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Towards Sustainable Water Use in the Indus River Basin: Assessing Groundwater Dynamics, Environmental Flows, associated Controlling Factors and Management Options

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Summary

In many regions worldwide, intensive water abstractions are motivated by the attempt to enhance socio-economic development. Although this is often achieved in short-term consideration, high water abstraction rates, in the long run, pose a significant threat to water resources' sustainability. Moreover, it may raise concerns about existing water distribution treaties' viability and adversely affect the riverine ecosystems, especially in the transboundary basins. The Indus River Basin (IRB) is among such important transboundary basins, which is a lifeline for 268 million people living in the basin, where agriculture and the environment are the two significant water users, yet with contrasting objectives and effects. The water diversion for agricultural purposes has significantly disturbed the downstream flows and ecosystems, highlighting the necessity of sustainable water resource management, which requires balancing the agricultural and environmental needs in the IRB. Varied surface water allocations within the basin (legit by Indus Water Treaty-1960 & Water Apportionment Accod-1991) and high-water abstraction for agriculture are putting pressure on the groundwater storage changes and attainment of Environmental Flow (EFs) in the Indus Basin Irrigation System (IBIS) of Pakistan. Groundwater is crucial and serves as a buffer to sustain agriculture and ecological needs in the basin. Therefore, monitoring groundwater storage changes and environmental flows is essential to safeguard food production, conservation of the groundwater reserves and riverine ecosystems. However, assessing and monitoring groundwater storage changes in the IRB is challenging, mainly due to the limited and sparse distribution of observation wells and piezometers.

The Gravity Recovery and Climate Experiment (GRACE) satellite mission offers a novel avenue for studying groundwater storage changes on a large scale. However, its rather coarse spatial resolution has hindered its application for assessing groundwater storage changes at canal command areas of Irrigated Indus Basin in Pakistan. Consequently, enhancing the spatial resolution of groundwater storage through downscaling techniques becomes imperative. The main objectives of the dissertation were to (1) assess spatiotemporal groundwater storage changes and associated controlling factors such as climatic and anthropogenic at various spatial segregation levels (the knowledge gap), i.e., the basin, river reach, provinces using GRACE satellite information (1° x 1° latitudinal and longitudinal resolution at the equator), the Global Land Data Assimilation System (GLDAS) (1° x 1°), and the WaterGAP Hydrological Model data 0.5° x 0.5°; (2) improve GRACE resolution (0.05° x 0.05°) by introducing two steps downscaling method (methodological gap) using hydrological and land surface variables at canal command areas of the Indus Basin Irrigation System (IBIS) in Pakistan; (3) assess the EFs requirement using various hydrological methods in the rivers of the basin and evaluate the attainment of EFs within the IBIS after the apportionment of water among the provinces of Pakistan.

On a temporal scale, groundwater storage declined at an average rate of -0.64 mm per month (equal to 129 km^3 of groundwater abstraction over the study period from January 2003 to December 2016, whereas the annual inflow to IBIS is about 145 km^3. Spatially, the groundwater storage changes/depletion rates were high in Himachal Pradesh, Indian Punjab, and Haryana (ranging from -131 to -48.5 mm per month), while groundwater storage changes were rather mild for Pakistan Punjab (-48.5 mm to -20.3 mm per month) over the study period within the basin using GRACE and GLDAS datasets. The downscaled GRACE dataset (0.05°) using a novel two-step downscaling method revealed that groundwater was declining, ranging from -1.0 to -18.3 mm per year over the study period (2002-2020) in the canal command areas of IBIS of Pakistan, and 49.7% of the IBIS (2972 out of 5976 pixels at 0.05°) showed a significant declining trend ($p < 0.05$) dominant in the Punjab province compared with the Sindh province within IBIS of Pakistan.

The dissertation highlights the need to release enough discharge as EFs to conserve ecosystems and found that the Chenab, Ravi, and Sutlej Rivers of IRB are particularly vulnerable to the ecosystem as the estimated EFs were not attained during most of the months and seasons of the year during the study period. These findings underscore the urgent need to take appropriate measures for area-specific groundwater monitoring and for ensuring the release of required EFs for conserving the downstream ecosystems. The varied water allocations within the basin are the main controlling factors for groundwater depletion and attainment of EFs in the basin. The dissertation builds a foundation to consider groundwater depletion and EFs (missing aspects in water allocation treaties) to start and support a discussion on revisiting the Indus Water Treaty-1960 and Water Apportionment Accord-1991. The study contributes to the discussion within the scientific community but is also helpful for stakeholders from water management (water users, water administration) and policymakers to include groundwater depletions and EFs in the water allocations.

Keywords: Sustainable groundwater management, Varied Water Allocation and allowance, GRACE, Irrigated Indus Basin

Zusammenfassung

In vielen Regionen der Welt werden hohe Wasserentnahmen damit begründet, die sozioökonomische Entwicklung zu fördern. Obwohl dies oft bei kurzfristiger Betrachtung erreicht wird, stellen jedoch hohe Wasserentnahmen langfristig eine erhebliche Gefährdung für einen nachhaltigen Umgang mit den vorhandenen Wasserressourcen dar. Dies kann zur Folge haben, dass bestehende Verträge zur Wasserverteilung in Frage gestellt und Fließgewässer sowie angrenzende Ökosysteme geschädigt werden, insbesondere in grenzüberschreitenden Einzugsgebieten. Das Einzugsgebiet des Flusses Indus (IRB) ist eines der wichtigen grenzüberschreitenden Einzugsgebiete. Der Indus ist eine Lebensader für 268 Millionen Menschen, wobei die Wassernutzungen für die Landwirtschaft und die Umwelt von großer Bedeutung sind, allerdings mit unterschiedlichen bzw. sogar konträren Zielsetzungen. Die Ableitung von Wasser für landwirtschaftliche Zwecke hat die Abflüsse im Unterlauf des Indus stark vermindert und Ökosysteme erheblich gestört, was die Notwendigkeit einer nachhaltigen Bewirtschaftung der Wasserressourcen und eines Ausgleichs zwischen den Bedürfnissen der Landwirtschaft und der Umwelt im Einzugsgebiet unterstreicht. Unterschiedliche Zuteilungen von Oberflächenwasser innerhalb des Einzugsgebiets (legitimiert durch: Indus Water Treaty von 1960 und dem Water Apportionment Accord von 1991) und die hohen Wasserentnahmen für die Landwirtschaft erhöhen den Druck auf Grundwasserspeicheränderungen und das Einhalten ökologisch notwendiger Abflüsse (ökologischer Mindestabfluss; Environmental Flow, EF) im IRB aus. Als Ressource und ausgleichender Speicher ist das Grundwasser von entscheidender Bedeutung für die Bewässerungslandwirtschaft und den Erhalt der ökologischen Bedürfnisse im Einzugsgebiet. Daher ist das Monitoring von Änderungen der Grundwasserspeicherung und der ökologischen Mindestabflüssen von wesentlicher Bedeutung für die Sicherung der Nahrungsmittelproduktion, die Erhaltung der Grundwasserreserven und Flussökosysteme. Das Erfassen und Bewerten von Grundwasserspeicheränderungen im IRB ist jedoch eine Herausforderung, vor allem wegen der begrenzten Anzahl und unzureichenden Anordnung von Beobachtungsbrunnen und Piezometern.

Die Satellitenmission GRACE (Gravity Recovery and Climate Experiment) bietet eine weitere Möglichkeit zur Untersuchung von Veränderungen der Wasserspeicherung in großem Maßstab. Die beschränkte räumliche Auflösung hat jedoch bisher die Anwendung für die Bewertung von Veränderungen der Grundwasserspeicherung in den Versorgungsgebieten von Kanälen im bewässerten Indus-Einzugsgebietes in Pakistan behindert. Folglich ist eine

Verbesserung der räumlichen Auflösung zur Erfassung der Grundwasserspeicherung durch Downscaling-Verfahren unumgänglich. Die Hauptziele der vorliegenden Dissertation waren: (1) die Bewertung raum-zeitlicher Veränderungen der Grundwasserspeicherung und der damit verbundenen Einflussfaktoren, wie Klima und anthropogene Einflüsse, auf verschiedenen räumlichen Ebenen (derzeitige Wissenslücke), d.h. Einzugsgebiet, Flussabschnitt und Provinzen - unter Verwendung von GRACE-Satelliteninformationen (Auflösung 1° x 1° geografische Länge und Breite am Äquator), dem Global Land Data Assimilation System (GLDAS) (1° x 1°) und den Daten des großskaligen hydrologischen Modells WaterGAP (0.5° x 0.5°); (2) Verbesserung der GRACE-Auflösung (auf 0,05° x 0,05°) durch Einführung einer zweistufigen Downscaling-Methode (derzeitige methodische Lücke) unter Verwendung von hydrologischen Variablen und Kenngrößen zur Landoberfläche sowie -nutzung in den Versorgungsgebieten der (Haupt-)Kanäle des Indus-Basin-Bewässerungssystems (IBIS) in Pakistan; (3) Abschätzung der ökologisch notwendigen Mindestabflüsse in den wichtigen Flüssen des Indus-Einzugsgebiets und Bewertung der Erreichung dieser Mindestabflüsse innerhalb des IBIS nach der Aufteilung des Wassers auf die Provinzen Pakistans.

In zeitlicher Hinsicht ging der Grundwasserspeicher von Januar 2003 bis Dezember 2016 mit einer durchschnittlichen Rate von 0,64 mm pro Monat zurück (dies entspricht einer Grundwasserentnahme von 129 km^3 im Untersuchungszeitraum, während der jährliche Zufluss zum IBIS 145 km^3 betrug). In dieser Zeit waren die Grundwasserspeicheränderungen räumlich unterschiedlich stark ausgeprägt: während die Änderungsraten in Himachal Pradesh, dem indischen Punjab und Haryana verhältnismäßig hoch waren (zwischen -131 und -48,5 mm pro Monat), waren diese im pakistanischen Punjab mit -48,5 mm bis -20,3 mm pro Monat eher gering ausgefallen. Der mit der neuartigen zweistufigen Downscaling-Methode skalierte GRACE-Datensatz verdeutlicht, dass die Grundspeicherung im IBIS tendenziell abnimmt; ein signifikanter Abwärtstrend ($p < 0,05$) konnte für 50 % der Fläche des IBIS (2972 von 5976 Pixeln bei 0,05°) erkannt werden, mit einem größeren Anteil der Provinz Punjab im Vergleich zur Provinz Sindh.

In der Dissertation wurde die Notwendigkeit der Einhaltung von ökologischen Mindestabflüssen hervorgehoben. Es konnte festgestellt werden, dass die Ökosysteme der Flüsse Chenab, Ravi und Sutlej des IRB besonders gefährdet sind, da die als notwendig abgeschätzten ökologischen Mindestabflüsse in den meisten Monaten und Jahreszeiten innerhalb des Untersuchungszeitraum nicht erreicht wurden. Diese Ergebnisse unterstreichen die dringende Notwendigkeit, geeignete Maßnahmen für eine Grundwasserüberwachung mit hoher räumlicher Auflösung zu ergreifen und die Einhaltung der ökologisch erforderlichen Mindestabflüsse zum Schutz der flussabwärts gelegenen Ökosysteme sicherzustellen. Die unterschiedliche Verteilung von Wasser an die Nutzer (vor allem Bewässerung) innerhalb des Einzugsgebietes sind die Haupteinflussfaktoren für die Verminderung der Grundwasserressourcen und die Gefährdung ökologischer Mindestabflüsse im Einzugsgebiet. Die Arbeit schafft eine Grundlage zur Ergreifung von Maßnahmen für eine nachhaltige Bewirtschaftung der Grundwasserressourcen und zur Sicherung ökologischer Mindestabflüsse. Die Ergebnisse der Arbeit sollen den Beginn von Diskussionen stimulieren und unterstützen, damit die wichtigen Verträge zur Regelung der Allokation von Wasserressourcen (Indus Water Treaty von 1960 und dem Water Apportionment Accord von 1991) so überarbeitet werden, dass Grundwasserressourcen nachhaltig bewirtschaftet und ökologische Mindestabflüsse eingehalten werden.. Die Studie trägt zur Diskussion innerhalb der wissenschaftlichen Gemeinschaft bei, ist aber auch hilfreich für Interessenvertreter aus der Wasserwirtschaft (Wassernutzer, Wasserverwaltung) und politische Entscheidungsträger.

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Chapter 1

Introduction

1 Introduction

International water treaties among upper and lower riparians significantly shape water allocation and use in transboundary river basins (Yang et al. 2014). These treaties continue to serve their purpose of governing water resources and providing a framework for cooperation, negotiation, and avoidance or the resolution of conflicts related to water sharing between upper and lower riparians (Kalair et al. 2019). However, it is important to recognize that these treaties may have missing aspects or areas (Kamran et al. 2017) that require further attention. For example, climate change (Qamar et al. 2019), groundwater dynamics (Mittha 2021), and environmental flows (E-flows) are not addressed in shaping the surface water allocations in the transboundary Indus River basin (IRB). The varied surface water allocations within the basin exacerbate the dynamics of groundwater depletions and E-flow attainments (Zawahri & Michel 2018) in the IRB. This research addresses missing aspects and identifies controlling factors that impact groundwater dynamics and E-flows within the context of the Indus Water Treaty (IWT)-1960 and the Water Apportionment Accord (WAA)-1991.

1.1 Background

The transboundary Indus River basin covers an area of around 1.12 million km^2, which is shared among Pakistan (47%), India (39%), China (8%), and Afghanistan (6%) (Frenken 2012). The Indus River originates on Tibetan Plateau near Mount Kailash in Tibet and flows into the Arabian Sea, with a length of about 3000km (Archer et al. 2010). The main tributaries of the IRB are the Indus, Jhelum, Chenab, Ravi, Sutlej, Bias, and the Kabul River (Iqbal Abdul Rauf 2013) as shown in Figure 1.1.

Historically, inundation canals, used during periods of high river flow as part of irrigated agriculture, serve as the basis for the development in the IRB and the 4,000-year-old Indus civilization. However, in 1859, the Upper Bari Doab Canal (UBDC) was completed, marking the beginning of the canal irrigation development (Jurriens et al. 1996). Subsequently, the Sirhind Canal, Sidhnai Canal, Lower Chenab, and Lower Jhelum Canals were constructed, along with other canals in Khyber Pakhtunkhwa, between 1872 and 1914 (Frenken 2012). By the early 1900s, it became evident that the water resources of individual rivers in the Indus Basin were unevenly distributed in relation to potential irrigable land. The Triple Canal Project (Farooq & Bhatti 2018) was implemented between 1907 and 1915 to address this issue. This project interconnected the Jhelum, Chenab, and Ravi rivers, enabling the transfer of surplus water from the Jhelum and Chenab rivers to the Ravi river (Frenken 2012). The Triple Canal Project marked a significant milestone in integrated inter-basin water resource management and served as a conceptual basis for the (later) resolution of the Indus waters dispute between upper riparian (India) and lower riparian (Pakistan) in 1960 through the Indus Waters Treaty. Additional developments took place, including the completion of the Sutlej Valley Project in 1933; the construction of the Sukkur barrage and its canal system; the completion of the Haveli, Rangpur, and Thal Canals (Malik 2005). The irrigation system inherited by Pakistan in 1947 encompassed the Indus Basin Irrigation System (IBIS), the largest contiguous irrigation system globally. The division of the irrigation system between India and Pakistan during independence led to an international water dispute in 1948, which was resolved with the signing of the Indus Waters Treaty in 1960 under the auspices of the World Bank (Zawahri & Michel 2018).

Under the IWT-1960, the eastern rivers (Ravi, Sutlej and Beas) were given to upper riparian while the western rivers (Indus, Jhelum, Chenab) were given to lower riparian (World Bank 1962). Subsequently, the Indus Basin Project (IBP) was implemented in accordance with the Indus Waters Treaty, which included the construction of the Tarbela Dam on Indus river, five barrages, inter-river link canals, and Mangla Dam (on Jhelum River) for diverting water from western rivers to irrigate areas of eastern rivers (as these rivers were given to upper riparian). The main advantage of the treaty is that both nations were able to share the water of IRB. Yet, the drawback is that instead of dividing the waters of the rivers and allocating water for E-flows, the rivers were divided. After partition of sub-continent, Kotri, Taunsa, and Guddu barrages were constructed on the Indus River, providing controlled irrigation to areas previously served by inundation canals in Pakistan. The Taunsa barrage, completed in 1958, facilitated irrigated agriculture in approximately 1.18 million hectares of arid landscape in the Punjab province. Pakistan's water apportionment accord was signed in 1991 to distribute surface water among the provinces (IRSA 1991). As a result of significant developments, Pakistan now possesses the world's largest contiguous irrigation system, covering a vast area of 14.87 million hectares. This system is primarily supported by three major reservoirs: Tarbela, Mangla, and Chashma. It includes 23 barrages, headworks, and siphons as well as 12 inter-river link canals and 45 canal commands (Frenken 2012). Since the implementation of the Indus Water Treaty in 1960 and the Water Apportionment Accord in 1991, the irrigation system has undergone significant development. However, this progress has had adverse effects on the groundwater levels and the attainment of Environmental Flows (E-flows) in the basin. The variable water allocation has contributed to groundwater depletion, as certain regions may receive more water for irrigation, leading to overexploitation of groundwater resources. As a consequence, maintaining sufficient E-flows to support the ecological health of the basin has become a challenging task and persistent threat for the health of IRB.

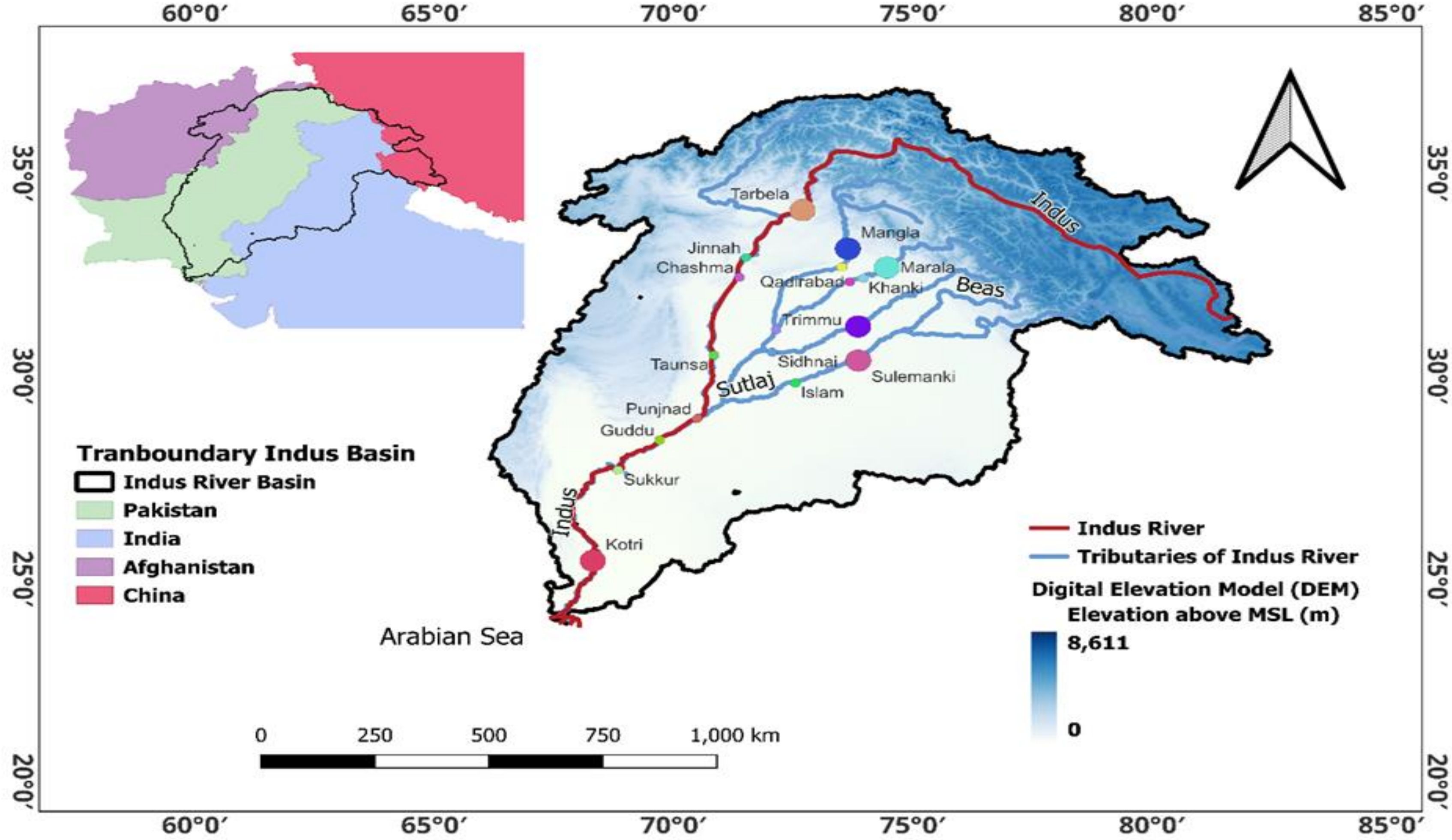

Figure 1.1. Transboundary Indus River basin with its tributaries and major hydraulic structure on each river

There is a serious threat to the integrity of the Indus Basin regarding water governance, management, and usage of its water due to its complex, diversified hydrology and geopolitical nature (Cheema & Qamar 2019).The main drivers mainstreaming the economy of the basin are currently agriculture (its contribution to Gross Domestic Product is 25%) (Janjua et al. 2021) and industry. The already sharp competition among the major users i.e. agriculture, industry, domestic and ecology (represented by E-flows), is rising due to intensification in agriculture, population growth, population migration to the cities and water distribution agreements in the basin which are insufficiently considering the current situation. Exponentially growing population (Amin et al. 2018; Zawahri & Michel 2018), constant or declining agricultural and crop productivity, high dependence on groundwater (Saeed et al. 2021), climate change & unplanned urban growth are the bitter challenges of the Indus River Basin.

Snow & glacier melt and rainfall in the monsoon season are the main sources of water in the IRB. There is an increase in runoff due to glacier melt in the short or mid-term, yet once (as expected in the middle of this century), glacier mass will be clearly declined (Archer et al. 2010) and their 'buffer' function in the hydrological system will be reduced and therefore, the basin is highly vulnerable to climate change (Shrestha et al. 2019). The role of water-sharing agreements in mitigating or exacerbating the response of the Indus River Basin to climate change is largely unknown (Yang et al. 2014). Due to climate change and anthropogenic activities, it is expected that there will be an increased risk of freshwater security. The reduction in water quality and quantity will likely increase tension among water users (Lee et al. 2018).

Pakistan, an already water-stressed country, will become increasingly water stressed when comparing withdrawals of water to runoff (standing for a renewable share of water resources) and per capita water availability along with projected population growth in the country (Archer et al. 2010). Pakistan's population was growing fast from 40 million in 1950 to 204 million in 2017 and the population is expected to increase between 238 and 314 million by 2050 (UN 2019). The water availability per person per year is declining at an alarming rate due to this high population growth (Cheema & Qamar 2019). It was reported that per capita water availability declined by 400 % as there was 5,260 m^3 of water available per person per year in the early 1950s declined to 1,040 m^3 in 2010. Assuming the continuous constant population growth, it has been estimated that the per capita water availability will amount to 725 m^3 by 2025 and decline further to 415 m^3 by 2050, as indicated in the study conducted by Archer et al. (2010).

The sustainability of Indus Basin water resources in the long run is closely intertwined with various factors, including climate change, population growth, sustainable use of groundwater and longevity of riverine ecosystems. These drivers play a significant role in determining the future viability of the basin's water supply and its sustainable use. However, amidst these challenges, one crucial aspect to consider is the need for environmental flows to preserve the aquatic and interconnected ecosystems within the basin. By ensuring and allocating a minimum amount of water to sustain the natural environment, we can help safeguard the delicate balance of the ecosystem. Moreover, the sustainability of existing water distribution agreements, such as the Indus Waters Treaty of 1960 and the Water Apportionment Accord of 1991, becomes even more critical, particularly under constantly declining of groundwater and non-attainment of E-flows in the basin. Effective groundwater management can help ensure the availability of water resources in the long term while preserving the ecological balance of the surrounding environment. The storage capacity of Indus Basin groundwater aquifer is at least 80 times the storage capacity of major dams in Pakistan (Lytton et al. 2021) and damming the rivers leads to non-attainment of E-flows, biodiversity loss in the basin. The groundwater could provide buffer to meet crop water requirement for food production against unreliability of surface water supply and leaving water for ecological needs of the rivers against the odds of climate change, population growth, and snow and glacier receding. Therefore, it is crucial to prioritize groundwater management over damming rivers for food production to ensure the long-term sustainability of highly political agreements i.e., IWT-1960 and WAA-1991.

1.2 Problem Statement

Groundwater supply is considered the backbone for the subsistence of Pakistan's agriculture. Around 40 to 60% of the crop water requirement is met through groundwater in Punjab, the largest food-producing province of Pakistan (Kazmi et al. 2012a). However, the uncontrolled and unregulated application of groundwater to irrigated fields is posing serious threats and challenges to water resources (Shah et al. 2003). Consequently, the excessive use of groundwater is the main cause of declining of the water table in the canal commands area (CCA) of Punjab and Sindh (Sarwar & Eggers 2006; Kazmi et al. 2012b). The water table decline is accompanied by groundwater quality deterioration which is caused by agricultural activities (for example leaching of fertilizers) and industry as well as settlement leading to a reduction in crop yields (Shah et al. 2003) and endangering to provide drinking water for the population in sufficient amount and appropriate quality.

In the Indus Basin, the overall water supply from groundwater has increased by 60% since 1960 as fresh aquifer systems are continuously pumped to meet the growing domestic and agricultural water demands (Qureshi et al. 2010; Lytton et al. 2021). Therefore, the groundwater aquifer system must be carefully assessed through critical long-term analysis of the groundwater storage changes (GWCs) to build a baseline for sustainable groundwater management. Observation wells and/ piezometers could monitor groundwater storage changes in the region. However, ground-based observations are expensive, limited and sparsely located, especially in IRB, so groundwaters cannot be thoroughly monitored at different spatial levels (basin, reaches, regions and canal command area). In particular, the limited network of observation wells reduces the understanding of the water cycle (Lin et al. 2019; Mahmood et al. 2020). Policymakers and researchers believe that because there is a lack of in situ observations, groundwater regulation and the adoption of area-specific management strategies are severely compromised for effective groundwater management. Due to subsequent development in the transboundary Indus Basin, it is imperative to monitor the groundwater storage changes at the basin level as the water distribution in IRB is administered under the Indus Water Treaty 1960 at the international level (World Bank 1962). Administrative regulations to manage surface water are implemented province-wide under the Water Apportionment Accord 1991 at the national level (IRSA 1991). Therefore, in addition to basin-scale studies, it is imperative to investigate the groundwater monitoring at the regional (provincial) level to provide management options for each management unit. Due to the heterogeneity that exists among different reaches of IRB in terms of topography, land use, climate and agroecological conditions, and surface water distribution quotas, IRB was further divided into three reaches (i.e., upper, middle, and lower). Due to the heterogeneities, there is considerable variability in the socio-economic conditions of the above-mentioned reaches. Therefore, hypothetically, human and natural controlling factors do vary among these reaches. In this regard, it is imperative to examine the groundwater storage changes both in space and time at the reach level in IRB. In the Chapter 2 (knowledge gap), the groundwater dynamics at three tier levels (TTLs), i.e., the basin, river reach, and region (provincial), using Gravity Recovery and Climate Experiment (GRACE) satellite information (1° x 1°) and Global Land Data Assimilation System (GLDAS) are investigated to explore their implications on regional water resources management.

The allocation of water within the IBIS of Pakistan is made based on water allowance (WA) i.e. the amount of water allowed in cusec (ft^3/sec) to each canal command per 1000 acres. Water allocations for canal commands are not uniform and water allowance differs from 2.5 to

15 cusec per 1,000 acres (i.e. 0.18 – 1.1 lps/hectare) for various canal commands throughout Irrigated Indus Basin of Pakistan (Cheema et al. 2016) as shown in Figure 1.2. Monitoring groundwater storage changes in each canal at the command area level is limited and challenging due to the sparse distribution of observation wells and the coarse resolution of GRACE datasets (Miro & Famiglietti 2018). Therefore, downscaling approaches are needed to improve GRACE dataset's spatial resolution, which provide high-resolution data (0.05°) for decision-makers to manage water resources at canal command areas level (Miro & Famiglietti 2018), and to make an informed decision about groundwater abstraction and allocations. In chapter 3 (knowledge and methodological gap), a two-step downscaling technique is introduced to (i) increase performance in applications of downscaled datasets (ii) reduce noise and artifacts in the output i.e., Groundwater Storage Anomalies (GWSA) for effective groundwater management.

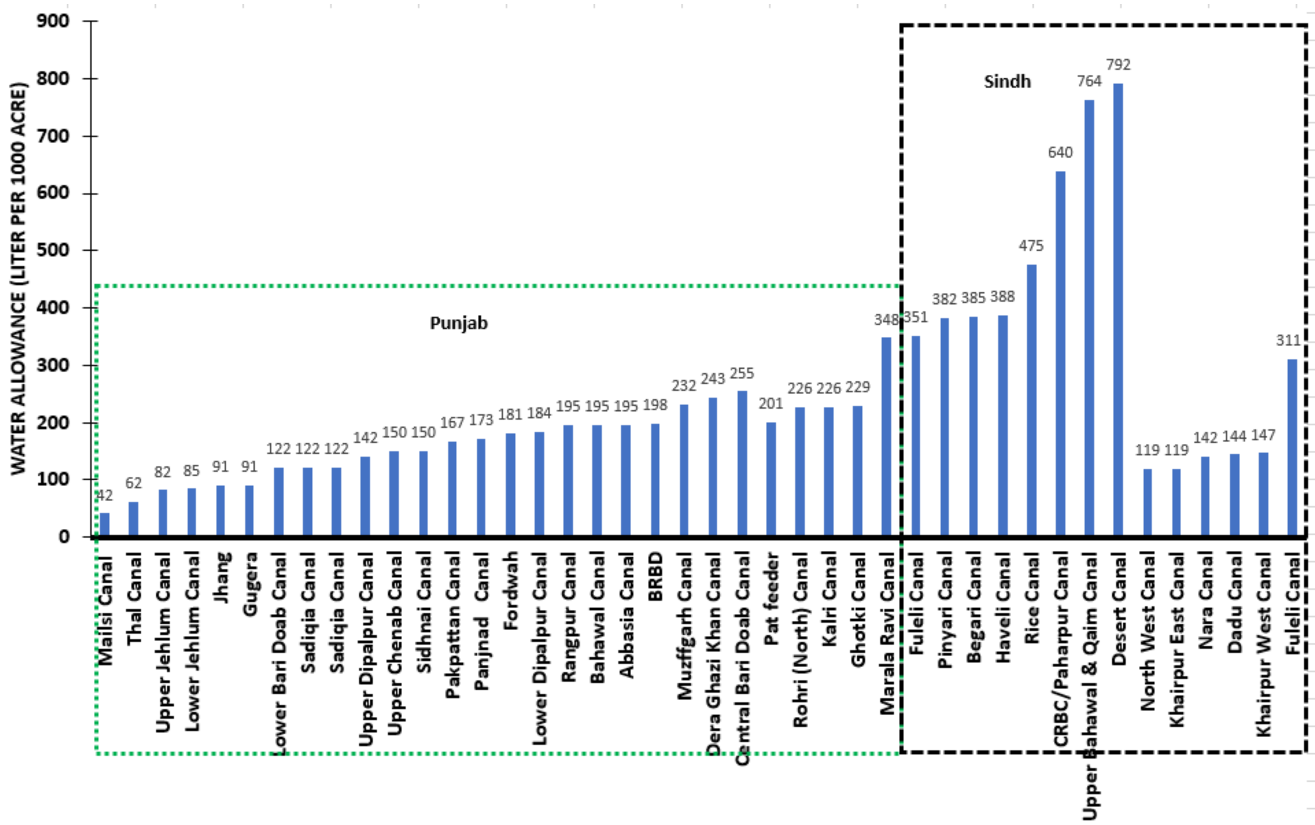

Figure 1.2. Variable water allowance in canal commands of Irrigated Indus Basin

Apart groundwater monitoring, provision of environmental flow helps in sustaining the water resources and freshwater biodiversity (Pander et al. 2019), longevity and functioning of riverine ecosystem. Dams and barrages serve as the primary source of irrigation water during the Kharif (summer: April to September) and Rabi (winter: October to March) seasons and have contributed significantly to irrigation-based food production in Pakistan. Yet, they have also created environmental flow issues. Boon and Raven (2012), Syvitski et al. (2013), and Qureshi et al. (2003) reported a reduction in downstream flows of the Indus River and its tributaries due to modification and/ or addition of dams and barrages in the system during the 19^{th} and 20^{th} century and the natural flow reductions up to 90 % reported in the IRB (Giosan et al. 2006). The partition of water resources between upper riparian and lower riparian via the IWT-1960, as well as within the provinces of Pakistan via the Water WAA-1991, has resulted in a notable decrease and modification of natural hydrological processes. The modification in the characteristics of the Indus and its tributaries significantly impacted the downstream flows, spread, and range of biodiversity (Syvitski et al. 2013), and this impact posed a persistent threat to ecosystems. The various water agreements recognize the importance of environmental flows such as the water apportionment accord-1991(IRSA 1991), the national policy on Climate change-2012 (Ministry of Climate Change 2012) and the national wetland policy-2007 (Arshad et al. 2012). However, the decision of how much amount of water is to be released downstream of Kotri Barrage (the most downstream barrage) is deferred to further studies (Anwar & Bhatti 2017a). In this dissertation, knowledge gap is filled by estimating E-flows and examining the existing situation of E-flows whether these are being met after the apportionment of water among provinces of Pakistan in 1991 (WAA-1991) and IWT-1960 when the flows for different rivers, canal commands, upper riparian, lower riparian and provinces were established and guaranteed. The identified knowledge and methodological gap are shown in Table 1.1.

1.3 Dissertation aim and research questions

The dissertation addresses the missing aspects in the water agreements, and builds upon the foundation to consider groundwater depletion and E-flows to achieve sustainability of the Indus Water Treaty-1960 and the Water Apportionment Accord-1991. It emphasizes the significance of releasing water for the environment along with the diversion of surface water for agriculture.

1.3.1 Specific objectives and Research Questions

The specific objectives of the dissertation were defined and each objective corresponds to a separate chapter:

Objective 1. To estimate the spatio-temporal dynamics in groundwater storage changes at spatial segregation levels, including basin-wide, specific river reaches, and provincial scales utilizing GRACE satellite data **(Chapter 2)**

Objective 2. To improve GRACE resolution for estimation of spatio-temporal dynamics in groundwater changes at canal command areas of Irrigated Indus Basin **(Chapter 3)**

Objective 3. To assess E-flows in the Indus Basin using hydrological methods and examine the attainment of E-flows within the IBIS of Pakistan **(Chapter 4)**

Research Question 1. How do groundwater dynamics vary at different spatial scales (basin, river reach, and provincial level), and what are their implications for regional water resources management?

Research Question 2. What are the key controlling factors, both climatic and anthropogenic, that influence groundwater dynamics at each spatial level, and how can they be effectively managed to mitigate vulnerability?

Research Question 3. How can the two-step downscaling approach effectively downscale groundwater storage change data from a coarse resolution of 0.5° x 0.5°to a finer resolution of 0.05° x 0.05°?

Research Question 4. What are the patterns and trends of groundwater depletion in the canal commands of the Irrigated Indus Basin when using the downscaled groundwater storage change data?

Research Question 5. What is the prescribed minimum requirement of E-flow at the uppermost structures on each river and below Kotri Barrage?

Research Question 6. How does the E-flow vary across different rivers and months of the year? Are the estimated Environmental Flow Requirements (EFRs) at each hydraulic structure being met on a daily, monthly, seasonal, and annual scale?

Table 1.1 Matrix of identified knowledge and methodological gap

Research Questions	Gap 1 Understanding of groundwater dynamics and their implications at different scales.	Gap 2 Identification of controlling factors impacting groundwater dynamics and management strategies.	Gap 3 Development of a two-step downscaling approach for finer spatial resolution estimation of groundwater storage change data.	Gap 4 Knowledge of prescribed minimum Environmental Flow Requirements (EFRs) at specific locations.	Gap 5 Understanding of variations in E-flow across rivers and time periods.
How do groundwater storage changes vary at spatial segregation levels?	X				
What are the key controlling factors, both climatic and anthropogenic, that influence groundwater dynamics at each tier level?		X			
How can the two-step downscaling approach effectively downscale groundwater storage change data from a coarse resolution of 0.5° to a finer resolution of 0.05° x 0.05°?			X		
What is the prescribed minimum requirement of E-flow at the uppermost structures on each river and below Kotri Barrage?				X	
How does the environmental flow vary across different rivers and months of the year? Are the estimated EFRs at each hydraulic structure being met daily, monthly, seasonal, and annual?					X

1.4 Dissertation Structure

This dissertation comprises five distinct yet interconnected chapters.

Chapter 1 delves into the development of the irrigation system in Pakistan and the associated challenges faced by the basin. It also identifies the problem in the Indus River Basin and highlights existing knowledge and methodological gaps concerning the understanding of groundwater depletions and E-flows in the Indus Basin.

Chapter 2 addresses objective number 1 and encompasses research questions (1 and 2) that underscore the significance of groundwater monitoring for the Indus Basin at various spatial levels, along with the factors that influence it. This section presents methodologies employed to monitor groundwater storage changes using GRACE satellite and global datasets. Additionally, it identifies controlling factors and management options at each spatial level to effectively conserve groundwater resources in the basin.

Chapter 3 tackles objective number 2 (research questions 3 and 4), focusing on the importance of groundwater monitoring in the canal areas of the Irrigated Basin of Pakistan. Here, a two-step downscaling approach is introduced to downscale GRACE datasets (0.5° x 0.5°) to a higher spatial resolution (0.05° x 0.05°) at the canal command area. Water deficit is calculated for each canal command area, and groundwater depletions are compared with water allowances to gain insights into groundwater variations in the irrigated Indus Basin.

Chapter 4 takes on objective number 3 and addresses research questions (5, 6) aimed at estimating E-flows using various hydrological methods. These methods include flow duration curve shifting, flow duration curve analysis, low flow indices, the Tennant method, the Smakhtin approach, the Tessman method, and the Pastor method. The estimation is carried out at six locations within the Indus Basin to explore the relative contribution of each river in fulfilling the EFRs. Furthermore, the estimated E-flows are compared with the downstream flows at each location to assess the attainment of E-flows in the basin.

Chapter 5 provides a comprehensive summary of the results from chapters 2 to 4. Additionally, it offers a generalized discussion of the findings, strengths, and limitations of the dissertation. This section also presents an outlook and the implications of the study for further research activities, along with recommendations tailored for policymakers and stakeholders.

1.5 Dissemination

The dissertation findings in Chapter 2 were disseminated through a research article published in a reputable scientific journal, while the findings in Chapter 3 were presented as a poster at a prestigious academic conference. The findings from Chapter 4 were presented through a conference talk at a conference. Details are given below in Table 1.2 and Table 1.3:

Table 1.2 Dissemination of chapters in SCI Journals

Chapter	SCI Journal	Impact Factor	Title	Status
2	Water	3.4	Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin	Published
3	International Journal of Applied Earth Observation and Geoinformation	7.6	Downscaling GRACE to monitor groundwater changes at the Canal Command area level of Irrigated Indus Basin	Submitted
4	Ecohydrology	2.6	Analyzing and Evaluating Environmental Flows through Hydrological Methods in the Regulated Indus River Basin	Published

Table 1.3 Dissemination of chapters in conferences

Chapter	Conference Proceedings	Status
3	Mehmood, K.; Bernhard, T.; Flörke, M.; Akhtar, F. Improving and Evaluating GRACE Resolution Using Geographical Weighted Regression. In Proceedings of the Sustain Valencia 2022.Achieving Sustainable Groundwater Management: Promising Directions and Unresolved Challenges; Gomez-Hernandez, J.J., Butler Jr., J.J., Eds.; Valencia, 2022; p. 75.	Poster presentation
4	Preliminary Assessment of Environmental Flows in the Indus River Basin and Vulnerability of downstream ecosystems **Conference:** GEO BON Global Conference: Monitoring Biodiversity for Action, October 10-13 2023, Montreal-Canada	Conference talk

Chapter 2

Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin

This chapter has been published as:

Mehmood, K.; Tischbein, B.; Flörke, M.; Usman, M. Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin (2022). Water, 14, 3254. https://doi.org/10.3390/w14203254

2 Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin

2.1 Abstract

Intensive groundwater abstraction has augmented socio-economic development worldwide but threatens the sustainability of groundwater resources. Spatiotemporal analysis of groundwater storage changes is a prerequisite to sustainable water resource management over river basins. To estimate the groundwater storage changes/anomalies (GWCs) in the Indus River Basin (IRB), where observation wells are sparse, Gravity Recovery and Climate Experiment, the Global Land Data Assimilation System, and the WaterGAP Hydrological Model data were employed. The groundwater storage changes and controlling factors were investigated at three tier levels (TTLs), i.e., the basin, river reach, and region, to explore their implications on regional water resource management and provide management options at each level. Overall, the IRB groundwater declined from January 2003 to December 2016, with a relatively higher rate during 2003–2009 than during 2010–2016. Spatially, according to a reach-specific analysis, 24%, 14%, and 2% of the upper, middle, and lower reaches of the IRB, respectively, were indicated by a 'severe groundwater decline' over the entire period (i.e., 2003–2016). The GRACE-based GWCs were validated with in situ data of two heterogeneous regions, i.e., Kabul River Basin (KRB) and Lower Bari Doab Canal (LBDC). The analysis showed a correlation (R^2) of 0.77 for LBDC and 0.29 for KRB. This study's results reveal those climatic variations (increase in evapotranspiration); anthropogenic activities, i.e., pumping for irrigation; and water allocations in these regions mainly drive the groundwater storage changes across the Indus Basin.

2.2 Introduction

According to global estimates, approximately 43,000 km^3 of renewable freshwater resources are being fed to rivers, lakes, and aquifers annually, among which 70% is consumed by agriculture, 19% by industry, and 11% by households (Kinzelbach et al. 2003; FAO, 2012). Presently, 38% of the global irrigated area (i.e., 307 million hectares) is contingent on groundwater (Siebert et al. 2010). In the Indus River Basin (IRB), where canal water supplies are unreliable and insufficient, groundwater is used independently or in conjunction with surface water. As irrigation in this region is sourced mainly from groundwater (Cheema et al. 2014; Usman et al. 2020), the IRB aquifer is on the brink of an alarming water crisis due to large-scale groundwater extraction (Lytton et al. 2021). Therefore, the basin's sustainability requires proper water governance, management, and usage, especially given the complex, diversified hydrology and geopolitical nature of IRB. The key drivers of the basin's economy are agriculture and industry. Competition among the primary users (agriculture, industry, domestic, and the environment) is spiraling as agriculture intensifies, the population grows, and people migrate to the cities (Cheema et al. 2014). Over the past several years, the continuously varying climate conditions and expansion of agricultural lands have altered the crop irrigation requirements, placing new demands on surface and groundwater resources (Arfan et al. 2019; Sun et al. 2019). Consequently, the groundwater resources in IRB have been overexploited (Watto 2015).

In the Indus Basin, the overall water supply from groundwater has increased by 60% since 1960 as fresh aquifer systems are continuously pumped to meet the growing domestic and agricultural water demands (Qureshi et al. 2010; Lytton et al. 2021). Therefore, the groundwater aquifer system must be carefully assessed through critical long-term analysis of the groundwater storage changes (GWCs). Such an assessment builds a baseline for sustainable water use and its management. Ground-based measurement could provide a best estimate of changes in groundwater storage. However, ground-based observations are expensive and limited on spatial and temporal scales, especially in IRB, so groundwaters cannot be thoroughly monitored at different levels (regions and reaches). In particular, the limited network of observation wells reduces the understanding of the water cycle (Lin et al. 2019; Mahmood et al. 2020). Policymakers and researchers believe that because there is a lack of in situ observations, groundwater regulation and the adoption of area-specific management strategies are severely compromised, especially under the effects of climate change (Young.W.J et al. 2019). To address these issues, many researchers are observing groundwater storage variations in real time by remote sensing observations supported by land-hydrological models at global and regional scales (Cheema et al. 2014; Yin, Han, et al. 2020; Liu et al. 2021). For example, Cheema et al. (2014) employed satellite-based evapotranspiration (ET) and precipitation (P) data in the process-based Soil and Water Assessment Tool and estimated the groundwater depletion in the irrigated Indus Basin. Since the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite, groundwater storage variations have been observed at different spatial and temporal scales (Rodell et al. 2009) and the WaterGAP v2.2d Hydrological Model (WGHM) has emerged as a robust and qualitatively high-performing dataset of groundwater variations. The temporal changes in gravity observed by twin satellites reflect the changes in terrestrial water storage (TWS) (H. Chen et al. 2019). TWS, obtained by summing the groundwater, snow water equivalent (SWE), soil moisture (SM), and surface water storage, represents the water stored above and underneath the Earth's surface (Tapley et al. 2004). Therefore, to isolate GWCs from TWS estimated by GRACE, water storage components must be subtracted from other auxiliary datasets of hydrological models. Many researchers have already combined GRACE data with land-hydro models to study the inter-annual changes in TWS and GWCs over the Indus Basin (Iqbal et al. 2016; Iqbal et al. 2017; Tang et al. 2017) and other aquifer systems around the globe (Papa et al. 2015; Ghebreyesus et al. 2016; Fallatah et al. 2017; Huang et al. 2019; Verma & Katpatal 2019; Moghim 2020; Srivastava & Dikshit 2020). However, most of these studies analyzed TWS and GWC variations on the catchment scale; a comprehensive evaluation of GWCs over the Indus Basin is lacking at different tier levels, i.e., the basin, river reach, and region. Normally, TWS and GWC variations are mainly caused by the combined effect of climate variability and human interventions (Li et al. 2020). Climatic parameters, i.e., precipitation (P), runoff (R), evapotranspiration (ET), and glacier recession, are influential factors of the changes in TWS and GWC (Yu Zhu, Shiyin Liu, Ying Yi, Miaomiao Qi, Wanqiu Li & Wu 2020). Anthropogenic activities, i.e., groundwater abstraction, land use, and irrigation, also impact TWS and GWCs in populated areas (Huang et al. 2015). Hence, it is important to investigate GWC and its controlling factors in IRB to ensure sustainable development of the basin as a whole. The water management in IRB is administered under the Indus Water Treaty 1960 at the international level (World Bank 1962), and administrative regulations are implemented province-wide under the Water Apportionment Accord 1991 at the national level (IRSA 1991). Therefore, in addition to basin-scale studies, it is imperative to investigate the spatiotemporal dynamics of groundwater and its controlling factors at the regional (provincial) level to provide management options for each management unit. Due to the heterogeneity that exists among different reaches of IRB in terms of topography, land use, climate and agroecological conditions, and surface water distribution quotas, IRB was divided into three reaches (i.e., upper, middle, and lower). Due to these heterogeneities, there is considerable variability in the socio-economic conditions of the above-mentioned reaches. Therefore, hypothetically, human and natural controlling factors do vary among these reaches. In this regard, it is imperative to examine the groundwater changes both in space and time at the reach level in IRB.

Considering the limitations of previous studies in the Indus Basin (Rodell et al. 2009; Cheema et al. 2014; Shekhar et al. 2015; Iqbal et al. 2016; Iqbal et al. 2017; Ali et al. 2021; Akhtar et al. 2022; Ali et al. 2022; Arshad et al. 2022), the novelty being captured in this study includes the following: (i) investigation of the groundwater dynamics at three tier levels (TTLs), i.e., the basin, river reach, and region, using GRACE and GLDAS for the period 2003–

2016 to explore their implications on regional water resources management; (ii) assessment of the controlling factors (climatic and anthropogenic) at three tier levels to mitigate the vulnerability of groundwater resources; and (iii) identification of the hotspots of groundwater change patterns by decomposing and analyzing time series of the GRACE-extracted GWC, the Potential Groundwater Use (PGWUSE), and the Potential Groundwater Withdrawal (PGWWW) to explore groundwater management options.

2.3 Materials and Methods

2.3.1 Study Area

The area coverage of IRB is approximately 1.12 million km^2. It is shared among Pakistan (47%) and India (39%), followed by China (8%) and Afghanistan (6%) (Frenken 2012) and is situated between 66.3–82.47° E longitude and 24.63–37.05° N latitude (Figure 2.1). The Indus River (approximately 3000 km long) originates in the Tibetan Plateau near Mount Kailash (altitude 5500 m) and traverses towards the Arabian Sea (Archer et al. 2010). The tributaries of IRB are the Indus, Jhelum, Chenab, Ravi, Sutlej, and Bias Rivers. The eastward-flowing tributary is the Chitral River, which originates in Pakistan, flows towards Afghanistan, and then drains into the Indus River in Pakistan (Iqbal Abdul Rauf 2013). The basin's climate ranges from subtropical arid and semiarid to temperate sub-humid on the plains of the Sindh and Punjab provinces to alpine in the northern mountainous highlands (Frenken 2012). The average annual precipitation varies from 100 to 500 mm in the lowlands to approximately 2000 mm in the mountainous ranges. Moreover, the snowfall at higher altitudes (>2500 m) accounts for a significant part of the river flows in IRB. Although the higher peaks in the Upper Indus Basin (UIB) restrict the intrusion of monsoons, the low-lying areas in the northwest of the basin are subjected to monsoon rainfall, influencing GWCs over the basin.

IRB is divided into upper, middle, and lower reaches based on its topography and climate. The upper reach includes Kashmir, Gilgit Baltistan, and Himachal Pradesh, which constitute the major watershed of IRB (points A to B). The middle reach (points B to C) comprises the major portions of Pakistani Punjab and Indian Punjab (the food basket of Pakistan and India), which produces most agricultural products and secures the region's food supply. The lowest part of the reach consists of Sindh (points C to Arabian sea), as shown in Figure 1. Agricultural production is influenced by waterlogged and saline agricultural lands in Sindh and some portions of Baluchistan.

Geologically, IRB is dominated by thick quaternary sediments. These sediments are mainly alluvial and deltaic deposits of fine- to medium-grained silt, sand, and clay. Coarser sands and gravels are present on the plain's upland margins while sand deposits can be found at the east of the Indus Plain (i.e., Thar and Cholistan). Cenozoic and Mesozoic sedimentary rocks can be found in a north–south region located at the west of the Indus Plain, which stretches from Peshawar to Karachi. Older sediments (Paleozoic) and crystalline base rocks (e.g., granites and metamorphic) are mainly found in the north, including Khyber Pakhtunkhwa, Jammu and Kashmir, and Gilgit regions. Groundwater yields from these sediments are typically in the range of 50–300 m^3/h down to a depth of 150 m.

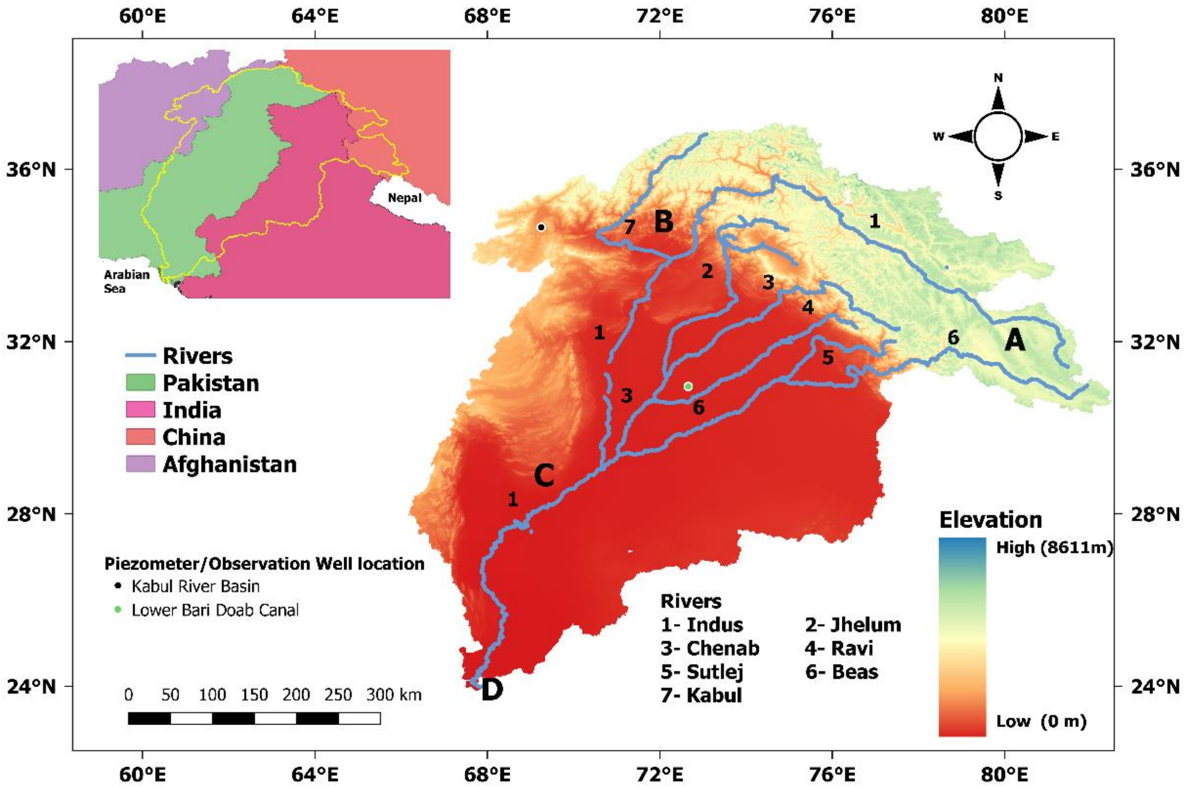

Figure 2.1 Transboundary Indus Basin with its tributaries and digital elevation model

2.3.2 Data Sources

We extracted the monthly TWS data of GRACE RL-06 released by the National Aeronautics and Space Administration (NASA) from 2003 to 2016, covering the globe with a spatial resolution of 1° × 1°. The GRACE landmass datasets of three laboratories, namely, the Centre for Space Research (CSR), Jet Propulsion Laboratory (JPL), and Geo Forschungszentrum Potsdam (GFZ), were obtained from the NASA website (www.jpl.nasa.gov accessed on 17 December 2019) supported by the NASA MEASUREs Programme (Landerer & Swenson 2012; Landerer 2019a; Landerer 2019b; Landerer 2019c). The gridded surface-mass anomalies were derived from GRACE mission measurements and estimated the Earth's mean gravity at the specified time. For the JPL datasets, scaling factors were applied to convert the 3-degree gaussian filter resolution to 1-degree spherical harmonics solutions. These grids represent the storage of the terrestrial water cycle and ice magnitudes over the entire land. Furthermore, the non-captured atmospheric and oceanic processes are included in the corresponding GRACE component. The SM, SWE, and canopy water storage (CWS) were collected from GLDAS_NOAH10_M_001 at a 1° × 1° spatial resolution (Rodell & Beaudoing 2007). The data from WGHM by the Institut für Physische Geographie, University of Frankfurt, accurately simulates the changes in all forms of terrestrial water storage and GWC except glaciers (Müller Schmied et al. 2020) to observe the agreement with GRACE-based GWC. The outputs of this model have been widely used in recent years (Wei Feng, C. K. Shum 2018; Yu Zhu, Shiyin Liu, Ying Yi, Miaomiao Qi, Wanqiu Li & Wu 2020). The present study used the recent GWC, PGWUSE, and PGWWW data collected from 2003 to 2016, with a monthly temporal resolution and a spatial resolution of 0.5° × 0.5° (Müller Schmied et al. 2020). To explore the controlling factors of TWS and GWC, we extracted the data of three hydrological fluxes (P, ET, and runoff (R)) from different sources. The precipitation data of the Tropical Rainfall Measuring Mission (TRMM, version TRMM-3B43 Level-3) with a temporal resolution of 1 month and a spatial resolution of 0.25° × 0.25° were obtained from NASA (Huffman et al. 2014). The monthly ET, P, and R data, output of WGHM with a spatial resolution of 0.5° × 0.5°, were taken from data published on the Earth and environmental science website (Müller Schmied et al. 2020).

2.3.3 Methods

The TWS data of IRB was obtained from the three laboratories using a specialized program written in R and averaged to compute GWC. To calculate the monthly GWC, SM, SWE, and SWS were excluded from the average gridded TWS values of the JPL, CSR, and GFZ laboratories. The groundwater storage change/groundwater anomaly ΔGWC was calculated as given in Equation (1) (Voss et al. 2013; Frappart & Ramillien 2018):

$$\Delta GWC = TWS - \Delta SM - \Delta SWE - \Delta CWS \qquad (1)$$

where ΔSM, ΔSWE, and ΔCWS are the anomalies for soil moisture, snow water equivalent, and total canopy water, respectively. All variables in Equation (1) (downloaded on a rectangular grid) were imported into a geographic information system (GIS) to mask the irregular boundaries of the Indus River Basin. The centroids of the rectangular grids were obtained as the grid coordinates, and the variables of Equation (1) extracted by the R-code quantified the spatiotemporal groundwater dynamics at various levels. The TWS values for missing months were determined by a linear interpolation technique (Yin et al. 2017), and statistical analyses were performed by Mann–Kendall tests, regression, and Spearman's rho correlation.

2.3.4 Time-Series Decomposition

A filtering procedure that decomposes a time series into its seasonal (S), trend (T), and residual (R) components using locally weighted scatterplot smoothing is commonly known as the STL method (Cleveland, Robert B. William S. Cleveland, Jean E. McRAe 1990). Numerous hydrological studies (Shamsudduha et al. 2009; Buma et al. 2016) have used STL to clarify, refine, and obtain the detailed characteristics of variations in timing data. STL decomposition based on LOESS at the time i in a time series Yi is given as:

$$Yi = Si + Ti + Ri \qquad \text{where } i = (1,2,3 \ldots, N). \qquad (2)$$

In this study, the time series of GRACE-based GWC, PGWUSE, and PGWWW were decomposed, and the characteristics of each decomposed component were analyzed to extract valuable information. Figure 2.2 summarizes the datasets and research methodology as a flowchart.

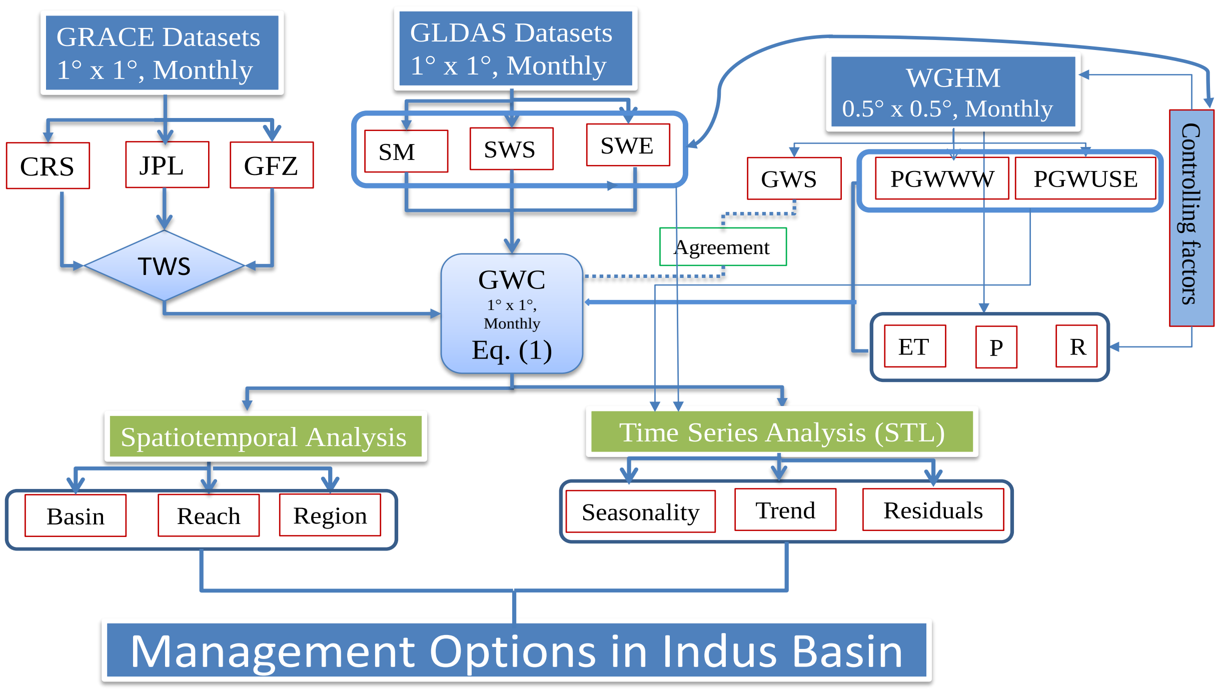

Figure 2.2 Flowchart of the datasets used and analyses performed

2.3.5 Spatial and Temporal Analysis

Spatiotemporal analysis was performed to understand the groundwater dynamics of the basin using the available datasets. The 112 grids of the GRACE and GLDAS datasets covering the entire IRB were extracted using the GIS tool. The GRACE-based groundwater anomaly was averaged from January 2003 to December 2016 in each grid cell in the spatial analysis. The temporally averaged GWC values were then categorized into five classes based on GWC threshold values, providing more direct information for groundwater resource management options and planning (Lin et al. 2019). The groundwater thresholds were identified by observing the range of GWC values over the IRB grids. The anomaly categorization is given in Table 2.1.

Table 2.1 Groundwater change categories in the Indus River Basin

Sr. No	Groundwater Changes (mm)	Indication of Groundwater Change
	<−100	Severe decline
2	−100 to −50	Minor decline
3	−50 to 0	Normal variation
4	0 to 50	Minor rise
5	>50	Abnormal rise

2.3.6 Performance Assessment of the Groundwater Storage Changes

GWCs estimated in this study across the wider IRB were evaluated at two random pixels both at the very extreme northwestern part (KRB) and at the downstream LBDC. The piezometric data of KRB was obtained from Taher et al. (Taher et al. 2014), which are monthly records and available for a period of 2005–2013 while for that of LBDC's, there are only two records available per year (i.e., pre and post monsoon) available from 2003 to 2015. The observation wells' data for LBDC was obtained from the Punjab Irrigation Department (Pakistan).

2.4 Results

The estimated spatial and temporal changes in GWC revealed a groundwater decline over the study period. The fluctuations in GWC were higher before 2010 compared to the later period (2010–2016), i.e., reflecting a substantial decrease in the GRACE-based groundwater storage anomaly in the earlier period (Figure 2.3a,c).

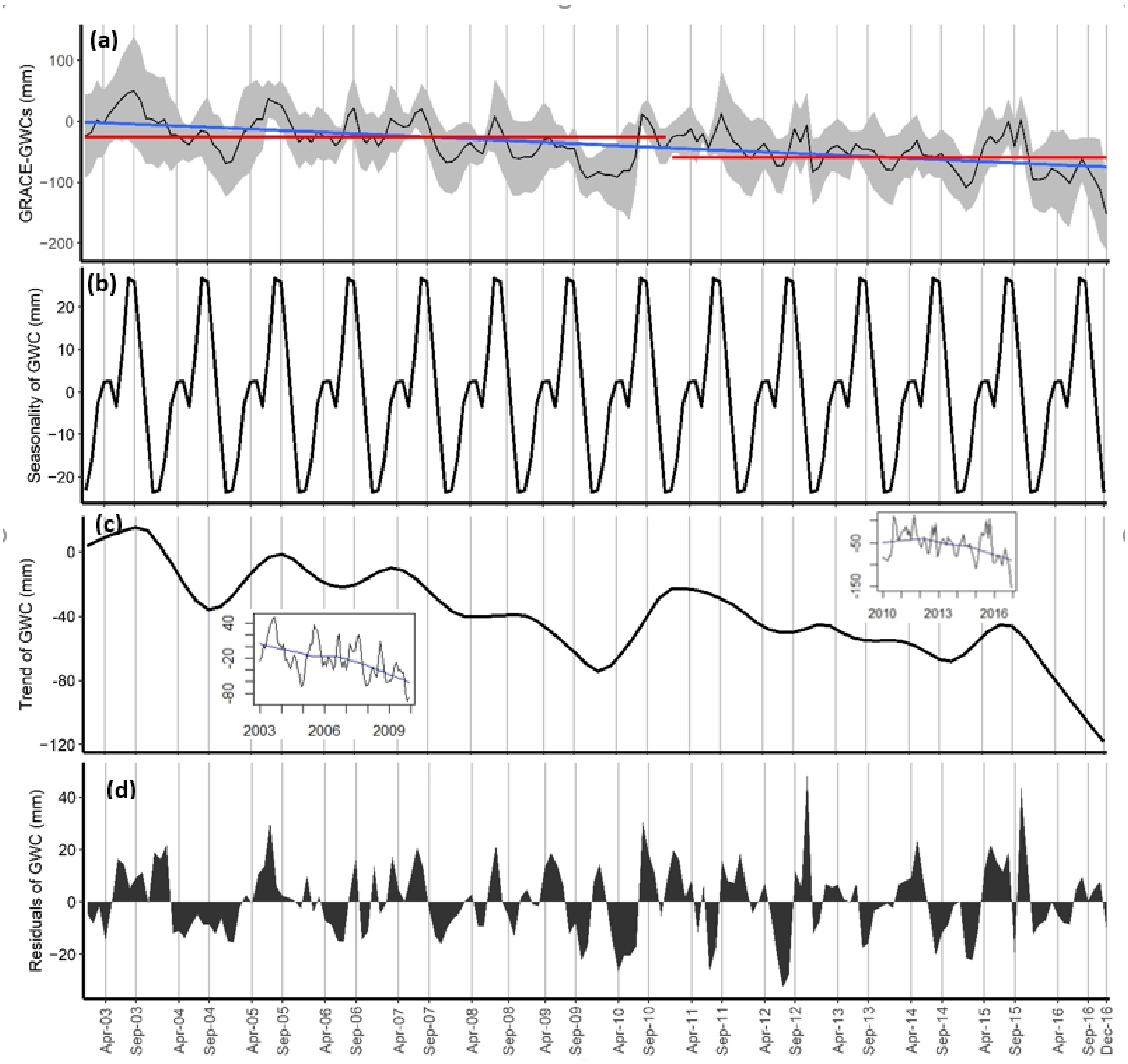

Figure 2.3 GRACE-derived GWC time series, (b) seasonality, (c) trend, and (d) residuals of the decomposed GWC signals

2.4.1 Spatiotemporal Groundwater Dynamics and Controlling Factors at the Basin Level

Figure 2.3a shows the temporal changes in the groundwater resources at the basin level. During the study period (January 2003 to December 2016), GWC decreased ($p = 2.2 \times 10^{-16}$; t-test) over the entire IRB. The mean GWC was −25.67 mm for the period of January 2003–December 2009 and −54.33 mm for January 2010–December 2016 (red lines in Figure 2.3a), confirming both a decline and shift in the mean GWC over the study period, and the fitted regression line (blue line in Figure 2.3a) showed an overall decreasing trend of 0.44 mm per month.

For the whole study period 2003–2016, the GWC trend declined at −0.44 mm/month in the GRACE model and −0.64 mm/month in WGHM. To identify the hotspots and understand the characteristics of GWC, the GRACE-based GWC time series was decomposed to observe its seasonality, trend, and abnormalities (see Figure 2.3). Across the entire IRB, the decomposed GWC signal showed a strong seasonality, with annual losses in the pre-monsoon period (around April) and annual gains in the post-monsoon period (around September) (Figure 2.3a,b). In each year, the seasonality curve dipped after April (Figure 2.3b) as excessive pumping for rice cultivation began. No significant changes were observed within the years in the seasonal component. The decomposed trend component (Figure 2.3c) of the GWC signal significantly declined until the end of the drought year (2009). Accordingly, groundwater changes (Figure 2.3c) were steeper in the first half of the study period, indicating an alarming decline in groundwater resources during this period as evident from the Mann–Kendall trend analysis, which indicated that the mean GWC was highly significant during the study period from January 2003 to December 2009 ($p = 1.65 \times 10^{-7}$) compared to January 2010–December 2016 ($p = 1.99 \times 10^{-4}$).

The groundwater level maximally declined in 2009, when the weak monsoon created drought conditions in the basin before the flood years (Yu et al. 2013). Subsequently, it rose in the flood years, indicating the changes in groundwater mainly depend on the trend component. The residual component (a powerful indicator of abnormalities such as flood and drought events in the region) displayed abnormal signals in the winters of 2012 and 2015 (Figure 2.3d). In the Federal Flood Commission report (2017), the years 2010–2016 were identified as flood years. Indeed, the groundwater levels showed a significant rise during these years, indicated by a wet period (Figure 2.3a) in the present analysis.

The spatial analysis revealed an overall decrease in groundwater resources throughout the basin. As shown in Figure 2.4, GWC declined from south to north and from west to east. A strip of severe GWCs was observed in Gilgit Baltistan, Kashmir, Himachal Pradesh, and Indian Punjab. In UIB, GWCs dominated in the range from −131 to −81 mm, indicating high groundwater storage variations with higher standard deviations. In the southwest part of IRB, the groundwater storages are minimum and with low variance. In general, the regions where the standard deviation of groundwater storage was high showed greater groundwater decline.

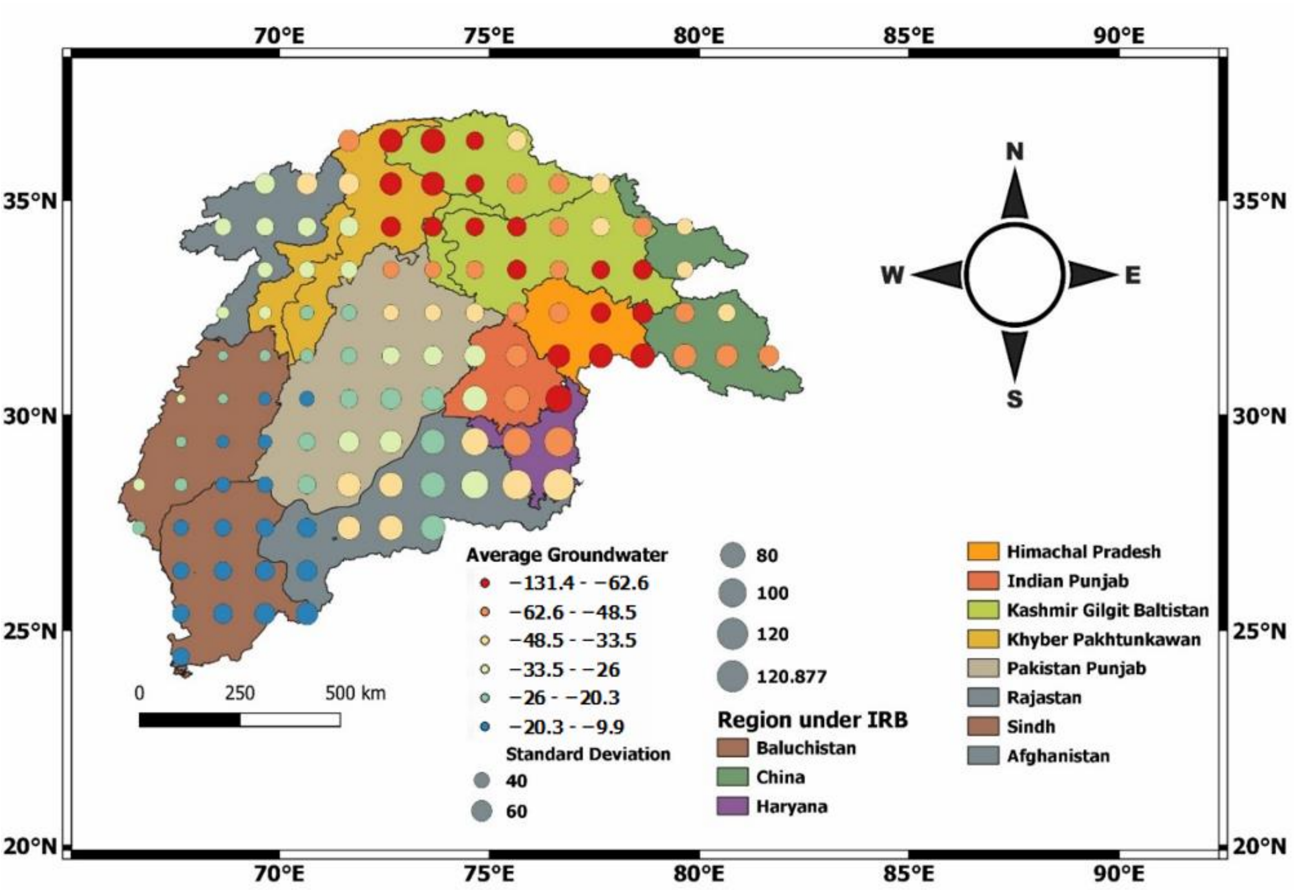

Figure 2.4 Spatial analysis of the time-averaged GWCs in IRB

Groundwater storage changes were further explored using the SM, SWS, and SWE data from the GLDAS Noah model. Groundwater changes showed a declining trend in the study area (Figure 2.5a), and SWS contributed little to GWCs and their tendency (Figure 2.5b,c). The snow changes remained around zero because snow and ice concentrate in the mountainous part of the basin (upper IRB) and only cover parts of the Indus Basin. The SWE, which significantly affected the changes in groundwater storage, trended downward, particularly after 2005 (Figure 2.5c). The main contributor to GWC was SM, which is necessary for the growth and survival of flora. The occurrence of drought depends on when the current soil moisture cannot meet the plant's requirements. As shown in Figure 2.5c, SM and GWC exhibited the same declining trend patterns after the winter of 2007, indicating that GWC and SM are heavily dependent on each other in IRB. Precipitation markedly affects the spatial pattern of TWS and GWC and accelerates the spatial variation signal in the north–south direction. Figure 2.5d compares the mean monthly precipitation data from TRMM and the mean monthly TWS and GWC. The precipitation generated by TRMM varied from 2.28 (October 2007) to 107 mm/month (July 2010), whereas GWC ranged from −152.43 (December 2016) to 50.46 mm (September 2003).

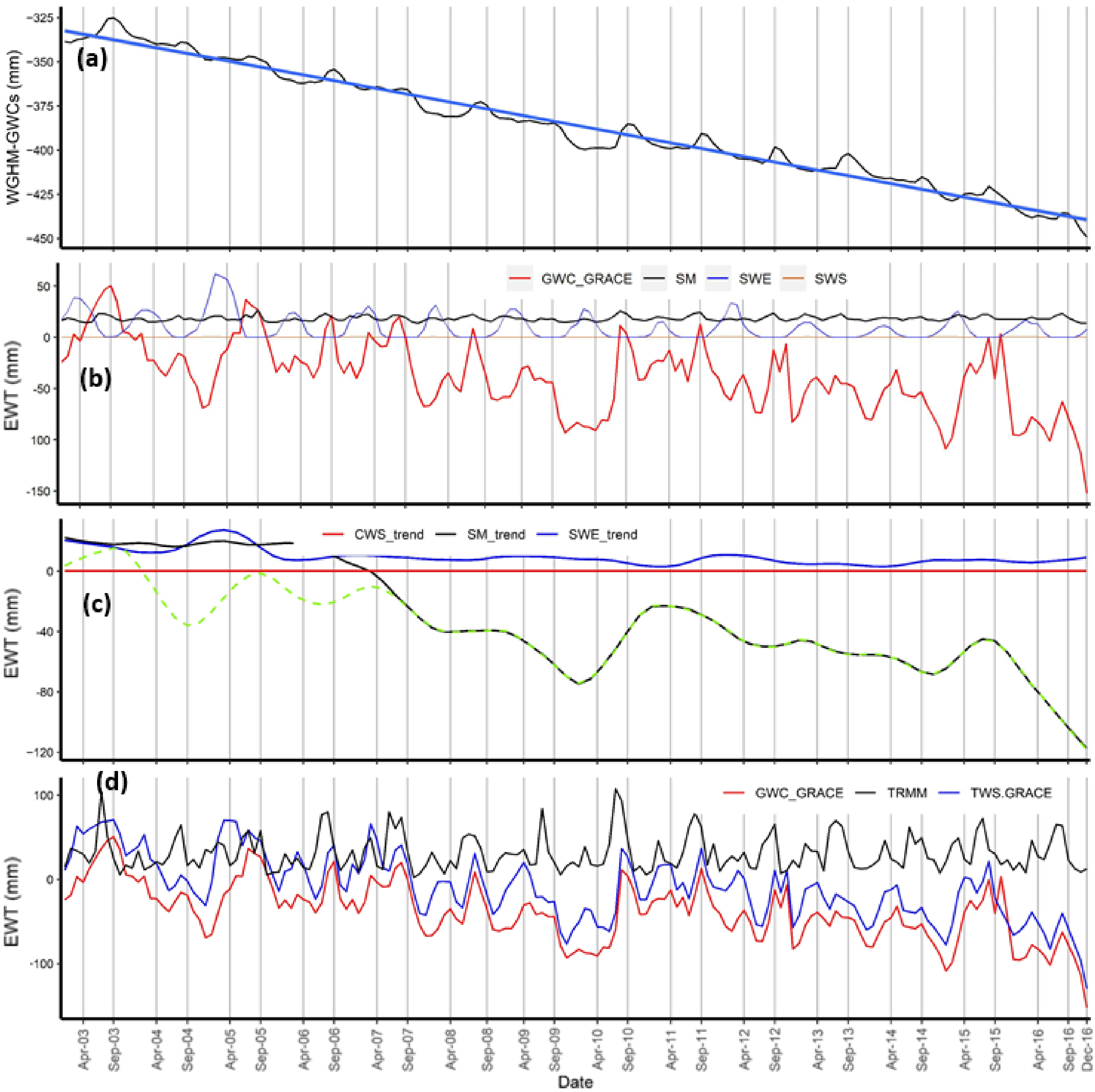

Figure 2.5(a) Groundwater storage changes in WGHM (black line indicates the groundwater storage of WGHM and blue line indicates the fitted regression line); (b) changes and (c) trends of GWC, soil moisture (SM), canopy water storage (SWS), and snow water equivalent (SWE); (d) comparison of monthly time series of the GRACE-based GWC and TWS values and TRMM precipitation data in IRB

The spatial differences in TWS and GWC were analyzed from the variabilities in ET, P, and R. We mainly analyzed the entire IRB, UIB, Middle Indus Basin (MIB), and Lower Indus Basin (LIB). In the Indus Basin, TWS and GWC declined at a rate of −0.545 and −0.640 mm/month, respectively; and ET, P, and R varied by a rate of 0.0417, 0.0659, and 0.034

mm/month, respectively (Figure 2.6a). The positive variability rates of ET, P, and R indicated that all these variables were sensitive to TWS and GWC. However, R is generated by precipitation and snowmelt in the study area, and contributed a minor amount to TWS and GWCs. Thus, we inferred that the ET increase was the main controlling factor of the groundwater and total water storage dynamics across IRB during the study period.

In UIB, TWS trended upward at an amount of 0.018 mm/month, whereas GWC declined at an amount of 0.22 mm/month. Both P and R showed a positive tendency with higher variability than ET (Figure 2.6b). P increased at an amount of 0.025 mm/month, whereas ET increased at an amount of 0.012 mm/month, indicating that the P increase mainly caused the TWS increase. The increasing trend of regional R was not consistent with the P variation (Figure 2.6b), suggesting that there is an additive water supply from snowmelt and glacier recession. Muhammad et al. (2019) reported a negative mass balance in upper IRB, with the most negative values ranging from −0.34 ± 0.31 to 0.44 ± 0.27 m w.e., with − 1 in the Jhelum, Chenab, and Ravi sub-basins of the Himalaya. SWE in UIB changed by −1.02 mm/year (the glacier area was 115,675 km^2 in 2016). Therefore, our analysis suggests that glacier recession (not ET) is an important controlling factor of TWS and GWC variations in UIB.

In MIB, TWS and GWC significantly declined at an amount of −0.89 and −0.9604 mm/month, respectively. P and ET showed a positive tendency over time and higher variations in MIB than in the Indus Basin as a whole (Figure 2.6c). The rising ET trend accounts for most of the TWS loss. Meanwhile, the increasing trend in regional R (Figure 2.6c) is consistent with the P variation. Therefore, ET, groundwater usages and withdrawal were inferred to be the main factors that increase the TWS deficit and reduce the groundwater in MIB.

In LIB, TWS increased at a rate of 0.17 mm/month, whereas GWC declined at a rate of −0.138 mm/month. The variations in P, R, and ET were small and inconsistent with the TWS changes (Figure 2.6d), suggesting that precipitation and evapotranspiration are not the main factors leading to changes in the total water storage and GWC in this region. Instead, the surface water supply in terms of high-water allowances to the canals provided by the Water Apportionment Accord (WAA) 1991 might explain the small groundwater and total water storage changes. The century-old irrigation system of IRB has allowed a variable allocation of surface water by its design (Basharat et al. 2014). The provincial bodies reviewed surface water allocations (WAs) at many stages to establish water rights and distribute the water of IRB among the four provinces of Pakistan, and these reviews led to a mutual consensus policy document: the Water Apportionment Accord (WAA) 1991 (Basharat et al. 2014).

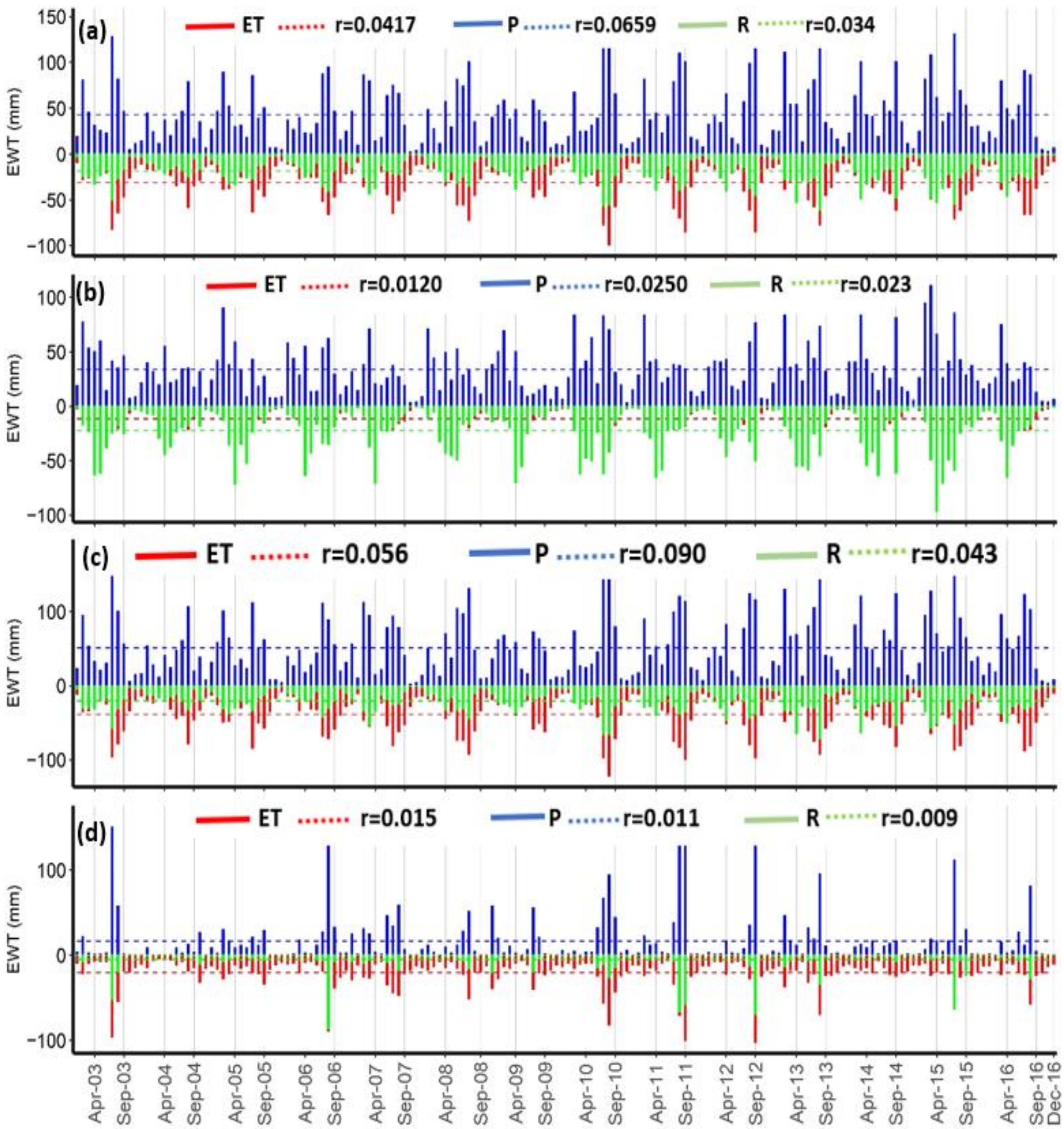

Figure 2.6 Time series analysis of P, ET, and R in (a) the entire Indus Basin, (b) Upper Indus Basin (UIB), (c) Middle Indus Basin (MIB), and (d) Lower Indus Basin (LIB). Here, 'r' (mm/month) denotes the rate of change from 2003 to 2016

As shown in Table 2.2, the TRMM, TWS, GWC, and SM data were positively correlated, indicating that the GWC values are affected not only by precipitation but also by parameters associated with anthropogenic activities, such as pumping. As shown in Figure 2.7a,b, the groundwater use in each year was lowest in February and highest in October. The PGWUSE started to increase after April as the rising temperature accelerated ET and rice cultivation activities in the basin. The decomposed trend components of PGWUSE and PGWWW showed highly reciprocal correlations with the trend of GWC (when PGWUSE was maximum, GWC was minimum; see Figure 2.7c). The monthly potential total water withdrawals from the groundwater resources were highly seasonal, minimal in April, and highest in November each year (Figure 2.7d,e). These results imply that much of the groundwater is withdrawn during cropping seasons and consumptive use. The trend component of the decomposed time series of PGWWW increased as the area became more dependent on groundwater (Figure 2.7f).

Table 2.2 Correlations between TRMM precipitation, TWS, and GWC

Correlations

		TRMM	TWS	GWC	SM
	TRMM	1.000	0.214 *	0.188 *	0.743 *
Spearmen's Rho	TWS	0.214 *	1.000	0.907 *	0.299 *
	GWC	0.188 *	0.907 *	1.000	0.241 *
	SM	0.743 *	0.299 *	0.241 *	1.000

* Correlation is significant at the 0.01 level (two-tailed).

2.4.2 Spatiotemporal Groundwater Dynamics in Different Reaches

Reach-wise groundwater storage analysis revealed that changes in groundwater storage were diverse among the three reaches of IRB (Figure 2.8a) during the study period. The lower reach showed relatively higher groundwater storage than the middle reach while GWC in the upper reach was much smaller than in the middle reach (Figure 2.8a). These differences can be explained by variations in ET, R, P, and groundwater withdrawals as described above. GWCs in the upper and middle reaches declined more rapidly in later years than in previous years. Moreover, after 2009, GWC was higher in the middle reach than in the other reaches. Contrarily, GWC as determined for each of the reaches showed monotonous behavior during the study period. In the lower reach, the minor increases during 2007 and 2011 were contributed by groundwater recharge from flooding periods in previous years, explaining the smaller declining trend than the other reaches (Figure 2.8a).

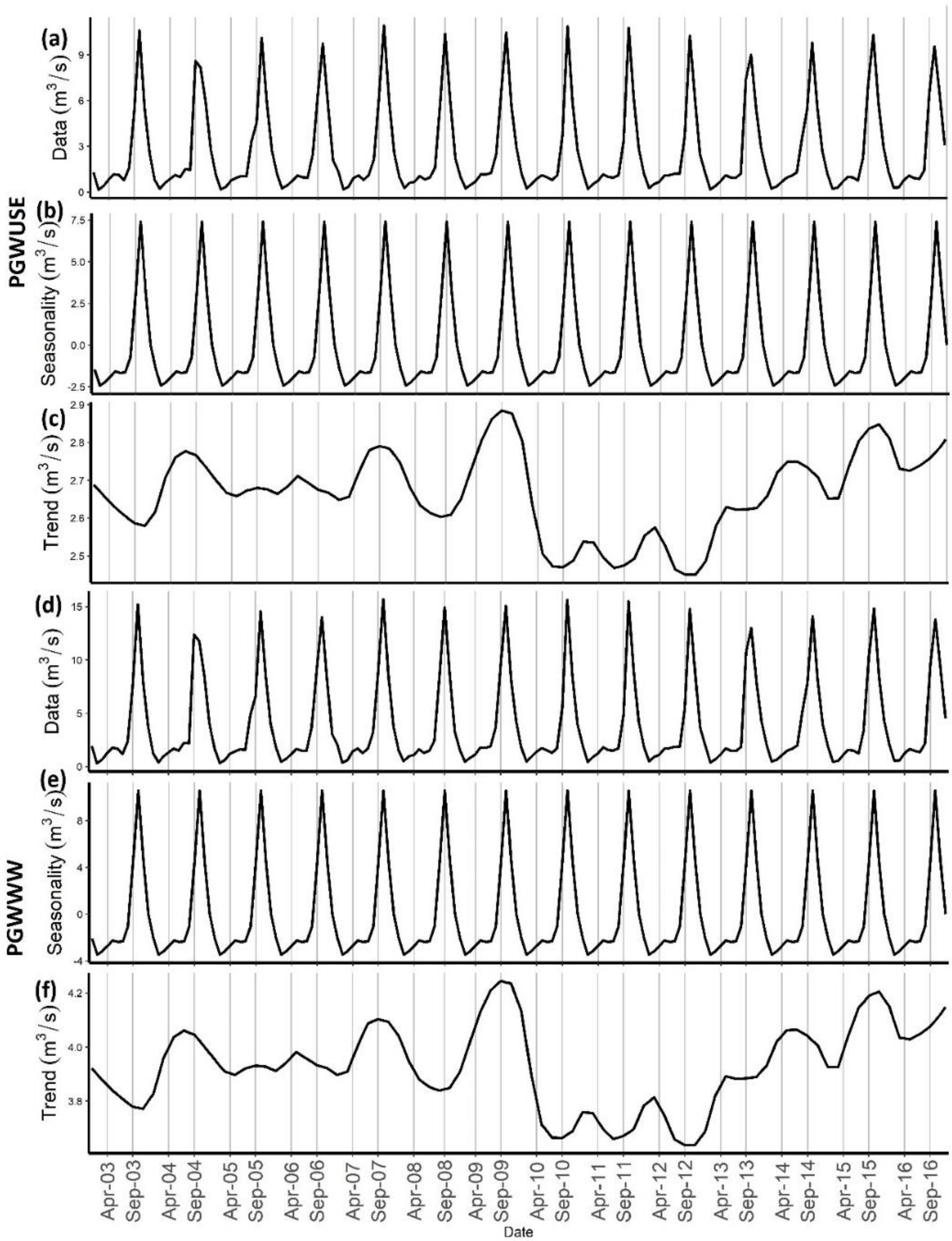

Figure 2.7 Time series: (a) data—PGWUSE; (b) seasonality—PGWUSE; (c) trend—PGWUSE; (d) data—PGWWW; (e) seasonality—PGWWW; and (f) trend—PGWWW over IRB during the 2003–2016 period

Looking at the monthly scale groundwater changes (Figure 2.8b), we found no consistency in groundwater storage fluctuations among the three reaches during 2003–2009. However, the upper and lower reaches showed some consistency in their fluctuations during 2010–2016 (Figure 2.8b). In the upper reach, groundwater storage remained low in winter (~December) throughout the study period except for rising trends during the summer of 2005–2007 and 2010. The groundwater storage changes remained high during 2003–2008, and low in the rest of the study periods. The lower reach depicted high groundwater storage in the summer (~September). After the year 2009 (tipping year), groundwater storage values were continuously negative in the upper and middle reaches, indicating that the groundwater storage continuously remained lower when compared with the base period (2004–2009). Prior to 2010, all the reaches showed groundwater storage fluctuation in the range of −150–150 mm. After 2010, there was a less declining trend of the groundwater storage due to floods, and the annual minimum values were recorded during the study duration. The most recent study year (2016) showed severe signs of depletion in groundwater storage, especially in the middle reach, as shown in Figure 2.8b.

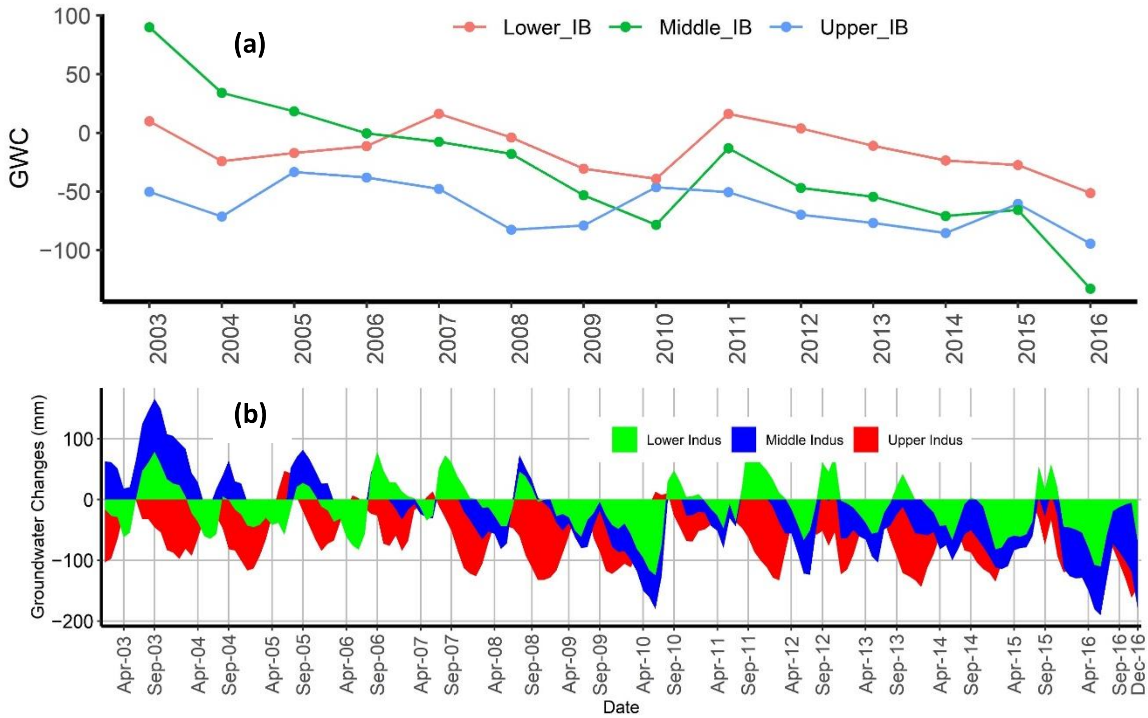

Figure 2.8 (a) Annual time series of the mean spatial groundwater storage changes in the three reaches of IRB. (b) Mean monthly GWC (mm/month) at different reaches in IRB

The most recent study year (2016) showed severe signs of depletion in groundwater storage. The upper reach showed surprisingly strong groundwater declines (<−100 mm) in all years except 2006, whereas the middle reach showed strong declines in groundwater storage from 2010 to 2016 onwards (Figure 2.9a,b). In general, the upper reach had the highest number of months that experienced severe groundwater declines compared with the other reaches during the study duration (Figure 2.9c). At the same time, there were no months with an abnormal rise (>50 mm) in the upper reach. The reach-specific analysis revealed that more rapid fluctuations in the upper reach make its ecosystem vulnerable, which may require further attention. Groundwater depletion in the upper reach should be mitigated with climate mitigation strategies.

In the reach-specific analysis, 24%, 14%, and 2% of the time span of the groundwaters in the upper, middle, and lower reaches, respectively, were severely depleted over the entire period. These findings indicate the vulnerability of groundwater resources in the upper Indus reach (Figure 2.9d). During the same period, GWC rose abnormally in the middle reach. The reach-wise analysis revealed more rapid fluctuations in the upper reach, which may require further attention. In particular, groundwater depletion in the upper reach should be mitigated with climate mitigation strategies.

2.4.3 Spatiotemporal Groundwater Dynamics at the Regional Level

To study GWCs in a spatially explicit way, the study area was subdivided into eight regions: Kashmir and Gilgit Baltistan, Tibet–China, Khyber Pakhtunkhwa, Afghanistan, Punjab, Sindh, Baluchistan, and Indian Punjab–Himachal Pradesh–Haryana (hereafter referred to as the Indian part), along the Indus River from upstream to downstream. All eight regions of IRB exhibited irregular annual patterns of continuous decline in GWC after 2003 (Figure 2.10). China, Afghanistan, KP, and Sindh showed consistent groundwater storage changes within the range from 0 to −50 mm except in 2016. Before 2009, groundwater changes were within −50–100 mm for all the regions while after 2010, all the regions showed a rise in groundwater storage in 2011 and then a continuous decline. In the Indian part, the groundwater storage declined until 2010, but in the years beyond 2010, GWCs were in the range of −150 mm. The low GWC values in the Tibet–China and Indian part of IRB in the second phase and particularly in the final year of the study period (2016) indicate a severe groundwater decline in these regions (see Figure 2.10). In the province of Sindh, the groundwater rose abnormally in 2011 and, after that, continuously declined at a lesser rate than in the other regions.

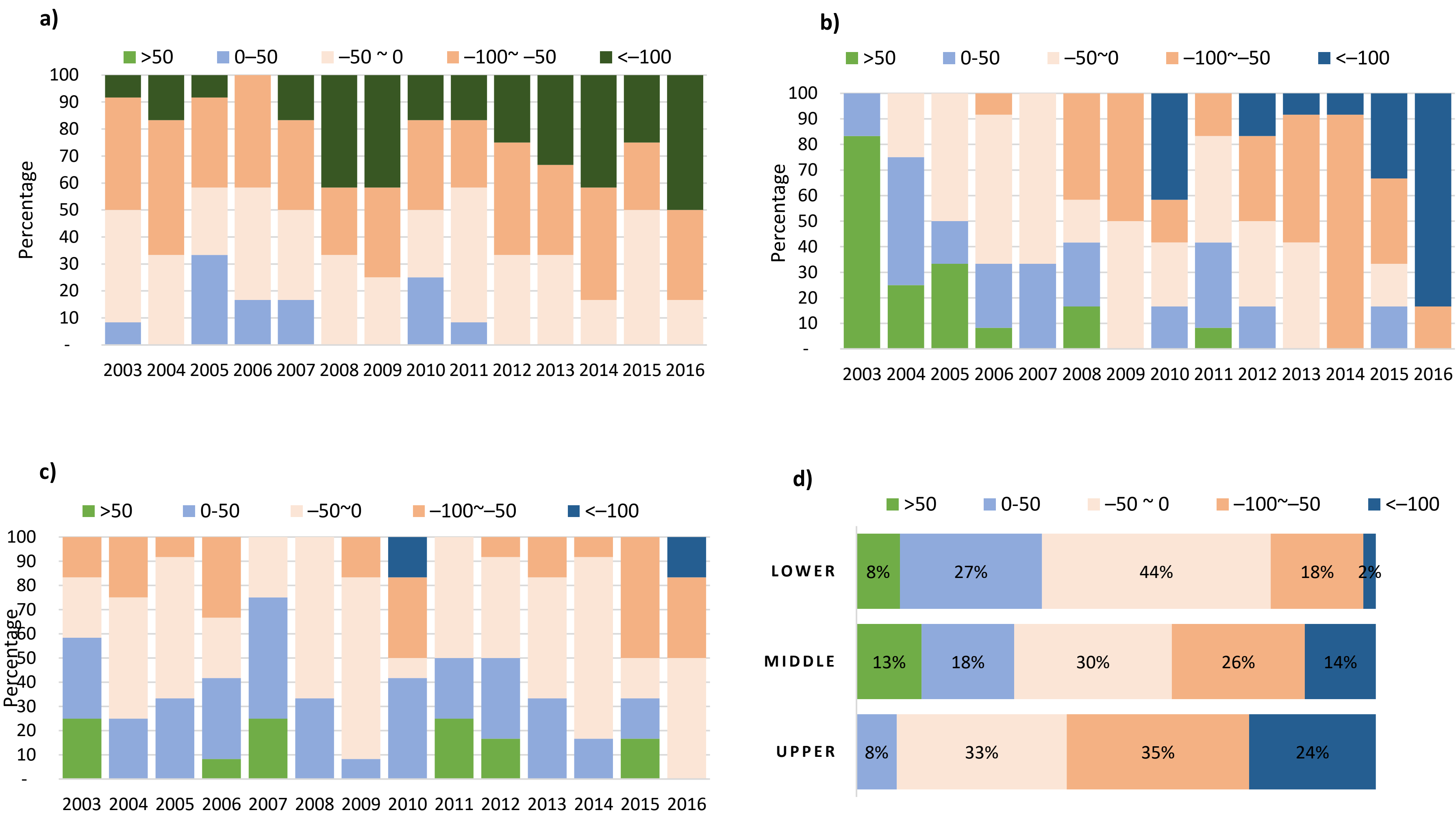

Figure 2.9 (a) Upper reach groundwater changes, (b) middle reach groundwater changes, (c) lower reach groundwater changes, and (d) annual severity of GWCs in the different reaches of IRB

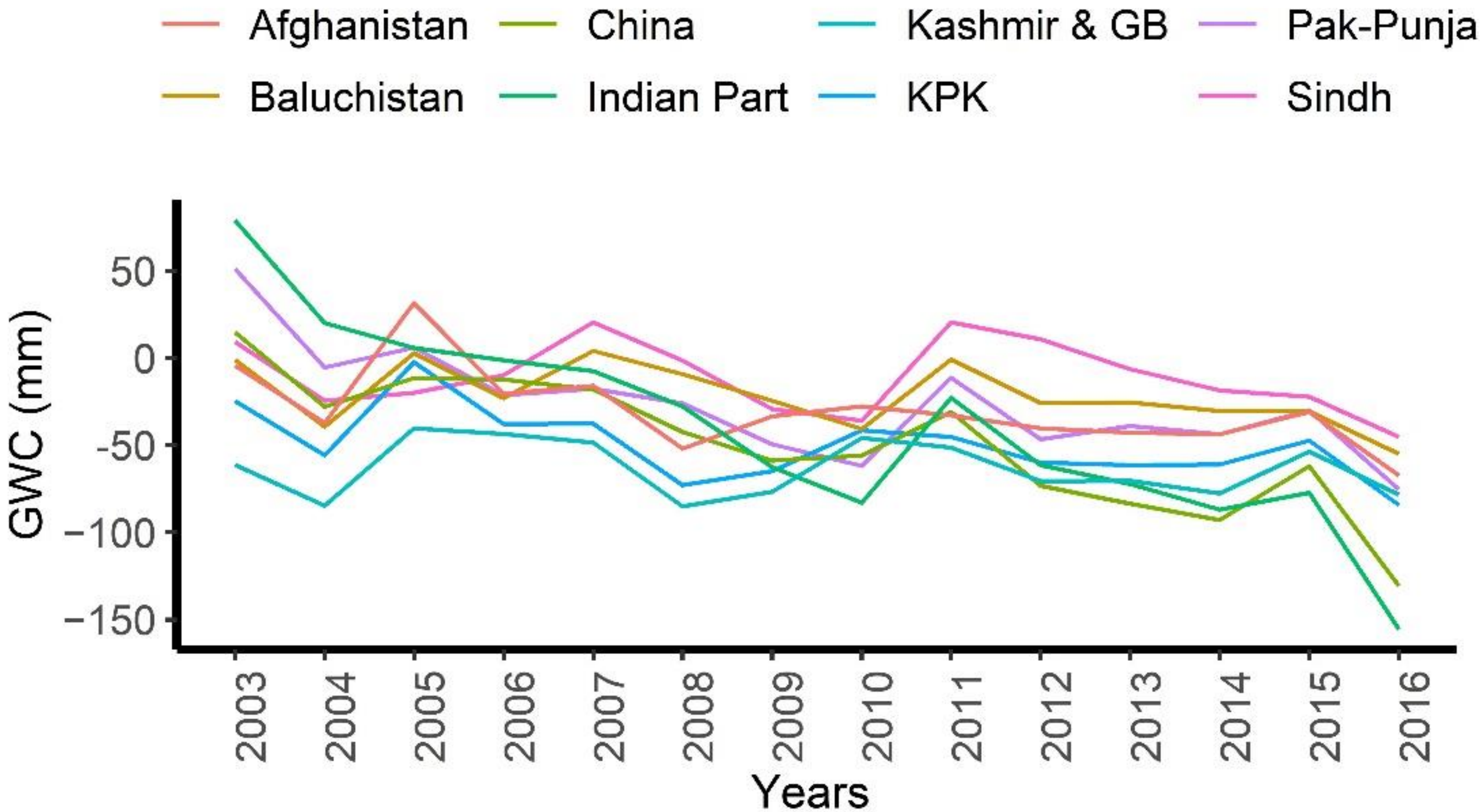

Figure 2.10 The annual time series of spatially averaged changes in groundwater storage in different regions

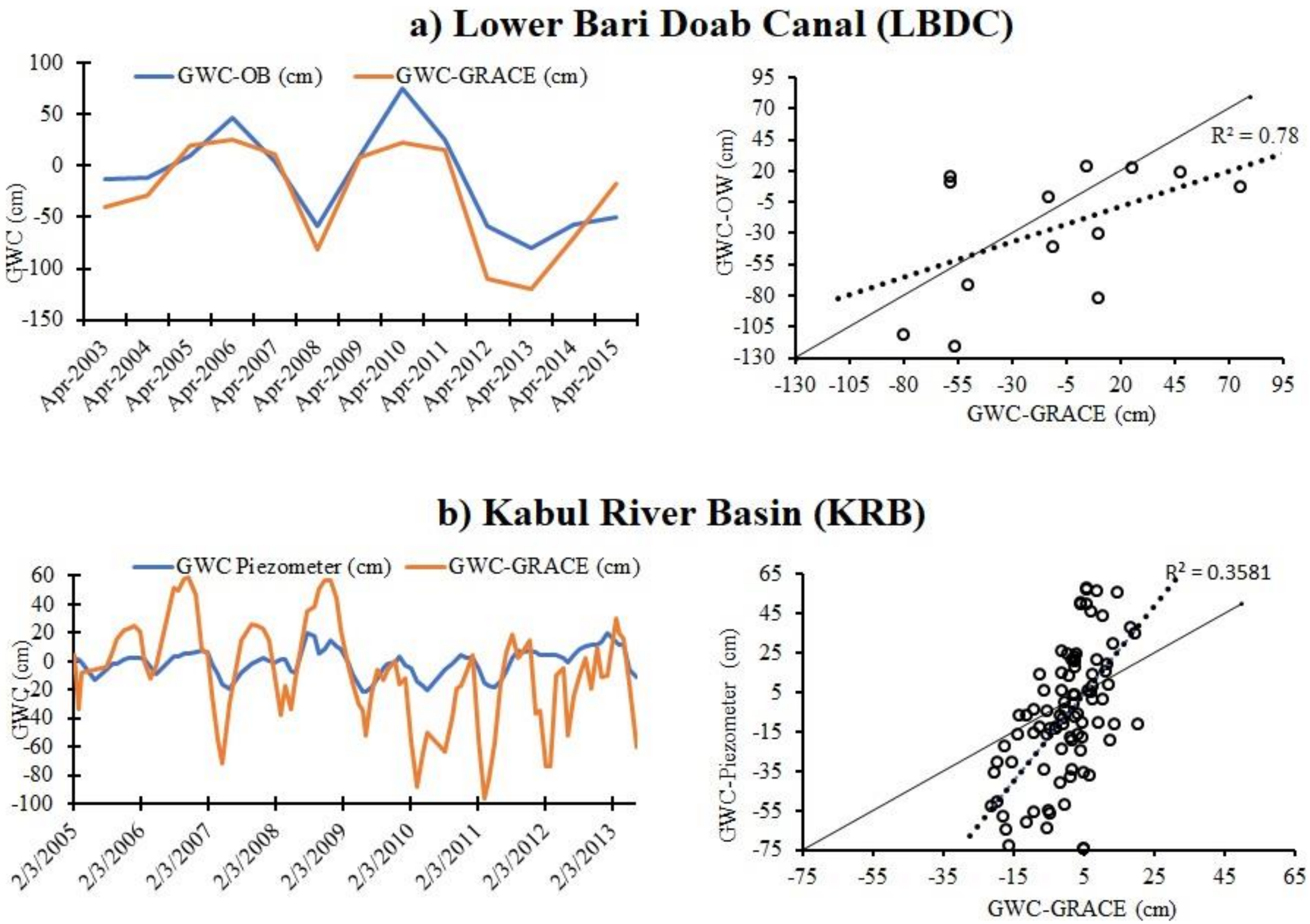

Figure 2.11 (a) Correlation of the observed (observation well data) and estimated (GRACE-based) groundwater storage anomalies in LBDC. (b) Correlation of the observed (piezometric data) and GRACE-based groundwater storage changes in the Kabul River Basin

The GRACE-based estimates of groundwater storage changes were compared to in situ measurements (1 piezometer data for KRB and 1 observation well for LBDC). In situ measurements for KRB and LBDC were available from 2003 to 2015 and 2005 to 2013, respectively. When the GWC and in situ measurements were compared, the correlation coefficients for LBDC and KRB were 0.78 and 0.35, respectively (Figure 2.11).

2.5 Discussion

Overall, our analysis revealed that regional GWCs in time and space could be derived from remote sensing data (GRACE) and data assimilation models (GLDAS). In the temporal analysis, a significant decline in GWC ($p = 2.2 \times 10^{-16}$) was observed over the entire study period (January 2003 to December 2016). The observed decreasing trend and fluctuations were larger before 2010 than in the second half of the study period, which is driven by the higher values in 2003 and very low numbers in 2010. The second phase of the time series is characterized by lower levels and extreme lower levels of GWC in 2016.

In the spatial analysis, a significantly declining trend in GWC was observed in the upper Indus reach, indicating a dominant snow receding effect (Ali et al. 2020). On the regional scale, the aquifer storage showed a declining trend in upper Punjab (especially in Gujranwala, Sialkot, and Hafizabad) because the pumping rate was high in these regions. Similar results were reported by Qureshi et al. (2003), Shoaib et al. (2022), Arshad et al. (2022), and Iqbal et al. (2017), who mentioned that water is over-pumped at an alarming rate in areas where high delta crops (i.e., rice) are grown at a high tube well density. The groundwater depletion was moderate in the districts (Faisalabad, Vehari, Pakpattan, and Khanewal) of Pakistani Punjab because groundwater is overexploited to meet the crop water requirements (Iqbal et al. (2017). Qureshi (2020) reported that groundwater is declining to below 6 m in more than 50% of the irrigated area of Punjab, causing groundwater quality deterioration and increased pumping costs.

Groundwater storage changes were severe in the Indian part of IRB, reaching a maximum in 2016. Dominant changes in groundwater were observed in the south-eastern regions of the IRB, covering Himachal Pradesh, Indian Punjab, Haryana, and Rajasthan (the northern Indian states, which account for 95% of groundwater use in the region). High groundwater-based irrigation can explain these large changes, which has expanded to meet the wheat and rice demands of Indian government policy (Mishra et al. 2018). Other causes of groundwater decline are exponential population growth and rapid economic development (NASA 2009), which have increased the pumping of groundwater (Cheema et al. 2014; Chen et al. 2016), in addition to the provision of subsidies on electricity and diesel for groundwater abstraction, an increased number and density of tube wells (>30/km^2 in different districts), augmented groundwater draft, expansion of rice and wheat areas (Arshad et al. 2022), and spikes in cropping intensity (Shah et al. 2003; Baweja et al. 2017). Similarly, Rodell et al. (2009) detected a significant groundwater depletion in the north-western part of India based on the GRACE datasets. They calculated a mean depletion rate of 40 ± 10 mm/year equivalent height of water, whereas Asoka et al. (2017) estimated a 20 mm/year groundwater decline rate in the same region. Singh and Bhakar (2020) reflected upon the alarming groundwater situation in Rajasthan and concluded that there is an uncertain future for this commodity. Steenbergen et al. (2015) attributed groundwater exhaustion in the Baluchistan province of Pakistan to the intensive use of water for agricultural purposes. The Sindh province of Pakistan, the southwest part of IRB, showed lower GWC fluctuations than the other parts of the basin and similar results were revealed by Arshad et al. (2022). Basharat and Azhar (2014) attributed the lower GWCs to the higher water allowance of canals under WAA 1991. Therefore, the authority responsible for the WAA 1991 should rationalize water allowances over IRB to counteract waterlogging and salinity in the lower reach (i.e., the Sindh province of Pakistan) and over-abstraction of groundwater in the upper part of the basin. The observed in situ groundwater anomalies were compared with the estimated GRACE-based groundwater storage anomalies (Figure 2.11). The results were consistent with the study conducted by Akhtar et al. (2022) and Ali et al. (2022).

Due to drought conditions, the groundwater declined maximally in 2009 while during flood periods, groundwater storages were improved. Chen et al. (2019) reported in Songhua River Basin that flood and drought conditions characterize the fluctuation in groundwater storage. GWS recovery was attributed to an increase in precipitation (Yin, Li, et al. 2020) in the Tasmania region, Australia, after 2010. However, Indus Basin exhibited a decline in groundwater storage that was inconsistent with the precipitation variation till 2010 (Figure 3.5c). Afterwards, it showed a continuous decline due to the significant impact of anthropogenic activities, i.e., mainly pumping in agriculture (Figure 2.7c,f). In addition, Feng et al. (2022) also reported that the pumping of groundwater for irrigation and coal mining activities was a major contributing factor in North China.

The spatiotemporal patterns of groundwater behavior extracted from the GLDAS and GRACE data might assist the implementation of sustainable groundwater management by policymakers and managers. Admittedly, the spatial resolution of the GRACE mission is too coarse to monitor the finer surface mass changes in large water bodies such as dams and lakes. Although the applied datasets are the best current data sources for determining GWCs in this area, they are insufficient for understanding groundwaters in canal command areas. Moreover, the mission ended in 2017, necessitating a new perspective of groundwater dynamics. To this end, statistical modeling of the GRACE time series and downscaling of GRACE to the local scale of groundwater dynamics are required. By connecting the data of GRACE, the latest launched GRACE-FO, and statistical modeling, we can ensure the continuity of the groundwater dynamics for prediction, especially when data are missing during the operation period of GRACE-FO. Issues such as sea water intrusion, how surface water bodies affect groundwater quality and quality, and land subsidence are not addressed by GRACE (Alley & Konikow 2015). The uncertainties in hydrological models, i.e., GRACE and GLDAS, could be considered in the perspective studies.

2.6 Conclusions

The GRACE and GLDAS datasets were combined into a novel algorithm that estimates the spatial and temporal changes in groundwater, thereby providing water-resource management options at the basin, reach, and regional levels. Groundwater resources in the whole basin have declined over time but exhibited a spatially heterogeneous change pattern. The main conclusions of this study and outlooks for future research and policy intervention are summarized as follows:

When analyzed over time, almost all GWC values were negative, with an overall decreasing trend from January 2003 to December 2016. The fluctuations in GWCs were stronger before 2010 than in the second half of the study period. An increase in evapotranspiration was found to be the main controlling factor for the groundwater and total water storage changes across IRB.

In the spatial analysis, GWC trended downward over the whole Indus Basin. The decline was severe (−131 to −108 mm) in UIB, highlighting a need for sub-basin analysis. We recommend the development of quantitative groundwater aquifer-related maps to visualize water withdrawals, groundwater recharge, groundwater storage changes, groundwater levels, aquifer thickness and yields, and tube well density over the whole IRB. These maps provide useful support to develop area-specific groundwater management strategies.

The reach-specific analysis showed that the upper reach is more vulnerable to groundwater decline compared to the other reaches due to glacier recession. We recommend the adaption of climate mitigation strategies to cater for the climate change impact on glacier recession. This study concludes that groundwater abstraction and groundwater consumption are the most significant driving factors in the middle reach. These results highlight the need for a robust mechanism to monitor the quantity and quality of groundwater abstractions in the middle reach. The outcomes for the lower reach reveal that the high-water allowances provided to the canals under WAA 1991 are the main driver of lower groundwater storage change. So, surface water allowances in Pakistan should be allocated based on a detailed understanding of groundwater withdrawals and depletion.

On the regional scale, the groundwater decline was severe in Himachal Pradesh, Indian Punjab, Haryana, upper Punjab of Pakistan, and China. Due to these regional differences, it is evident that a region-specific groundwater strategic framework is necessary. Hence, a comprehensive mechanism for monitoring and establishing regulatory and permitting arrangements and pricing structures should be developed to envisage sustainable management of the land area and water resources. Because the number and density of tube wells and boreholes have largely increased in recent years, we propose the construction of a database containing georeferenced locations of all existing and new tube wells and boreholes in the regions. Such a database would not only support but also improve management decisions.
The correlation between the observed and estimated GWC both at KRB (i.e., $R^2 = 0.35$) and LBDC (i.e., $R^2 = 0.78$) shows that there are spatial heterogeneities across IRB, which needs to be considered during planning initiatives.

In a nutshell, basin-wide groundwater monitoring infrastructures must be established using the latest technologies (GIS, remote sensing, and Heliborne technology). Such infrastructures are essential for the development of a sound database and maps for groundwater regulation and sustainable management. These will also enable robust monitoring of the quantity and quality of groundwater resources and their use.

Chapter 3

Downscaling GRACE to monitor groundwater changes at the Canal Command area level of Irrigated Indus Basin

A part of this chapter has been presented in conference:

Mehmood, K.; Bernhard, T.; Flörke, M.; Akhtar, F. Improving and Evaluating GRACE Resolution Using Geographical Weighted Regression. In Proceedings of the Sustain Valencia (2022). Achieving Sustainable Groundwater Management: Promising Directions and Unresolved Challenges; Gomez-Hernandez, J.J., Butler Jr., J.J., Eds.; Valencia, 2022; p. 75.

3 Downscaling GRACE to monitor groundwater changes at the Canal Command area level of Irrigated Indus Basin

3.1 Abstract

Groundwater plays a crucial role in water storage and serves as a vital source for agricultural irrigation in arid and semi-region of the world. The introduction of the Gravity Recovery and Climate Experiment (GRACE) Satellite has offered a novel avenue for studying water storage on a large scale. However, its limited spatial resolution has hindered the application of GRACE data in assessing local water resources. Consequently, enhancing the spatial resolution of groundwater storage becomes imperative for effective regional water management. In this study, two steps downscaling method was introduced to downscale GRACE datasets using six hydrological and three land surface variables to reduce artifacts in the downscaled groundwater storage datasets due to resampling of GLDAS components in the Indus Basin Irrigation System (IBIS). The study revealed that groundwater depletion was trending downward through the IBIS, and 50% of the IBIS showed a significant declining trend ($p < 0.05$) dominant in the Punjab province of Pakistan, where surface water allocations are low as compared to the downstream parts of IBIS (i.e., Sindh province). The variable water allocation in the regions mainly drives the groundwater storage changes in the regions.

3.2 Introduction

Water is increasingly becoming a priority policy issue at the international level (Cosgrove & Loucks 2015) and national level. Groundwater is arguably an essential resource for the sustainability of agriculture at a global scale and in transboundary aquifers, for instance, the Indus River Basin (IRB), where the pumping exceeds the recharge of aquifers (Lytton et al. 2021). The century-old Indus Basin Irrigation System (IBIS) has allowed variable surface water allocation by its design (Basharat et al. 2014). The provincial bodies reviewed surface water allocations at many stages to establish water rights and distribute water of the Indus River Basin (IRB) among the canal commands of four provinces of Pakistan. These reviews led to a mutual consensus policy document- Water Apportionment Accord (WAA)-1991 (Basharat et al. 2014). In general, the water allowance (WA) represents the amount of water allowed in cusec (ft^3/s =28.3 L/s) to 1000 acres (405 ha) of land and gradually increases from north to south in Pakistan's IRB. The variations of WA in different canal commands might be due to the availability of good quality groundwater to supplement available surface water (Cheema et al. 2016). The average water allowance in Pakistan is around 3.49 cusecs per 1000 acres and is the lowest among the other agricultural countries, e.g., India (4.86 cusecs), Egypt (5.31 cusecs), and Mexico (10 cusecs) (Tarar 1997). Variable surface water supply provided to different canal command areas (CCAs) resulted in implications of groundwater declining in CCAs of IBIS where the WA was low and vice versa. Assessment of groundwater dynamics in canal command areas (CCA) would be helpful in addressing water management issues and analyzing the implications of variable surface water availability on groundwater. Gravity Recovery & Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) products provide coarse-resolution data to analyze groundwater storage variations (GWS) at the basin scale. These datasets have been used widely around the globe (NASA 2009; Lin et al. 2019; Shamsudduha & Panda 2019). However, GRACE datasets application at the local level is limited and challenging to link groundwater change estimation with local groundwater observations (Miro & Famiglietti 2018) due to its coarse resolution. Therefore, downscaling approaches are needed to improve GRACE datasets' spatial resolution, which could provide novel high-resolution data for decision-makers to manage water resources at regional scale (Miro & Famiglietti 2018), and to make an informed decision about groundwater abstraction and allocations.

Various statistical downscaling methods have been employed for GRACE datasets from coarse (0.5°) to fine resolution (0.25° or to further 0.05°) using high-resolution hydrological predictor variables (Sahour et al. 2020; Zhang et al. 2021). The widely used machine learning statistical tools include the Random Forest method (L. Chen et al. 2019), Boosted Regression Tree (Milewski et al. 2019), partial least square regression (Vishwakarma et al. 2021) and Artificial Neural Network (Verma & Katpatal 2019). The basic assumption for these methods is that there is no spatial relationship between the GRACE datasets and predictor hydrological variables. In contrast, the geographically weighted regression (GWR) studies the stationarity of spatial relationships amongst predictor hydrological variables by location (Wheeler & Paez 2010). Therefore, GWR model was used for the prediction of high-resolution GRACE based TWSA data using various hydrological and land surface variables.

In order to derive groundwater storage anomalies (GWSA) from the TWSA, auxiliary GLDAS components (SM, CWS, SWE, SWS) are subtracted from TWSA. Many researchers first downscale TWSA to finer resolution (1 km) then subtracting auxiliary GLDAS (resampled from 0.25° to 0.05°) to estimate GWSA using hydrological variables i.e., evapotranspiration (ET), Precipitation (P), Runoff (R), Canopy water storage (CWS), Soil moister (SM) and Snow Water Equivalent (SWE) and land surface variables (i.e., elevation, land surface temperature (LST), normalized difference vegetation index (NDVI), population). The resampling GLDAS components from 0.25° to 0.05° can (i) impact performance in applications of downscaled datasets (ii) can amplify noise and introduce artifacts in the output i.e., GWSA. In this study, two step downscaling technique is introduced to retrieve the best GRACE dataset to be used on local scale using hydrological and land surface variables. The first step involved downscaling TWSA from 0.5° to 0.25°, followed by determining GWSA by subtracting TWSA from the retained GLDAS component at a resolution of 0.25°. In the second step, GWSA was further downscaled from 0.25° to 0.05° using the land surface variables (Actual Evapotranspiration [Eta], NDVI, LST). The downscaled datasets were then applied to investigate the extent to which they explain groundwater changes at the local level, considering the diverse water allowances and deficit in each canal commands area of IBIS.

3.3 Material and Methods

3.3.1 Study Area

The Pakistan Indus Basin has the largest contiguous irrigation system in the world. A significant portion of its total cropland, approximately 150,000 km^2 out of 190,000 km^2, relies on the Indus Basin Irrigation System (IBIS) for irrigation purposes. The IBIS spans across regions in four provinces, namely Punjab, Sindh, Baluchistan, and Khyber Pakhtunkhwa (KP), and encompasses 48 main canals, 16 barrages, and 2 major reservoirs (Figure 3.1). The basin's topography exhibits a wide range, from the highest elevation (~8611 m) in the Himalayas to the low-lying areas in Sindh. The IBIS receives its water supply from two sets of rivers: the eastern rivers (Ravi and Sutlej) and the western rivers (Jhelum, Chenab, and Kabul). The irrigation supply in each cultivated plain within the basin is derived from both surface water and groundwater sources, with their contribution varying based on factors such as the cropping system, surface water diversion, and availability of groundwater. The upper irrigated plains rely more heavily on groundwater for irrigation (Usman et al. 2015), while the lower plains tend to depend on surface water diversions. The study area encompasses diverse cropland systems, including rice-wheat, cotton-wheat rotation/orchard, cotton-wheat rotation/sugarcane, rice-fodder, and fodder-wheat. The rice-wheat cropping system predominates in the southeastern regions, such as Punjab. In recent decades, agricultural intensification has led to increased water usage by crops, resulting in a shortfall of available surface water to meet the crop water requirements (Arfan et al. 2019).

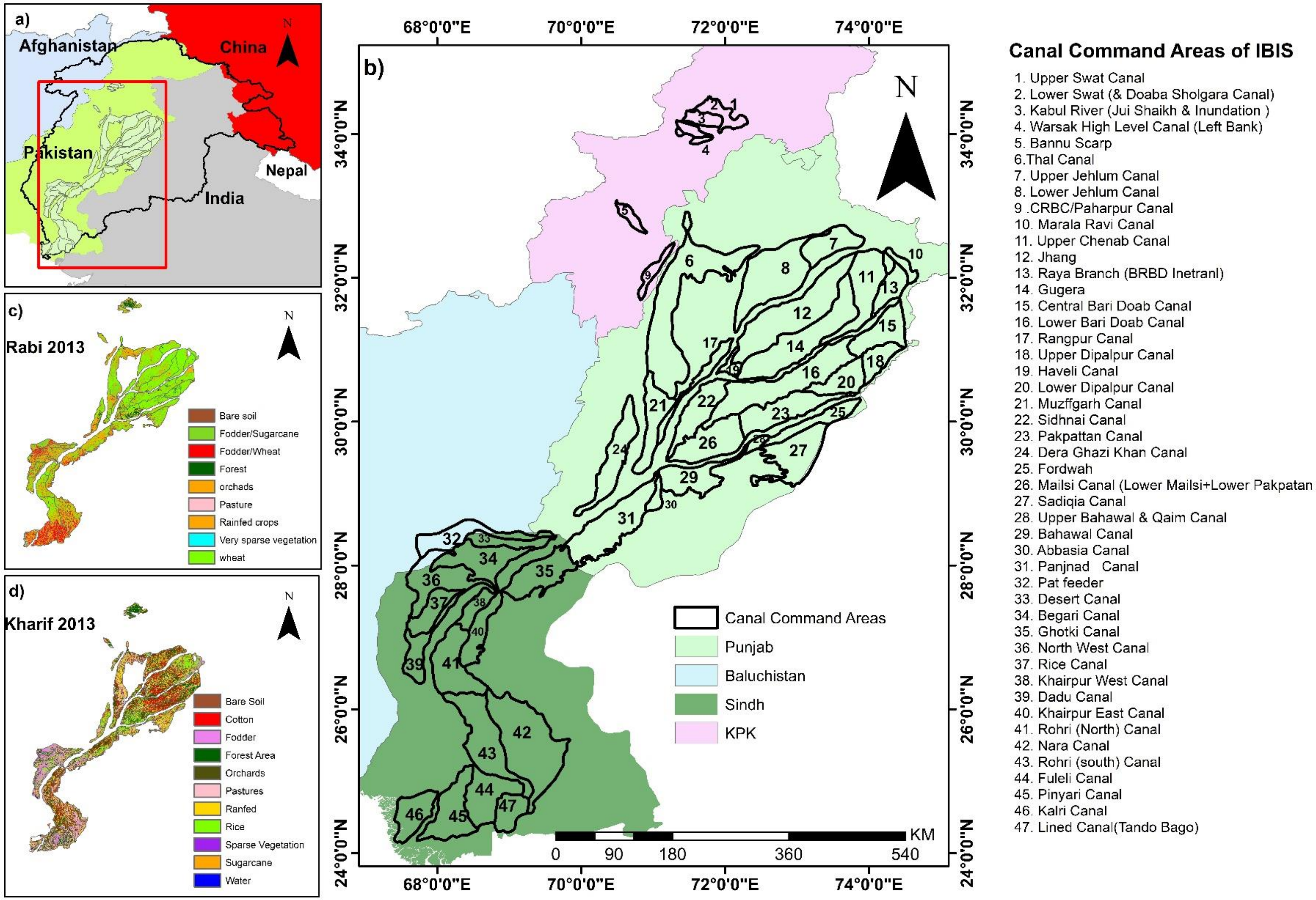

Figure 3.1 a) Transboundary Indus Basin, b) Canal Command areas of Indus Basin Irrigation System, **c)** Land use-Rabi Season 2013, and **d)** Land use Kharif Season-2013

3.4 Data sources used in the study

3.4.1 GRACE total water storage

Monthly TWS data of mascon GRACE-FO RL-06Mv2, released by the Jet Propulsion Laboratory (JPL) of National Aeronautics and Space Administration (NASA) with spatial resolution of 0.5º x 0.5º covering globally, was extracted. Gridded surface mass anomalies derived from mass concentration solution representing an estimate of Earth's mean gravity during the specified time period derived from GRACE mission measurements. These grids represent the hydrology and ice magnitude of the entire land. GRACE-FO is a joint mission of NASA (USA) and the German Research Center for Geosciences (GFZ).

3.4.2 TRMM precipitation

This satellite was developed by NASA and Japanese Space exploration agency (NASDA). Precipitation data of Tropical Rainfall Measuring Mission (TRMM) version TRMM-3B43 Level-3 at the temporal resolution of 1 month and a spatial resolution of 0.25º x 0.25º was collected from NASA (Huffman et al. 2014).

3.4.3 GLDAS datasets

The Goddard Space Flight Center (GSFC) provides Global Land Data Assimilation Systems (GLDAS). The GLDAS land surface assimilation system includes three land surface process models (CLM, Mosaic, NOAH) and a hydrological model (VIC), and it mainly includes two versions of data sets (GLDAS-1 and GLDAS-2). Among them, GLDAS-1 provides four sets of models to simulate global runoff, evapotranspiration, soil moisture, snow water equivalent, and canopy water, and other hydrological variables. The spatial resolution is $1^{\circ} \times 1^{\circ}$, the time resolution has 3 h and monthly scale, and the data set of NOAH model from 2000 to now is $0.25^{\circ} \times 0.25^{\circ}$. While GLDAS-2 only has NOAH model, provided data from 1948 to 2010, with spatial resolution of $1^{\circ} \times 1^{\circ}$ and $0.25^{\circ} \times 0.25^{\circ}$. In this study, we mainly used the data of GLDAS-1 NOAH model with the $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution, which can be found in the Goddard Earth Sciences Data and Information Services Center (GES DISC).

3.4.4 MODIS datasets

The MODIS is orbiting around the earth with both the Terra and Aqua spacecraft and it collects data at different spatial resolutions 0.25 km, 0.5km, and 1km. The NDVI, LST and Actual evapotranspiration data was at a spatial resolution of 1km was used in this study.

3.4.5 Ground based measurements

In this study, depth to water table (DTW) data of around 2500 observation wells were collected from International Waterlogging and Salinity Research Institue (IWASRI) and Punjab Irrigation Department (PID) from 1980 to 2016 for pre-monsoon and post monsoon seasons. These observation wells are distributed in the different Doabs (land between two rivers) of Irrigation system.

3.5 Geographical Weighted Regression (GWR)

Non-parametric technique was developed in 1996 to study the spatial relationship between predictand (TWSA) and predictor variables (SM, R, CWS, SWE, P, ET, LST, NDVI) on a specific location and it is also known as locally weighted regression (Páez & Wheeler 2009). To downscale TWSA/GWSA, predictor variables are introduced into the GWR along with predictand variable to produce different coefficients of each predictor variables. Mathematically, it is given below:

$$Y_i(u_i, v_i) = \beta_{0_i} + \sum_1^N \beta_{n_i} X_{n_i} + \varepsilon_i(u_i, v_i) \quad \textbf{(1)}$$

Where Yi is the predictand (i.e., TWSA/GWSA), β_{0i}, β_{1i} are the coefficients each predictor variable and $\varepsilon_i(u_i, v_i)$ are the uncertainties/residuals at a spatial location (u_i, v_i). The coefficients were determined using different Kernels i.e., Fixed gaussian (FG), Adaptive gaussian (AG), Adaptive Bi-square (AB) and Adaptive gaussian (AG) and the kernel which perform best in predicting the TWSA/GWSA was selected. Fixed and varying coefficients at spatial scale were found using geographical variability test (GVT) which predicts best output i.e., TWSA/GWSA based on model prediction criterion i.e., Akaik information Criterion (AICc), Difference of Criterion (DIFF). For example, a smaller value of AICc and positive value of DIFF suggest that there is no spatial variability among predictand and predictor variables. The overall flow chart is shown in Figure 3.2.

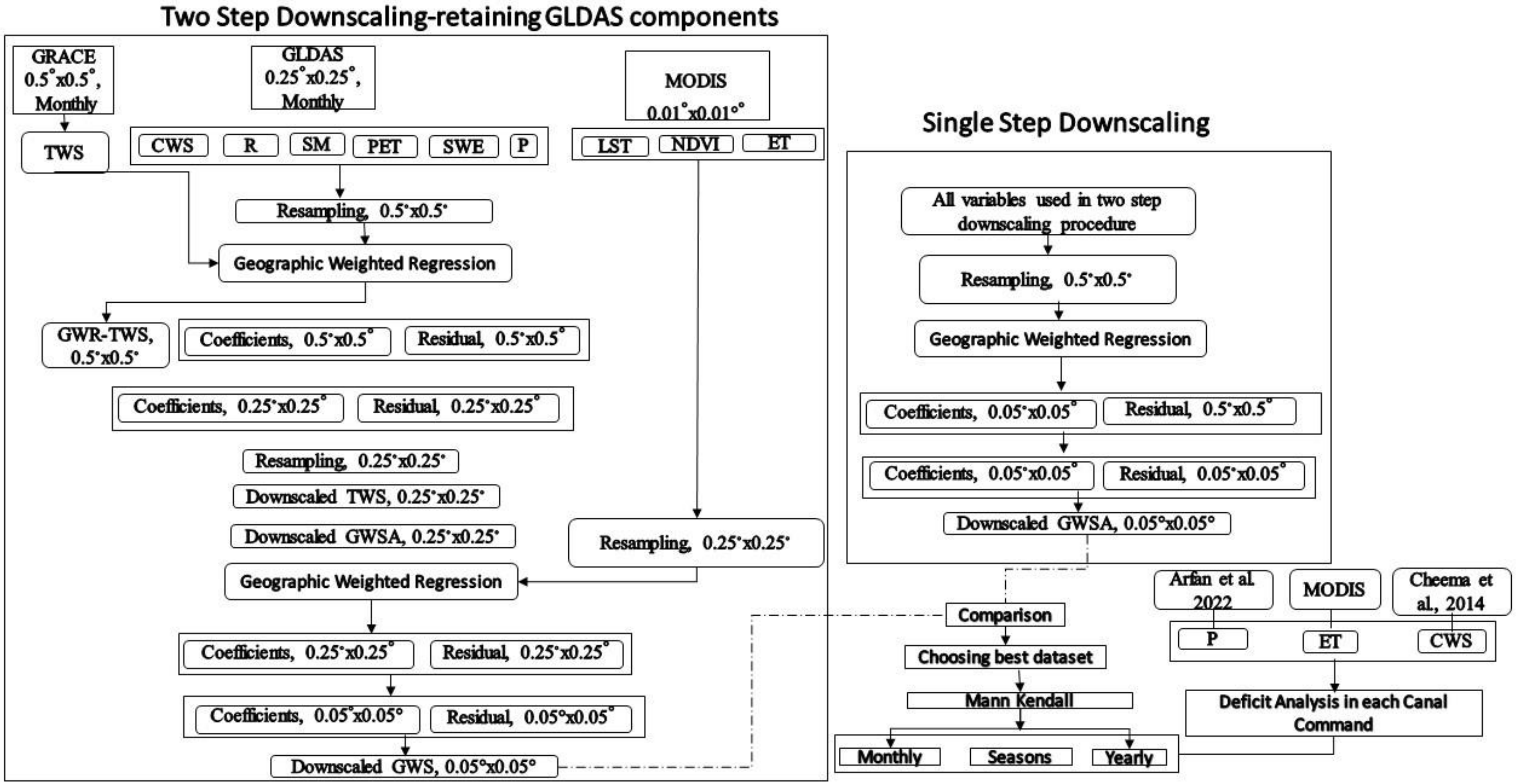

Figure 3.2 Flow Chart of the study conducted in the Indus River Basin

3.6 Results

3.6.1 Performance evaluation of different kernels of GWR

The Figure 3.3 depitcs the coefficient of correlation between GRACE based TWS and GWR based TWS. Higher value of R^2 in Fixed Gaussian (FG) kernel shows that it is performing better in predicting the TWSA because the FG kernel assumes a constant bandwidth, meaning that the range of influence for neighboring observations remains the same across the study area. This assumption is appropriate when the underlying relationships are stationary, and the strength of the spatial influence does not vary significantly. Table 3.1 depitcs the values of R^2, AICc and CV during different months of the year for FG and Adaptive Gaussian (AG) kernel for the study area and these indicators showed the suitabiltiy of approach in estimating high resolution datasets. Table 3.2 and Table 3.3 summarize the results of the GVT test, which included estimates of coefficients and DIFF of Criterion values characterizing the spatially varying and fixed coefficients of the en- vironmental variables. The coefficients for NDVI and Actual ET were introduced as fixed terms into the GWR model based on their higher positive DIFF values (i.e., 65.36 and 40.47), while other coefficients were input as spatially varying terms.

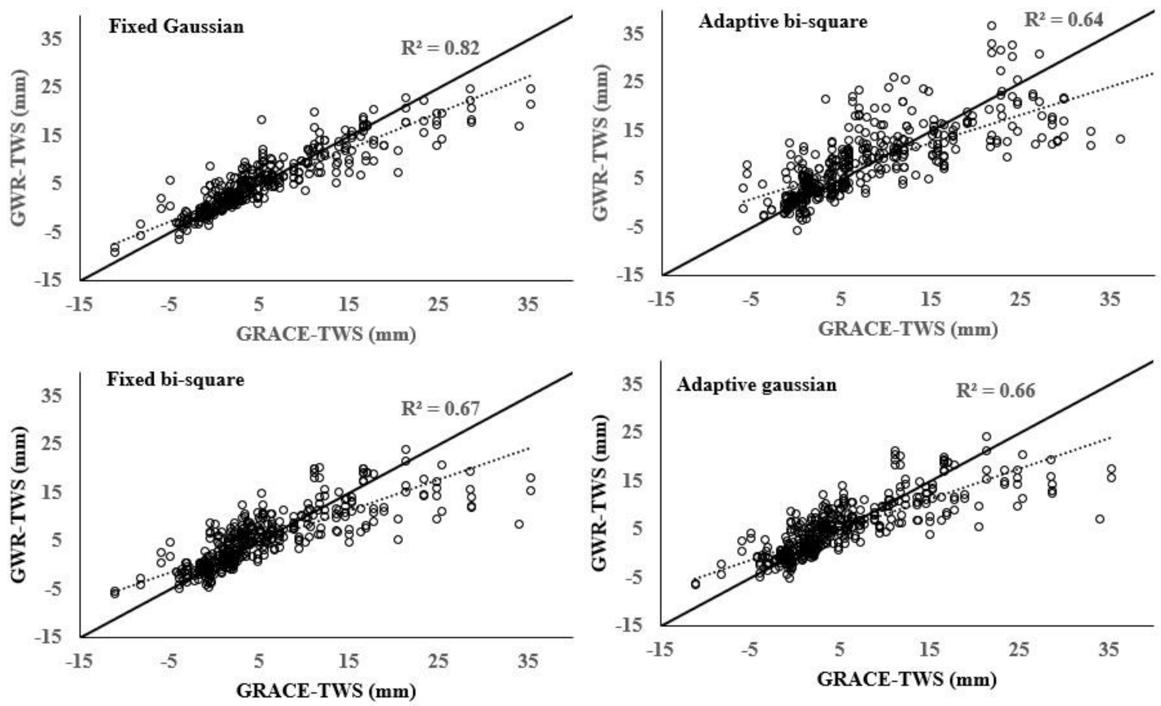

Figure 3.3. Comparison of different kernel of GWR model. GRACE based TWS on x-axis and GWR based TWS

Table 3.1 Performance comparison of two different kernels of GWR predictions

		Jan.	Feb.	Mar	Apr	May	Jun	July	Aug	Sept	Oct.	Nov.	Dec.
FG	AICc	2194	2403	2780	2780	2901	2736	2589	2419	2318	2138	2095	1985
	CV	9.67	15.39	42.80	44.67	55.00	38.43	32.53	20.13	28.92	21.09	14.45	9.98
	R^2	0.75	0.82	0.83	0.87	0.86	0.87	0.83	0.78	0.82	0.83	0.82	0.81
AG	AICc	2390	2538	2942	2959	3067	2960	2734	2553	2492	2420	2395	2258
	CV	14.61	20.53	53.39	57.50	74.33	57.10	33.32	25.41	19.20	18.83	20.00	12.45
	R^2	0.48	0.67	0.66	0.73	0.72	0.71	0.68	0.59	0.64	0.59	0.54	0.55

Table 3.2 Geographical variability test (GVT) of hydrological variables based on Diff of Criterion

Variables	Min	Max	Range	Diff of Criterion
Intercept	-145.80	110.14	255.94	-39.34
Canopy Water Storage	-1857.1	760.50	2617.62	-28.93
Potential ET	-3.23	2.80	6.03	-46.02
Precipitation	-1.33	1.77	3.11	-0.19
Runoff	-438.56	1119.96	1558.52	-13.60
Soil Moisture	-0.24	0.22	0.46	-4.32
Snow Water Equivalent	-6.47	11.56	18.03	-18.92

Positive value of diff-Criterion (DIFF) suggests that there is no spatial variability in terms of specifying hydrological variables as local parameter.

Table 3.3 Geographical variability test (GVT) of land surface variables based on Diff of Criterion

Variables	Min	Max	Range	DIFF of Criterion
LST	-5.84	7.24	13.09	-6628
Actual ET	-0.02	0.03	0.04	65.36
NDVI	-0.14	0.12	0.25	40.47

Positive value of diff-Criterion (DIFF) suggests that there is no spatial variability in terms of specifying hydrological variables as local parameter.

3.6.2 Two step downscaling of GRACE

In the initial step of downscaling, the GRACE-TWSA dataset with a resolution of 0.5° was downscaled to a finer resolution of 0.25° (referred to as GWR-TWSA) for the Indus River Basin. This downscaling process utilized six hydrological variables including soil moisture (SM), precipitation (R), snow water equivalent (SWE), precipitation (P), plant canopy water storage (PCWS), and potential evapotranspiration (PET) as shown in Figure 3.4a. Subsequently, the downscaled GWR-TWSA was subtracted from the auxiliary components of GLDAS to calculate the groundwater storage anomaly (GWSA) at the resolution of 0.25°. In the subsequent downscaling step, the GWSA dataset with a resolution of 0.25° was further downscaled to a finer resolution of 0.05° using land surface variables such as land surface temperature (LST), actual evapotranspiration (ET), and normalized difference vegetation index (NDVI), as shown in Figure 3.4b. Comparing the time series of the original coarse-scale GRACE-based data with the downscaled results in the first downscaling step, it was observed that they exhibited similar variation amplitudes.

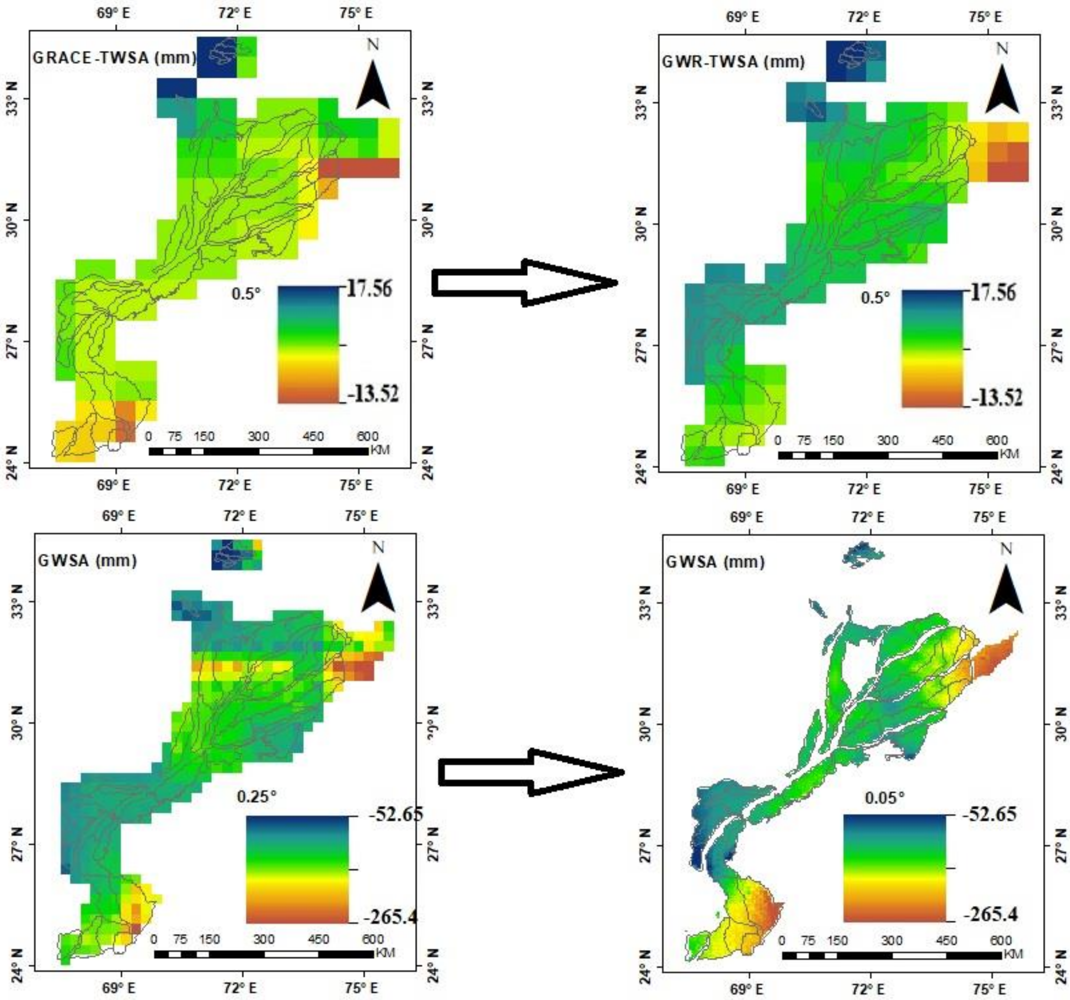

Figure 3.4(a) Original-GRACE -TWSA (0.5º ×0.5º), (b) predicted TWS by the GWR model at the coarse resolution (0.5° ×0.5°), (c) Downscaled TWSA (0.25° ×0.25°) and (d) Downscaled GWSA (0.05°x0.05°)

The values of total water storage anomaly (TWSA) remained consistent before and after downscaling, indicating the suitability of the downscaling approach in predicting changes in TWSA using the current data streams and methods (see Fig. 3.5a). The downscaled results also exhibited consistent amplitude and variation in predicting GWSA (see Fig. 3.5b). Furthermore, the analysis revealed a notable decline in regional total water storage (TWS) within the IBIS, with a rate of -80.65 mm/year from 2003 to 2019. This decline in TWS is primarily attributed to extensive groundwater pumping for human consumption and irrigation water supply, leading to a decrease in groundwater storage (GWSA) over the same period.

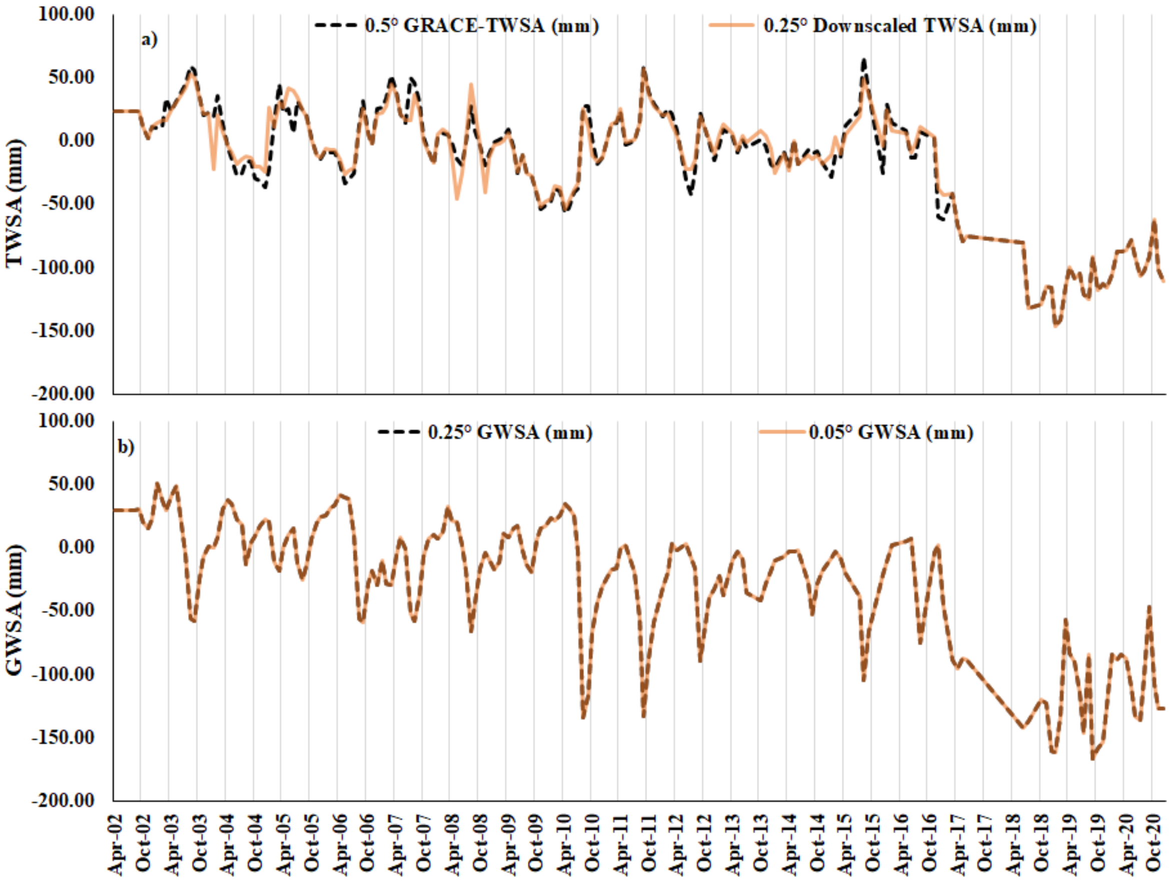

Figure 3.5 **(a)** Time series of grace derived TWSA (0.5°) and GWR derived TWSA (0.25°) i.e., first step of downscaling. **(b)** Time series of coarse GWSA (0.5°) and fine resolution GWSA (0.05°) i.e., second step of downscaling

Spatial variations in groundwater storage anomaly (GWSA) are influenced by both human activities and the arid characteristics of the study region (Feng et al. 2022). The downscaled GRACE data provides a reasonable resolution for understanding GWSA variations at the canal command scale. In this study, we investigated GWSA variations in 47 canal command areas, each characterized by different water allocations and cropping systems (Basharat 2019). Over the period from 2003 to 2019, there was a general decline in GWSA, with pronounced hotspots of groundwater storage decline observed in the canal command areas of Punjab (see Fig. 3.6). Notably, the decline in GWS was more significant in the upper canal command areas compared to those in the lower Indus Basin (see Fig. 3.6). This pattern can be attributed to the fact that a higher proportion of irrigation demand (rice cultivation) in the upstream canal command areas relies heavily on groundwater, and the consumptive fraction of irrigation withdrawal is larger in these regions (Simons et al. 2020).

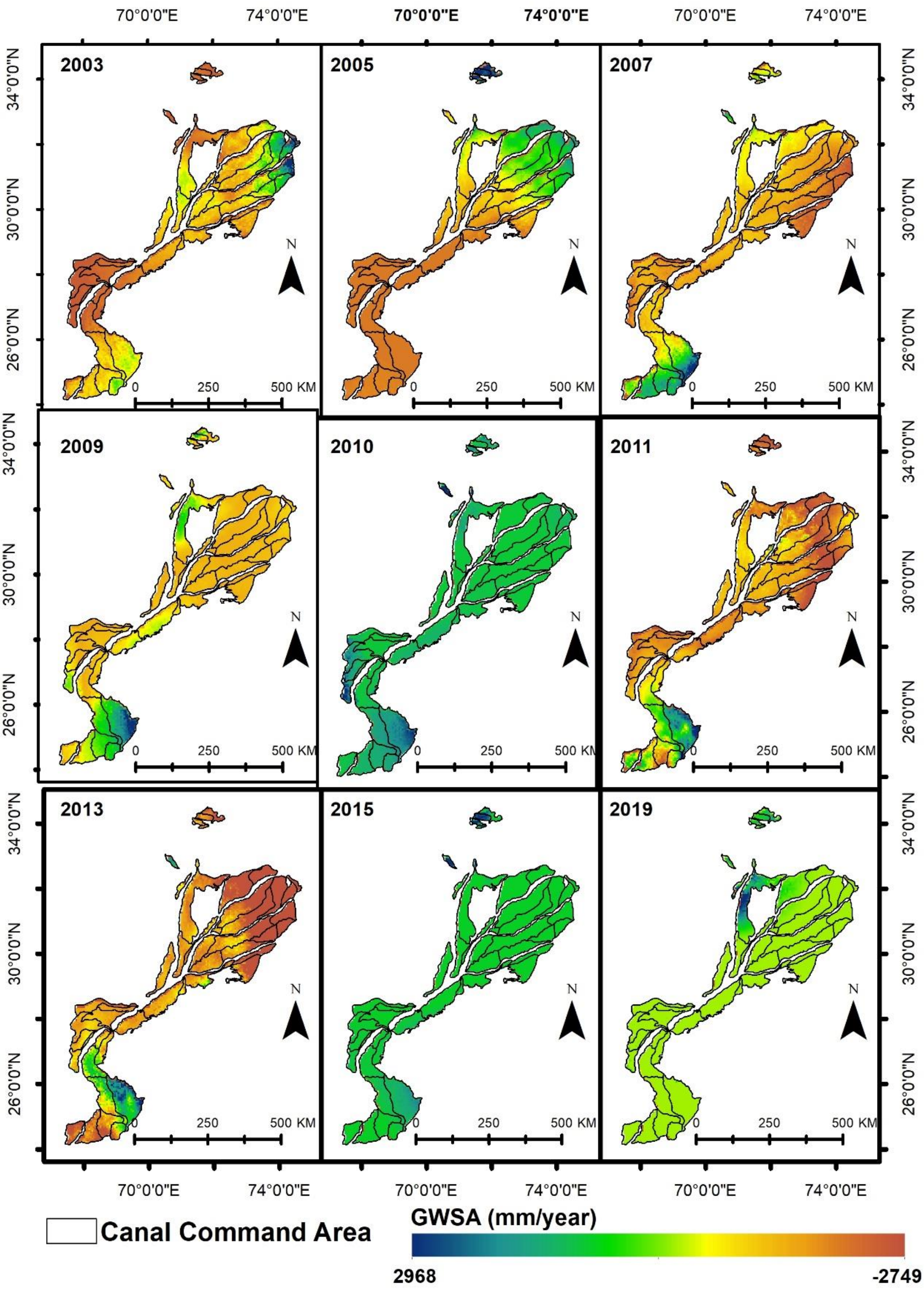

Figure 3.6 Spatial distribution of downscaled GWSA over the IBIS

3.6.3 Groundwater storage variations in canal command areas of Irrigated Indus Basin

Table 3.5 provides an overview of the changes in groundwater storage anomaly (GWSA), depletion rate, and deficit/surplus in relation to average rainfall, surface water diversions, and water allocations for each canal. Notably, canal command areas in KP (such as Lower Swat, Bannu and Warsak Canal) exhibited an upward trend in groundwater storage, ranging from 0.2 to 12.6 mm/month over the study period. This trend can be attributed to the prevalence of rainfed agriculture in the region despite the relatively low allocation of surface water to these canals (Qureshi 2020).

The study findings reveal a downward trend in groundwater levels across each canal command in Punjab, ranging from -1.0 to -18.3 mm per year which implies that most command areas rely substantially on water not diverted at the head of the primary canal rather on the groundwater. The analysis indicates particularly high rates of groundwater depletion in the Marala Ravi Canal, Central Bari Doab Canal, BRBD internal, and Dipalpur Canal (both Lower and Upper sections) which are attributed to high evapotranspiraiton in these canal commands (Ahmad et al. 2021). Conversely, the CRBC/Paharpur Canal and Mailsi Canal demonstrate a decline in groundwater levels that aligns with the allocation of surface water supplies. The CRBC/Paharpur Canal exhibits less depletion due to its higher water allowance, while the Mailsi Canal experiences higher depletion attributed to its lower water allowance. Interestingly, the Muzaffargarh Canal displays the smallest groundwater deficit (-9mm), despite exhibiting a relatively high depletion rate of -8.1 mm per month over the study period. In contrast, both the Thal Canal and Upper Jhelum Canal maintain a surplus balance; however, the trend of depletion remains significantly high. It is striking that a major part of Thal CCA largely depends on rainfed agriculture (PID 2022). These findings underscore the pressing issue of declining groundwater levels in Punjab's canal commands and highlight the varying depletion rates across different canal systems. The results emphasize the importance of considering water allowances and surface water supplies in managing and mitigating groundwater depletion in the region.

The situaion of groundwater is comparitivlely better in Sindh province of Pakistan. The groundwater were trended upward in Pat feeder, North West canal, Rice canal, Dadu canal ranging from 0.1 to 1.3 mm per month which resulted in water logging in thes canal commands due to high water allocations. Low depletion rates were estimated ranging from -0.2 mm per month to -2.3 mm per month in some canal commands of Sindh (Deseart, Begari, Ghotki, Khairpur west, Khair East, Rohri Canal and Nara Canal). The results are in line with the stuy conducted by Ahmed et. Al., (2021) where the Khairpur East, Khairpur West and Rohri/Moro canal command showed the declining trend in these canals.

Table 3.4 Surplus/Deficit to each canal command area and spatial trend over the study period

Sr. No .	Canal command area	P (mm)	ET (mm)	CWS (mm)	Surplus/Deficit (mm)	Trend (mm/ month)	WA (L/1000acre)
1	Upper Swat Canal	888	1063	200	25	-0.9	76
2	Lower Swat (& Doaba Sholgara Canal)	791	1156	180	-185	0.2	62
3	Kabul River (Jui Shaikh & Inundation)	766	1024	200	-58	0.5	65
4	Warsak High Level Canal (Left Bank)	741	855	180	66	1.6	91
5	Bannu Scarp	638	986	170	-179	12.6	93
6	Thal Canal	548	829	325	45	-6.3	62
7	Upper Jehlum Canal	777	1212	720	285	-4.4	82
8	Lower Jehlum Canal	622	1141	300	-219	-3.1	85
9	CRBC/Paharpur Canal	558	993	200	-235	-4.8	640
10	Marala Ravi Canal	892	1195	180	-123	-18.3	348
11	Upper Chenab Canal	686	1220	325	-208	-10.6	150
12	Jhang	548	1122	400	-174	-4.9	91
13	Raya Branch (BRBD Inetranl)	734	1192	250	-208	-11.7	198
14	Gugera	484	1182	430	-268	-7.7	91
15	Central Bari Doab Canal	583	1107	400	-124	-12.7	255
16	Lower Bari Doab Canal	378	1277	500	-399	-6.1	122
17	Rangpur Canal	373	1237	500	-364	-6.3	195
18	Upper Dipalpur Canal	493	1261	250	-518	-11.3	142
19	Haveli Canal	392	1299	700	-206	-7.1	388
20	Lower Dipalpur Canal	398	1343	530	-415	-11.6	184
21	Muzffgarh Canal	327	1236	900	-9	-8.1	232
22	Sidhnai Canal	330	1373	500	-543	-4.7	150
23	Pakpattan Canal	329	1370	450	-591	-5.4	167
24	Dera Ghazi Khan Canal	302	1244	800	-142	-5.8	243
25	Fordwah	347	1280	400	-533	-3.9	181
26	Sadiqia Canal	316	1037	545	-175	-6.4	122
27	Mailsi Canal (Lower Mailsi+Lower Pakpa	289	1390	550	-551	-4.0	42
28	Upper Bahawal & Qaim Canal	293	1303	900	-111	-1.0	195
29	Bahawal Canal	257	1093	640	-196	-4.2	195
30	Abbasia Canal	242	998	300	-456	-4.0	195
31	Panjnad Canal	237	1278	600	-441	-2.8	173
32	Pat feeder	160	1166	800	-206	0.1	201
33	Desert Canal	153	1245	740	-352	-0.6	792
34	Begari Canal	151	1184	700	-333	-0.5	385
35	Ghotki Canal	174	1145	700	-271	-1.1	229
36	North West Canal	158	1148	550	-440	0.1	119
37	Rice Canal	156	1252	900	-196	0.3	475
38	Khairpur West Canal	160	1433	630	-643	-0.2	147

39	Dadu Canal	167	957	630	-160	1.3	144
40	Khairpur East Canal	172	899	440	-286	-0.3	119
41	Rohri (North) Canal	181	1201	530	-491	-1.0	226
42	Nara Canal	275	1167	700	-192	-2.3	142
43	Rohri (south) Canal	226	1473	530	-717	-5.1	142
45	Fuleli Canal	278	1299	900	-121	-5.0	351
46	Pinyari Canal	271	1062	630	-161	-7.9	382
48	Kalri Canal	269	990	750	29	-4.7	226
49	Lined Canal(Tando Bago)	320	1263	500	-443	-6.4	311

3.6.4 Overall trends in Groundwater Storage Anomaly Changes in Irrigated Indus Basin

The estimation of trends in downscaled groundwater storage at 0.05-degree grids employed a combined approach utilizing the Seasonal Mann-Kendall trend test for detecting the significance of a monotonic trend and the Sen Slope estimator for quantifying the magnitude of the trend. Nonparametric trend methods were employed in this study to circumvent the violation of assumptions associated with parametric trend tests, thereby ensuring the reliability of the results. The selection of these nonparametric trend methods was made to maintain the integrity of the analysis. Figure 3.7 illustrates the gridded trends observed over the period from April 2002 to December 2020. Approximately 50% of all gridded trends exhibited statistically significant downward trends (N=5976, n=2972, $p < 0.05$) in the Irrigated Indus Basin. The spatial variability in groundwater trends is generally associated with land use patterns and varying water allocations in the regions (Qureshi 2020; Mehmood et al. 2022). Significant declines in groundwater storage were observed in the Punjab canals, consistent with previous spatial studies highlighting groundwater depletion in this area. In the Punjab province of Pakistan, decreases in groundwater storage are well-documented and attributed to extensive water extraction for agricultural purposes. In the southwest part of the irrigated basin, increases in groundwater storage have been identified, linked to the potential for flooding, higher contributions of baseflow from groundwater sources, and elevated water allocations. Northern portions of the High Plains Aquifer in KKP have experienced increases in groundwater storage attributed to rainfed agriculture. According to van Steenbergen et al.(2015), excessive canal supplies in several Sindh canal command areas have been observed to cause extensive waterlogging issues and waterlogging issues.

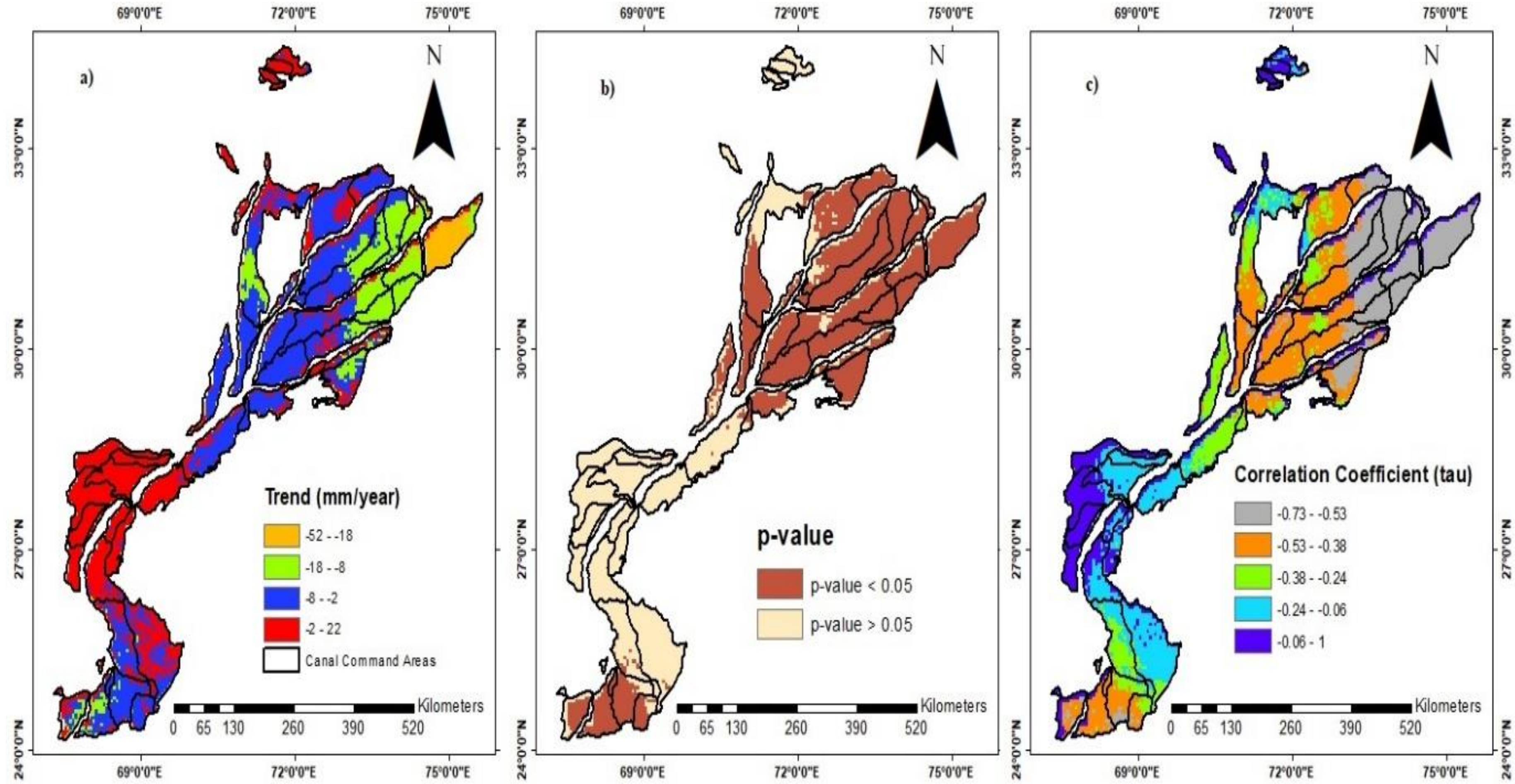

Figure 3.7 (a) Trends-Sen Slope in Downscaled GRACE-derived groundwater storage anomalies determined by Seasonal Mann-Kendall trend tests (b) Slope Significance (c) Correlation coefficient to highlight the strength and direction of trend over the study period (Jan. 2003 to December 2020)

3.7 Conclusions

The utilization of an advanced two-step down-scaling method to produce high-resolution GRACE-based groundwater storage (GWS) analysis significantly enhances the capacity to identify areas of concentrated groundwater storage variation and depletion within distinct irrigated plains featuring diverse cropping systems in the IBIS. The changes in GWS exhibit notable spatial heterogeneity, with the most pronounced decline observed in upstream regions like Punjab, although a minor decrease is also evident in the lower Indus Basin. Our findings demonstrate a strong correlation between the temporal and spatial heterogeneity of GWS changes and the distribution of surface water allocation, types of cropping systems within different canal command areas. Generally, irrigated plains characterized by limited water flow and reduced precipitation are witnessing substantial groundwater abstraction and a decline in groundwater storage. Uncontrolled groundwater extraction consistently surpassing recharge is exacerbating groundwater stress, consequently posing a threat to the sustainability of groundwater reserves in the IBIS.

Chapter 4

Analyzing and Evaluating Environmental Flows through Hydrological Methods in the Regulated Indus River Basin

A part of this chapter has been presented in conference as:

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4 Analyzing and Evaluating Environmental Flows through Hydrological Methods in the Regulated Indus River Basin

4.1 Abstract:

Environmental flows (EFs), essential for upholding the ecological integrity of rivers and aquatic habitats, have been disrupted significantly by diverting water for agricultural, industrial, and domestic uses. This underscores the imperative of implementing sustainable water resource management to harmonize agricultural and environmental needs. The study was conducted in the Indus River basin (IRB), a region extensively transformed by human interventions. Environmental flows (EFs) were determined through various techniques, including the flow duration curve shifting method, flow duration curve analysis, low flow indices, the Tennant method, the Smakhtin approach, the Tessman method, and the Pastor method. Analyzing the estimated EFs alongside downstream flows unveiled specific timeframes (days, months, and seasons) of unmet environmental flow requirements. To safeguard the downstream ecosystems, the following EFs were estimated for the respective locations: 880 m^3/s (38% of the Mean Annual Flow (MAF)) for the Indus River at Tarbela Dam, 412 m^3/s (48% of the MAF) for the Jhelum at Mangla Dam, 425 m^3/s (44% of the MAF) for the Chenab at Marala headworks, 389 m^3/s (56% of MAF) for the Ravi at Balloki headworks, 184 m^3/s (50% of MAF) for the Sutlej at Sulemanki headworks, and 231m^3/s (38% of MAF) below Kotri barrage. The study revealed that violations of EFs occurred 41%, 43%, 44%, and 52% of the time during the study period for the Chenab at Marala headworks, the Ravi at Balloki headworks, the Sutlej at Sulemanki headworks, and the Indus river below the Kotri barrage, respectively. The results highlighted that the Chenab, Ravi, and Sutlej Rivers are particularly susceptible to vulnerable, as the estimated EFs were not consistently upheld in these rivers. These findings underscore the urgent need to take appropriate measures to ensure EFs are not violated, thus safeguarding the downstream ecosystems.

4.2 Introduction

On a global scale, the availability of freshwater resources is declining due to the rapidly increasing population, proliferation of cities, and increase in demand of water for agriculture and industries (Cheema & Qamar 2019). Currently, humans utilize 50% of the world's accessible surface water, and this figure is projected to rise to 70% by 2050 (Acreman & Ferguson 2010), given the limited availability of freshwater. In the past and currently, human water requirements have been prioritized over the freshwater needs of species and ecosystems (Liu et al. 2018). A river, one of the main sources of freshwater, plays a crucial role in upholding the hydrological cycle and serves as a natural habitat for freshwater ecosystems (Gleeson et al. 2020).

In terms of worldwide discharge, approximately 65% of rivers fall into the category of facing moderate to high threats with respect to biodiversity (Vörösmarty et al. 2010). Furthermore, notable alterations in fish biodiversity have been observed in 53% of rivers, and the connectivity of 48% of global river stretches has been compromised due to damming, as noted by Grill et al. (2019) and Su et al. (2021). The primary reason for this degradation is human interference with the natural flow regime of rivers, which involves modifications in the quantity (timing, frequency, duration), quality, and damming of the rivers. (Poff et al. 1997; Leigh et al. 2012; Belmar et al. 2013). The anthropogenic activities, i.e., flow regulation and water diversions by dams/barrages, have severely strained the ecosystems (Best 2019) and have severely reduced the downstream flows in the world. The natural streamflow has been altered in almost all the major rivers worldwide (Günther Grill et al., 2015). In the Lake Chad basin, the downstream flows declined to 45% because of human intervention (66%) and climatic variability (34%) (Mahmood & Jia 2019). Reduced stream flow and dried lower river reach was reported by Li et al. (2019) in the Yellow River due to human activities and climate change, which is affecting the downstream ecosystem and flow regime in the basin. The flow regime plays a critical role in sustaining the ecological condition and well-being of riverine ecosystems because of its significant impact on the river's physical habitat (Poff & Zimmerman 2010). Therefore, minimum flow is essential to maintain the river's eco-environmental health besides flow regulation for food production. A global water survey involving water specialists revealed that 88% of the respondents acknowledged the significance of EFs to sustain water resources and fulfilling the long-term requirements of society (Uday Kumar & Jayakumar 2021).

For its significant importance in safeguarding riverine ecosystems (Poff & Matthews 2013), Environmental Flows (EFs) have been defined by Arthington et al. (2018) as " encompassing the necessary requisite volume, timing, and quality of freshwater flows and levels. This definition serves to ensure the viability of aquatic ecosystems, which, in turn, provide the foundation for human cultures, economies, sustainable livelihoods, and overall well-being. Meanwhile, Environmental Flow Requirements (EFRs), as elucidated by Pastor et al. (2014), refer to the minimum discharge essential for upholding the health and functionality of riverine ecosystems.

A multitude of frameworks and approaches with varying levels of complexity, time requirements, and data requirement have been established to investigate the EFRs of rivers. These approaches are discussed in detail and used by various researchers (Acreman & Dunbar 2004; Linnansaari et al. 2013; Abdi & Yasi 2015; Theodoropoulos et al. 2018; Zeiringer et al. 2018; Virkki et al. 2021). Among the options for assessing EFRs of rivers (Tharme 2003; Zeiringer et al. 2018), more than 200 techniques are currently available worldwide, broadly grouped into hydrological methods, habitat simulation methods, hydraulic rating methods, and holistic solutions. Some techniques are simple and only require statistical indicators, such as Q_{90}, Q_{95}, and $7Q_{10}$. For instance, Q_{90} is used to assess the low flows conditions or to develop a threshold for warning of critical water levels in different parts of the world (Smakhtin 2001; Rivera-Ramírez et al. 2002) and Q_{95} is used as EFRs in the UK to develop limit values associated with water withdrawal from diversion structures. On the other hand, some methodologies, such as Building Block Methodology (BBM), Scientific Panel Approach (SPA), Expert Panel Assessment Method (EPAM), and Bench Marking Methodology (BMM), are complex and demand considerable knowledge regarding hydrological and ecological characteristics as well as the assistance of experts such as hydrologists, geomorphologists, ecologists, and biological scientists (Acreman & Dunbar 2004). The selection of an approach depends on the goals of the study and data availability, as each approach has its particular benefits and drawbacks. Lack of river ecological data in the IRB necessitated the use of hydrological methods to assess the situation of EFs within the cascade environment of diversion structures.

The dams and barrages on the Indus River basin (IRB), including Tarbela Dam and Kotri Barrage on the Indus River, Mangla Dam on the Jhelum River, Marala Barrage on the Chenab River, Balloki headworks on the Ravi River, and Sulemanki barrage on the Sutlej River, have contributed significantly to irrigation-based food production in Pakistan. Yet, they have also created environmental flow issues. In the IRB, water flow is regulated daily, and water accumulated during the rainy and snowmelt season is utilized to meet the water demands during the non-rainy and dry spells of the year, leading to changes in the low and high flows of rivers (Uday Kumar & Jayakumar 2021). This practice leads to modifications in water quality and negatively impacts aquatic ecosystems along the river and flood plain, aquatic and linked terrestrial ecosystems. Water withdrawal affects low flows, while flood control operations reduce high flows. Boon and Raven (2012), Syvitski et al. (2013), and Qureshi et al. (2003)

reported a reduction in downstream flows of the Indus River and its tributaries due to modification and/ or addition of dams and barrages in the system during the 19th and 20th century and the natural flow reductions up to 90 % reported in the IRB (Giosan et al. 2006). The partition of water resources between upper riparian (India) and lower riparian (Pakistan) via the Indus Water Treaty-1960 (IWT-1960), as well as within the provinces of Pakistan via the Water Apportionment Accord-1991 (WAA-1991), has resulted in a notable decrease and modification of natural hydrological processes. The modification in the characteristics of the Indus and its tributaries significantly impacted the downstream flows, spread, and range of biodiversity (Syvitski et al. 2013), and this impact posed a persistent threat to ecosystems. The violation and non-attainment of EFs have had negative impacts on aquatic ecosystems, including fish populations and water quality (IUCN 2010). The environmental challenges faced by IRB include rapid reduction in sediment flux, seawater intrusion, soil salinity and erosion, and coastal retreat (Syvitski et al. 2013). In addition, a reduction in mangrove cover and diversity, reduction in marine life, and endangering of the Indus dolphin and green turtles were reported (GoP 2000; Braulik & B:D: 2017) in the basin. The range of the Indus dolphin has been reduced by almost 80% because of damming on the Indus River and its tributaries (Braulik & B:D: 2017). To meet these challenges faced by freshwater ecosystems, the river flows must meet the minimum flow required to conserve the ecosystem (Poff et al. 2010). Indus River System Authority (IRSA) (1991) agreed that there is an urgent need to establish certain minimum flow levels for environmental purposes through WAA-1991 but the signatories were unable to agree on the quantity to be discharged (Anwar & Bhatti 2017a). Water is a scarce commodity within the Indus Basin and across various provinces of Pakistan. The allocation of water resources for agricultural purposes takes precedence over releasing water to support environmental needs. This prioritization stems from intense competition among provinces vying for irrigation water to sustain food production. Therefore, the signatories could not agree on the quantity of water to be released as E-flows. Consequently, there is a diminished emphasis on allocating water resources for environmental preservation.

To address the pressing environmental challenges, it is imperative to assess the existing EFRs for the preservation of the riverine ecosystem situated downstream of the diversion structure. Unfortunately, there is currently no infrastructure in place to gather ecological data in relation to river flows in the study area. Such data is crucial to establish a comprehensive understanding of the interplay between the riverine ecosystem and natural flows, which will ultimately aid in identifying a suitable environmental flow necessary to maintain the health of the riverine ecosystem. This study utilized a diverse range of hydrological methods – including

Tennant method, Flow Duration Curve Analysis (FDCA), Low flow indices, Global Environmental Flow Calculator (GEFC), Pastor et al., (2014) method considering Low Flow (LF), High Flow (HF) and Variable flow (VF) months, Smakhtin et al., (2004), and Tessmann (1980) approaches. While previous studies by Salik et al. (2016), Kamal (2008), and Gonzalez et al. (2005) have primarily assessed EFRs solely at the Kotri Barrage, the last diversion structure on the Indus River, the present study expands its scope significantly. By incorporating multiple hydraulic structures – Tarbela dam on the Indus river, Mangla dam on the river Jhelum, Marala Barrage on the river Chenab, Balloki headworks on the river Ravi, and Sulemanki barrage on the river Sutlej – a holistic understanding of the relative contributions of each tributary in attaining EFs in the basin was explored. This inclusive approach takes on added significance against the backdrop of water division among upper and lower riparian regions. Moreover, this study introduces a granular analysis of temporal scales – daily, monthly, seasonal in different years– to pinpoint the specific instances when EFRs are not met. Furthermore, violation ratios were estimated for (Chenab, Ravi and Sutlej) river to highlight the frequency and severity of environmental flows un-attained in the IRB. This information was then utilized to dig the underlying reasons for non-attainment of EFs in the basin. The findings of this study are expected to prove invaluable to water resource managers and policymakers to devise effective strategies aimed at improving the EFRs and, by extension, the health of the riverine ecosystem.

4.3 Study area and data description

The Indus River, which is a vital source of water for billions of people residing in the river basin shared by India, Pakistan, China, and Afghanistan, plays a crucial role in supporting a diverse range of ecosystem services that are fundamental to the region's sustained economic growth, poverty alleviation, prosperity, food security, energy demands, and, notably, political stability (Romshoo 2012; Cheema & Qamar 2019). Originating from the Tibetan Plateau, the river and its tributaries flow through the Himalayan valleys to the northwest, before meandering through Pakistan, the Kashmir region, and eventually reaching the Arabian Sea (Archer et al. 2010). The upper catchments of the Himalayan Mountains contain glacial ice and permanent snow, which serve as the foundation for one of the world's most comprehensive irrigation networks.

There are several diversion hydraulic structures for providing irrigation water for food production. While the dams and barrages on the Indus River system, including Tarbela on the Indus River, Mangla on the Jhelum River, Marala on the Chenab River, Balloki on the Ravi

River, and Sulemanki on the Sutlej River (Figure 1), have contributed significantly to food production in Pakistan, they have also created environmental flow issues. These hydraulic structures provide water for irrigation, which is essential for the cultivation of crops like wheat, rice, cotton, and sugarcane. The fertile soils and favorable climate in the region also contribute to high agricultural productivity.

The Indus River and its tributaries support a rich biodiversity of aquatic species, including fish, turtles, amphibians, and mammals. The Indus dolphin is one of the most endangered freshwater species in the world, with a population of only a few hundred individuals (Waqas et al. 2012; IUCN 2020) and is found only in the Indus River and its tributaries. The Indus River system supports several species of freshwater turtles and the populations of freshwater turtles in the Indus River system have declined significantly due to habitat loss, overfishing, and pollution (IUCN 2020). The smooth-coated otter is a semi-aquatic mammal that is found in the Indus River system and the species is listed as vulnerable due to habitat loss, pollution, and human disturbance (Khan et al. 2010). The flows data used in the study is shown in Table 1 and the methodology is explained as a flow chart in Fig. 2. The study period 1990–2021 was selected to monitor the existing situations of EFs after the apportionment of water among provinces of Pakistan in 1991 through the WAA-1991 when the water allowance to different canal command, provinces and rivers were established and guaranteed under the umbrella of water distribution treaties in the basin.

4.4 Methods

4.4.1 Tennant method (1976)

The hydrological technique introduced by Tennant (1976) is recognized as the most commonly utilized method for assessing environmental flow, owing to its swift implementation (Shaeri Karimi et al. 2012) and the method has been utilized in over 25 countries (Tharme 2003). Tennant collected field data from more than 100 different gauges of eleven distinct rivers in Montana, Nebraska, and Wyoming, and presented his findings following physical, biological, and chemical examination of the river. The outcomes of his research include an empirical relationship that proposes the % of mean annual flow (MAF) required to sustain the river ecosystem and provide favorable conditions for fish. In his research, Tennant (1976) employed the proportion of MAF for the low flow (LF) period (October–March) and high flow (HF) period (April–September) in the North-Central USA, as indicated in Table 2. Nevertheless, these intervals can be modified to correspond to the low and high flow periods of a river (Linnansaari et al. 2013). For instance, Orth & Maughan (1981) utilized July–

December as a LF period, corresponding to 10% of the MAF, in Oklahoma, USA. In the present study, the LF period was assigned as October–April, while May–September was designated as the HF period, to evaluate environmental flow in the IRB.

Table 4.1 Hydraulic structures in the Indus River Basin used

Sr. No.	Station Name	River	Longitude	Latitude	Time Period
1	Tarbela Dam	Indus	73.64502	33.14208	1990-2021
2	Mangla Dam	Jhelum	72.69833	34.08972	1990-2021
3	Marala Barrage	Chenab	74.4644	32.6724	1990-2021
4	Balloki Barrage	Ravi	73.8585	31.2236	1990-2021
5	Sulemanki Barrage	Sutlaj	73.8663	30.3779	1990-2021
6	Kotri Barrage	Indus	68.3166	25.4423	1998-2018

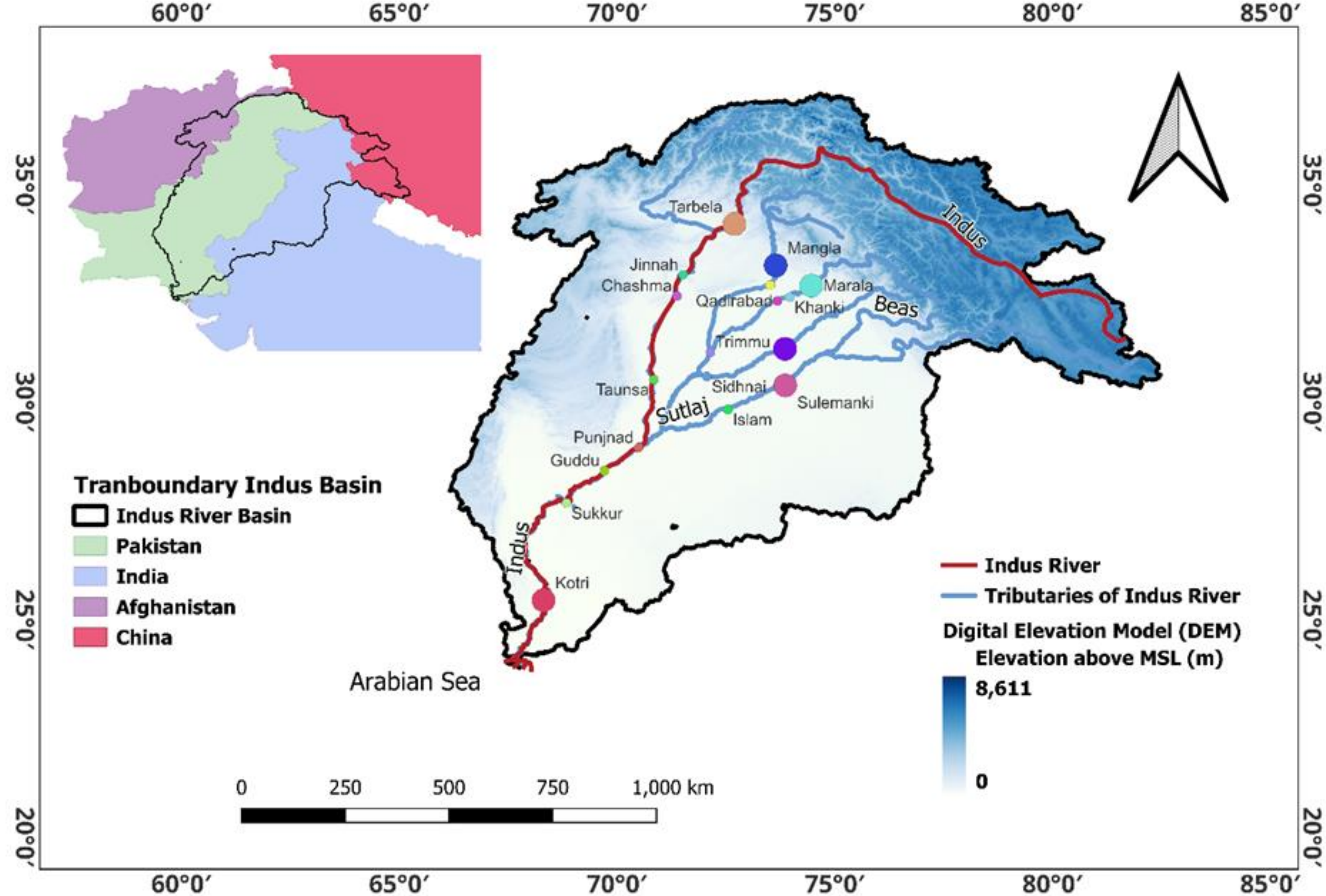

Figure 4.1 Transboundary Indus River Basin with its major tributaries. The large and small circles of different color on each river represent the major hydraulic structures. However, large circles represent the study area points where the Efs were assessed and monitored

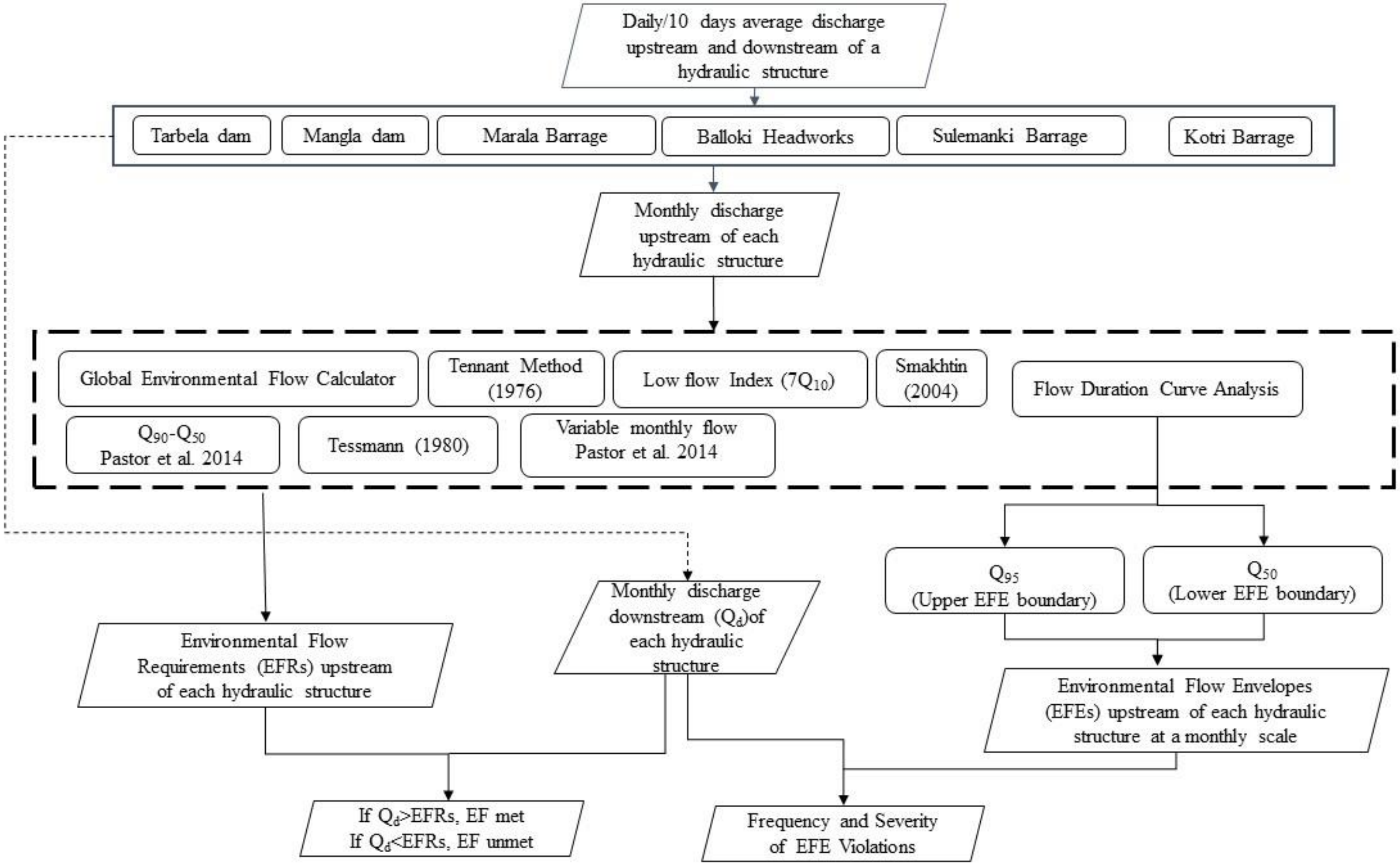

Figure 4.2 Flow chart of study: the data and methods use

4.4.2 Low flow index method ($7Q_{10}$)

The hydrological index known as the $7Q_{10}$ is commonly utilized in the United States as the primary method for assessing environmental flow and is the second most commonly used index for this purpose (Smakhtin 2001; Linnansaari et al. 2013; Abdi & Yasi 2015). It is defined as the lowest average flow that occurs for seven consecutive days and has a return period of ten years (Smakhtin 2001). This approach is based on the identification and selection of an extreme value, whereby the lowest flow from each year of the record is computed and examined for a series of years. The calculation of the $7Q_{10}$ metric involves the derivation of a time series of 7-day averages using daily streamflow data. Subsequently, an annual series of minimum streamflow is derived from the 7-day averages. The flow rate that corresponds to the 10-year recurrence interval is then computed from the minimum annual time series, representing the minimum necessary environmental flow.

Table 4.2 Recommended Environmental Flow by Tennant (1976)

Description	Low flow (LF) period (Oct-April)	High flow (HF) period (May-November)
Flushing	200% of MAF	
Optimum Range	60 to 100% of MAF	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Severe degradation	Less than 10%	Less than 10%

4.4.3 Flow Duration Curve Analysis (FDCA)

The low flow frequency method also referred to as the exceedance probability method, is an additional environmental flow approach that has been implemented in many parts of the globe (Linnansaari et al. 2013; Hua & Cui 2018; Stamou et al. 2018). This method is defined as the proportion of time during which a certain flow threshold level is equaled or exceeded in a given river or region, and it is calculated using data collected over multiple years, typically more than 20 years. According to FDCA analysis, the Q_{95} and Q_{90} flows are commonly utilized as low-flow indices (Abdi & Yasi 2015) and are among the most widely used parameters for establishing environmental flow requirements (Shaeri Karimi et al. 2012).

4.4.4 Global Environmental Flow Calculator (GEFC)

In collaboration with the Water Systems Analysis Group of the University of New Hampshire, the International Water Management Institute (IWMI), situated in Sri Lanka, has successfully developed a freely available software application known as the Global

Environmental Flow Calculator (GEFC) (Shaeri Karimi et al. 2012) . This application, extensively utilized for evaluating Environmental Flow Requirements (EFRs) across various river basins, is based on the flow duration curve shifting (FDCS) method. The FDCS method, devised by (Anputhas 2006), consists of four distinct steps for estimating EFRs, as detailed below. The effectiveness of GEFC has been demonstrated through its application in different river basins, as highlighted in studies by Mahmood et al. (2020), Pastor et al. (2014), and Salik et al. (2016).

The initial step in the process of estimating environmental flows is to compute a reference flow duration curve (FDC) utilizing monthly flow time series data obtained from a given river. This approach involves the creation of FDCs against 17 fixed points, such as 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, and 99.99%, as shown in Figure 4.3, which indicate the flow values that were equaled or exceeded for a specific percentage of the time in the river. Two main reasons exist for determining flows against these points: (1) they adequately cover the entire flow range and facilitate the creation of a smooth FDC, and (2) they are convenient to use during the creation of environmental flow time series (Steps 2-4).

The second step entails determining the desired environmental state or ecological/environmental management classes (EMCs) that must be maintained or attained by providing the EFRs. The EMCs can be established through empirical relationships between flow and eco-environmental conditions. This can be challenging since these thresholds may not be explicitly defined. In this method, six EMCs are employed, which are described in Table 4.3. The third step in this process involves computing environmental Flow Duration Curves (FDCs) for each Environmental Management Class (EMC) using a reference FDC. Smakhtin and Anputhas (2006) introduced a simple approach for calculating the FDC for each EMC, wherein the reference FDC is shifted by 1-6% along the probability axis to obtain FDCs for classes A-F, with a fixed 1% difference between each, as shown in Figure 3. For instance, a 1% shift denotes a flow that was equaled or exceeded 80% of the time in the reference FDC now being equaled or exceeded 70% of the time in class A, with corresponding changes in the flow at other probabilities.

The last step involves the generation of flow time series for each EMC by spatially interpolating monthly environmental flow time series using available data on the reference Flow Duration Curve (FDC), environmental FDC, and reference monthly time series. Figure 3 displays the resulting FDCs for each EMC at the Tarbela dam on the Indus River, offering a more comprehensive understanding of the shifting procedure.

Table 4.3 Environmental Management Classes (EMCs) with ecological conditions (Anputhas 2006)

EMCs	Ecological condition
A (natural)	Rivers that haven't been changed too much, except for some small adjustments to the plants and animals that live in and around them
B (slightly modified)	Rivers that have undergone minor modifications yet possess ecological significance, retaining largely unaltered biodiversity and habitats despite anthropogenic alterations to the water resources and basin morphology
C (moderately modified)	The biotic communities have experienced habitat and dynamic disturbances, but the core ecological processes remain unaffected. However, there has been a loss or reduction in population size of delicate species and the introduction of alien species has altered the existing biotic relationships.
D (largely modified)	Significant alterations in the natural habitat, biotic communities, and ecological processes have taken place, resulting in a decrease in species richness from expected levels. The diminished presence of intolerant species further indicates the extent of the disturbance, while the dominance of non-native species highlights the role of human activity in the ecosystem's current state.
E (seriously modified)	The reduction in habitat diversity and availability has led to a significant decline in species richness below expected levels, leaving only tolerant species to thrive. Additionally, the inability of indigenous species to breed highlights the severity of the disturbance, while the introduction of non-native species has further disrupted the ecosystem's delicate balance.
F (critically modified)	The extent of modifications to the ecosystem has reached a critical level, resulting in a complete alteration of the natural habitat and biotic communities. In the most severe cases, the destruction of basic ecosystem functions has occurred, and the changes may be irreversible, further emphasizing the need for immediate and effective conservation measures.

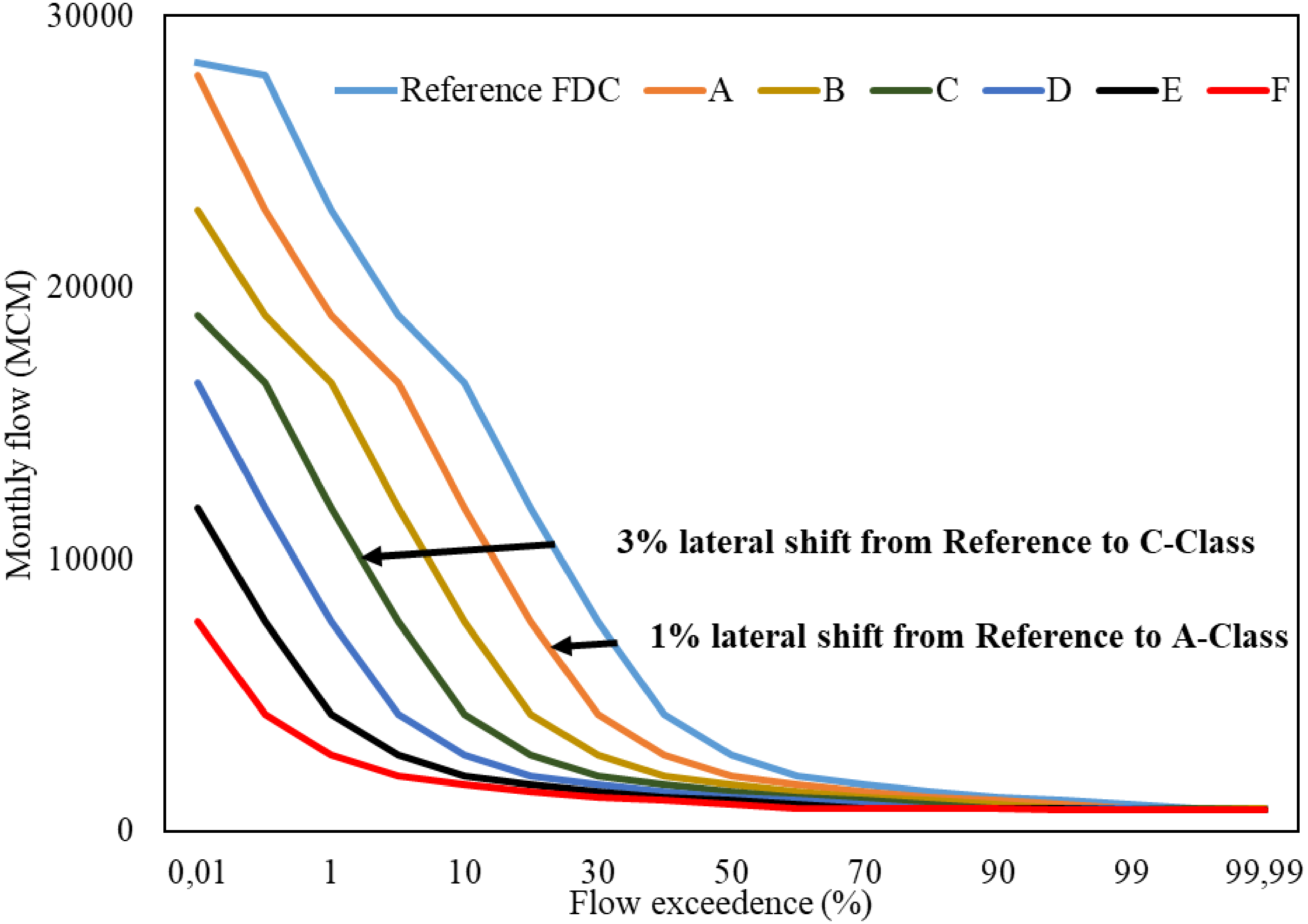

Figure 4.3 Estimation procedure for environmental FDCs for each EMCs. (The FDCs for Tarbela Dam on the Indus River)

4.4.5 Environmental Flow Envelopes (EFEs) coupled with different EFRs methods

In this study, the method developed by Virkki et al. (2021) was employed to determine the minimum and maximum flow requirements for a river or stream to maintain its ecological integrity and to explore the violation ratio in the IRB. Environment flow envelopes (EFEs) are a boundary of discharge limits within which river ecosystems are not disturbed. This approach employed EFEs along with various EFRs methods (Table 4.4) i.e., Pastor et al. (2014) for VF months and Q_{90}-Q_{50} method, Tessmann (1980), Tennat (1976), Smakhtin et al. (2004) and FDCA based flow indices Q_{90} as upper EFE bound, Q_{50} as lower EFE bound. The EFRs from these methods are compared with the downstream flows of each hydraulic structure to explore the frequency (%) and severity of EFs violations. The violation ratios were estimated using equations provided in Table 4.5.

The range of violation ratios depends on the specific environmental flow criteria and desired ecological outcomes for a particular river. In general, the ideal situation is to have violation ratios as close to zero as possible, indicating that the actual flow regime is very close to the desired flow regime required for maintaining ecological health. However, in practice, some degree of deviation from the desired flow regime may be acceptable or even necessary, depending on local conditions and priorities. In this section, violations in terms of frequency were discussed which is the ratio of the number of times a flow event occurs in the actual flow regime to the number of times the same event occurs in the desired flow regime. The frequency ratio can be used to assess the degree to which the actual flow regime deviates from the desired flow regime in terms of the frequency of flow events. Table 4.5 presents the VR into three classes i.e., VR <0, VR ranging from 0 to 100% and, V.R >100%. A VR less than 0 does not make sense mathematically. However, if we interpret a VR less than 0 as indicating a negative deviation from the desired flow regime, then it would imply that the actual flow regime is less than the minimum flow required for maintaining ecological health. a VR of 100% indicates a complete failure to meet the environmental flow requirements, while a VR of 0% indicates complete success in meeting the requirements. The VR between 0 and 100% provides a useful tool for environmental managers and policymakers to evaluate the effectiveness of water management decisions and strategies in maintaining ecological health in freshwater ecosystems. The violation ratios were estimated using equations provided in Table 4.5.

Table 4.4 Method employed to estimate EFRs in the study (Pastor et al. (2014)). MMF = mean monthly flow of each month, MAF = mean annual flow (the average of monthly flow of all months within a year), Q50 and Q90 refer to flow exceeding 50% and 90% of the flows during the period of interest respectively, and coefHF to high-flow coefficient used in Smakhtin's method

Hydrological season	**Smakhtin (2004) (Method-1)**	**Tennant (1976) (Method-2)**	**Q_{90}-Q_{50} (Pastor et al. 2014) (Method-3)**	**Tessmann (1980) (Method-4)**	**Variable monthly flow (Pastor et al. 2014) (Method-5)**
LF month	MMF ≤ MAF	MMF ≤ MAF	MMF ≤ MAF	MMF ≤ 0.4 x MAF	MMF ≤ 0.4 x MAF
EFR of LF month	Q_{90}	0.2 x MAF	Q_{90}	MMF	0.6 x MMF
HF month	MMF > MAF	MMF > MAF	MMF > MAF	MMF > 0.4 x MAF and 0.4 x MMF > 0.4 x MAF MMF > 0.8 x MAF 0.4	MMF > 0.8 x MAF
EFR of HF month	coefHF[(a)] x MAF	0.4 x MAF	Q_{50}	0.4 x MMF	0.3 x MMF
VF month	-	-	-	MMF > 0.4 x MAF and 0.4 x MMF ≤ 0.4 x MAF	MMF > 0.4 x MAF and MMF ≤ 0.8 x MAF
EFR of VF month	-	-	-	0.4 x MAF	0.45 MMF

(a)coefHF = 0 if Q90 > 0.3 x MAF; coefHF = 0.07 if 0.2 x MAF < Q90 ≤ 0.3 x MAF; coefHF = 0.15 if 0.1 x MAF < Q90 ≤ 0.2 x MAF; coefHF = 0.2 if 175 Q90 ≤ 0.1 x MAF.

Table 4.4 Computing the EFE violation ratio. Q stands for monthly downstream discharge between 1990 and 2021; EFElower for the lower boundary of the EFE, and EFEupper for the upper boundary of the EFE.

Condition	Violation ratio equation	Violation ratio (VR)
$Q<EFE_{lower}$	$\frac{Q-EFE_{lower}}{EFE_{lower}} x100$ (1)	<0
$EFE_{lower} \leq Q \leq EFE_{upper}$	$\frac{Q-EFE_{lower}}{EFE_{upper}-EFE_{lower}} x100$ (2)	0 - 100 (no EFE violation)
$Q>EFE_{upper}$	$\left[\frac{Q-EFE_{upper}}{EFE_{upper}}+1\right] x100$ (3)	>100

4.5 Results and Discussion

4.5.1 EFRs for the Indus Basin Rivers

The estimated EFRs are presented in Table 4.6 for the Indus River and its tributaries, including the Jhelum, Chenab, Ravi, and Sutlej, computed for the period 1990-2021 at Tarbela dam, Mangla dam, Marala barrage, Balloki headworks, Sulemanki barrage and for the period 1998-2018 at Kotri barrage. Table 4.3 suggests that the EMC-C of a river can be regarded as a moderately modified eco-environmental condition, which means that the river retains basic ecosystem functions but has lost sensitive species up to a specific limit, which can be called a critical condition. EMC was considered as C for the Indus River (Salik et al. 2016) and the Shahr-Chai River in Iran (Shaeri Karimi et al. 2012). Using the GEFC method, the study recommends that to maintain ecological conditions in the Indus basin, the EFRs should be at 38% of the Mean Annual Flow (MAF) of the Indus River at Tarbela, 48% of the MAF of the Jhelum River at Mangla, 44% of the MAF of the Chenab River at Marala, 56% of the MAF of the Ravi River, 50% of the MAF of the Sutlej River, and 38% of the MAF at Kotri (as shown in Table 4.6). In order to conserve the ecosystem and ensure favorable conditions for these rivers, the analysis suggests that EFRs of 880 m^3/s (Tarbela), 412 m^3/s (Mangla), 425 m^3/s (Marala), 389 m^3/s (Balloki), 184 m^3/s, and 231 m^3/s (Kotri) are required, respectively (as shown in Table 4.6). Figure 4.4 presents the monthly environmental flows for ecological classes at different locations in the Indus River Basin.

According to the Tennant method (1976) (Table 4.2), the minimum flow required to maintain the ecological condition of a river is between 20-48% of its MAF, and any percentage within this range is considered good. On the other hand, if the flow is less than 10% of MAF, the river is considered to have severely compromised environmental flow conditions, during both low and high flow periods (Shaeri Karimi et al. 2012). If extensive modifications such as dam constructions and/or heavy irrigation projects are being planned in a river system, Tennant recommended that the minimum environmental flow requirement for rivers should be 10% of MAF (low flow period) and 30% of MAF (high flow period). Using the Tennant method, the EFRs for low flow periods (October to April) were calculated as 232 m^3/s, 86 m^3/s, 96 m^3/s, 76 m^3/s, 36 m^3/s, and 107 m^3/s (10% of MAF) for the Indus river (at Tarbela), the Jhelum River (at Mangla), the Chenab (at Marala), the Ravi river (at Balloki), Sutlej river (Sulemanki),

Table 4.5 Environmental flow requirements for the five rivers using hydrologic methods

Method	EMCs	Indus at Tarbela (2324 m^3/s)		Jhelum at Mangla (856 m^3/s)		Chenab at Marala (961 m^3/s)		Ravi at Balloki (699 m^3/s)		Sutlej at Sulemanki (364 m^3/s)		Indus at Kotri (1072 m^3/s)	
		% of MAF	EFRs (m^3/s)	% of MAF	EFRs (m^3/s)	% of MAF	EFRs (m^3/s)	% of MAF	EFRs (m^3/s)	% of MAF	EFRs (m^3/s)	% of MAF	EFRs (m^3/s)
GEFC	A	73	1705	80	683	77	744	83	581	79	287	74	616
	B	53	1224	62	534	59	564	68	478	63	229	53	368
	C	38	880	48	412	44	425	56	389	50	184	38	231
	D	28	659	37	315	34	324	45	314	40	146	29	153
	E	23	527	28	240	26	253	36	250	31	113	23	106
	F	19	451	22	186	21	205	28	196	23	85	19	77
Tennant Method	Oct-Apr	10	232	10	86	10	96	10	70	10	36	10	107
	May-Sept	30	697	30	257	30	288	30	210	30	108	30	322
FDCA (Daily flow)	Q_{90}	-	-	23	193	20	194	35	244	31	113	-	-
	Q_{95}	-	-	19	162	18	175	14	101	7	25	-	-
$7Q_{10}$ (Daily flow)	$7Q_{10}$	-	-	21	176	21	200	14	100	28	100	-	-

and Indus river at Kotri barrage, respectively. For high flow periods (May to September), the calculated EFRs were 697 m^3/s, 257 m^3/s, 288 m^3/s, 210 m^3/s, 108 m^3/s, and 322 m^3/s (30% of MAF) for the same rivers. Since, the Government plans to construct more hydropower project in the IRB such as Diamer Basha Dam, Dasu Hydropower Project, Mohmand Dam, Tarbela 5th Extension, K-IV, Nai Gaj Dam, Kurram Tangi Dam, and Kachhi Canal (International Water Power and Dam Construction 2023) to meet the needs of exponential increasing population and socio-economic development in the region, it is recommended to allocate 20-48% of MAF to ensure the sustained development of the region and the conservation of the riverine ecosystems in good condition.

The FDCA method was used to determine the environmental flow recommendations for various rivers. As per this approach, the EFRs were estimated to be 193 m^3/s (23% of MAF), 194 m^3/s (35% of MAF), 244m^3/s (35% of MAF), and 113 m^3/s (31% of MAF) for the Jhelum River (at Mangla), the Chenab (at Marala), the Ravi river (at Balloki), and Sutlej river (Sulemanki), respectively (as shown in Table 4.6). The Low-flow-index method ($7Q_{10}$) provided similar results for both FDCA and Tennant methods at Marala, Balloki, and Sulemanki while higher values of EFRs were calculated at the Tarbela and Mangla. Since the results of GEFC provided higher values of EFRs as compared to $7Q_{10}$, FDCA, and Tennant method, we suggest using the findings of GEFC as the EFRs to maintain the ecosystem in good health of these rivers as future major modifications, such as dam and irrigation projects could disturb the hydrological regime of the rivers.

Salik et al. (2016) proposed that 29.8% of the Mean Annual Flow (MAF) below Kotri, the last hydraulic structure on the Indus River. However, our analysis suggests that there is a need for 38% of the MAF below Kotri barrage to conserve ecosystem services and should be allocated as EFRs for the Indus River, based on GEFC. Kamal (2008) presented EFRs for the entire lengths of the Indus, Jhelum, Chenab, Ravi, and Sutlej rivers, which were 175, 75, 100, 48, and 75 m^3/s, respectively. Our analysis recommends EFRs of 880 m^3/s (Tarbela), 412 m^3/s (Mangla), 425 m^3/s (Marala), 389 m^3/s (Balloki), and 184 m^3/s (Sutlej), respectively, using GEFC. Furthermore, Kamal (2008) suggested a minimum discharge of 1000 cusecs (28.3 m^3/s) below Kotri for all except four long and dry reaches of the rivers during periods of low flow. For the aforementioned four dry reaches, a discharge of 3000 cusecs (85 m^3/s) was recommended, assuming that approximately 30% of this discharge would be consumed within the reach. However, our analysis suggests an EFR of 231 m^3/s for the Indus River below the Kotri barrage. During the Kharif season (monsoon period), when water demand is high for wetlands and recharge, and water availability is also high, Kamal (2008) recommended a minimum flow of 10% of the natural inflow in each river, of which approximately one-third is anticipated to be consumed. Gonzalez et al. (2005) recommended a flow of ≥143 m^3/s (≥0.3 MAF or 5000 cusec) during each HF month (April-Sept.) and 143 m^3/s (0.3 MAF or 5000 cusec) to be discharged below the Kotri barrage to control seawater intrusion. However, our analysis proposes EFRs of 322 m^3/s during HF months and 107 m^3/s for LF months for the Indus River to be discharged below Kotri to conserve ecosystems and aquatic life. The present study emphasizes the need for recommended EFs to ensure the sustainability of the IRB's ecosystem in the face of impending threats.

4.5.2 Examination and assessment of the status of environmental flow downstream of barrages/dams

The environmental flow, calculated using $7Q_{10}$, Q_{90}, and Q_{95}, GEFC and Tennant method was compared to the downstream flow of the Indus River (at Tarbela), Jhelum River (at Mangla), the Chenab (at Marala), the Ravi river (at Balloki), and Sutlej river (Sulemanki), respectively in order to analyze whether the environmental flow requirements (EFRs) were being met or not.

4.5.3 Evaluation and monitoring of unfulfilled EFs in comparison to low flow indicators

The analysis indicated that during the study period, the number of days when the environmental flow was not met was less than 50 at Mangla Dam. From 1990 to 1999, the EFRs were consistently met, while in the years 2002–2005 and 2016–2021, the EFRs were not met for less than 50 days as shown in Figure 4.5 (a). Overall, the situation regarding EFRs was found to be satisfactory downstream of Mangla Dam, indicating that the ecosystem is being protected. All the low indices remain consistent in displaying the results. Figure 4.5 (b) illustrates that the EFRs unattained are in the range of 75 to 250 days. The years 1994, 2001, 2009, 2018, and 2021 exhibited the highest unmet conditions downstream of the Marala barrage, indicating that the EFRs were satisfied only for 184, 167, 235, and 112 days for these years, respectively. Conversely, the years 1996, 2003, and 2015 showed that the EFRs were met for a maximum of 285 days. Unfortunately, the year 2021 was the worst in fulfilling the EFRs to preserve the downstream ecosystem of Marala. Figure 4.5 (c) presents that the EFRs were not met downstream of the Balloki barrage within the range of 160 to 324 for all the years, except for the year 2019, which had the lowest unmet condition. The $7Q_{10}$ and Q_{95} indices exhibited similar results, while the Q_{90} index showed severely compromised EFRs conditions, and the unmet days were above 250 for most years. In 2019, the fulfillment of the EFRs condition was found to be optimal for the $7Q_{10}$ and Q_{95} indicators. Analysis of the data in Figure 4.5 (d) indicated that, except for 1995, all years exhibited unmet EFRs for 200 to 350 days on both the $7Q_{10}$ and Q_{90} indices the downstream of Sulemanki barrage. The years 1992, 2001-2006, 2017, and 2021 were found to be the worst years in terms of EFRs unmet, with more than 300 unmet days in the study period. The downstream of Marala, Balloki, and Sulemnki barrage was found to be severely impacted due to the consistent unmet EFRs in each year during the study period Figure 4.5 (b, c, d). If the EFRs are not met, it could have severe consequences on the ecosystem and aquatic life in the Indus River basin (Awais et al. 2022). The studies conducted by Shafiq et al., (2020) and Immerzeel et al., (2009) have shown a decreasing streamflow trend in the IRB due to glacier recession, also illustrated in Figure 4.6 which could be reasons for the non-attainment of EFs in the basin. Failure to meet EFRs can lead to habitat degradation, loss of biodiversity, and even extinction of certain species (IUCN 2003).

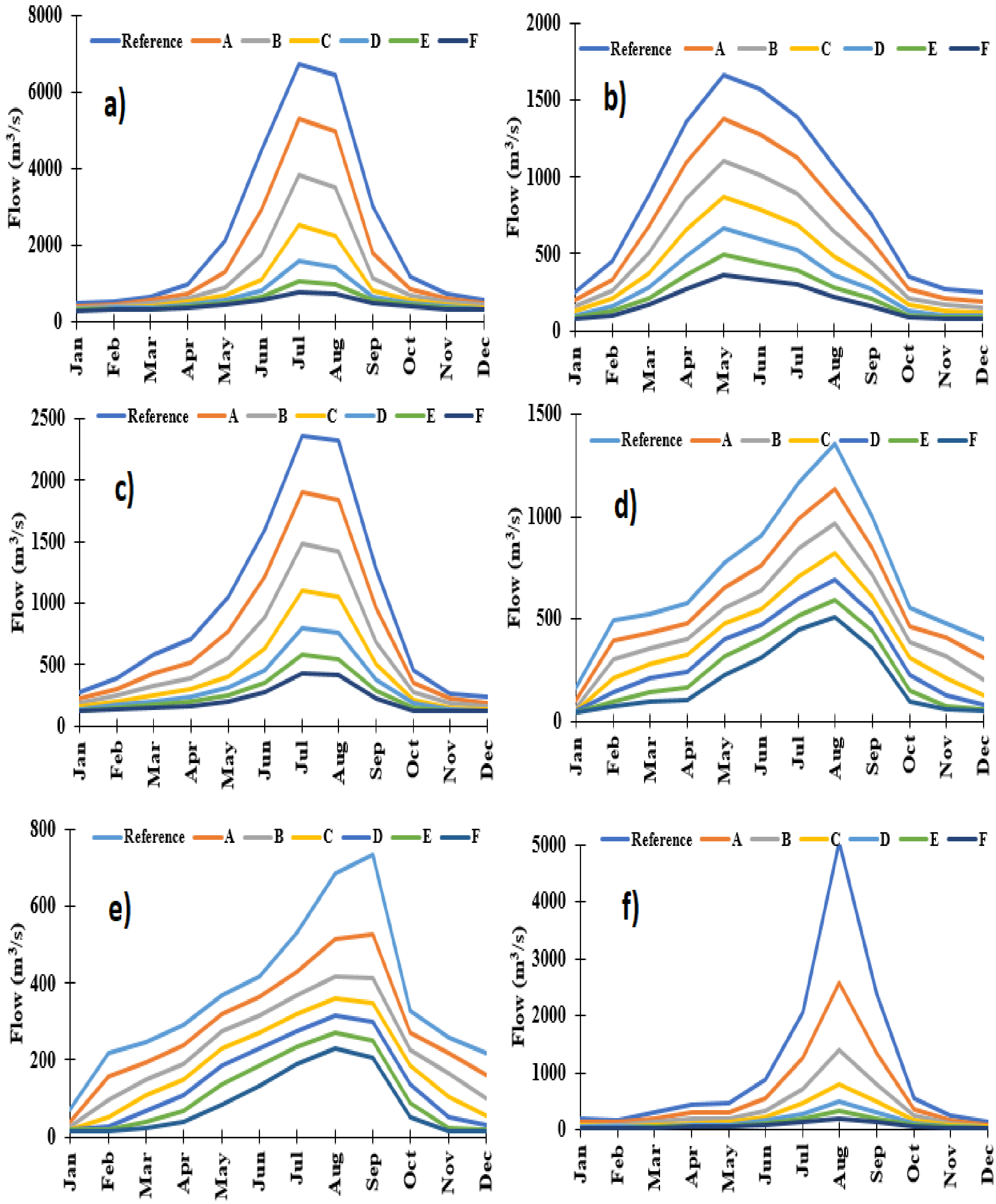

Figure 4.4 Monthly environmental flows calculated for different eco-environmental classes in the IRB at a) Tarbela, the Indus River b) Mangla, the Jhelum River c) Marala, the Chenab River d) Balloki, the Ravi River e) Sulemanki, the Sutlej River and, f) Kotri, the river Indus

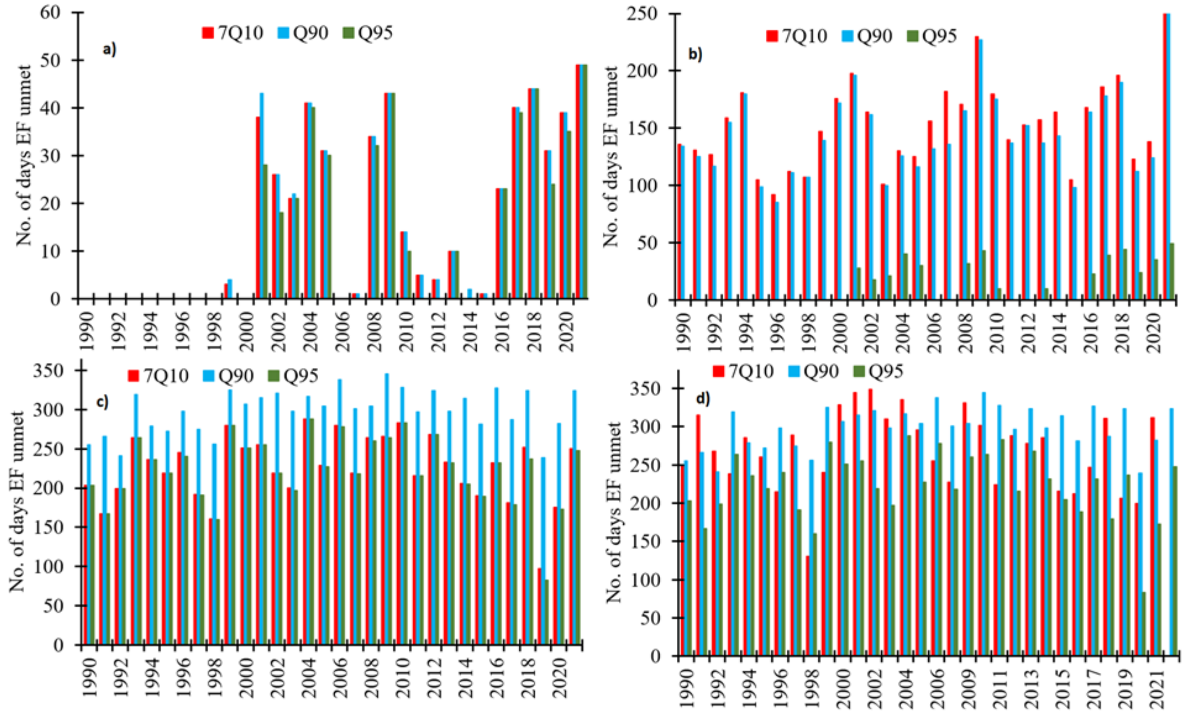

Figure 4.5 Environmental flow requirements (EFRs) unmet in different years downstream of a) Manga, the Jhelum River b) Marala, the Chenab River c) Balloki, the Ravi River d) Sulemanki, the Sutlej River

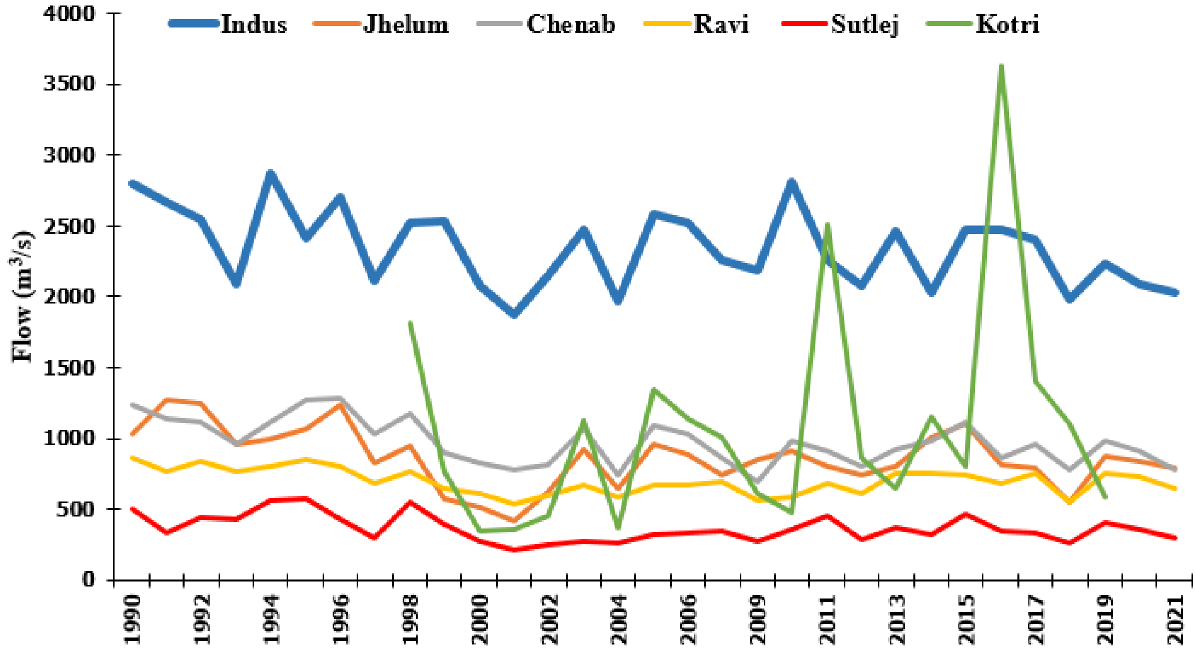

Figure 4.6 Annual stream flow of the Indus River at Tarbela, the Jhelum River at Mangla, the Chenab River at Marala, the Ravi River at Balloki, the Sutlej River at Sulemanki, and the Indus River at Kotri barrage

4.5.4 Assessment and examination of unmet EFRs based on approaches described by Pastor

During the study period, a monthly analysis was conducted to assess compliance with EFRs downstream of various dams and barrages. The analysis demonstrated that downstream of Tarbela dam, the EFRs were consistently met (Figure 4.7(a)), as indicated by Pastor et al. (2014) approaches (Table 4.5). However, the analysis showed that EFRs were not met during January (50% of the time), March (15%), April (10 to 45%), and October (5%) during the study period. Despite these few instances of unmet EFRs, the overall results suggest that the ecosystem downstream of Tarbela Dam is being protected by meeting the required environmental flow conditions. Figure 4.7(b) illustrates that the EFRs were not fulfilled during the summer months July-August (5-10%), with the highest unmet condition observed in January (20%). In contrast, during February-April and September-December, EFRs were completely met in each month of the study period downstream of the Mangla dam. Hence, the months of January are critical in the non-compliance of EFs at Tarbela Dam and Mangla Dam. Rasheed (2013) highlighted that a substantial discharge of water was being utilized during January to fulfill the water requirements of wheat cultivation, despite experiencing minimal inflows and storage at the Tarbela and Mangla reservoirs which could be the cause of noncompliance of EFs during January. However, downstream of the Marala barrage, the situation was severely compromised during February, March-April, and October-December for every year (Figure 4.7(c)) based on all the methods (M-1 to M-5). This suggests that EFRs were not met during these months and that the ecosystem is at risk of being negatively impacted. Hence, the analysis showed that all the months are critical except summer months in fulfilling the EFs at the Marala barrage. Shakir & Khan (2009) have highlighted that the river Chenab's flow at Marala surpasses the planned discharge capacity of the Marala Ravi link canal and Upper Chenab canal during summer months. Therefore, there is an ample amount of water accessible to achieve the EFs during these months, in addition to the water diverted into these canals. However, the operational timeline of the Marala Ravi link canal begins in mid-April and concludes in mid-October, coinciding with a period of low river flow. Consequently, EFs are being jeopardized during the low-flow seasons. All methods showed similar results regarding the frequency of non-attainment of EFs except Q_{50}–Q_{90} method which showed inconsistent results in the summer months at Tarbela Dam, Mangla Dam, and Marala barrage.

Furthermore, the analysis of the downstream of Balloki and Sulemanki showed serious concerns about EFRs not being met. The results showed that the EFRs were not met in all the months of the study period with frequency ranging from 15-100%. The frequency of unmet conditions was up to 100% in most of the months during the study period (Figure 4.7(d,e)). These findings suggest that urgent measures are needed to ensure compliance with EFRs downstream of Balloki and Sulemanki barrages to prevent further negative impacts on the ecosystem. At Kotri barrage, a similar pattern of non-compliance of EFs was observed (Figure 4.7(f)). Hence, all the months are critical in the non-attainment of EFs in the study period at Balloki, Sulemanki, and Kotri barrage. Overall, this study highlights the importance of regular monitoring and compliance with EFRs to protect downstream ecosystems from adverse impacts.

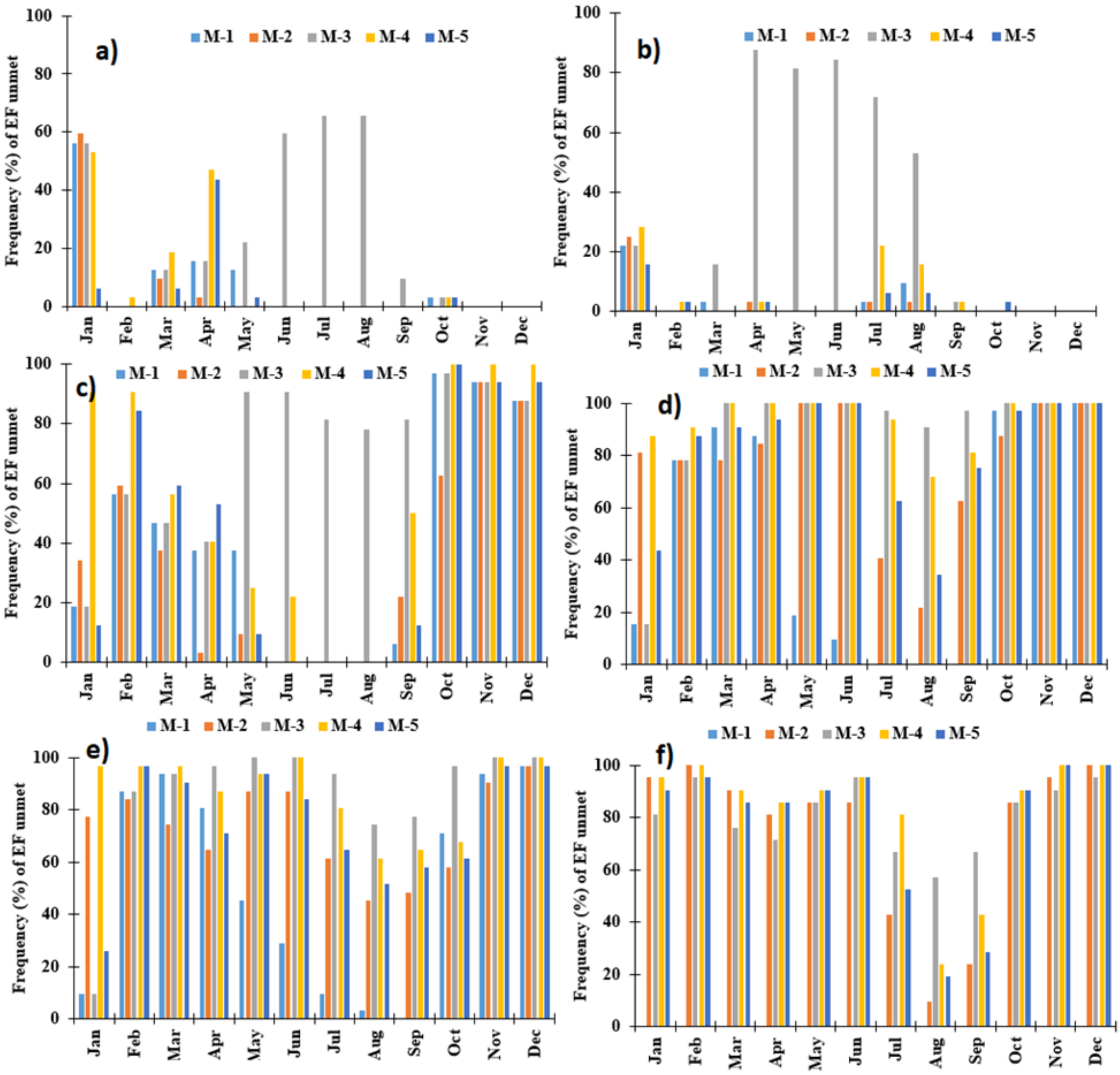

Figure 4.7 Frequency of EFs unmet during the study period downstream of a)Tarbela, the Indus River b) Mangla, the Jhelum River c) Marala, the Chenab River d) Balloki, the Ravi River e) Sulemanki, the Sutlej river using Paster et al. 2014 approach described in Table 4. M-1 is Smakhtin (2004) method, M-2 is Tennant Method (1976), M-3 is Q90-Q50 (Pastor et al. 2014), M-4 is the Tessmann method (1980) and M-5 is the Variable monthly flow (Pastor et al. 2014)

4.5.5 Assessment and examination of unmet EFRs based on long-term average monthly flow

Figure 6 displays the outcomes obtained by analyzing the 30-year average flow data for a specific month, which is known as the "mean monthly flow" or "long-term average monthly flow" to highlight the location, the time, and duration during which EFs are not being met. Mean monthly flow data is commonly utilized in hydrology and water resources management to comprehend seasonal streamflow patterns and evaluate the availability of water resources for various uses. The results indicate that the downstream flow at Tarbela and Mangla is either equal to or higher than the EFs for all the respective months, as illustrated in Figure 4.8 (a, b), it means that there is no issue of EFs at these locations. Conversely, the results obtained for the Marala barrage demonstrate that the EFs are satisfactorily met based on the Q_{95} indicator for all months, except for October-December and January to April based on $7Q_{10}$ and Q_{90}. The EFs were not met for the months from May to December, as shown in Figure 4.8c. The Balloki and Sulemanki barrages were found to be severely damaged as the EFs were not met for all months based on all three low flow indices, except for January and September (Figure 4.8 d, e). The results indicate that the downstream flow at Kotri barrage is either equal to or higher than the environmental flows (EFs) for all the summer months (July-September), as illustrated in Figure 4.8 (f), it means that there is no issue with EFs at Kotri barrage during summer months. However, all the other months except (July-September) were critical in attaining EFs at Kotri barrage.

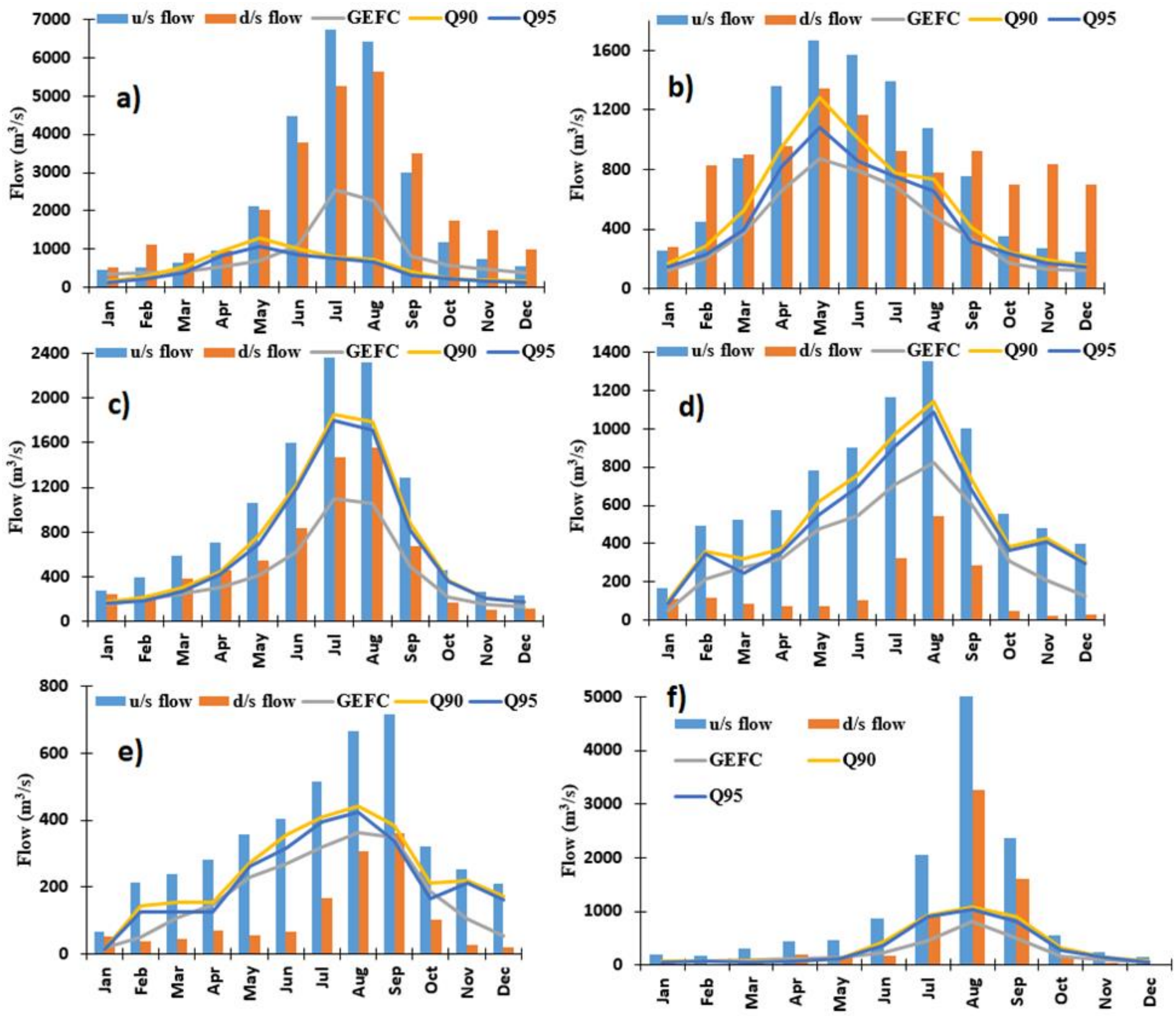

Figure 4.8 Long-term monthly upstream flow, downstream flow, Long-term monthly low flow indices i.e., GEFC, Q90, Q95 at a) Tarbela, the Indus River b) Mangla, the Jhelum River c) Marala, the Chenab River d) Balloki, the Ravi river e) Sulemanki, the Sutlej river f) Kotri, the Indus

4.5.6 Seasonal analysis of EFRs unmet based on the Tennant method

Figures 4.9a,b demonstrate that the EFRs were fully complied with the downstream of Tarbela and Mangla dams during both Low Flow (LF) and High Flow (HF) seasons. However, at the downstream of Marala barrage, the EFRs were only met during the HF months throughout the study period and in only 9 out of 32 years during LF months, as illustrated in Figure 4.9c. Moreover, the analysis at the downstream of Balloki barrage indicated that EFRs were not met in 16 out of 32 years during HF months and 10 out of 32 years during LF months (Figure 4.9d). Similarly, the analysis at the downstream of Sulemanki barrage revealed that EFRs were not met in 17 out of 32 years during HF months and 16 out of 32 years during LF months (Figure 4.9e). At the downstream of Kotri barrage, the EFRs were never attained during LF months for all the years except 1998, 2007, and 2015 and were consistently complied during HF seasons for all the years except 2000-2002 and 2018. Overall, these findings suggest that compliance with EFRs is not uniform across different locations and seasons, which highlights the need for effective water management strategies to ensure that EFRs are met consistently in all locations and throughout the year.

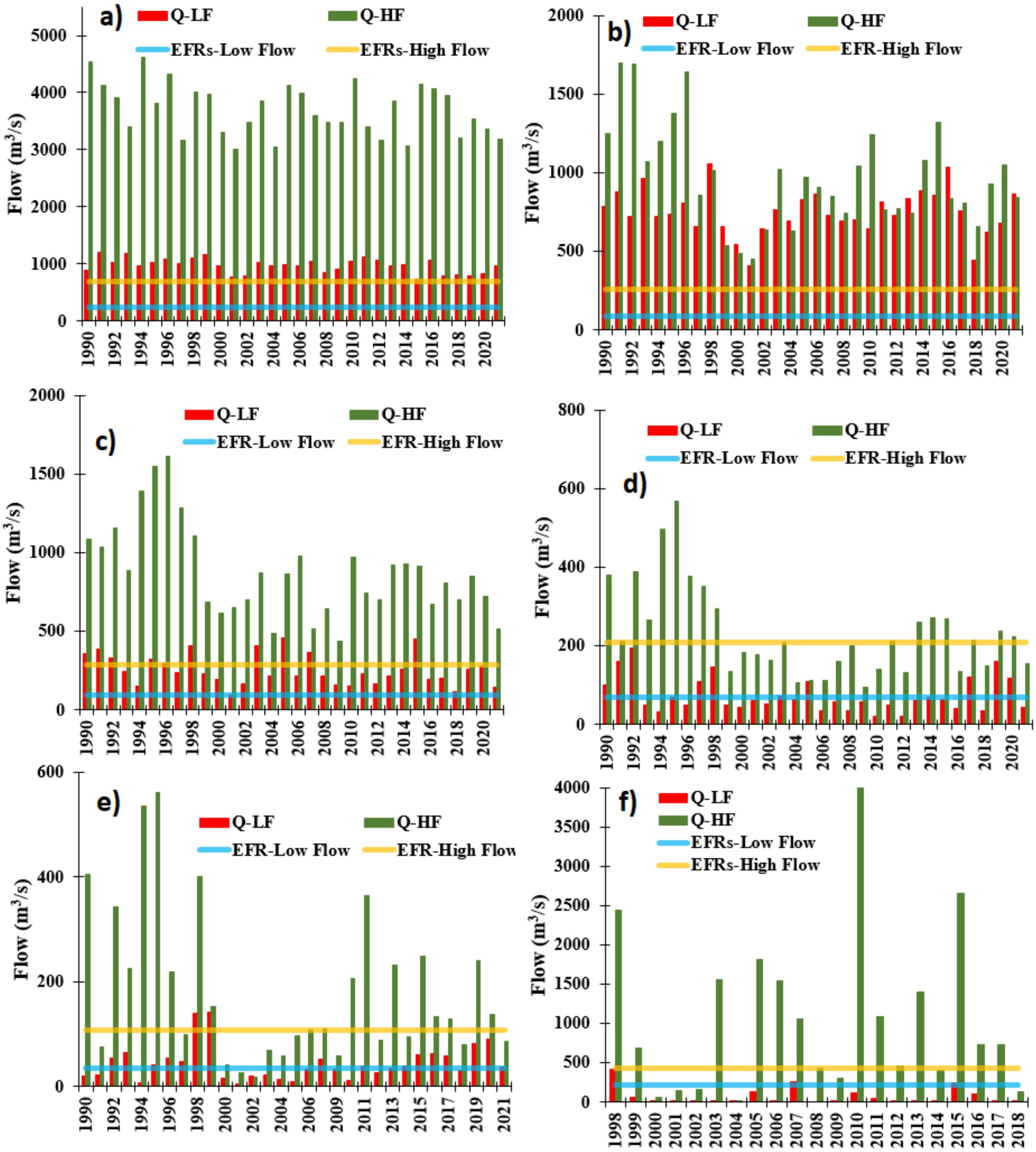

Figure 4.9 Seasonal High Flow (HF-Q), Low flow (LF-Q), and Environmental Fow requirements (EFRs) unmet in different years downstream of a) Tarbela, the Indus River b) Mangla, the Jhelum River c) Marala, the Chenab River d) Balloki, the Ravi River e) Sulemanki, the Sutlej River f) Kotri barrage, the Indus River

A detailed examination of temporal scales under section 4.2 – encompassing daily, monthly, and seasonal intervals – revealed that non-attainment of Environmental Flows (EFs) at the daily scale was rather ambitious, as it is based on the general statement that water must be present in the rivers (allocating all water for environmental needs). However, in the examination at the monthly scale, EFs were consistently met at Tarbela and Mangla dams, indicating a balanced allocation between food production and environmental preservation. Marala Barrage exhibited a moderate compromise, whereas Balloki and Sulemanki Headworks demonstrated severe compromise in meeting EFRs, highlighting an imbalanced allocation between water usage for food production and environmental requirements. Overall, the Chenab at Marala headworks, the Ravi at Balloki headworks, the Sutlej at Sulemanki headworks, and the Indus River below the Kotri barrage exhibited vulnerability at the monthly, long-term average, and daily scales in different years which implied further digging and exploring the violations of EFs for these rivers at specified locations within the basin.

4.5.7 Non-compliance of EFs in terms of violation ratio (VR): Frequency and Severity of Violations in the IRB

Figure 10a depicts the frequency of VR < 0 were dominant (more than 50%) in most of the years at Marala barrage. The VR of 0 to 100% was not observed in any year of the study period which depicts sheer violations of EFs attained (Fig 10 a-d). A VR greater than 100 indicates that the actual flow regime is outside the range of flows considered in the desired flow regime, and it is therefore not possible to assess the potential environmental harm associated with that flow regime using the desired flow regime as a reference. In practice, VRs greater than 100 may occur when the actual flow regime includes flow events that are outside the range of flows considered in the desired flow regime, such as very high or very low flow events that were not considered in the development of the desired flow regime. In such cases, alternative ecological indicators or reference conditions may need to be used to assess the potential environmental harm associated with the actual flow regime. Figure 10 a-d depicts the years at each location in which the frequency of VR was 100% different years. Overall, VRs greater than 100 are not commonly used in the assessment of environmental flows, as they imply a flow regime that is outside the range of flows considered in the desired flow regime, making it difficult to assess the potential environmental harm associated with that flow regime. Figure 10e depicts that EFs were violated 41%, 43%, 44%, and 52% of the time during the study period for the Chenab at Marala headworks, the Ravi at Balloki headworks, Sutlej at Sulemanki headworks, and below Kotri barrage, respectively.

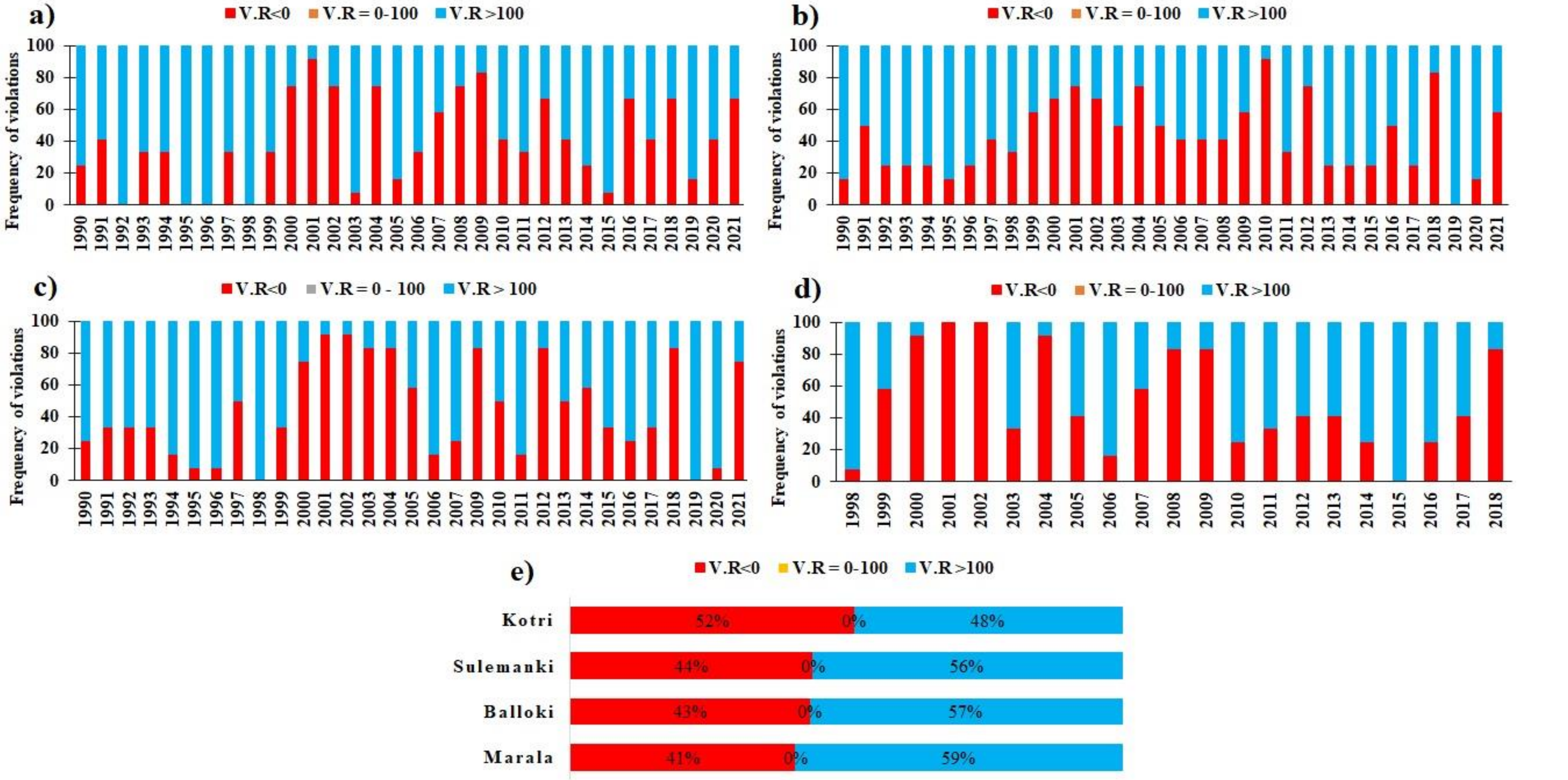

Figure 4.10 Severity of monthly EFs unmet in the IRB. Violation ratio values are categorized into three classes to examine the severity of the EFs unmet. Vertical bar graphs show the percentage of months in each year with various levels of EFs unmet at a) Marala, the Chenab River b) Balloki, the Ravi River c) Sulemanki, the Sutlej river and, e) Kotri, the river Indus g) Months in same categories are summed up from 1990 to 2021 to see the overall pattern in each river

In general, the fulfillment of EFRs was found to be more satisfactory on a daily, monthly, seasonal, and yearly basis at Mangla and Tarbela Dam. Conversely, there were instances where the EFRs were not met, and this trend was particularly pronounced at Marala, Balloki, and Sulemanki locations. These areas exhibited significant deviations from the required EFRs, and the situation persisted across various temporal scales, including daily, monthly, yearly, and seasonal timeframes. The underlying factors contributing to the failure of meeting EFs can be comprehended by considering the genesis of the rivers, the partition of the subcontinent, and subsequent advancements within the basin resulting from the implementation of the Indus Water Treaty of 1960 and the Water Apportionment Accord of 1991. The origin of three river i.e., Jhelum, Chenab, and, Ravi is Jammu & Kashmir, and Sutlej and Beas river collects water from the drainage basin of Himachal Pradesh and these were the main sources of Irrigation in Pakistani-Punjab in pre-partition era of subcontinent and till the signing of IWT-1960 between India as upper riparian and Pakistan as lower riparian (Mirza 2016). Upper riparian was allowed to use the waters of the Sutlej, Beas, and Ravi Rivers for their own use without restriction which was not used before the partition (World Bank 1962; Mirza 2016), while lower riparian was granted unrestricted use of the waters of the Indus, Jhelum, and Chenab rivers. The treaty allowed upper riparian to divert 34 million acre-feet (MAF) of water out of eastern rivers and before entering into the land of lower riparian (Kalair et al. 2019) which has led to a reduction in the flow of water in the eastern rivers, including the Ravi and Sutlej rivers. The flow of the Ravi and Sutlej rivers prior to the signing of the Indus Waters Treaty (IWT) between India and Pakistan, spanning from 1922 to 1961, was measured at 7 and 14 MAF, respectively. However, following the implementation of the IWT in 1960, these values decreased to 5.51 and 3.51 MAF, respectively, during the period of 1976-99. Subsequently, the flow of these rivers has further diminished to 1.20 and 0.78 MAF, respectively (Basharat 2019). On the other hand, Mirza (2016) pointed out a total pre-Partition use of 8.0 MAF withdrawals increased to 13.3 MAF in 1960-61, to 16.05 MAF in 1961-62, and 27.3 MAF in 1968-69 and the withdrawals further increased to about 30 MAF due to development on the Ravi river and Rajasthan canal. Wu et al. (2023) revealed the narrowing extent of the Sutlej River due to human intervention with the river, climate change, and an increase of evapotranspiration. Gonzalez et al. (2005) acknowledged the alteration of river flows resulting from the implementation of the Indus Water Treaty in 1960 has had a significant impact on the flow regime of the Indus River and Eastern Rivers. As a result, the Eastern Rivers experience prolonged periods of low flow and even complete dryness, while the flow in the Indus River below Tarbela Dam and the Chashma Barrage has been severely altered and reduced. The consequences of these changes on wildlife, fisheries, riverine forests, riverine agriculture, groundwater, water quality (IUCN 2003), and social impacts have been reported by Gonzalez et al (2005). However, it should be noted that the reduced flow of water in the Ravi and Sutlej rivers is not solely due to the Indus Water Treaty. Other factors such as climate change, deforestation, and the construction of dams and other infrastructure along the rivers have also contributed to the decrease in water flow in these rivers (IUCN 2003; Archer et al. 2010).

The diversion of water for agriculture is more than 95% in the Indus basin and overall efficiency is not more than 36% (Mustafa 2010) which depicts that the water scarcity is not absolute but rather prioritizing the use of water to agriculture and leaving no water for the environment. The advocacy group in favor of damming in Pakistan employs the occurrence of floods to advocate for additional reservoirs along the Indus River (Mustafa 2010) which could further alter the natural flows of the rivers in the IRB. However, these calamities also necessitate a more discerning and all-encompassing appraisal of the water governance framework. An appraisal of this sort is expected to foster a novel equilibrium between the river system's advantages and risks. Anwar & Bhatti (2017b) analyzed that EFRs were met until 1999-2000 as the discharge into the Arabian Sea below Kotri barrage were consistently exceed the EFRs suggested by Gonzalez et al. (2005) while the EFs were not met after 2001 as the discharge into Arabian were short of the threshold of 4.55 Gm^3 per year.

Additionally, reduced streamflow and water availability can negatively impact water quality, which can have a cascading effect on the food chain and affect the health and well-being of local communities who rely on the river for their livelihoods and basic needs such as drinking water and agriculture. Therefore, it is crucial to ensure that EFRs are met to sustain the ecosystem services and the livelihoods of people who depend on them. This can be achieved through effective water management policies and practices that prioritize the conservation of ecosystems while meeting the water demands of different sectors such as agriculture, industry, and domestic use. The study provides valuable insights into the status of environmental flow downstream of barrages/dams and underscores the need for continued monitoring and assessment of EFRs to protect the ecosystem and the communities that depend on it. In order to ensure the sustainability of the Indus River and its associated ecosystem, it is crucial to incorporate environmental flow requirements into any agreement reached between the upper and lower riparian of the Indus for river sharing. This may entail modifications to the existing allocation formula at the international level i.e., IWT-1960 and national level i.e., WAA-1991, which has resulted in the Ravi (a running sewer) and Sutlej (river of sand) rivers becoming severely degraded in their respective stretches in Pakistan (Sarfraz 2013). Therefore, a holistic approach that balances the needs of both human populations and the natural environment is essential for ensuring the long-term health of the river in the Indus River Basin. Prior to making any determinations regarding significant alterations to the area, it is imperative that a thorough investigation be conducted, utilizing a comprehensive approach that integrates ecological data and insights from relevant experts in various fields such as hydrology, ecology, geomorphology, biology, and hydrogeology.

4.6 Conclusion

The study aimed to assess the required Environmental Flow Requirements (EFRs) for the Indus, Jhelum, Chenab, Ravi, and Sutlej Rivers to maintain the riverine ecology in the Indus River basin. The results were calculated through various methods, including GEFC, Tennant, FDCA, and Low-flow-index. The GEFC method's minimum EFRs are recommended to ensure optimal river health, which were estimated to be 38% of MAF of the Indus River at Tarbela, 48% of the MAF of the Jhelum River at Mangla, 44% of the MAF of the Chenab River at Marala, 56% of the MAF for the Ravi River at Balloki, 50% of the MAF for the Sutlej River at Sulemanki. The EFRs were compared with the downstream flows to highlight the time (days, months, years, season) when the E-flows were unmet. The study found that the EFRs were consistently met downstream of Tarbela and Mangla dams. However, the month of January was critical in attaining the required EFs as the storages and inflow are low despite the demand for wheat being high, while the downstream of Marala, Balloki, Sulemnki, and Kotri barrages experienced compromised EFRs conditions during the study period. The failure to meet EFRs can have severe consequences on the ecosystem, including habitat degradation, loss of biodiversity, and even extinction of certain species. Furthermore, reduced streamflow and water availability can negatively impact water quality, affecting the health and well-being of local communities that rely on the river for their livelihoods and basic needs. Therefore, it is crucial to ensure that EFRs are met to sustain the ecosystem services and the livelihoods of people who depend on them. Effective water management policies and practices, coupled with public awareness campaigns about the importance of EFRs, can lead to increased support for sustainable water management practices.

Chapter 5

Conclusion and Outlook

5 Conclusions and Outlook

5.1 Main conclusion of the dissertation

The study's main conclusions are summarized below, which contribute to the discussion within the scientific community, but are also helpful for stakeholders from water management (water users, water administration) and policymakers. The conclusions are structured under three main headings:

a) Key conclusion from the groundwater storage changes in the transboundary Indus Basin (Chapter 2)

1. Groundwater storage changes were declining at -0.44 mm per month and -0.64 mm per month over the study period (2003-16) using the GRACE-based dataset and results from the WGHM on the basin scale. Notably, the computed average groundwater depletion translates into a substantial quantity of approximately 129 km^3, which stands in stark comparison to the annual inflow of 145 km^3 observed within the Indus Basin. Such a high groundwater depletion poses potential implications for crucial sectors i.e., agriculture, domestic and environment. For the agricultural sector, which heavily relies on groundwater for irrigation, diminishing groundwater resources could pose significant challenges. Crop yields might be adversely affected, potentially leading to reduced agricultural productivity and income for farmers. This could result in food insecurity, impacting both local communities and the broader regional food supply. The declining trend of groundwater storage at temporal scales needs special attention to conserve the precious resources for utilization by future generations.
2. Decomposing the groundwater storage time series derived from GRACE data using the Seasonal Trend and Loess (STL) method provided insights into understanding and highlighting the critical seasons for groundwater in the basin. The decomposed groundwater storage changes showed a high seasonality with critically minimum values (-30mm) during the pre-monsoon season (around April) and maximum values (30mm) during the post-monsoon season (September). The seasonality graph dipped after April, which denotes that groundwater usage was high during May-June which is the rice cultivation season in the region. The study suggests adopting dry seeding rice and advanced rice irrigation strategies (e.g. laser guide levelling, alternate wetting and drying technique) in the study area.
3. In the spatial analysis, the examination of groundwater storages revealed an overall downward trend in the entire Indus Basin. The average decline in groundwater storages ranged from -131 mm to -9.9 mm, indicating a worrisome reduction in available

groundwater resources across the basin. Particularly concerning were the severe depletions observed in the North-East areas of the Indus Basin, encompassing regions such as Himachal Pradesh, Indian Punjab, Haryana, Kashmir, and Gilgit Baltistan, where groundwater levels experienced significant drops ranging from -131 to -48.5 mm. In contrast, the South-West part of the basin, including Sindh, exhibited comparatively milder depletions, ranging from -20.3 to -9.9 mm. A noteworthy comparison between two adjacent regions with similar climatic conditions, namely Pakistani Punjab and Indian Punjab, indicated considerable disparities in groundwater depletions. Pakistani Punjab experienced depletion rates within the range of -48.5 to -20.3 mm per month, while Indian Punjab exhibited notably higher depletions, ranging from -181 to -48.5 mm per month. These variable depletions underscore the necessity for region-specific groundwater management strategies, as each region or province adopts distinct approaches to manage its water resources. Initiatives like subsidizing solar pumping and providing subsidies on electric tubewells are some examples of the diverse management practices adopted in different areas. To address the challenges posed by declining groundwater levels and to inform effective water resource management, we recommend the development of comprehensive groundwater aquifer-related maps. These maps should encompass key aspects such as water withdrawals, groundwater recharge rates, groundwater storage changes, groundwater levels, aquifer thickness, yields, and tube well density, offering valuable visual insights across the entire IRB. Such data-driven maps serve as crucial tools to support the formulation of area-specific groundwater management strategies. By incorporating this quantitative information, policymakers, water resource managers, and stakeholders can gain a comprehensive understanding of the groundwater dynamics within distinct regions of the Indus Basin. Armed with this knowledge, they can make informed decisions and implement tailored approaches to effectively conserve and sustainably manage groundwater resources. Ultimately, the development and utilization of area-specific groundwater management strategies hold the potential to safeguard the availability of this precious resource for both current and future generations, ensuring the resilience and prosperity of the entire Indus Basin.

4. In the reach-specific analysis, an investigation spanning the study period (2003-2016, comprising 180 months) revealed that, on average, groundwater levels fell below -100 mm for 43 months in the upper reach, 25 months in the middle reach, and 4 months in the lower reach. These notable disparities underscore the vulnerability of groundwater resources, particularly in the upper Indus reach. Delving deeper into the controlling factors driving

this decline in the upper reach, we identified glacier recession as the primary contributing factor. The receding glaciers, a consequence of climate change, have substantially impacted the groundwater dynamics in the region, exacerbating the situation. Consequently, our study underscores the urgent need for proactive initiatives, with a specific emphasis on climate mitigation measures, to mitigate the adverse effects of groundwater depletion in the upper Indus reach. Such interventions, if conscientiously pursued, hold the promise of preserving this vital resource and ensuring the sustenance of livelihoods and ecosystems dependent on the equitable distribution and availability of groundwater resources.

5. The validation results in two different hydrogeological natures (i.e., Lower Bari Doab Canal and Kabul River Basin) of the regions revealed that the results are fairly good where the hydrogeology of the (unconfined) aquifer was fairly simple. We recommend to consider the heterogeneity within the IRB while using the GRACE datasets for planning initiatives.
6. Coarse-resolution datasets of GRACE could provide valuable insight into managing the groundwater resources in the IRB where the observation wells were sparse and limited.
7. Investigation of groundwater storage changes and controlling factors such as climatic and anthropogenic impacts at spatial segregated units (the basin, river reach, and region) has yielded valuable insights into the implications of these variations on regional water resource management; this has also provided management options at each level, empowering decision-makers to make informed choices in effectively managing water resources within the region.

b) Key conclusion from the groundwater storage changes in the Irrigated Indus Basin of Pakistan at canal command area

1. The application of the two-step downscaling method proved highly beneficial in providing higher resolution GRACE datasets (0.05° x 0.05°: downscaled from 0.5° x 0.5°) for a comprehensive assessment of groundwater storage variations in the canal command areas of the Irrigated Indus Basin.
2. Upon analysing the downscaled datasets, a concerning trend emerged, revealing that groundwater levels were declining at various rates (ranging from -0.9 to -18.3 mm per month over the study period) across most of the Irrigated Indus Basin canal commands. However, the canal commands in the KP region, including Warsak, Bannu, and Kabul River canal commands, exhibited a positive trend in groundwater storage changes. The observed declining trends were found to be correlated with the water allowances granted

to each canal command, aligning with the hypothesis that higher water allowances resulted in less groundwater decline and vice versa. This downward trend raises alarms as it points towards potential groundwater depletion in these canal command areas. Urgent attention is required to address this situation and implement effective groundwater management strategies to safeguard this vital resource for future generations.

3. The study revealed that groundwater depletion was trending downward through the IBIS, and around 50% (2972 out of 5976 pixels) of the IBIS showed a significant declining trend ($p < 0.05$) dominant in the Punjab province of Pakistan, where surface water allocations are low as compared to the more downstream parts of IBIS (i.e., Sindh province). The declining trend is expected to further escalate in the coming years due to the Punjab Government's provision of subsidies (with the government covering 80% of the cost and farmers contributing 20%) for the installation of solar irrigation pumps. The downward trend in groundwater levels suggests a continuous decline in available water resources, which could lead to water scarcity and associated challenges for agricultural, domestic and ecological needs in the Punjab province (the food basket) of Pakistan.
4. Key results from the environmental flow assessment in the Indus River basin
5. In order to conserve the ecosystem and ensure favourable conditions for the Indus Basin Rivers, the analysis suggests that environmental flows of 880 m3/s (Tarbela), 412 m3/s (Mangla), 425 m3/s (Marala), 389 m3/s (Balloki), 184 m3/s, and 231 m3/s (Kotri) are recommended, respectively. Failure to meet the recommended environmental flows could lead to severe ecological consequences in the Indus Basin Rivers. Insufficient water flow can disrupt the natural balance of the ecosystem, impacting aquatic habitats, biodiversity, and overall river health.
6. E-flows were being attained at Tarbela Dam and Mangla Dam at different times of the month, seasons, and years. However, due to the planned construction of more hydropower projects such as Diamer Basha Dam, Dasu Hydropower Project, Mohmand Dam, Tarbela 5th Extension, K-IV, Nai Gaj Dam, Kurram Tangi Dam, and Kachhi Canal to meet the needs of exponential increasing population and socio-economic development in the region, it is expected that E-flows would not be met in the future due to these developments. So, the study suggests to increase the allocation of E-flows in the range of 20-48% of MAF in a different month and seasons of the year to ensure the sustained development of the region and the conservation of the riverine ecosystems in good condition.
7. The E-flows attainment at Marala barrage was attained at a monthly scale from January to September in all the years (1991-2021). However, the E-flows were not attained during

the low flow season (Oct-Dec) within the study period. The non-attainment of E-flows could further worsen because the upper riparian had planned various projects i.e., Rattle, Dul Hasti, Pakal Dul Project, Kiru, Kwar, Bursar and Kirthai projects upstream of Marala. This calls for urgent attention and action from water resource managers and policymakers to devise strategies that ensure a more consistent and sustainable provision of E-flows throughout the year.

8. The analysis of river discharge downstream of Balloki and Sulemanki showed serious concerns about E-flows not being met. The results revealed that the EFRs were not met in all the months of the study period, with frequency ranging from 15-100%. The frequency of unmet conditions was up to 100% in most of the months during the study period. The failure to meet the desired E-flows can be attributed to the division of water between upper and lower riparian through the Indus Water Treaty (IWT) of 1960. The study suggests revisiting the IWT-1960, which allocated waters based on geographical divisions rather than considering the specific allocation of water for E-flows. Revisiting the IWT-1960 offers an opportunity to enhance the treaty's effectiveness in promoting equitable water distribution while safeguarding the ecological integrity of the river system. Collaborative efforts among the riparian states to redefine water allocations, particularly for environmental needs, can lead to improved water management practices and foster sustainable coexistence and utilization of shared water resources." These findings suggest that urgent measures are needed to ensure compliance with EFRs downstream of Balloki and Sulemanki barrages to prevent further negative impacts on the ecosystem.
9. The study on E-flows assessment in the IRB suggests that compliance with EFRs is not uniform across different locations and seasons. This highlights the need for effective water management strategies to ensure EFRs are consistently met in all locations and throughout the year.

5.2 Strengths and limitations of the study

Among the strengths of the work is the consideration of the two challenging needs, i.e., agriculture which is heavily dependent on groundwater and E-flows in rivers of the Indus basin, which could improve the understanding of overall water management in the study area.

1. Groundwater dynamics were studied at spatial segregation units (the basin, reach, provinces and canal command areas). The study used different datasets to understand groundwater dynamics at the basin, river reaches, and provincial levels because groundwater is managed differently in different management units from the basin to the

provincial and canal command area levels. Management options were proposed at each spatial level to bridge the gap toward enhancing the management from the basin to the canal command level to better utilize this valuable resource for future generations.

2. The study addresses two important aspects, groundwater dynamics, and E- flows in the context of the Indus Water Treaty-1960 and Water Apportionment Accord-1991. This could be a starting point for discussion on future water use in the basin, taking into account the ecological needs of the basin with a higher priority.

However, the dissertation had some limitations, which are described below:

1. The groundwater dynamics were investigated using a spatial segregation approach. However, issues such as how surface water bodies affect groundwater quality and quality and land subsidence are not addressed by the datasets used in this study i.e., GRACE. The uncertainties in hydrological models, could be considered in the perspective studies.
2. The present study assessed E-flows using various hydrological methods. However, a holistic approach should be used to assess the E-flows that focussed on certain species in the endangered list of IUCN and balance the needs of both human populations and the natural environment, which is essential for ensuring the river’s long-term health in the Indus River Basin.

5.3 Outlook

This work examined groundwater dynamics in the Indus Basin using a spatial separation approach, and the assessment of E-flows at multiple locations offers a promising way forward to start a discussion on rethinking and revisiting the existing water allocation in the basin which currently is strongly driven by considering the demand from irrigated agriculture. However, the study recommends that the following issues be considered for further investigation.

1. Because groundwater is declining on a temporal and spatial scale and the number and density of tube wells and boreholes have increased dramatically in recent years, there is a need to develop a database of georeferenced locations of all existing and new tube wells and boreholes in the regions. Such a database would support and improve the basin's management decisions and water allocations.

2. Differences in water allowances of canal command of regions and water allocation within canal commands put pressure on groundwater resources in the basin. Rice production is known to be water-intensive, requiring significant amounts of water for irrigation, especially for paddy fields, and rice exports of Pakistan amount to about 2 billion US

dollar per year. Analysis showed that groundwater storage during rice cultivation was declined maximally in the basin. To ensure sustainable water management, it becomes imperative to carefully evaluate the economics of various crops and establish a rational approach to water allocation. The water-intensive nature of rice cultivation must be weighed against the potential economic benefits while considering the availability and sustainability of surface and groundwater resources.

3. The declining trends of groundwater and non-attainment of E-flows in the basin suggest that a discussion should be initiated on changes to the existing allocation formula at the international level, i.e. IWT-1960, and at the national level, i.e. WAA-1991, which has resulted in severe degradation of the Ravi (a running sewer) and Sutlej (river of sand) in their respective stretches in Pakistan.

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