , Ca, Mg, Cd, Ni, Cu, Mn, and As	Lab analysis, machine learning techniques, and WQI	-	[62]
	Dokri	40	Precipitation	Cl and As	Lab analysis, GIS, and WQI	-	[152]
	Isa Khel, Mianwali	43	Not specified	EC and fluoride	Lab analysis	-	[153]
	Jhelum Basin	59	Air pollution through factories	Na ⁺ , Ca ²⁺ , Mg ²⁺ , K ⁺ , HCO ₃ ⁻ , SO ₄ ²⁻ , Cl ⁻ , NO ₃ ⁻ , F, and As	Lab analysis, GIS, and WQI	x	[21]
	Lahore	39	Anthropogenic activities	Pb, Cr, Ni, and Cd	Lab analysis	-	[154]
	River Sutlej	111	Anthropogenic activities	EC, HCO ₃ ⁻ , Cl ⁻ , and SO ₄ ²⁻	Lab analysis	x	[155]
	Southern Punjab	68	Silicate minerals and anthropogenic	HCO ₃ ⁻ , SO ₄ ²⁻ , Cl ⁻ , F ⁻ , Na ⁺ , Ca ²⁺ , Mg ²⁺ , and K ⁺	Lab and Statistical analyses	-	[156]
	Lahore	1305	Textile mills and paper, electronic, plastic, paint, and pharmaceutical industries	Fe, NO ₃ ⁻ , K, F, SO ₄ ²⁻ , and As	Lab analysis, WQI, and entropy water quality index	x	[157]
	Sanghar	61	Anthropogenic and geogenic cause	As	Lab and statistical analyses and hadrochemical facies	-	[158]
2020	Sindh	425	Not specified	TDS, EC, Cl, turbidity, and hardness	Lab analysis and WQI	x	[159]
	Sindh Industrial Trading Estate, Karachi	24	Industrial	pH, EC, TDS, TH, Na, K, Ca, M, Cl, SO ₄ , HCO ₃ , NO ₃ , Fe, and Zn	Lab analysis and GIS	-	[160]
	Vehari	129	Not specified	Pb, Cd, and Fe	Lab analysis and risk assessment	x	[161]
	Vehari	75	Anthropogenic	As	Lab analysis and risk assessment	x	[162]

Table 3. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2019	Malir Karachi	8	Domestic and industrial	<i>E. coli</i>	Lab analysis and WQI	x	[163]
	Lower Jhelum Canal	20	Industrial pollution	<i>E. coli</i>	Lab analysis, WQI, and GIS	x	[71]
	Sujawal	94	Anthropogenic and geogenic causes	Ca	Lab analysis, WQI, and SPI	x	[164]
	Central Indus Basin	50	Mining activities	Fe, Mn, Ni, Cd, and Se	Lab analysis	x	[73]
	Islamkot, Tharparkar	40	Natural	pH, EC, TDS, salinity, Cl, total alkalinity, Fl, and As	Lab analysis, WQI, and GIS	x	[165]
	Punjab	242	Agriculture	EC and residual sodium carbonate (SAR)	Lab and spatial variability analyses	-	[166]
	Karachi	42	Plumbing	As, TDS, hardness, and chloride	Lab analysis	x	[167]
	Indus Delta	180	Anthropogenic and geogenic causes	TDS, Cl, Ca, and Mg	Lab analysis, WQI, and SPI	x	[164]
	Thatta	100	Not specified	TDS, Cl, and Ca	Lab analysis, WQI, GIS, and SPI	-	[168]
	Punjab and Sindh	6	Anthropogenic	TSS, <i>E. coli</i> , HCO_3^- , SO_4^{2-}	Lab analysis	-	[169]
	Balochistan	30	Anthropogenic and geogenic causes	F^- , As, Hg, Ni, Cd, Cr, Fe, and Pb	Lab and statistical analyses	-	[170]
	Faisalabad	48	Textiles, ice, pharmaceuticals, flour, cotton, sugar, and food	Al, As, Ba, Cd, Cr, Cu, Fe, Pb, Ni, and Zn	Lab analysis, WQI, and health risk assessment	x	[75]
	Bajaur Agency	44	Anthropogenic	Na^+	Lab analysis and HCA	x	[171]
	2018	Gujranwala	08	Anthropogenic	Bacterial, Cr, Cu, Zn, As, Co, Ni, and Cd.	Lab analysis and GIS	x
Lower Indus Plain		360	Irrigation	As	Lab analysis	x	[77]
Central Sindh		59	Anthropogenic and natural sources	Ca, Mg, Cl, and Na-Cl	Lab analysis and WQI	x	[173]
Industrial Hub of Pakistan		31	Industries	Cr	Lab analysis	x	[78]
Tharparkar		2170	Natural	TDS and F	Lab and statistical analyses	-	[174]
Gujrat		10	Industries	Heavy metals	Lab and statistical analyses and PCA	x	[175]
Peshawar		52	Anthropogenic and natural sources	Fe, Cu, pH, TSS, Cl, Cu Zn, Ni, and Pb	Lab and statistical analysis	x	[176]
Swat		139	Human and animal fecal material	Coliform bacteria	Lab analysis, questionnaire survey, and statistical analysis	x	[80]
Jaffarabad		50	Natural disasters, residues from pesticides, fertilizers, and other domestic and industrial waste	Turbidity, hardness, TDS, Cl, SO_4^{2-} , and Fe	Lab analysis and risk assessment	x	[81]

Table 3. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2017	Eastern Punjab, Pakistan	66	Not specified	As	Lab analysis, saturation indices, and statistical analysis	-	[177]
	New Karachi Town	25	Domestic	TDS, Mg, K, Ca, Na, Cl, SO ₄ , and HCO ₃	Lab analysis and WQI	-	[178]
	Nagarparkar	29	Natural	EC, TDS, Ca, lead, Ni, and Zn	Lab analysis and WQI	-	[179]
	Sindh	13	Domestic and pit	Alkalinity, HCO ₃ , Ca, CO ₃ , Turb, Cl, Mg, pH, K, Na, TDS, SO ₄ , NO ₃ , and microbials	Lab analysis	x	[119]
	Sukkur	20	Not specified	TDS, sodium, fluoride, and magnesium	Lab analysis	-	[180]
	Shaheed Benazir Abad	40	Agriculture and industry	TDS, Cl, sulfate, Na, and hardness	Lab analysis	x	[25]
	Lahore	380	Natural and anthropogenic	As	Lab analysis and GIS	x	[181]
	Indus Valley	1200	Natural and anthropogenic	As and pH	Lab analysis and GIS	x	[182]
	Mansehra	40	Human	NO ₃ ⁻ , PO ₄ ³⁻ , Fe, Pb, and Cd	Lab and statistical analysis	x	[87]
	Hakra Command Area	134	Not specified	EC	Lab analysis	-	[133]
	Lahore	73	Natural and anthropogenic	TDS and turbidity	Lab analysis, WQI, and GIS	x	[88]
	Khipro	39	Geological processes and source rock	pH, EC, TDS, TH, Na ⁺ , K ⁺ , Ca ²⁺ , Mg ²⁺ , Cl ⁻ , SO ₄ ²⁻ , and HCO ₃ ⁻	Lab analysis	-	[183]
	2016	Peshawar	74	Industries	Pb, Cr, Cd, and Ni	Lab, statistical analysis, pollution index, and risk assessment	x
Lahore		983	Anthropogenic	pH, TDS, and Mg	Lab analysis, WQI, and GIS	x	[184]
Southern Lahore		50	Natural	Fluoride	Lab analysis	x	[185]
Lakki Marwat		17	Not specified	Zn, lead, and Cd	Lab analysis	x	[186]
Khyber Pakhtunkhwa		54	Solid waste and sewage	Giardia, Crypto, T. Gondi, Fasciola, B. coli, and entamoeba	Lab and statistical analysis	x	[187]
Lower Indus Plain		218	Sewage, urban runoff, and industrial wastewater	EC, TDS, Na, Cl, SO ₄ , HCO ₃ , turbidity, and hardness	Lab analysis, WQI, and GIS	x	[188]
Mailsi, Punjab		44	Anthropogenic and natural sources	As	Lab and statistical analyses	x	[189]
Islamabad	42	Domestic	Fecal coliform bacteria	Lab analysis	-	[190]	

Table 3. Cont.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2015	Tharparkar	200	Natural	As	Lab analysis	x	[191]
	Sindh	200	Natural	As	Lab analysis	x	[192]
	Pakistan	1903	Natural and anthropogenic	Ca, Cr, Fe, Ni, and Pb	Lab and statistical analyses and risk prediction	x	[97]
	Northern Pakistan	82	Natural and anthropogenic	Mn, Fe, Ni, Cr, and Co	Lab and statistical analyses and risk prediction	x	[98]
	Nawabshah	65	Point and nonpoint sources	TDS, pH, bicarbonates, hardness, chloride, and sulfate	Lab analysis	x	[101]
	Badin	170	Not specified	TDS, turbidity, and pH	Lab analysis	x	[193]
2014	Peshawar	105	Not specified	TDS, EC, hardness, Ca, Mg, and Cl	GIS and lab and statistical analyses	-	[138]
	Haripur Basin	98	Natural and anthropogenic	Fe, Mn, Zn, Ni, Pb, Co, Cr, Cu, Cd, As, Hg, and Zn	Lab and statistical analyses and risk assessment	x	[105]
	Rawalpindi	262	Natural and anthropogenic	pH, TDS, and EC	GIS, lab analysis, and WQI	-	[194]
	Lahore	340	Poor drainage systems	TDS, pH, alkalinity, and turbidity	Lab analysis and GIS	-	[195]
	Punjab	36	Human sewage, agricultural	Fe, Ir, Ba, Al, and Cr	Lab analysis	-	[196]
	Dir Lower	11	Not specified	EC	Lab and Statistical analyses	-	[197]
2013	Bannu	197	Refuse dump and domestic sewage	pH, EC, TDS, hardness, salinity, alkalinity, Na, K, Li, Ca, Mg, Ba, Cu, Fe, Mn, Ni, and Zn	Lab and statistical analyses	-	[198]
	Charsadda	951	Anthropogenic	Pb, Cd, Fe, Ni, and Zn.	GIS, lab and statistical analyses, and risk assessment	x	[199]
	Tharparkar	30	Natural	As and F	Lab and statistical analyses	-	[200]
2012	Tharparkar	99	Natural	Fe, Ca, Cu, and Zn	Lab analysis	-	[201]
	Rawalpindi	96	Anthropogenic	TDS, turbidity, TOC, and E-Coli	Lab analysis	x	[202]
	Hangu	35	Natural and anthropogenic	Fecal coliforms, pH, and turbidity	Lab analysis	x	[203]
Total	97	18220				63	

x—included health issues in paper. —did not include health issues.

Major Pollutants and Their Sources in the Groundwater of Pakistan

Chemical (organic and inorganic) and biological pollutants are the two categories of natural pollutants found in groundwater. While inorganic pollutants come from natural origins, the majority of organic pollutants in groundwater are formed by anthropogenic activities. Numerous substances have been identified as inorganic pollutants and claimed to be sensitive aquatic pollutants. Organic pollutants such as oil and pesticides are the most frequent pollutants. Pathogens (bacteria, protozoa, and viruses), water-soluble radioactive compounds, and anions and cations are examples of toxic elements [204]. These compounds

are dangerous and may seriously harm people and other ecosystem inhabitants if any amount of them exceeds the allowable limit. Heavy metals, including As, Cd, Pb, and Ni, as well as anions such as NO_3 and F, are prominent pollutants and are seen as a danger to groundwater quality in Pakistan [205,206]. Solid trash has increased as a result of population expansion and radical efforts to raise life quality [207]. Municipal waste is distinguished as household, commercial, or institutional garbage, whereas solid waste is categorized as dangerous, clinical, urban, or radioactive [208]. As is clear from the preceding paragraph, solid waste dumps primarily exist in urban areas of developing countries and pose serious risks to groundwater sources, which are an important source of residential water supplies in these places [209]. Groundwater supplies may become contaminated by bacteria and other diseases from municipal waste dumps [149].

Regarding human health, ensuring the bacteriological safety and purity of drinkable water is an ongoing challenge. The transfer of harmful germs, such as microorganisms, infections, and protozoa, occurs through water. In the entire world, 80 percent of illnesses are caused by contaminated water [113]. Fecal and total coliforms in drinking water are indications of the existence of disease-causing microorganisms and pathogens; microbiological safety and groundwater quality are established and monitored by analyzing their occurrence [119]. In both urban and rural parts of Pakistan, bacterial pollution in drinkable water is a major public health concern since it carries germs that can cause infectious illnesses [44]. Multiple studies have found bacterial pollution in groundwater; the country ranks 80th out of 122 nations with low-quality drinking water [117]. In Islamabad, nearly half the samples were polluted with *E. coli* and fecal coliform bacteria, rendering the water unfit for consumption [190]. A systematic review in 2011 was carried out in four provinces of Pakistan. The study found that coliform bacteria were present in 64% of the samples from Punjab Province, 67% of samples from Khyber Pakhtunkhwa Province, 83% of samples from Sindh Province, and 80% of the samples from Balochistan [210]. Empirical research was conducted recently in Kohistan (MIS1), Shangla (MIS2), and two organizations, namely, Malakand (MIS3) and Mohmand (MIS4). Fecal coliform bacteria were present in the study region at concentrations of BDL-60.0, BDL-32.0, BDL-97.0, and BDL-89.0 colonization units per 100 mL (CFU/100 mL), respectively. The water samples from MIS2 were found to have the lowest mean concentration of fecal bacteria (8.45 CFU/100 mL), whereas the water samples from MIS3 had the highest mean concentration (18.25 CFU/100 mL). In the research region, 78% of groundwater sources had coliform bacteria contamination when contrasted with the permissible threshold (0 CFU/100 mL) of water established by the WHO and Pak-EPA. This high fecal contamination bacteria pollution may be caused by poor sanitation, poor-quality sewage tanks, and animal and human waste [211]. In the Sindh province of Pakistan, this is due to the application of fertilizers in agriculture and the discharge of untreated wastewater into nearby water bodies [125]. A study also found that the presence of nitrates was higher in groundwater samples collected from areas with a higher population density and intensive agricultural activities [4]. In conclusion, the biological contamination of groundwater in Pakistan is a serious problem that is caused by a variety of factors, including the discharge of untreated wastewater, the presence of septic tanks and latrines, the disposal of industrial waste, the use of pesticides in agriculture, and the application of synthetic fertilizers [7]. This problem is particularly severe in areas with a higher population density and intensive agricultural activities, and it poses a significant threat to the health and well-being of the population (Table 3).

The physical and chemical characteristics of groundwater that can determine its quality and appropriateness for different purposes are referred to as physicochemical parameters. Temperature, pH, conductivity, turbidity, dissolved oxygen, and concentrations of different dissolved ions and compounds, such as nitrates, chlorides, and heavy metals, are some of the characteristics that make up this list [87]. These variables can be used to evaluate the general condition of a groundwater system and spot any possible deterioration or pollution. Monitoring these variables over time can also assist in observing changes in groundwater quality and spotting any possible problems. Chemical contaminants such

as fertilizers and pesticides come through industry, soil sediments, and fertilizer runoff and then reach surrounding sources of water [44]. These sources of water include harmful metal contaminants as a result of the dissolution of these chemicals during a hydrological cycle [4,44]. Research was conducted to assess the total dissolved solids, hardness, pH, alkalinity, and turbidity of groundwater. Groundwater chemistry analysis data from Lahore were used to assess the quality of drinking water regions using a GIS. The study found that 61% of the zone was excellent, 27% was good, 9% was moderate, and 3% had poor quality. However, when using PSQCA guidelines, only 5% of the region is perfect, 29% is satisfactory, 34% is medium, and 32% is not acceptable for drinking [195]. In a study by Shahab et al. (2016) [188], water samples collected in Sindh were found to be unsafe to drink. In addition, 62.84 percent of EC samples, 34.86 percent of TDS samples, 43 percent of Na^+ samples, 17.88 percent of Cl^- samples, 26.60 percent of SO_4^{2-} samples, 39.44 percent of HCO_4^- samples, 41.7% of turbidity samples, and 35.32 percent of hardness samples were above the WHO standard limit for drinking water. The highest concentrations were recorded in lower Sindh (Thatta, Badin), Tharparker, and central Sindh, where seawater intrusion occurs. Principal component analysis and correlation studies confirm the positive link between As and Fe, which may be the reason for As mobilization in Sindh's water table. Moreover, in Malakand city, water samples were taken from 75 groundwater sources to determine the quality of drinking water by analyzing the physicochemical characteristics. Among the basic measures, only TH (1500 mg/L) surpassed the WHO and NSDWQ guidelines. These sources of drinking water represent a grave risk to the community's health [212]. By collecting 10 samples of drinking water from different sources, the physicochemical quality of drinking water in new urban areas of Peshawar was analyzed. The pH fell within the WHO-permitted range; however, TSS levels in five samples and NTU levels in six samples exceeded WHO and NSDWQ recommendations. Pathogens and bacterial illnesses, including diarrhea, nausea, and abdominal pains, can be caused by elevated levels of NTU and TSS [213].

Heavy metal contamination in groundwater is a major concern in Pakistan, and studies have reported the presence of heavy metals such as lead, cadmium, chromium, and nickel in many samples above the permissible limits set by the WHO [161,175]. The sources of heavy metal contamination are varied, including industrial activities, agricultural practices, and municipal waste disposal. It is important to continue research on the extent and sources of the contaminations and implement measures to protect groundwater resources [142]. Trace metals are elements such as iron (Fe), cobalt (Co), and zinc (Zn) that are necessary for the proper growth and functioning of the human body in extremely minute quantities. Heavy metal often relates to a metallic element with a very high density or that is hazardous in trace levels, although excessive amounts of these substances might have negative consequences. Heavy metal examples contain lead (Pb), mercury (Hg), and arsenic (As) [214]. Numerous study studies have been published between 2012 and 2022 stressing the adverse consequences of heavy metals found in drinking water, particularly groundwater. As a result of a lack of economic and technological means, protecting the human population from the harmful consequences of metal poisoning is far more difficult in developing countries than in industrialized nations. Table 3 shows a brief description of the major and heavy metals present in different areas of Pakistan groundwater. Research has examined the levels of various pollutants present in the drinking water and the potential health hazards in Charsadda District, Khyber Pakhtunkhwa, Pakistan. The levels of nitrates in 13 locations exceeded the limit of 10 mg/L set by the US EPA, with concentrations ranging from 10.3 to 14.84 mg/L. Similarly, sulfate levels in nine sites exceeded the limit of 500 mg/L established by the WHO, with concentrations ranging from 505 to 555 mg/L. Additionally, concentrations of Pb, Cd, Ni, and Fe exceeded the permissible limits set by various organizations in certain areas [215]. Nickel is present in groundwater from all of Pakistan's main cities, with Lahore and Karachi being the worst affected (Table 3). The concentrations range from 0.001 to 3.66 mg/L. The WHO-recommended level is 0.07 mg/L, but PCSQA's allowed limit is 0.02 mg/L [204]. When it comes to the poisoning of groundwater with arsenic and fluoride,

Pakistan is ranked fourth internationally [216]. Regions of Sindh and Punjab have the highest levels of arsenic and fluoride contamination. In Sindh, arsenic and fluoride ground-water contamination has been recorded in the districts of Sukkur, Karachi, Tharparkar, and Hyderabad [204,210]. The groundwater in the Pakistani province of Punjab has significant arsenic concentrations in the districts of Kasur, Lahore, Multan, Sheikhpura, GI Khan, Mianwali, and Vehari. A little under 30,000 wells have been examined as part of this general investigation. As was found in 79% of the wells; 11% had almost 0.01 and 0.05 mg/L, and 10% of the samples had As concentrations of more than 0.05 mg/L [217].

4.3. Research on Filtration Plant Water Quality

The development of water treatment facilities and the encouragement of secure water storage and hygienic practices are only a few of the actions taken by the government of Pakistan to improve the quality of the water supply. However, a lack of financing and infrastructure has hampered many of these initiatives. In Pakistan, there are also a lot of nongovernmental groups that are striving to raise water quality through community-based projects and education. Few studies have been conducted to assess filtration plant water quality (Table 4). One study focused on evaluating the water quality of filtration plants in two populated cities of Pakistan, Rawalpindi and Islamabad. Samples were collected from plants run by the Capital Development Authority in Islamabad and the Water and Sanitation Agency in Rawalpindi. The results showed that several physiochemical parameters and metals were above the acceptable limit set by the World Health Organization. Many samples in both cities were found to be of poor quality with a water quality index greater than 100. The study also found that children are more vulnerable to health hazards from contaminated water. The study suggests that the proper management of limited underground water resources is necessary to ensure the sustainability of safe drinking water in these cities [123]. Another study in the same city assessed the quality of drinking water in the distribution network by collecting 80 samples of water in triplicate from treatment plants and residential taps. Samples were analyzed for various parameters such as free total coliforms, chlorine residue, chloramines, trihalomethanes, total chlorine, total organic carbon, fecal coliforms, and turbidity. The results revealed that some areas of Islamabad City, such as sectors F-6, F-10, and F-11, were free of fecal contamination, while other areas, such as E-7 and F-7, had contamination at a few stations among all the collected samples. The most contaminated areas were found to be sectors F-8, G-9, G-8, I-9, and I-8 of Islamabad, with high levels of *E. coli* at most sampling stations. Additionally, high concentrations of trihalomethanes and chloroform were detected in sector F-8 [218] (Table 4). It is crucial to evaluate the water quality in filtration facilities since it has a direct influence on people's health and well-being. The sources of water for these filtration plants were groundwater and surface water [123]. It is essential to systematically research the water quality in filtration facilities in Pakistan, where access to clean drinking water is a key challenge. The scarce water resources are under stress due to a growing population and human activities, making it even more crucial to monitor and preserve them. In developing nations, where water quality monitoring and maintenance are frequently insufficient, the situation is more serious. Given the importance of this problem, it is essential that further research be conducted to thoroughly examine the water quality of Pakistani filtration facilities. The microbiological and health concerns related to water should also be studied, in addition to the physiochemical characteristics. Researchers can then pinpoint issues and provide workable remedies to raise the nation's water quality. In order to guarantee the population's access to potable drinking water for the foreseeable future, the research should also take sustainable management of subsurface water resources into account. Furthermore, evaluating the water quality in filtration facilities in Pakistan is essential to safeguarding the population's health and welfare. To thoroughly examine the water quality and provide practical strategies to enhance it, further research is required. In order to guarantee the population's access to clean drinking water over the long term, this research should also take sustainable water resource management into account.

Table 4. Research on filtration plant water quality in Pakistan.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2020	Rawalpindi and Islamabad	85	Not specified	Electrical conductivity, alkalinity, and arsenic	Lab analysis	x	[123]
	Pakistan	638	Not specified	Microbiological, Fe, and Mn	Lab analysis	x	[219]
2014	Islamabad	80	Not specified	<i>E. coli</i>	Lab analysis	x	[218]
Total	03	803				03	

x—included health issues in paper.

4.4. Research on Rainwater Quality

Rainwater quality assessment is an important field of research in Pakistan since it is a key supply of water for many people. The country's semiarid and desert regions rely largely on precipitation as a supply of water for drinking, irrigation, and other purposes. However, numerous variables, such as industrial and agricultural operations, urbanization, and climate change, can have an impact on the quality of rainfall [220]. There have been several studies on the rainwater quality in Pakistan in recent years. These studies have focused on various aspects of rainwater quality, including chemical and physical parameters, as well as microbiological and health risks. In order to solve the water scarcity problem in the chosen research region, a study was undertaken to analyze the quality of roof-harvested rainwater. The research team also attempted to discover any potential health risks linked with rainwater drinking in the study location. With the exception of pH, turbidity, and trace amounts of certain elements such as Fe and Pb, the examination of the samples found that all of the physicochemical parameters were within the allowed range stated in the World Health Organization's drinking water standards. The samples' mean pH values varied from 5.18 to 6.26, representing mild acidity. The greatest mean turbidity level measured was 5.77 NTU. Furthermore, the mean amounts of Fe and Pb were 0.95 mg/L and 0.056 mg/L, respectively, exceeding the World Health Organization's drinking water recommendations. The study's findings show that, while roof-harvested rainwater can be a possible supply of drinking water, it may require further treatment to fulfill the WHO's drinking water quality requirements [220].

Several contaminants and characteristics have been identified in rainwater in Pakistan that may constitute a health risk if swallowed. Due to industrial pollution and pesticide usage in agriculture, rainwater in Pakistan has been discovered to have high amounts of heavy metals, such as Pb, Cd, and Cr [221]. Rainwater in Pakistan has also been shown to be rich in bacteria, including *E. coli* and fecal coliforms, which can cause waterborne illnesses. Furthermore, organic contaminants such as pesticides and herbicides are found in significant concentrations in rainfall samples. These contaminants have the potential to harm aquatic life and taint drinking water supplies [222]. Several studies evaluating rainwater quality in Pakistan have been conducted recently. The studies in Table 5 concentrated on different elements of rainwater quality and demonstrated that a number of variables, such as industrial and agricultural activity, urbanization, and climate change, can have an impact on rainwater quality. According to the research, the good management of rainwater resources is necessary to guarantee that there is enough clean drinking water for the entire population [220].

Table 5. Research on rainwater quality in Pakistan.

Year	Sample Location	Number of Samples	Pollution Source	Flagged Pollutants and Parameters	Method Used	Health Issues Assessment	References
2022	Lower Dir	35	Vehicular and industrial pollution and spray drift	Fe and Pb	Lab analysis and risk assessment	x	[220]
2019	Punjab	20	Industries, fuel burning, and vehicles	Cd and Pb	Lab analysis	-	[221]
2018	Jamshoro	4	Natural	Alkalinity, nitrogen, sodium, Cl, silicates, and phosphate	Lab analysis	x	[222]
2017	Toba Tek Singh	72	Not specified	pH, EC, and TDS	Lab analysis	-	[223]
	Tharparkar	9	Natural	As and F	Lab analysis and statistical analysis	-	[224]
2014	Karachi	54	Industries, fuel burning, and vehicles	NO ₃ ⁻	Lab analysis	x	[225]
	Karachi	35	Industries, fuel burning, and vehicles	TDS and F	Lab analysis	x	[226]
Total	7	229				4	

x—included health issues in paper. —did not include health issues.

5. Pollution Sources, Assessment Techniques, and Sustainable Development Importance

5.1. Water Pollution Sources in Pakistan

Rising water scarcity and pollution in Pakistan pose a serious danger to the economy and human life, unveiling the importance of the bioeconomy to sustainability [227,228]. Water contamination has been a major concern in the country as the population and economy have grown [44]. The situation is exacerbated by a lack of water treatment technology and knowledge [229]. The overuse of chemical fertilizers and pesticides in agriculture [178], the discharge of industrial waste [175] and untreated sewage into nearby bodies of water [209], and contamination from leaks and malfunctioning pipes used for water delivery are the primary water pollution sources [87]. Industrial wastewater is directly discharged into near water bodies. Pollutants can enter surface water and then groundwater from industrial areas such as textile mills, tanneries, and chemical plants due to leaks or inappropriate waste disposal. Toxic materials such as heavy metals, chemicals, and other harmful substances are examples of pollutants [2,230]. Sewage discharge is another type of groundwater pollution in Pakistan, where improper sewage disposal can contaminate groundwater with bacteria and other contaminants. This can happen when sewage is not adequately treated before disposal or is not disposed of in a way that prevents it from leaking into groundwater [231]. In Pakistan, landfills and the open dumping of solid waste are also sources of surface contamination. Pakistan produces over 48.5 million tons of solid waste yearly [149,156]. Pakistan faces many of the same environmental concerns as other developing countries due to a lack of garbage disposal facilities. The majority of municipal garbage is often burnt, discarded, or dumped in vacant lots in many areas, which has an impact on the well-being of the populace. Major cities in Pakistan are estimated to produce 87,000 tons of solid trash daily by the government (GOP) [51]. Solid waste

placed in landfills can produce leachate and harm groundwater [232]. This can happen if the landfill is not adequately planned or managed or if garbage is not confined effectively.

Water quality can be changed by a large number of factors, including agricultural practices, industrial activity, and poor waste disposal. Agricultural activities are a major source of groundwater and surface water pollution in Pakistan [156]. Farmers frequently rely on agrochemicals to keep their crops healthy and protect them from bacterial and insect attacks. However, these pollutants can leach into the soil and eventually pollute groundwater [233]. Furthermore, these chemicals combine with precipitation and run into water bodies, eventually leaking into the sea and contributing to water contamination. Furthermore, pesticides can combine with irrigation and rainwater and penetrate aquifers, polluting these crucial water sources even further. Pesticides and fertilizers include a wide range of hazardous substances that can affect human health and aquatic life [234]. Improper sewage disposal can contaminate groundwater with bacteria and other contaminants. This can occur when sewage is not adequately treated before disposal or is not disposed of in a way that prevents it from leaking into groundwater. This form of pollution may have a considerable influence on the population's health and well-being, as well as the environment [235].

Mining is another source of groundwater contamination. Water contamination can result from mining minerals in mines [73]. This may happen if the mining activity is not sufficiently monitored or if the mining site is not properly cleaned up afterward. Furthermore, Pakistan is facing many climate change issues. Climate change is also altering the quality and availability of water resources in Pakistan [44,134]. Surface water supplies are being reduced as snow and ice cover in the Himalayas and Hindu Kush Mountains, which feed the Indus River system, decreases. The melting of glaciers has a significant influence on the supply of water for agriculture and residential usage, as well as the region's hydropower potential [236]. The contamination of both groundwater and surface water is a major concern in Pakistan, putting people's health and well-being at risk. To address this challenge, important steps must be taken, such as strengthening environmental laws and policies, initiating public education programs, and undertaking more research to identify effective solutions.

5.2. Method Used for the Water Quality Assessment

Water quality assessment is a crucial aspect of ensuring the safety and health of the population. Pakistan faces a number of challenges in terms of providing safe drinking water, including a lack of infrastructure and limited resources [97,237]. However, there have been several methods used in different studies in the period from 2012 to 2022 to assess the drinking water quality in Pakistan. One of the most commonly used methods is lab analysis [92,118]. This involves collecting samples of water from different study areas (such as lakes and rivers) and analyzing them for various contaminants (such as physicochemical ones, bacteria, and heavy metals). Water testing can be performed using various techniques, such as PCR, ELISA, and microscopy. Another method for assessing drinking water quality is through the use of water quality indicators [82,238]. While all WQIs have a similar framework, each was created with one of two goals. These goals may be broader, such as measuring the quality of life in a specific area, or more particular, such as implementing a new water treatment system. These methods have been used for both surface and groundwater. Furthermore, Tables 2–5 also list, for each of the WQIs under evaluation, the context in which it was created or is being used.

A comprehensive assessment is meant to provide individuals with an idea of the overall water quality, while specialized evaluations are meant to ensure that water is "suitable" for those who want to do certain things with it [65,71]. Some authors also used some recently developed modeling-based methods (SWAT and AI) to assess rain surfaces and groundwater quality [50]. Different studies have used geographical information systems (GISs) to create maps and visualize data, such as water quality test results, and can help identify patterns and trends in water quality. This is useful for identifying areas where

water quality is poor and developing plans to improve it [54,239]. Furthermore, community-based monitoring is another important method for drinking water quality assessment in Pakistan. This approach involves engaging local communities in the assessment and monitoring of surface and groundwater quality. Different studies have used the questionnaire survey method to understand water quality and health issues [153,240]. Furthermore, to evaluate data and detect patterns and trends in water quality, statistical analysis methods are extensively employed in water quality evaluation in Pakistan. Principal component analysis (PCA) [168]; cluster analysis (CA) [87]; multivariate statistical techniques (MST), such as factor analysis (FA) and discriminant analysis (DA) [84,198]; and statistical process control are among these methodologies (SPC). In addition, along with these, various other methods are now being used to characterize and evaluate the quality of groundwater. Some of these methods include the blind number approach, the fuzzy mathematical method, cluster analysis, and a collection of pair analysis approaches [241]. These approaches can be used to detect probable sources of pollution, assess the efficacy of water treatment processes, classify water samples, and track water quality over time. Remote sensing technology can be used by future researchers in surface water quality analysis. This involves using satellite imagery and other remote sensing techniques to map and monitor water resources, such as surface water and groundwater bodies. This can provide information on water availability and quality, as well as help identify potential sources of pollution [242,243]. It is important to note that the evaluation of water quality in Pakistan also takes into account other variables, including TDS, BOD, and DO. To obtain a thorough evaluation of water quality in Pakistan, these factors are employed in addition to the ones described above.

Moreover, there are various methods that can be used in the future to assess drinking water quality in Pakistan. These methods can be used in combination to provide comprehensive knowledge of water quality and to identify potential sources of contamination. Recent years have observed an expanding necessity for a real-time sensing system capable of appositely recognizing occurrences of contamination in water distribution systems. A study by Piazza et al. (2020) [9] suggests a numerical optimization methodology that involves the utilization of the NSGA-II genetic algorithm combined with a diffusive-dispersive hydraulic simulator to optimize the efficiency of sensor configurations [244–246]. Due consideration of diffusion in the placement of water quality sensors is of the greatest importance if reliable monitoring networks are to be established, according to the findings of the research. Furthermore, the identification of sources of contamination is essential for the successful management of water pollution, which is an important issue in the water sector. The Bayesian method has also been used by different researchers to identify the most contaminating effluents in pressurized distribution systems and urban drainage networks. This can be achieved by the installation of real-time water-quality-measuring sensors [247]. Researchers in Pakistan can potentially utilize these methods in the future to assess water quality.

5.3. Importance of Water Quality in Combating Climate Change and Achieving Sustainable Development

Water quality is an important component of both sustainable development and climate change mitigation [248,249]. Water is a fundamental human right that is required for the existence and well-being of all living creatures. Poor water quality can cause health issues, financial losses, and environmental deterioration. The United Nations Sustainable Development Goals (SDGs) comprise explicit aims to achieve universal access to and the sustainable management of water and sanitation [250]. This includes Objective 6.1, which seeks to provide universal and equal access to clean and cheap drinking water for all, and Target 6.2, which aims to provide universal and equitable access to sanitation and hygiene for all [251,252]. The lack of access to water, whether resulting from human activity or natural phenomena, can have catastrophic consequences for the health, dignity, and economic prosperity of billions of people around the globe. SDG 6, commonly referred to as the “water goal”, serves as a guideline for achieving water security and is indispensable

for the achievement of the goals of the remaining SDGs [253]. Climate change also has an impact on water quality in a variety of ways. Changes in precipitation patterns and rising temperatures can cause more frequent and severe flooding, droughts, and other extreme weather events, contaminating water supplies and disrupting water infrastructure. These occurrences can also cause increased sedimentation and erosion, which can damage water infrastructure and make it more difficult to provide populations with clean and safe water [251,254]. Furthermore, climate change can cause changes in water temperature and chemistry, which can harm aquatic habitats and the animals that rely on them. This can eventually disrupt the entire water cycle, resulting in water shortages and compromising sustainable development goals. Improving water quality is thus critical for attaining a variety of long-term development goals and mitigating the effects of climate change. Investing in water infrastructure and improving water management methods, as well as decreasing pollution and safeguarding water sources, are all part of this [255]. This also entails striving to reduce the effects of climate change by lowering greenhouse gas emissions and adapting to existing changes [256,257]. Water quality is critical not just for human consumption but also for agricultural and industrial applications. Poor water quality can result in lower agricultural yields and higher expenses for farmers and companies. This has an impact on food security and may result in economic losses. Water shortages and poor water quality can also boost rivalry and conflict over water resources, undermining long-term development [258]. Water quality is an important component of both sustainable development and climate change mitigation. Addressing water quality challenges necessitates a multifaceted approach that includes establishing integrated water resource management, investing in water infrastructure, and employing cutting-edge technology. This can eventually lead to better access to clean and safe water, higher food security, and long-term economic prosperity. Furthermore, it is critical to reducing the consequences of climate change, which is increasing water quality problems.

6. Conclusions

This comprehensive review of water quality assessments and monitoring in Pakistan has offered a complete picture of the country's present water quality situation. In order to properly manage and safeguard Pakistan's water resources, improved monitoring and evaluation methodologies are required, as evidenced by the data in this research. This review indicates that Pakistan has substantial water quality challenges, including high levels of industrial and agricultural pollution. In addition, restricted access to reliable data and a lack of cooperation between many stakeholders are significant obstacles to successfully resolving these concerns. The assessment found that the quality of water resources in Pakistan, both surface and groundwater, is highly inconsistent and often falls short of the standards set by the WHO and national standards. The presence of pollutants in water sources, including heavy metals, pesticides, and microorganisms, poses a significant danger to human health and the environment. Industrial and agricultural activities have been found to have a serious impact on the water quality of Pakistan's major rivers, including the Indus and the Chenab. Furthermore, the water quality of groundwater resources is at risk due to excessive extraction and inadequate management. The low availability of reliable data and information on water quality is another key problem. Despite the presence of several monitoring programs, the data collected is frequently insufficient, inconsistent, and difficult for the public to access. This makes it challenging for policymakers and decision-makers to make informed water management and protection decisions. Moreover, a lack of coordination between many stakeholders, such as government agencies, industry, and local populations, limits the effective management of water resources.

This examination also highlighted the necessity of enhanced monitoring and evaluation procedures. Actual monitoring and evaluation methods in Pakistan are frequently out of date and do not correctly reflect the current water quality situation. In addition, our analysis uncovered a lack of ability and resources for monitoring and evaluation at the local level. This makes it challenging for local communities to monitor and manage their

water supplies properly. This review recommends a variety of initiatives for governments, businesses, and local communities to adopt to address these challenges. Industry must be held accountable for its effect on water quality. The government should impose more stringent rules on industrial and agricultural activities and hold enterprises accountable for any water contamination caused by their operations. Finally, local communities should be given the authority to actively monitor and safeguard their water supplies. The government should assist local communities with the skills and resources necessary to successfully monitor and manage their water supplies. Additionally, local communities should be included in water management and protection decision-making processes.

Limitations of This Study

Several intriguing discoveries have been made due to this thorough evaluation of water quality monitoring and assessment in Pakistan that might be pursued in future research. The Indus River is the most polluted river in terms of microplastic particles in the world. This river is the principal source of potable water for agriculture and human consumption in Pakistan. Our water sources have not been studied for these contaminants in the past. Future research can examine the presence of pharmaceuticals, soaps, detergents, body lotion, and other personal care items in sources of drinking water. GISs have been used in water quality monitoring and evaluation, although this is still uncommon. This method may be used to collect data on water contamination across a larger area, as opposed to still-popular city-by-city study investigations. In addition, this study has mostly focused on surface and groundwater resources and may have overlooked other significant water sources, such as bottled water, filtered water, rainfall harvesting, and desalination. These water sources are gaining significance, particularly in countries where water shortages are a significant concern. Consequently, future studies may expand into these areas. High levels of pollution from industrial and agricultural sources have been highlighted as the most significant water quality challenges in Pakistan. However, no concrete advice for correcting these difficulties is provided. Therefore, further studies and research are required to comprehend the complexities of water quality challenges and find viable strategies to address them. Furthermore, the economic component of water quality monitoring and evaluation has not been explored. The cost of adopting the proposed solutions has not been analyzed, nor have the potential benefits and costs of these solutions. It is crucial to assess the economic viability of the suggested alternatives. Lastly, there is a lack of studies on the relationship between water quality and its health effects. Therefore, future research should focus on finding the link between water and health.

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Abbreviations

Ministry of Environment, Pakistan (MOE-PAK), biochemical oxygen demand (BOD), copper (Cu), lead (Pb), zinc (Zn), dissolved oxygen (DO), manganese (Mn), molybdenum (Mo), water quality index (WQI), multivariate analysis comprising principal component analysis (PCA), National Water Quality Monitoring (NWQM), spatial distribution using inverse distance weight (IDW), Pakistan Council for Research in Water Resources (PCRWR),

electrical conductivity (EC), soil and water assessment tool (SWAT), shared socioeconomic pathways (SSPs), vertical electrical soundings (VES), total suspended solids (TSS), geographical information system (GIS), hierarchical cluster analysis (HCA), pollution source apportionment methodology (PCA/MLR), chemical oxygen demand (COD), Pakistan Environmental Protection Agency (PAK-EPA), World Health Organization (WHO).

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