

IMPACTS OF SEISMIC HAZARDS ON SURFACE AND GROUNDWATER SYSTEMS IN PAKISTAN: IMPLICATIONS FOR TRADITIONAL KAREZ IRRIGATION

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Abstract

Pakistan's hydrological systems are strongly influenced by the country's tectonic and geological setting, as it lies within an active seismic zone formed by the collision of the Indian and Eurasian tectonic plates. Geological hazards such as earthquakes, crustal deformation, and associated geomorphological processes can significantly alter both surface and groundwater systems. These processes may result in river course diversion, fluctuations in groundwater levels, sediment redistribution, and damage to traditional irrigation infrastructures such as karezes. This review paper examines the influence of tectonic activity and seismic hazards on water resources in Pakistan by synthesizing historical records, geological studies, and hydrological observations. Particular emphasis is placed on the role of tectonic controls in shaping the Indus River system, the hydrological consequences of major earthquakes, and the vulnerability of groundwater-based irrigation systems in arid regions of the country. The study highlights how geological processes have historically contributed to changes in river networks and groundwater availability, with significant implications for agricultural productivity and water security. Understanding these interactions is essential for developing resilient water resource management strategies in tectonically active regions. The findings emphasize the need for integrating geological hazard assessments into water management planning to enhance long-term sustainability and disaster resilience in Pakistan.

Keywords: Earthquake, Geological hazards, Water resources, Karezes, Indus River system, Pakistan

1. Introduction

Water resources constitute a fundamental component of Pakistan's environmental sustainability and economic development. The country's economy is predominantly agrarian, and agricultural productivity largely depends on the availability of irrigation water. Pakistan possesses one of the largest contiguous irrigation systems in the world, primarily supported by the Indus River Basin irrigation network (Shah, 2006). Out of the total land area of approximately 79.6 million hectares, nearly 19 million hectares are irrigated, while approximately 3 million hectares are cultivated under rain-fed conditions.

The hydrological regime of Pakistan is strongly influenced by river systems originating from the Himalayan, Karakoram, and Hindu Kush mountain ranges. These glacial and snow-fed rivers provide essential water supplies for agriculture, domestic consumption, industry, and hydropower generation. In addition to supporting agricultural activities, water resources also contribute significantly to the national energy sector through hydropower production.

Despite the relative abundance of water resources, Pakistan faces increasing challenges related to water availability and sustainability. In addition to climatic variability and population growth, geological hazards pose a significant threat to the stability and functionality of water systems. The country lies within an active seismic region where the Indian tectonic plate converges with the Eurasian plate, resulting in frequent earthquakes and tectonic deformation. Seismic activity can significantly influence hydrological systems by altering river courses, affecting groundwater flow patterns, damaging irrigation infrastructure, and triggering landslides that modify watershed dynamics. These geological processes have historically contributed to major hydrological transformations across the region.

This review aims to examine the relationship between geological hazards and water resources in Pakistan. The study synthesizes available literature to evaluate how seismic activity influences surface water systems, groundwater resources, and traditional irrigation structures such as karezes (Wada et al., 2020). Understanding these interactions is crucial for developing resilient water resource management strategies in hazard-prone regions.

2. Methodology

This study adopts a qualitative review approach to examine the impacts of geological hazards on water resources in Pakistan. Relevant scientific literature, government reports, and historical records were systematically reviewed to identify documented relationships between seismic activity and hydrological systems. Sources were obtained from academic publications, disaster databases, geological reports, and hydrological studies focusing on Pakistan and the broader South Asian region. The collected information was analyzed to identify key mechanisms through which geological hazards influence river systems, groundwater resources, and traditional irrigation infrastructure such as karezes. Figure 1 demonstrates how tectonic activity and earthquakes trigger geomorphological processes that influence hydrological systems, which subsequently affect agricultural productivity, water availability, and socio-economic stability.

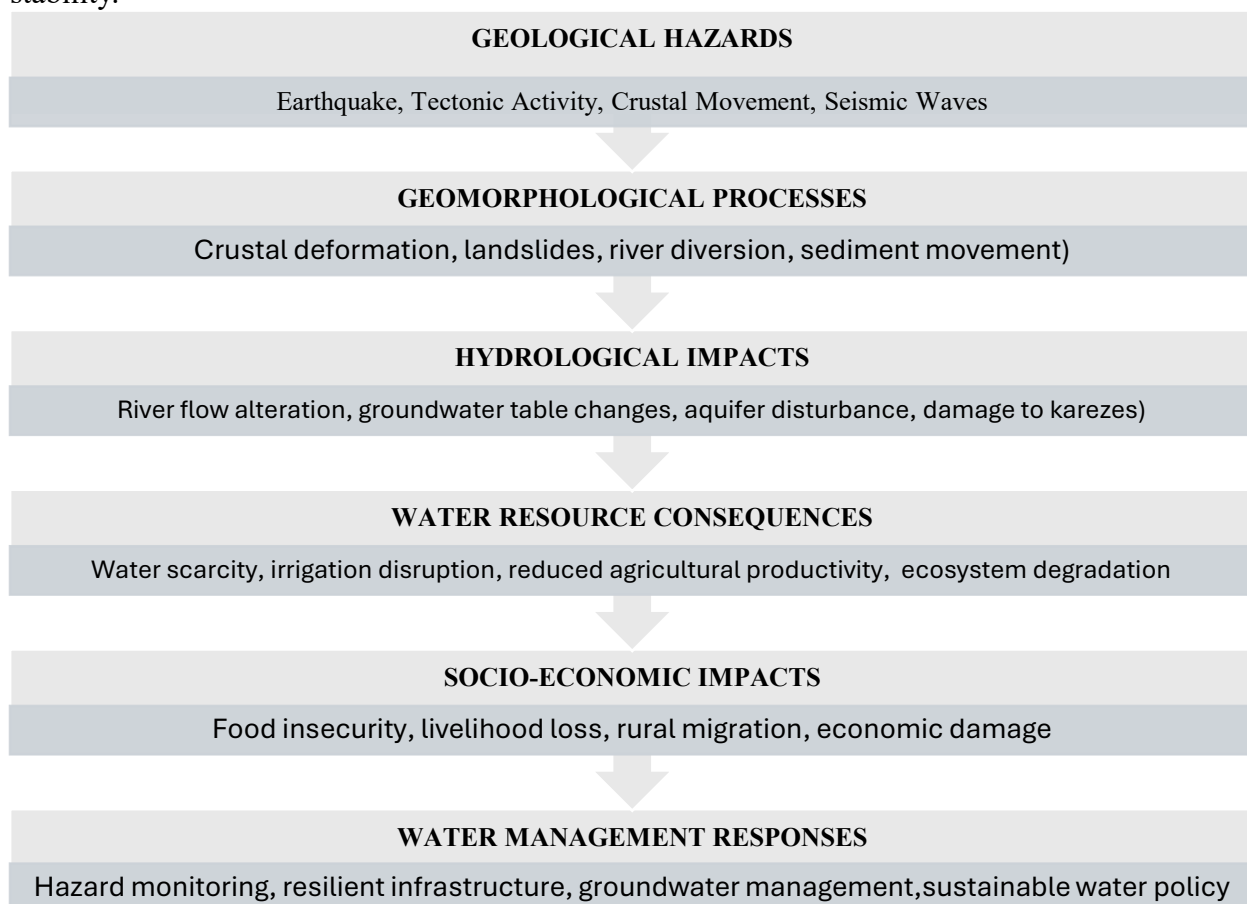


Figure 1. Conceptual framework illustrating the relationship between geological hazards and water resource impacts in Pakistan

3. Water Resources in Pakistan

Pakistan possesses a wide range of natural and artificial water resources that support its agricultural and economic activities. Natural water resources include precipitation, glaciers, rivers, lakes, streams, ponds, and groundwater reserves. Artificial water resources mainly

consist of dams, reservoirs, and irrigation infrastructure developed to regulate water supply and support agricultural production.

The Indus River system represents the backbone of Pakistan's water supply network. The Indus River originates from glaciers in the Himalayan region and flows through the country before discharging into the Arabian Sea. Several major tributaries contribute to the Indus River system, including the Jhelum, Chenab, Ravi, Sutlej, and Beas rivers. These rivers also originate from the Himalayan mountain ranges and collectively form the Indus Basin irrigation system (Ali et al., 2019). Additional tributaries such as the Swat, Kabul, Kurram, Gomal, and Gaj rivers originate from the Karakoram, Hindu Kush, and Kirthar mountain ranges (IRSA, 2015). The Indus Basin irrigation system is considered one of the largest irrigation networks in the world and plays a critical role in supporting agricultural productivity across Pakistan. However, the distribution and flow dynamics of these rivers have been influenced by long-term geological processes and tectonic activity (Kazmi et al., 2019).

Geological studies suggest that significant changes have occurred in the configuration of river systems within the region over geological time scales. For example, the Sutlej River was not originally part of the Indus River system. Approximately 4,000 years ago, a large independent river system known as the Sarasvati–Hakra River flowed parallel to the Indus River toward the eastern region. This river system eventually disappeared due to tectonic deformation and geomorphological changes associated with Himalayan uplift (Wilhelmy, 1969; Zaigham, 1994; Zaigham et al., 2005).

Satellite observations and geological analyses indicate that tectonic activity contributed to major shifts in river courses, including the diversion of the Sutlej River into the Indus system and the redirection of the Yamuna River toward the Ganges Basin. These tectonic adjustments ultimately resulted in the extinction of the Sarasvati–Hakra river system (Kazmi, 1984; Wilhelmy, 1969).

Such examples illustrate the strong link between geological processes and hydrological systems in the region.

4. Geological Hazards and Water Resources

Water resources are highly vulnerable to natural hazards, particularly floods and earthquakes. In Pakistan, flooding events are frequently associated with climatic variability, monsoon rainfall, and atmospheric circulation patterns. The monsoon season typically extends from July to September and contributes a substantial portion of the country's annual rainfall.

However, extreme weather events linked to climate variability, including the El Nino–Southern Oscillation (ENSO), can intensify rainfall patterns and lead to severe flooding. One of the most notable examples is the catastrophic flooding event of 2010, which caused widespread damage to infrastructure, agriculture, and water supply systems across Pakistan (Abbas et al., 2021; Khandekar, 2010).

In addition to climatic hazards, seismic activity represents a major geological threat to water resources. Pakistan is located within an active seismic belt characterized by the collision of the Indian and Eurasian tectonic plates. Major mountain ranges including the Himalayas, Karakoram, and Hindu Kush are particularly prone to seismic activity.

Earthquakes can significantly affect hydrological systems by causing crustal deformation, landslides, and changes in groundwater dynamics. These processes may alter river channels, disrupt irrigation infrastructure, and influence groundwater recharge patterns.

Historically, several major earthquakes have occurred in Pakistan, causing significant human and economic losses. Notable seismic events include the 1935 Quetta earthquake, the 2005 Kashmir earthquake, and the 2013 Balochistan earthquake. These events resulted in extensive damage to infrastructure and natural systems, including water supply networks.

Table 1. Major historical earthquakes recorded in Pakistan

Year	Magnitude	Estimated Deaths	Location
893–894	8.0	150,000	Shahbandar, Sindh
1668	7.6	50,000	Shahbandar, Sindh
1819	7.5	3,200	Allah Bund, Sindh
1827	7.8	1,000	Lahore, Punjab
1852	8.0	—	Kahan, Balochistan
1909	7.0	100	Sibi, Balochistan
1935	7.7	30,000–60,000	Quetta, Balochistan
1945	7.8	4,000	Makran Coast
1974	6.2	5,300	Hunza, Hazara & Swat
2005	7.8	80,000	Kashmir region
2008	6.4	215	Ziarat, Balochistan
2011	7.2	—	Balochistan
2013	7.7	825	Awaran, Balochistan

Source: Pakistan Disaster Knowledge Network; DRIP (2015)

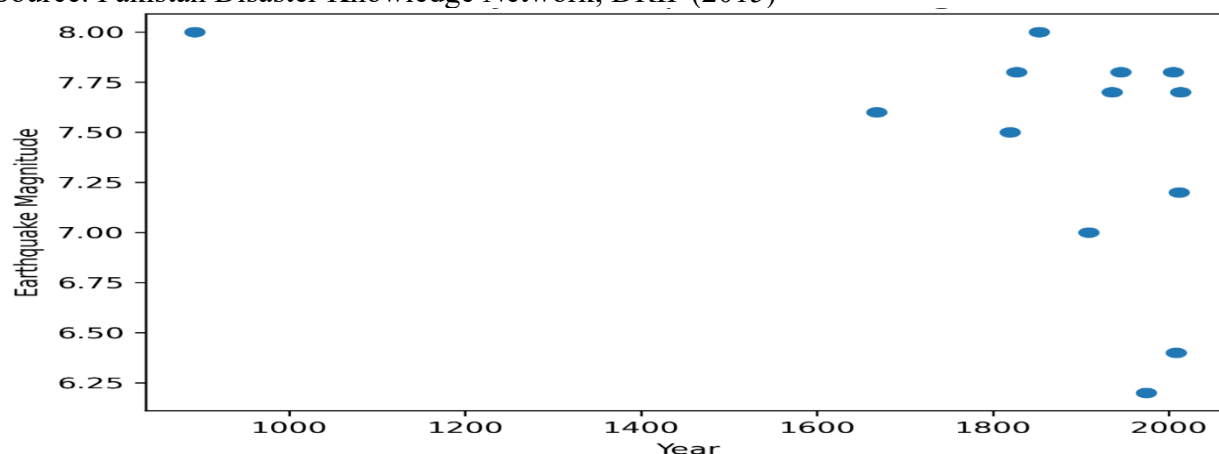


Figure 2. Historical major earthquakes affecting Pakistan.

The figure 2 illustrates the magnitude of major seismic events recorded in Pakistan from 893 AD to 2013. The data highlight the recurring occurrence of high-magnitude earthquakes (>7.0), indicating the country's significant seismic vulnerability due to tectonic plate interactions.

Table 2: Major Geological Hazards Affecting Water Resources in Pakistan

Hazard Type	Primary Causes	Hydrological Impacts	Affected Regions
Earthquakes	Tectonic plate collision between Indian and Eurasian plates	Groundwater table changes, river course modification, damage to karezes	Balochistan, Northern Pakistan
Landslides	Seismic activity, steep slopes, intense rainfall	River blockage, sediment deposition, watershed alteration	Gilgit-Baltistan, Kashmir
Tsunamis	Submarine earthquakes along Makran Subduction Zone	Coastal flooding, salinization of freshwater resources	Makran Coast, Karachi
Flooding	Monsoon rainfall, glacial melt, climate variability	River overflow, destruction of irrigation infrastructure	Indus Basin

5. Seismic Activity and Coastal Hydrological Disturbances

Seismic activity occurring beneath oceanic or coastal regions can also generate tsunamis that disrupt marine and coastal hydrological systems. Tsunamis are large ocean waves generated by underwater earthquakes, volcanic eruptions, or submarine landslides.

Historical records indicate that several tsunami events have occurred along the northern Arabian sea coastline, affecting coastal areas of Pakistan including Balochistan, Karachi, and the Rann of Kutch region. One of the earliest documented tsunami events in the region occurred around 326 BC when an earthquake-generated tsunami reportedly destroyed part of Alexander the Great's naval fleet near the Indus Delta (Lisitzin, 1974; Murty and Bapat, 1999).

Pakistan's coastline extends for approximately 1000 km along the Arabian Sea and includes several seismically active zones. Earthquake events recorded in 893 AD, 1668, 1819, and 1945 have been associated with tsunami activity along the Makran subduction zone.

These seismic disturbances can significantly impact coastal water systems, estuarine ecosystems, and sediment transport processes in the Indus Delta (Rasul et al., 2018).

6. Impact of Earthquakes on Traditional Irrigation Systems (Karezes)

Groundwater-based irrigation systems such as karezes represent an important component of traditional water management practices in arid regions of Pakistan, particularly in Balochistan. Karezes consist of underground tunnel systems that transport groundwater from aquifers to agricultural fields through gravity-driven channels.

Globally, approximately six percent of irrigated agricultural land relies on karez-type systems, covering nearly 15 million hectares. In Balochistan, karezes have historically supported rural livelihoods by providing reliable water supplies for agriculture and livestock.

However, seismic activity can significantly disrupt these systems. Earthquake-induced ground deformation may damage underground channels, reduce groundwater flow, and alter aquifer structures. As a result, many karezes in Balochistan have experienced declining water availability or complete failure.

One example is the Saro Valley in Kech district, where local communities rely heavily on the Saro Karez system for agriculture and livestock. The 1998 earthquake in the region caused substantial damage to the karez system, which subsequently contributed to prolonged water

scarcity and drought conditions between 1998 and 2002 (Ashraf et al., 2020; Sarfraz et al., 2013).

Such disruptions have forced many rural communities to abandon traditional irrigation systems and migrate to other areas in search of alternative water sources.

7. Discussion

The interaction between geological hazards and hydrological systems represents a critical environmental challenge for Pakistan. The country's location within the Himalayan collision zone makes it highly susceptible to tectonic activity, which can significantly influence both surface and groundwater resources. Earthquake-induced crustal deformation can alter river gradients, disrupt aquifer connectivity, and trigger landslides that reshape watershed morphology.

Historical geological evidence indicates that tectonic processes have played a major role in shaping the hydrological landscape of the Indus Basin. The diversion of the Sutlej River and the disappearance of the Sarasvati–Hakra river system demonstrate how tectonic deformation can fundamentally alter regional hydrology over long time scales. Such changes highlight the importance of integrating geological considerations into water resource management strategies. Seismic disturbances can also have immediate impacts on groundwater systems. Earthquakes often induce fluctuations in groundwater levels due to changes in aquifer permeability and subsurface pressure conditions. In arid regions such as Balochistan, where communities rely heavily on traditional karez irrigation systems, such disturbances can have severe consequences for agricultural productivity and water availability.

Furthermore, coastal seismic activity along the Makran subduction zone presents additional risks to marine and coastal hydrological systems. Tsunami events triggered by submarine earthquakes can lead to saltwater intrusion into freshwater aquifers, thereby degrading water quality and threatening coastal ecosystems (Mustafa et al., 2022).

The impacts of geological hazards are further exacerbated by climate variability and increasing water demand driven by population growth and agricultural expansion. Consequently, water resource management in Pakistan must adopt an integrated risk-based approach that accounts for both climatic and geological hazards.

Recent advances in geospatial technologies, remote sensing, and hydrological modeling provide valuable tools for monitoring geological processes and predicting their potential impacts on water systems. Integrating these technologies with disaster risk management frameworks can enhance resilience and improve long-term water security.

8. Conclusion

Pakistan's water resources are intrinsically linked to the country's geological and tectonic setting. The collision between the Indian and Eurasian tectonic plates has created a dynamic geological environment that influences the structure and functioning of regional hydrological systems. Evidence from historical records and geological studies indicates that seismic activity has played a significant role in shaping river systems, altering groundwater dynamics, and affecting traditional irrigation infrastructure.

Earthquakes and associated geological processes can disrupt water supply systems through river diversion, aquifer modification, and damage to irrigation networks such as karezes. These impacts can have far-reaching consequences for agriculture, water security, and rural livelihoods, particularly in arid and semi-arid regions.

Given the increasing pressures of climate change, population growth, and water scarcity, understanding the interactions between geological hazards and water resources is becoming increasingly important for sustainable development in Pakistan. Effective water resource management strategies should therefore incorporate geological risk assessments, strengthen

monitoring systems, and promote the protection and rehabilitation of traditional irrigation infrastructure.

Future research should focus on integrating geological, hydrological, and climatic data to improve predictive modeling of hazard impacts on water systems. Such interdisciplinary approaches will be essential for enhancing resilience and ensuring the sustainable management of water resources in tectonically active regions.

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