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Chapter

Vulnerability of Environmental Resources in Indus Basin after the Development of Irrigation System

Muhammad Irfan, Abdul Qadir, Habib Ali, Nadia Jamil and Sajid Rashid Ahmad

Abstract

The climatic and topographic characteristics of Indus Basin provided an excellent condition for the development of irrigation system. Archaeological remains of Harappa and Mohenjo-Daro indicated that several canals were constructed in this region. The Indus River System (IRS) was developed into a complex network of canals, and 74% of its water was utilized for irrigation after Indus Water Treaty. After 1947, Indus irrigation network was extended, and cropland area was increased from 8.5 to 18.2 MH in Pakistan and 2.02 to 8.5 MH in India. Construction of dams, barrages, and canals to divert the maximum river water for irrigation resulted in drying up the natural pathways of the rivers, except during monsoon season. The aquifer in the irrigated areas became high and created problems of waterlogging and salinity, but due to extensive groundwater extraction, water table near urban centers is lowered now. Water quality was degraded due to addition of fertilizers, pesticides, chemicals, municipal sewage, and industrial effluents. Due to climate change, the glaciers in the upper catchment areas are continuously retreating and the frequency of floods and droughts is increasing. The objective of this chapter is to provide a comprehensive review of irrigation system developments in Indus Basin and its implications on environmental resources.

Keywords: Indus River, trans-boundary rivers, cultivation, ecological degradation

1. Introduction

About 50 million years ago, in the Mesozoic era, the shallow sandy Tethys Sea upfolded and formed the Great Himalayan Ranges because of the collision of Indian plate and the Siberian plate. The Indus basin comprised of lofty Himalayan mountains in the north and flat plains of Punjab and Sindh in the east and south. These mountains with immense snow cover gave birth to the Indus River and its tributaries [1]. The Indus River originates from Lake *Manasarovar* in Tibet, China, which traverses a total length of 3200 km (**Figure 1**). From the point of origin, the river flows in the northwest direction and then turns southward after reaching the Hindu Kush Mountains [2]. Many smaller tributaries join the Indus River on its way including *Shyok*, *Zanskar*, *Gilgit*, *Swat*, and *Kabul*. Near *Kalabagh*, it enters into the alluvial plain of Punjab. Five tributaries, viz., Jhelum, Chenab, Ravi, Beas, and Sutlej, join and traverse in the form of Panjnad and then join the Indus River. The mighty river runs as a large single channel through the Sindh province and ends up draining into the Arabian Sea [3]. The alluvial plain of Indus River is further divided into upper and lower Indus basins based on topography and elevation. The upper Indus basin comprises of the high-altitude mountainous areas with rugged topography including western areas of Tibet and Ladakh, stretching to the Himalayan foothills. The lower Indus basin starts from *Attok* and ends at Indus delta and consists of vast plains of Punjab and Sindh. The climate of Indus basin is humid in the north, semiarid in Punjab, and arid in the Sindh province [4]. The Indus River shares 52% of water in Indus River system, whereas the rest of the 48% is contributed by the Indus River tributaries. The rivers of the Indus basin receive more than 50% water from the glaciers followed by well-defined monsoon system in the upper catchment during monsoon season. The data of the past one century highlights slight reduction in the water flow in the Indus River system (**Table 1**).

The regular flow in Indus basin rivers provided the conducive conditions for early human settlements. One of the oldest civilizations, Indus valley civilization emerged in western South Asia in the prehistoric era along the Indus River and its tributaries when fertile land converted into cropland to grow wheat and barley and pasture to rear the cattle, sheep, and goats [15]. Since that time, several cultures, languages, and religions have emerged, invaded, or mixed because of the good climatic conditions [16]. Several invasions have been documented in history since the prehistoric times, and invaders settled to use the natural and water resources for prospering life. The Indus River basin favored the development of a large irrigation system. In the British era, the irrigation system was developed to increase the crop production in order to develop the agriculture-based economy, which turned the basin into a densely populated area. By the development of irrigation system and introduction of fertilizers and pesticides, agricultural production increased many

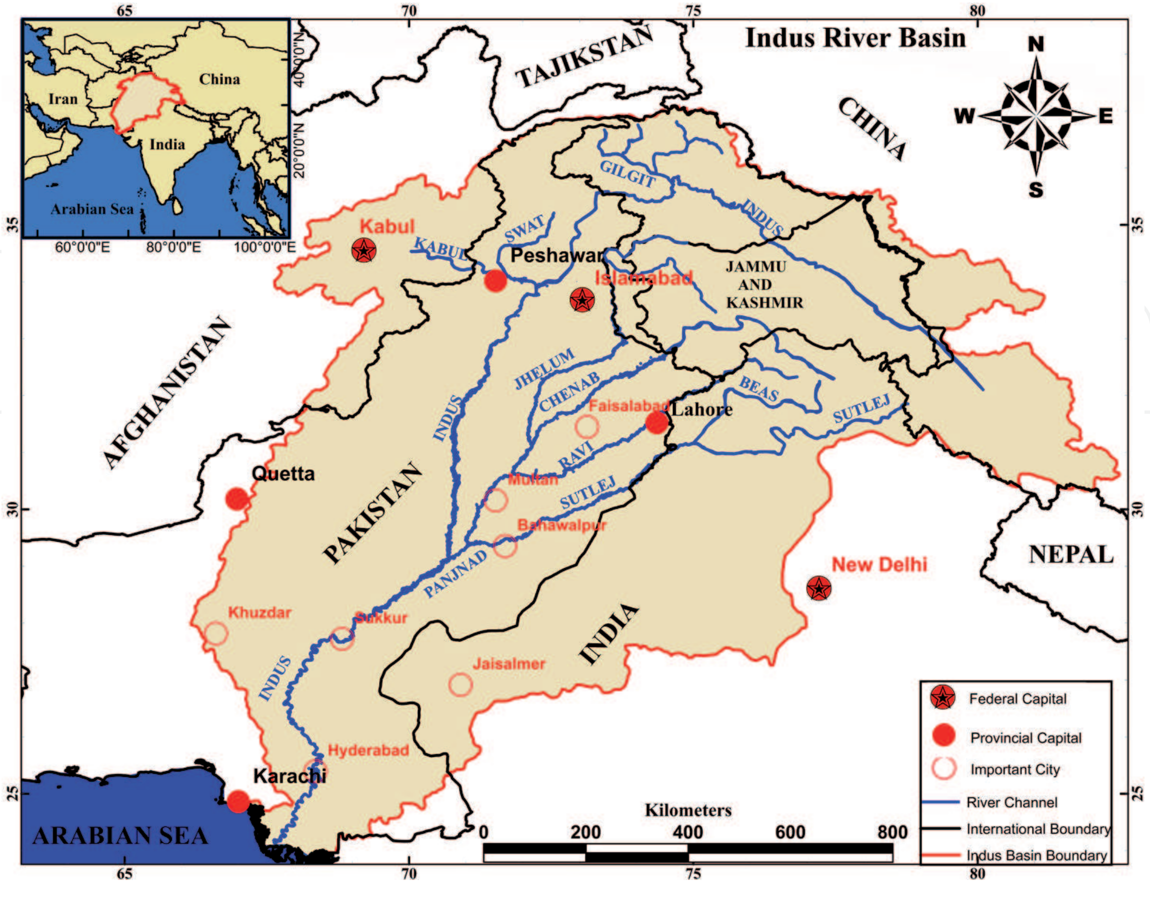

Figure 1.
Map representing river system, major cities, and the extent of Indus River basin.

<table>
<tr><th rowspan="3">River</th><th rowspan="3">Water Share in IRS</th><th rowspan="3">Share from snow and glaciers</th><th rowspan="3">Annual flow During monsoon season</th><th colspan="4">Mean Annual Flow</th><th rowspan="3">Catchment Area (km²)</th><th colspan="2" rowspan="2">Agricultural Area (Million hectares)</th></tr>
<tr><th colspan="2">Before IWT (1922-1960)</th><th colspan="2">After IWT (1961-2010)</th></tr>
<tr><th>MAF*</th><th>BCM**</th><th>MAF</th><th>BCM</th><th>1947</th><th>2015</th></tr>
<tr><td>Indus</td><td>52%</td><td>65%</td><td>54%</td><td>90</td><td>111</td><td>88</td><td>108</td><td>466,000</td><td colspan="2">In Pakistan</td></tr>
<tr><td>Jhelum</td><td>16%</td><td>50%</td><td>36%</td><td>23</td><td>28</td><td>22</td><td>27</td><td>63,500</td><td rowspan="2">8.5</td><td rowspan="2">18.2</td></tr>
<tr><td>Chenab</td><td>13%</td><td>49%</td><td>56%</td><td>25</td><td>31</td><td>25</td><td>31</td><td>67,600</td></tr>
<tr><td>Sutlej</td><td>8%</td><td>55%</td><td>62%</td><td>14</td><td>17</td><td>13</td><td>16</td><td>121,988</td><td colspan="2">In India</td></tr>
<tr><td>Ravi</td><td>4%</td><td>-</td><td>51%</td><td>6</td><td>8</td><td>7+</td><td>8.5+</td><td>40,400</td><td rowspan="2">2.02</td><td rowspan="2">8.5</td></tr>
<tr><td>Beas</td><td>7%</td><td>35%</td><td>67%</td><td>13</td><td>16</td><td>12</td><td>14.8</td><td>20,303</td></tr>
</table>

*MAF= Million Acre Feet **BCM=Billion Cubic Meter +Discharge from Ranjit Sagar Dam at gauging station near Mukteshwar

Table 1.
Water division, glacial contribution, mean annual flow, catchment area, and agricultural area of Indus River system (IRS) [5–14].

folds. This extensive human intervention in the Indus basin resulted in the adverse effects on the ecosystem of the Indus plain from the Himalayas to Indus delta [3].

Mohenjo-daro and *Harappa* are believed to be the two main centers of the Indus valley civilization. The ruins of *Harappa* excavation in the Punjab province highlighted that the grain commodity trade evolved which led to the development of earlier urban centers. The second center, *Mohenjo-daro*, found in the Sindh province, Pakistan, suffered from the change in the path of the Indus River. It is also believed that the continuous salinity problems and heavy flooding resulted in the collapse of Indus valley civilization [17, 18]. Early Harappans developed hydrological engineering practices like constructing *gabarbands* and dry masonry dams to divert the water toward the agricultural fields and digging wells and *karez* for the proper utilization of ground and river water. *Karez* system is still in use in Balochistan, while *gabarbands* are widely distributed in Balochistan and Kohistan [19].

2. Historical developments in the Indus basin irrigation system

In the development of early irrigation canals, the rulers of states in upper Indus basin areas played a vital role and paved the way to the construction of the complex irrigation system that exists today. Areas where significant work was done include Jammu and Kashmir regions, Punjab, and Sindh. Later on, further developmental work was carried out in several stages and different eras. Even today, an expansion of Indus irrigation system could be observed in different regions of Pakistan and India.

2.1 Early developments in Jammu and Kashmir

Development of the canal irrigation system started in the eighth century in the Kashmir region after the regular flooding of the valley and rise in the prices of crops that made the survival of the poor very difficult. In such a situation, King *Lalitaditya* set the drainage system in a suitable direction and distributed the Jhelum River water to different villages for increased production of crops. The Martand Canal was constructed in that period; starting from the left bank of *Liddar* River and terminating at *Karewa* of *Martands*, the canal irrigates about 3844.5 ha of land along its 50 km long channel. King *Avantivarman* started the channel cleaning, broadening, construction of stone embankments, and changing of the location of river junction. Villages were protected by constructing dykes, and in order to make the irrigation system of the valley more effective, a network of canals was constructed, and rain-dependent areas were provided with irrigation facilities. The *Nur* and *Nandikul* Canals were constructed with a length of 13 and 30 km, respectively. *Nur* canal originated from the Jhelum River and terminated at *Anderkot* Village, while *Nandikul* Canal was designed to irrigate 3237.5 ha of land of the northern *Anantnag* by receiving its water from the Nullah Anantnag. Sultan *Zain-ul-Abidin* constructed the *Zainagir* Canal on the *Madhumati* River, to irrigate the rice fields and apple orchards on 5463.3 ha in the district *Baramulla* [20].

2.2 Early irrigation system in Punjab

The Punjab province is located downstream to the Kashmir, and early developments in irrigation system of this region occurred during the thirteenth to sixteenth century. The first canal in Punjab was constructed about five centuries ago by the Mughal Emperors. In the beginning, only inundation channels were designed to deliver river water to the cropland during the high flow season. Because of some technical problems, viz., unpredicted high flow season, siltation, and breaching, these inundation canals could not deliver the water effectively to the cropland. Later on, some primitive types of headworks on rivers were constructed to get more control over the water. These headworks either did not extend across the entire stream or allowed the floods to pass over their crests. Mughal Emperor Jahangir constructed an 80 km perennial canal on Ravi River to deliver the water to the Gardens of Sheikhupura [21]. In 1643, Shah Nahr developed to provide water to the Shalamar gardens and other irrigational lands around Lahore city [22]. Later on, *Hajiwah* and *Tiwana* Canals were developed in Punjab with support of British rulers to irrigate croplands in the *Mailsi* and *Sargodha* regions. Furthermore, 11 canals were built on the Indus River to irrigate the agricultural lands of D.G. Khan Region during 1875 [23].

2.3 The modern irrigation system in Punjab and Sindh

The development of the existing modern Indus irrigation system started in the mid of nineteenth century during the British rule. Food demand and British economic interests in the agricultural products specifically cotton were a major driving force for the development of an extensive agriculture system in British India. A large number of inundation canals originating from the Indus River system were remodeled [24]. To ensure the water supply in cropland of Punjab, Sindh, and Khyber Pakhtunkhwa (KPK), several permanent headworks were constructed. The construction of Marala Headworks started on Chenab River in 1887 to irrigate the Upper Rachna Doab through Upper Chenab Canal, whereas, in 1890, Chenab water diverted to Sandal Bar from Lower Chenab Canal. In 1897, Rasul Headworks were constructed on the Jhelum River to feed the Lower Jhelum Canal to irrigate the agricultural land in the Chaj Doab [21]. In 1902, Madhopur Headworks were completed on the Ravi River to provide water for agriculture to the Upper Bari Doab. Furthermore, the Triple Canal Project was designed and sanctioned in 1905. It was the first project to transfer the river water from one to another river. A gate-regulated canal, the Upper Jhelum Canal, was designed to provide irrigation water to almost 139,212 ha per annum on its way from Mangla to Khanki. The construction work of the canal was completed in 1917 and drained its water into Chenab River in the upstream of the Khanki Barrage of Lower Chenab Canal. The second canal was the Upper Chenab Canal, originating 58 km upstream of Khanki from Marala Barrage, designed to irrigate almost 262,236.7 ha of cropland on its way from Marala to Balloki. The canal opened for irrigational purposes in 1912, and its water drained into the Ravi River above Balloki Headworks. The third canal, the Lower Bari Doab canal, originated from a 0.5 km long weir on the Ravi River near Balloki and irrigated almost 354,910 ha of lands in Montgomery District (Sahiwal) and Multan. It was one of the major irrigational projects executed during the British Era [24].

After the First World War, the British Government decided to remodel the pre-existing inundation canals along with the construction of new canals to irrigate the parched areas of Sutlej Valley in 1921. The project was aimed to provide perennial water supply to the inundation canals after remodeling them by controlling the river water with the help of barrages along with irrigating more and more areas of land. Construction of four barrages along with 11 canals on the Sutlej River was completed in 1933 to convert the arid land into cropland. The Ferozepur Barrage with three non-perennial canals, namely, Bikaner Canal, Eastern Canal, and Dipalpur Canal, was constructed near Ferozepur to irrigate cultivated areas of Bikaner State, Ferozepur district, northeastern areas of the Bahawalpur State, and Lahore and Montgomery (Sahiwal) Districts. Sulemanki Barrage with three perennial canals, namely, Eastern Sidiqia Canal, Fordwah Canal, and Pakpattan Canal, was constructed to irrigate some areas of the Bahawalpur State. Furthermore, Islam Barrage was constructed in Tehsil Hasilpur with three non-perennial canals, namely, Mailsi Canal, Qaimpur Canal, and Bahawal Canal, irrigating about 577,892 ha of cropland. After the confluence of Sutlej River and Chenab, Panjnad Barrage was constructed with a perennial canal (Abbasia Canal) and a non-perennial canal (Panjnad Canal) to irrigate 44,920 ha and 541,875 ha of cropland, respectively [24]. In 1922, Maharaja Ganga Singh constructed a canal to irrigate the Bikaner State originating from the left bank of the Sutlej River [25].

The Sukkur Barrage Project was the first-ever barrage to be built on the Indus River sanctioned in 1923 and completed in 1932 with seven canals [26]. The Trimmu Barrage with three canals was constructed on the Chenab River below the confluence of the Jhelum River during 1937–1939. It was the last barrage completed before the start of the Second World War. During the partition of subcontinent, the construction of Jinnah Barrage and Kotri Barrage on the Indus River was in progress. At that time, the Bhakra Dam was also under construction on the Sutlej River. Jinnah Barrage was completed in 1947, and Kotri Barrage was completed in 1955 [21].

2.4 Post-partition developments

Due to the partition of India and Pakistan, Ferozepur and Madhupur Headworks became the part of India, which triggered the Indus water dispute. India cut off the water supplies of Upper Bari Doab canal and made all of the downstream irrigation activities impossible to be carried out. In this situation of water scarcity, Pakistan immediately constructed Bombanwali-Ravi-Bedian (BRB) Link Canal to provide water supply to irrigate the Upper Bari Doab. It was a 164 km canal originating from Upper Chenab Canal and moving southward to Bedian. India also constructed two main canals from Sutlej River in order to divert the water of the river from flowing downstream into Pakistan. To maintain the water level in Sutlej River, the Balloki-Sulemanki Link canal was constructed from Balloki Headworks on Ravi River to Sulemanki Headworks on the Sutlej River. Both the BRB canal and Balloki-Sulemanki canals were completed within a duration of 3 years (1951–1954). Before the war of 1965, another canal named Marala-Ravi Link was constructed having a length of 101 km to add additional water in Ravi River from the Chenab River. In the Sindh Province, construction of Guddu Barrage on the Indus River started in 1957 and was completed in 1963. The aim of this project was to remodel the upper inundation canals in the Sindh area into perennial canals to increase the area under cultivation in Sindh and Balochistan, and it was designed to keep 1.13 million hectares of land irrigated throughout the year. Later on, Kotri Barrage was completed to ensure the supply to the inundation canals in the southern parts of Sindh. Both the Guddu and Kotri Barrage accounted for the conversion of a large deserted area into irrigational lands. A multipurpose barrage, Taunsa Barrage[1], on the Indus River was completed in 1958 to provide controlled water supplies for irrigation [21]. The Warsak Dam[2] was constructed in 1960, and along with providing water storage, it also produced 40 MW of electricity. Later on, the production capacity of the dam was increased by installing additional generators [23].

3. The Indus Water Treaty (IWT) and hydrological developments

In 1960, IWT was signed between Pakistan and India as an effort for resolving the disputes due to the partition of the Indus basin rivers. The headwater sources of Indus River and its tributaries are present in India. India got the control over water resources of Pakistan flowing downstream. During the first 10 years of independence, Pakistan experienced severe blockage or reduction of river waters, which badly affected the crop yield in Pakistan. The World Bank and British Government helped the twin states to reach an agreement called Indus Water Treaty (IWT). In this treaty, the water rights of eastern rivers, viz., Sutlej, Ravi, and Beas Rivers, were allocated to India, whereas the control of western rivers, viz., Indus, Jhelum, and Chenab Rivers, was given to Pakistan. After a period of 10 years, both the countries were authorized to utilize their share of water in their own way. After the treaty was signed, India started to construct projects on eastern rivers in order to divert the water flowing in eastern rivers, and water shortage started in the areas of Pakistan irrigated by the eastern rivers. To fulfill the shortage of water in the eastern rivers, the World Bank financed 8 billion US dollars project "Indus Basin Development Fund" for the construction of dams, barrages, and canals in Pakistan. Furthermore, link canals were constructed to inter-connect the western and the eastern rivers in Punjab for a sustainable supply of water to the cropland. The project was completed in two phases due to the inadequacy of funds. In the first phase, the key construction of Mangla Dam was completed on the Jhelum River in 1967.

Some of the barrages and canals were also modified and improved. After the completion of the first phase, another amount of 1.2 billion US dollars was approved by the World Bank, and the second phase of development started in 1968. The construction of Tarbela Dam on the Indus River was completed in 1976. This dam has sufficient storage capacity of water to supply during low flow season [34]. Both Mangla and Tarbela dams accounted for the major proportion of hydroelectricity generated in Pakistan. Several barrages were remodeled to divert the water from one river to another river such as Rasul, Sidhnai, Chashma, etc. Punjab and Sindh Governments are focusing on lining the canals and water courses to conserve the water. A number of projects have been completed for electricity generation like Ghazi-Barotha and Neelum-Jhelum hydroelectric projects [35]. Owing to the high demand of irrigation water and climate change, rivers in Pakistan are facing the reduction in water flow, and this shortage of water may be intensified in the near future. Considering these issues, the Government of Pakistan is planning to construct more dams to increase the water storage capacity on the Indus River. Details of the existing dams, barrages, link canals, and irrigation canals are given in **Table 2**.

India also carried out some projects in the Indus basin, like Harike Barrage with three canals, viz., Ferozepur Feeder Canal, Makhu Canal, and Rajasthan Feeder Canal, constructed on the Sutlej River in 1952. The Rajasthan Feeder Canal was later on

[1] Barrage is a weir-controlled system installed to divert and control the water flow into the canals with negligible water storage capacity.

[2] Dam is a high concrete walled structure built to store a large volume of water for agriculture and to use the potential energy of water for electric power generation.

River	***Dam(s) (Million m3)***	***Barrages/Head Works/Dam (No. of off taking Canals)***	***Link Canal(s) (Thousand Cusecs)***	***Irrigation Canal(s) (Thousand Cusecs)***
Indus	Nimoo Bazgo (120)	Jinnah Barrage (1)		Thal (6.0)
	Tarbela (11,900)	Chashma Barrage (2)	Chashma-Jhelum (21.7)	Chashma Right Bank (2.5)
		Taunsa Barrage (4)	Taunsa-Panjnad (12.0)	D.G Khan (8.8), Muzaffargarh (7.3), Kacchi (6.0)
		Guddu Barrage (4)		Thar (10.0), Ghotki Feeder (8.5), Pat & Desert Feeder (6.3,12.5), Beghari Feeder (15.3)
		Sukkur Barrage (7)		Khairpur West (1.9), Rohri (11.2), Khairpur East (2.7), Nara (13.4), Dadu (3.2), Rice Feeder (10.1), North West (5.1)
		Kotri Barrage (3)		Kaliari (9.0), Pinyari (14.4), Fuleli (13.8), Lined Channel (4.1)
Jhelum	Mangla (9,000)	Mangla Dam (1)	Upper Jhelum (12.0)	Lower Jhelum (19.0)
		Rasul Barrage (2)	Rasul-Qadirabad (19)	Upper Chenab (7.8), Bombanwali Ravi Bedian Dipalpur (3.1)
Chenab	Salal (285)	Marala Barrage (2)	Marala-Ravi (22.0)	Lower Chenab (16.0)
	Baglihar (395)	Khanki Barrage (1)		
		Qadirabad Barrage (1)	Qadirabad-Balloki (14.5)	Haveli (5.0), Rangpur (2.5)
		Trimmu Barrage (3)	Trimmu-Sidhnai (11.0)	Panjnad (9.0), Abbasia (1.1)
		Panjnad Barrage (2)		
Ravi	Ranjit Sagar Dam (3280)	Madhopur Headworks (2)	Madhopur-Beas (10.0)	Upper Bari Doab (8.2), Kashmir (0.8)
		Balloki Barrage (2)	Balloki-Sulemanki (15.4)	Lower Bari Doab (7.4)
		Sidhnai Barrage (2)	Sidhnai- Mailsi (10.1)	Sidhnai (4.0)
Beas	Pandoh (41)	Pandoh Dam (1)	Beas-Sutlej (16.7)	
	Pong (8,570)	Pong Dam (3)		Pong Left Main (12.5), Mukerian Hydel Channel (11.5), Kandi (0.5)
Sutlej	Bhakra (9,620)		Sutlej Yumna (6.5-7.4) *	
	Nangal (20)	Nangal Dam (2)		Bhakhra Main Line (12.4), Nangal Hydel Channel (14.5)
		Rupar Headworks (2)		Sirhind (12.6), Bist Doab (1.4)
		Harike Headworks (2)		Sirhind Feeder (5.2), Rajasthan Feeder/Indira Gandhi (18.5)
		Ferozepur Headworks (2)		Ferozpur Feeder (11.2), Abohar Branch Lower (1.7)
		Sulemanki Barrage (3)		Upper Pakpatan (6.6), Eastern Siddiqia (4.9), Fordwah (3.4)
		Islam Barrage (2)		Qaim (0.6), Bahawal (5.4)

*Incomplete Project

Table 2.
Hydrological developments (dams, barrages, headworks, link canals, and irrigation canals) on Indus River system (IRS) [4, 27–33].

upgraded in 1961 with the construction of Bhakra Main Line Canal and a large network of distributary canals under Indira Gandhi Irrigation Canal system to irrigate the Rajasthan desert [36]. In 1954, Ravi-Beas Link Canal was designed to transfer the water from Ravi River to Beas River. At the time of partition, the Bhakra Dam was in progress and completed in the early 1970s under the Bhakra Nangal Project. Bhakra Main Line Canal was constructed from Bhakra Dam for irrigation purposes. Downstream of Bhakra, at a distance of 13 km, another dam called Nangal Dam, was designed to control to feed the Nangal Hydel Channel. The whole project generates about 1325 MW of electricity and provides irrigation water for about 4.04 million hectares of land in Punjab, Himachal Pradesh, Haryana, and Rajasthan [37]. The Pong Dam was built in 1975 on Beas River to store water and use it through Shah Nahr. In 1977, Pandoh Dam was constructed along with the Beas-Sutlej Link Canal from the Beas River to Sutlej River. Sutlej-Yumuna Link Canal started from Nangal Dam in 1982, but it is still incomplete due to strong resistance from the Indian Punjab Government [33].

In 2014, Nimoo-Bazgo Dam was completed on Indus River in Ladakh region of Indian-held Jammu and Kashmir. Similarly, Kishanganga Dam is under construction by India, on the upstream of Neelum River near *Bandipore*, to divert the water flow into an underground powerhouse to generate electricity [38]. Besides these projects, a large number of projects are still in planning stages on both sides of the borderline. Majority of these projects are of hydroelectric nature, and water will mainly be used for electricity generation, for example, Diamer-Bhasha Dam and Mohmand Dam, from Pakistan's side and Pakal Dul Dam from the Indian side. But with the construction of these massive concrete structures, a huge amount of water will be stored and provided during low water season in order to fulfill the agricultural water requirements.

4. Socioeconomic impacts on local population

Early irrigation system in the Indus basin was developed for irrigational purposes. Due to the development of canals in the Kashmir region, the agricultural production was increased many folds [39]. The Indus basin irrigation system is one of the largest, complex irrigation networks and the largest weir-controlled system in the world with large reservoirs, barrages, syphons, and many types of canals and their watercourses [40]. Construction of new canals created favorable conditions for the colonies to be developed in the basin. Best examples can be seen as Lyallpur (Faisalabad) developed in the vicinity of the Lower Chenab Canal. Similarly, Sargodha and Montgomery (Sahiwal) were developed along the lower Jhelum Canal and the Lower Bari Doab Canal, respectively [25]. High crop productivity was found in irrigated areas than in the rainfed areas. High crop production leads to high per hectare employment. Additionally, irrigation system also made it possible for an extra crop to be raised, hence increasing per year yield, increasing household income, and decreasing poverty in irrigated areas [41].

Development of irrigation system benefited both at the local and governmental levels. A famine-prone area was converted into an area with high grain productivity that helped to prevent the famine conditions. Living style of the inhabitants was improved, and starvation was minimized. At the same time when the common population was benefitted, the British Government harvested a large volume of cotton crops from the irrigated areas, which provided them with a golden opportunity to cash the results of irrigation system development. Furthermore, the railway network increased access to agricultural products. Railway network facilitated the transport of food grains and cotton to local and international markets. Food grains produced from the area also helped to meet the food demands of other regions, hence making the region of South Asia's "breadbasket." Without the irrigation system, it seemed to be impossible because a large area was just barren and unproductive due to insufficient irrigation water. Similarly, livestock transformed from nomadic form to an organized industry to rear animals for milk and meat production as more fodder crops were available.

Construction of dams provided a platform for the production of electricity from river water. In order to fulfill the commercial and domestic electric requirements in the region, turbines were installed to produce the hydroelectric power. Industrial production increased due to the availability of a cheaper electric supply subsequently increasing the revenue from the industrial sector. Agricultural-based industrial development produced a large number of jobs to boost the local economy. Poverty was reduced, and livelihood increased favoring a better lifestyle in the families living near industrial areas.

5. Water sharing conflicts

At the time of partition of the subcontinent, the division took place in such a way that Kashmir became a territory of common interest being an origin for the most of rivers flowing downward to Pakistan. Additionally, India cut off the water flowing into all the canals of Pakistan originating from the headworks situated in India, which created a situation of restlessness among the people of both countries. In order to minimize the tension created between both countries over the river water issue, IWT was signed with the help of the World Bank [6, 42]. This agreement created an atmosphere of competition to build dams and barrages to not let their share of water be wasted. Especially, India constructed many dams and barrages in the upstream area of Jammu and Kashmir and on Rivers flowing through Indian territory, i.e. Ravi, Beas, and Sutlej. Due to the construction of these massive structures and diversion of water, a lot of detrimental effects have been produced in the Indus basin [43]. Construction of storage reservoirs on Indus River tributaries by India has lowered the downstream water flow creating a state of political unrest between India and Pakistan. Afghanistan is also planning to build dams on the Kabul River which may generate a new political issue between Pakistan and Afghanistan [40].

A hydrological disagreement between India and Pakistan has always been there since the very first instance being the construction of Salal hydroelectric project by India on Chenab River. Initially, Pakistan disagreed to the project, but after negotiations, the project was accepted in the 1970s. Afterward, many projects were subjected to disagreement including the Wullar Barrage and 430 MW Baglihar hydroelectric project. In the 1980s, India stopped the Wullar project due to extreme opposition from the Pakistan side [44]. In 1999, Pakistan complained about the second project, but negotiation continued on many forums. In 2007, after the acceptance of some modification suggested by Pakistan, the project was allowed to be completed [45]. Issues were also raised by Pakistan on the construction of Uri Dam on Jhelum River (1997) and Ratle Project on Chenab River (2013). The Ratle project consists of construction of a 170 m concrete wall to produce 850 MW electricity [46]. Uri dam was constructed during 1989–1997 with an installed capacity of 480 MW, but another project was run by India in 2005 to increase the production capacity of the Uri Dam. This Uri-II project increased the capacity by 240 MW through the construction of 3.61 km long tunnel with a diameter of 8.4 m [47]. In spite of the opposition from Pakistan's side, the project was completed in 2014. Recently, India started the construction of 330 MW Kishanganga hydroelectric project in 2007 which is considered as the most controversial project of the history till now. By the construction of this project, water flow in the Neelum River will become low and may cause failure of 969 MW Neelum-Jhelum project that has to be constructed downstream by Pakistan [44]. According to the opinion of John Briscoe, a water expert from South Africa, if all the projects designed by India are successfully completed on the Indus River, it will destruct the agricultural crops of the dry season in Pakistan as India will be able to hold up a month's worth river supply in these reservoirs. Unavailability of water will make the plantation difficult and will have negative effects on the agricultural sector of Pakistan [48]. Not only Pakistan is being affected, but in the Kashmir region, India is also producing electricity for its own provinces at the expense of only 12% given to Kashmir itself as a royalty. To fulfill the needs of electricity generation in the peak hours, Kashmir has to purchase the electricity generated from its own waters at an inflated rate despite having a production potential for 20,000 MW of electricity. At the same time, when IWT tried to resolve the water tension between Pakistan and India, it also opened the doors of discrimination for the disputed region of Kashmir because the agreement was signed without the consultation of Kashmir's prime minister [43].

After the partition, India started the construction of barrages and dams on eastern rivers, to divert the water flow to its own states rather than to Pakistan. Through the construction of Sutlej-Yumuna Link (SYL) Canal, a large portion of irrigational water (3.45 MAF) was planned to be moved from the Indian Punjab province to Rajasthan and other provinces. It was designed to irrigate about 446,000 ha land in Haryana and 128,000 ha in Punjab [49]. Inhabitants of Punjab claim that this diversion was not justifiable as it will turn irrigational areas of Punjab into desserts due to water scarcity. Nowadays, like most areas of the basin in Pakistan, the areas of Indian Punjab have become water scarce, and the water table has been lowered to a drastic level due to less availability of surface water. Farmers are forced to extract the groundwater which adds to the irrigational costs and negatively affects the income of the agricultural sector [50]. Water flow in the Sutlej River downstream of Harike Headworks is almost zero, and it is only flowing in case of high floods or due to any failure in Bhakra or Nangal Dam. It makes the downstream areas of Punjab dry during many parts of the year and flood-prone due to storage of large water in the upstream reservoirs. Construction of SYL is still incomplete due to interprovincial politics and concerns over the division of water [51].

Similarly, interprovincial conflicts also exist in Pakistan over the unequal distribution of Indus waters among the dominant province of Punjab and other smaller provinces mainly Sindh [52]. Unlike India, these conflicts have been limited to the political platforms. In the mid-nineteenth century, the construction of large canal structures by the British Government in Punjab gave birth to these conflicts. In 1945, Interprovincial water distribution was ensured by signing a treaty in which the Indus River water along with its tributaries was distributed between Sindh and Punjab. According to this treaty, majority of water from the eastern tributaries of Indus (94%) were allocated to Punjab and remaining to the Sindh. Meanwhile, Sindh was allocated with 75% water of the Indus main channel and Punjab with the remaining 25%. The Indus Water Treaty made the construction of link canals necessary for Pakistan in order to compensate for the upstream loss of water. As a majority of the link canals and storage reservoirs were to be constructed in the Punjab region, Sindh's population perceived it as a conspiracy to compensate Punjab at the expense of Sindh's share of the Indus River [45].

To settle the issues among the provinces, the "Water Accord 1991" was endorsed in which Indus water was distributed on the basis of average flow. Even after the accord, some insecurities existed in smaller provinces because the large quantity of water was allocated to only Punjab and Sindh [52]. Kalabagh Dam has been a focus of attention for many years due to political insecurities on the construction of the dam. People of Sindh claim that after the construction of the dam, water flow will be reduced causing droughts and saltwater intrusion in downstream areas. They also claim that Sindh is far more dependent on river waters because more than 80% of groundwater is saline in the region and construction of the dam will compromise their water requirements. This project was developed in the light of past destructive events of droughts in Sindh and subjected to opposition from politicians and bureaucrats of the Sindh province [45].

6. Ecological and environmental adversities

Since the prehistoric era, changes in irrigation system have a strong link with climate change [39]. Due to the increase in agricultural area and productivity, the human population has been increased in the Indus basin, followed by urbanization and industrialization, boosting the water demands for household, food production, and energy and industrial sectors. Population increased due to the availability of resources and settlement areas. A large area was converted into the urbanized area, and some of the native species vanished from the Indus Basin. In order to protect the urban area, a natural path of the Indus River should be restored along with its natural floodplains and wetland area. The presence of highly populated areas in the floodplains of rivers makes a large number of people prone to the flooding. In such circumstances, more economic loss has been observed by the flood as it happened in 2010 in Pakistan. In Kashmir region, the majority of the dams are constructed in a hazard-prone area and are called as "water bombs" by a glaciologist. About 15 dams were built by the Indian Government in the Himalayas, which were not recommended due to fragile mountainous land. The temperature in this mountainous region is increasing by human-induced global warming, and glaciers are retreating, creating a temporarily high flow in the Indus River, which may cause damage to the structures built [43]. The sediment load is constantly increasing in the river resulting in avulsion. With the passage of time, the storage capacity of the reservoirs started to decline due to the siltation increasing the area under inundation [53]. Reduction in the storage capacity increases the chances of flooding in the surrounding areas in high flow seasons. A detailed information about the impacts on the Indus River and mitigation measures is provided in **Table 3**.

Problem	Affected area(s)	Mitigation measure(s)	Recommendation(s)
Waterlogging and Salinity	Lower and middle Indus basin	Salinity Control and Reclamation Project	Changing irrigation techniques, using gypsum
Habitat fragmentation	Indus Blind Dolphin	Indus River Dolphin Conservation Project	Construction and proper maintenance of fish ladders, preventing low water level
Increased flooding	Lower floodplain areas	Construction of dikes, Flood prediction and migration	Increasing storage capacity, emergency response plan
Riverine pollution	Fish species, water quality	Solid waste management, Industrial and municipal wastewater treatment	Control over fertilizer and Pesticide usage, Organic farming
Groundwater extraction	Punjab and Sindh	Water re-use and conservation, Drought resistant crops	Rain water harvesting, Groundwater recharging, Increasing storage capacity, Awareness campaigns
Declining delta and estuaries	Mangroves	Mangroves restoration projects	Construction of levees along the coastline, mangroves plantation, increasing water flow, reducing mangroves burning as fuel

Table 3.
Environmental and ecological problems in Indus Basin, their mitigation and recommendations [53–62].

Since 1851, the salinity problem has been observed in different areas of the Indus basin. Firstly, the salinity issue was identified in the Jammu and Kashmir regions. Similarly, in Punjab, salinity problems were also reported. To check the overall groundwater level in the basin, a series of observatory wells were installed across the basin. In open water table wells, Punjab showed the remarkable increase in the water table level induced by man-made irrigation system in the area. The main reason for the high level of the water table, salinity, and water logging observed in the basin, although it was not that much prominent, was considered to be the diversion of the river channel and the construction of unlined irrigation canals during 1850–1950. The situation in Punjab is still considered better than Sindh because in this area water logging was more common than salinity due to salt-free upper layers and better drainage and topography. Salinity problems in Punjab were only confined to the areas with poor drainage and topography. In the central Indus basin, i.e., lower Punjab and upper Sindh, the water table was found to be highest in the 1940–1950s followed by the highest level of waterlogging in the 1960–1980s. Salinity conditions in this area are in transition to the upper and lower areas of the basin. The productivity of 20–30% of irrigated land was affected due to salinity and waterlogging during 1970–1980s [63].

A shift in climatic patterns and over the use of surface water reduced the availability of water, forcing the people to rely on groundwater aquifers, resulting in rapid depletion of subsurface water resources. The shift from surface irrigation to groundwater is the inability of the Indus basin irrigation system to accommodate the changing water requirements of crops over different seasons due to inefficient water management. Increase in food requirements due to population growth and economic competition emerged due to over demand of crop yield, and the farmer community moved from a conventional irrigated agriculture to more water-intensive agriculture that was beyond the capacity of the existing irrigation system. More than 80% of groundwater is extracted by small tube wells because of cheaper installation and easy operation. In the irrigated areas, groundwater is of poor quality, and its frequent use in agricultural has resulted in salinity of a large portion of the agricultural area in the Indus basin [53].

The Indus River delta is facing the high risk of salinity in upper parts due to vertical and lateral movement of saline groundwater into the fresh shallow aquifers [64]. Secondary salinization has been observed in 4.5 million hectares of land, and half of the lands are in the Indus basin irrigation area. About one million hectares of agricultural land is facing waterlogging problems due to seepage of canal water and poor irrigation techniques [45]. Food grain crops have been replaced with high-price crops, which require more water than the food grains, resulting in increased water demand. The canal water system, fed by Indus River, adds almost 16.6 million tons of salts into the irrigated and deserted strata of Indus basin including groundwater aquifers. Rainstorms cause a lot of agricultural and economic damages due to the restricted surface and subsurface water drainage, because of the plain topography of Indus basin [40].

Development of irrigation system structures such as dams and barrages has led to the fragmentation of Indus River into 17 sections which resulted in extirpation of dolphins from 10 sections. They were found to be present in only 6 out of 17 sections of the river due to the usage of river water for irrigation and low water discharges in the dry season. Spatial and temporal distribution patterns were affected by habitat fragmentation, and, combined with habitat degradation, it contributed to the decline of the dolphin population [55]. The whole length of the Indus River used to be the habitat of dolphins, but this area has now been restricted to only 20% of total length due to habitat fragmentation. Chemical pollution and accidental death by fishing gears are some of the potential factors for the decline in the dolphin population [65]. Sometimes, dolphins get trapped in the canals, fail to return back into the river, and eventually die. In the downstream area of Sukkur Barrage, the river channel is highly constricted, and dolphins are subjected to intensive fishing activities mainly in the winter season [66].

Natural processes have the potential to contaminate water resources, but with the development of irrigation system and residential colonies, the agricultural system became widespread, and a large number of industries came into existence. Anthropogenic activities in agriculture and industries cause discharges of fertilizers, pesticides, chemicals, heavy metals, and pathogens that can degrade the water quality and can cause negative effects on human health. Fertilizers and pesticides used in the agricultural areas are washed off and drained into surface and groundwater aquifers. The water requirements are high in the urban areas, and they contribute to water pollution by the production of municipal sewerage and leaching from solid waste generated. Water affected both qualitatively and quantitatively making it unsuitable for the human and animal consumption. As the Indus River flows downward, the effects of deterioration are intensified as a large volume of untreated effluents from agricultural, industrial, domestic, and commercial areas enter into the river on its way. Throughout the river channel, concentrations of nitrogen, phosphorus organic matter, pesticides, and mercury are present at an alarming level. Most of the effluent dumped into the river comes from the agricultural sector alone, while industries, households, and urbanized areas being the other major sources [67].

Indus delta is rich in biodiversity, and mangroves were a very important ecological resource in the lower Indus basin. Reduced water flow, pollution of rivers, and usage of mangroves as fodder and fuel have reduced the mangrove species. The population of mangroves has declined to a threatened level by pollution and anthropogenic activities [68]. With the decline in mangrove population, the spawning and rearing sites of many fish and macroinvertebrate species have been destroyed causing a decline in the population of those species. The flow of water in Sutlej River has almost gone to zero due to upstream storage by India. The river channel has been converted into a sandy desert with no water at all losing all the scenic values associated with its original aquatic ecosystem. As the river dried up, agriculture declined, and biodiversity was rapidly declined which disturbed the regional ecology. People moved from the dry areas, and all the developed infrastructure was destroyed. Sutlej Valley developed because the river began to die as the people migrated out of the area due to perished livelihood. Much of the culture of this valley has already been lost, and if not managed for a few more years, the civilization will be completely vanished [69].

7. Recommendations and conclusion

No doubt the Indus irrigation system is one of the largest irrigation systems in the world. It provides food, jobs, and recreational resources for Pakistani and Indian people, but in the race of extensive water use, the environmental resources of Indus basin have been compromised. Natural flow and discharge of rivers have been altered by the construction of massive structures. At the beginning of irrigation system development, the groundwater level raised, and it changed the vegetation pattern in the region along with the intensive agricultural activities favored by a large supply of irrigation water. Large-scale agricultural activities attracted the human population to be settled in this region, thus making it one of the thickly populated regions in the world. This situation created an environmental disaster in the region. Indiscriminate human activities contaminated surface and groundwater resources through industrial and agricultural chemicals. Several types of diseases and human abnormalities have been reported from this region due to excessive use of the chemicals in the urban and rural areas. The Indus River, once regarded as the Mighty Indus, has already turned into an ordinary polluted river. The situation is now or never, and we have to take some concrete measures to restore the natural flow of the river and develop efficient technologies to get maximum crop yield with minimum use of water. The sustainable approach could be beneficial for the future of rivers and human population.

After 150 years of the development of irrigation systems, most of the environmentalists come up with a conclusion that sustainable environmental management of rivers must be ensured. The authorities should maintain minimum ecological flow downstream to sustain the ecological conditions of river. Fish and other organism communities have been constantly declining due to decreasing water level and fragmentation of their habitat. Further pressure has been exerted on the fish population by intensive fishing and using illegal fishing nets. Policies must be implemented by keeping in view the maintaining of the minimum flow of water in river to support the ecological health of Indus River system. To avoid habitat fragmentation, upstream and downstream habitats should be connected through functional fish ladders. Fishing activities must be monitored regularly, and fishermen community should be encouraged to use legal gears for fishing activities.

Human activities in the catchment area and indiscriminate use of water from Indus River system are at full swing on both sides of Pakistan and India. Due to intensive agriculture, the river water is becoming insufficient to meet the irrigational demands despite a well-established irrigation system. Groundwater extraction is carried out for compensating the shortage of surface water resulting in the lowering of groundwater table. Increasing urbanization and development of industrial sector enhanced the utilization of subsurface water for the human consumption and industrial manufacturing. Groundwater aquifers have been exhausted down to the depth of several hundred feet in majority of the areas of Indus basin. Both countries must sign a new agreement for the stringent control of the noxious human activities. They must work on drought-resistant crop varieties to ensure the minimum use of surface and groundwater for irrigation purposes.

River pollution is one of the major threats to the ecological resources. It causes substantial damages to the fauna and flora of aquatic ecosystem. Industries use many types of chemicals in their manufacturing processes, and majority of water used to wash off the chemicals is drained into rivers without proper treatment. Commercial and residential areas also generate a large amount of municipal sewerage water that finds its way to the river without any treatment. Industrial and municipal waste water treatment should be ensured with strict rules and regulations. Continuous monitoring of treatment plants should be ensured to keep them in a proper working condition.

Pakistan and India are in a developmental race to take control over the Indus water resources in order to improve their economy and to minimize the shortfall of electricity in the region. Construction of massive hydroelectric projects and diversion channels has adversely affected the natural river course. Currently, it is impossible to predict the situation of Indus River in the upcoming years when the water resources are being exhausted rapidly. Sustainable use of water resources can be helpful in minimizing the ecological damages at the expense of economic development. Both countries should modify their developmental policies by limiting the human interventions in the natural course of rivers. In this way river system's natural condition could be sustained.

Considering the pace of hydrological development on the Indus River System, Integrated Water Resource Management (IWRM) must be implemented especially in Pakistan as it is the only water source of the country [70]. It is important to efficiently utilize all the available surface and groundwater. Optimum amount of water should be allocated to each sector and area to reduce the pressure on groundwater resources. Farmers can be educated to use the modern agriculture practices and drought-resistant crops in order to save water. Infrastructure for the storage of water can be enhanced by the government to reduce the impacts of low water season on the economy of agricultural community. Restriction on the excessive usage of pesticide and fertilizers on crops should be enforced to avoid water pollution. Moreover, it has been observed that Indus Water Treaty was the need of time, but it needs a lot of improvements to meet the environmental issues of changing climate and rising tensions between India and Pakistan. Both countries must negotiate to bring some new provisions in the treaty to maintain a minimum amount of water in the river system necessary for the ecological requirements of the basin. At this stage, if the Indus River system is not managed sustainably, the system may undergo irreversible damages that can never be undone.

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Conflict of interest

The authors hereby declare that there is no conflict of interest.

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