Assessment of Reliability, Resilience and Vulnerability of Terrestrial Water Storage over Indus River Basin using GRACE-Satellite

By

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THESIS ACCEPTANCE CERTIFICATE

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DEDICATION

To Almighty Allah

&

My Sweet & Dearest Cinderella

A special feeling of gratitude to my beloved Daddy, my Babbugosa, Baji and my family for their unwavering support, and encouragement throughout my journey.

Academic Thesis: Declaration of Authorship

I, **Sittara Bibi** declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

"Assessment of Reliability, Resilience and Vulnerability of Terrestrial Water Storage over Indus River Basin using Gravity Recovery and Climate Experiment (GRACE) satellite"

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Sittara Bibi

Table of Contents

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LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Explanation
GRACE	Gravity Recovery and Climate Experiment
TWS	Terrestrial Water Storage
EWT	Equivalent Water Thickness
MMK	Modified Mann- Kendall
IRB	Indus River Basin
UIB	Upper Indus Basin
LULC	Land use Land Cover
DEM	Digital Elevation Model
RRV	Reliability, Resilience, Vulnerability

ABSTRACT

Freshwater, a significant natural resource, is crucial for achieving sustainable development. However, escalating anthropogenic activities and the impact of climate change have imposed significant stress on freshwater resources. To address these challenges, it is essential to comprehend the spatial variation in water availability and sustainability. The main objective of the present study was to assess water sustainability in terms of terrestrial water storage in the Indus River basin, using three Gravity Recovery and Climate Experiment (GRACE) satellite solutions with a spatial resolution of 0.5°. Spatial variability of water sustainability was estimated by integrating reliability, resilience, and vulnerability. Additionally, the Modified Mann–Kendall (MMK) test and Sens slope estimator were employed to identify significant trends in water availability. The findings indicated a notable decline in the basin's water supply, particularly after 2011. The trend analysis revealed a higher declination in water availability, ranging from −0.15 to −0.10 cm/year in the southern and southwestern region of the basin, and a slight increase toward the eastern side of the study area. However, the sustainability analysis indicated that water resources in the north and northeastern regions of the basin exhibited a higher sustainability than other areas. The least sustainable regions, with values ranging from 0.0 to 0.4, were identified in the south and southwest. The study successfully demonstrated the applicability of GRACE's TWS data for analyzing water resource sustainability across the Indus River basin and the proposed method presented an effective approach for assessing water resource availability and sustainability, providing valuable insights to guide freshwater resource management and promote sustainable development in the Indus River basin, and potentially other regions facing similar challenge.

CHAPTER 1

INTRODUCTION

1.1. Background

Water is one of the most important natural resources in the world, with access to safe and clean drinking water being a fundamental human right (Li et al. ,2022). Water resources availability and water quality are impacted by human activities and climate change on a global scale. Due to the geographical and temporal variability in the availability of water resources, many parts of the world do not have enough of it to support human requirements. Human activities and climate change further exacerbate this deficiency, particularly in major basins where urbanization and population expansion are common (Ahmed et al., 2022).

Given its value and scarcity, water is one of the most important resources for maintaining a healthy ecosystem and human population. The main variables impacting on this limited resource's quality and quantity include land use changes, climate change, inadequate governance, and a lack of water treatment systems. Around 500 million people live in places where freshwater use is two times higher than when it is being replenished. (Molekoa et al., 2022).

Over the past 100 years, water demand has grown by around 1.8% year. By 2050, it is projected to rise by 55%, primarily because of population growth, climate change, and changes in land use, all of which raise questions about how much water will be available. As a result, the demand on the water system will increase as the population and the economy develop (Aguiar et al., 2022).

In addition, drought and water quality issues are anticipated to worsen in the upcoming years because of climate change, rising water consumption, urbanization, and population expansion (Bănăduc et al., 2022). With the world's population growth, the water demand has been rising tremendously. The globe needs almost six times as much water now as it did a century ago because of the growing population (Tehsin et al., 2019). Due to growing demands for and use of natural resources, along with poor water management, particularly in developing countries, there has been a progressive decrease in the amount of water availability (Natalia et al., 2020).

According to global approximations, almost 43,000 km3 of renewable freshwater resources are being supplied to rivers, lakes, and aquifers annually, amongst which 70% is spent by agriculture, 19% by industry, and 11% by households. Currently, 38% of the global irrigated area is contingent on groundwater (Li et al.,2022). Remarkably In the Indus River Basin, where canal water supplies are unpredictable and lacking, groundwater is used independently or in conjunction with surface water. Irrigation in this region is sourced mainly from groundwater (Lone et al., 2022).

Due to extensive groundwater exploitation, urbanization, and population increase, the Indus River basin aquifer is on the verge of an acute water catastrophe. Given the basin's complex, diverse hydrological and geopolitical context, efficient water administration, management, and utilization are thus necessary for the basin's sustainability. Agriculture and industry are the two main economic pillars of the basin. As agriculture becomes more intensive, the population increases, and more people move to the city, competition among the principal consumers is escalates (Zahra et al. ,2023).The changing climate and growing population make it difficult to save water and keep consumption at a sustainable level. As lifestyles evolve and improve, there is an unsustainable increase in the per capita demand for water. The Indus Basin will see a two-fold increase in water demand over the next ten years, which will cause severe water shortages and widespread migration (Jamali et al., 2023).

Therefore, efficient water administration, management, and use are necessary for the basin's sustainability, especially considering the basin's complex, diverse hydrology, and geopolitical context. To prevent impeding economic growth and the enhancement of people's standard of living, sustainability in water sources must be thoroughly understood. Managing and developing big basins' water resources sustainably is now a global priority, which calls for rigorous and thorough scientific study (Mishra et al., 2023).

1.2. Relevance to National needs

Over the last few decades, Pakistan has drastically changed from water-abundant country to a water-stressed one. With 2.8 percent of the global population, Pakistan accounts for 0.5 percent of global renewable water resources (FAO 2021). Worldwide, the country ranks 36th in total renewable water resources compared to India's rank at 8th and Bangladesh's at 12th. Country's cities are already facing problems of erratic piped water supply and unsafe and declining groundwater levels (PIDE, 2022). Only 36 percent of the population has access to safe drinking water. According to the Pakistan Council of Research in Water Resources (PCRWR): if water resources are not properly managed, the country will run out of water by 2025.

The Indus River System is a major source of life in Pakistan. A vast array of Pakistan's agricultural and domestic consumption needs is critically dependent on the Indus River System. The Indus River contributes 90% of Pakistan's food production and provides 25% to the nation's GDP. Pakistan may soon experience a serious food scarcity due to problems with water security. According to the World Bank study for 2020–2021, the water shortfall is expected to reach 32% by 2025, which will cause a food shortage of over 70 million tons (Janjua etal., 2021).

The main irrigation system in Pakistan is the Indus River System, which irrigates 80% of the country's 21.5 million hectors of agricultural land. 121.7 million people rely on the 3180 km long river for water for drinking, farming, navigation, and economic growth. The Indus Basin aquifer has been ranked as the 2nd most overstressed underground water reserve in the world (Janjua et al.,2021).Pakistan's surface water supplies are under growing strain due to its lone main river system, rising population, and declining snowfall over the Himalayan and Karakorum Mountain ranges. Due to exceptionally large withdrawals, underground water supplies are rapidly disappearing (Basharat et al., 2019).

The alarming decline in per capita freshwater availability, from 5,300 cubic meters (m3) at the time of Pakistan's founding in 1947 to about 1,000 cubic meters (m3) in 2011, points to several challenges, the most important of which is Pakistan's management of its water resources (World Bank, 2013). In the form of glaciated mountains, the Indus Basin River Water System (IRS), and a system of canals and distributaries, Pakistan is gifted with a rare combination of water resources (Giese et al., 2022).However, Pakistan is quickly transitioning from a water-stressed to a water-scarce country because to the growing population, inadequate water resource management and distribution, and a lack of attention on raising public awareness of water discipline. Pakistan is noted as having the fifth-highest population in the world with a 1.75 percent yearly growth rate. Pakistan's population, now projected to be at 225 million, is expected to expand to 250 million by 2025 (Yaqoob et al., 2021), with the urban population alone expected to rise by 52% by that time (Janjua et al., 2021).

The population is expected to grow by 80% by 2050, resulting in an 8% rise in water demand for home and industrial uses as well as agriculture. Pakistan had 5,000 m3 of water available per person in 1951, but that number dropped to 1,100 m3 in 2005 and is predicted to reach 800 m3 by 2025. According to the UN, Pakistan's water demand is growing at an average annual rate of 10% (Connor, 2015), which means that by 2025, the total amount of water available will remain between 240 and 258 km3 (Shahzad et al., 2015).

It is estimated that 74% of the available surface water is drained, while 83% of the groundwater is taken out for agricultural and other purposes, which is an incredibly high ratio for a nation like Pakistan where there is a shortage of water (Maguari et al., 2018).

Due to population growth, water waste, and an insufficient water resources management system, gap between supply and demand that prevents water from being used wisely. The Indus River system's inability to satisfy environmental and human demands in Pakistan results from rising water demand. In the Lower Indus River Basin, water management is very important. More than 50 million people depend on obtaining a certain amount of water in the Sindh Province, near the mouth of the Indus, to survive (Riaz et al., 2020).

Past water shortages caused significant harm to fertile land. Water shortages impact Pakistan's environmental conditions. Water scarcities have severely impacted our economy and destroyed more than 2400 km2 of riverine woods along the Indus River. Pakistan is facing a significant national security dilemma because of water constraint. It is also producing social unrest and inter-provincial strife and to problems with India over water. (Bhatti et al., 2019).

So, to avoid hindrances in economic development and improving people's livelihoods, it is crucial to comprehend the sustainability of water resources and effectively respond to the diverse water demands. With population growth, urbanization, and limited demand management measures, water demand will likely increase (Bhere et al.,2022).

1.3. Significance

This study is conducted to assess water sustainability in the Indus River basin, the largest river catchment of central Asia, using data from Gravity Recovery and Climate Experiment (GRACE) satellite. As water scarcity and proper resource management has become an increasingly critical global concern, understanding the dynamics of Terrestrial Water Storage (TWS) in such a prominent and environmentally sensitive region is vital. The findings of this study are expected to contribute valuable insights into the variability of TWS over the Indus River basin. By highlighting the fluctuations in water storage, policymakers and stakeholders will be better equipped to formulate informed strategies to conserve and sustain ground water. Particularly in water-deficit regions like the Indus River basin, where the demand for water exceeds its availability, the study's outcomes have the potential to impact water resource planning, management, and allocation.

Furthermore, the implications of this research extend beyond the immediate geographic area. As central Asia experiences interlinked hydrological systems, understanding TWS variations in the Indus River basin can provide insights into broader regional water dynamics. This study thus contributes to the broader understanding of water sustainability and has the potential to guide similar assessments in other river catchments facing similar challenges. Study findings will benefit the policy makers to conserve water resources for sustainable use in water deficit regions.

1.4. Objectives

- To estimate the monthly mean anomaly of Terrestrial water storage from 2002 to 2022 over study area.
- To estimate Terrestrial Water Storage trend using Sen’s slope estimator and modified Mann–Kendall (MMK) tests to assess the spatiotemporal variability of water mass change over the basin.
- To assess water sustainability in Terrestrial Water Storage using the concept of Reliability, Resilience, and Vulnerability (RRV) over the basin and to relate the Sustainability Index with LULC and population density of the study area.

CHAPTER 2

LITERATURE REVIEW

Increasing water demands and climate change have made freshwater resource depletion a regional and global danger to water security. Water security is a crucial goal for achieving sustainable development of human society and ecosystems. Incorporating water balance studies is imperative within the realm of hydrological research, as they provide a comprehensive understanding of water distribution, availability, and movement. However, the acquisition of accurate and extensive water-related datasets can often pose substantial challenges, thereby necessitating the exploration of innovative methodologies. In this regard, utilizing the Gravity Recovery and Climate Experiment (GRACE) satellite system emerges as a pivotal solution.

Various studies show the applicability of the GRACE's TWS data in various fields of hydrology, groundwater, glaciology, and earthquake studies. The GRACE data showed high potential in various water balance studies due to its ability to map the total changes in groundwater, soil moisture, and surface runoff altogether (Bhere et al., 2022). The large scale of the GRACE data makes it suitable for understanding the changes for more significant regions.

2.1. Assessment of Terrestrial water storage using GRACE data

The total amount of water on land and in the subsurface, known as terrestrial water storage (TWS), is a crucial component of the world's water cycle. In addition to being essential for understanding local and global water cycle processes, accurate estimates of TWS change are also useful for creating efficient water management policies (Jiao et al., 2022). Various research have utilized GRACE data for TWS assessment.

The Gravity Recovery and Climate Experiment (GRACE) and Follow-On (GRACE-FO) observation data was used in the study conducted by (Zhu et al. ,2021) to examine spatio-temporal variation on Terrestrial Water Storage (TWS) over the Indus River Basin. Their findings demonstrated that the TWS Anomaly (TWSA) significantly declined between 2002 and 2020, particularly in the Middle Upper Indus Plain and the upper Indus basin. This decline was attributed to accelerated glacier melting, and there was also a significant loss of groundwater (1.57 mm/month) because of inefficient water management and over-exploitation of groundwater resources.

Xu et al., (2019) had analyzed the spatiotemporal changes in the TWS in China between 2003 and 2016 based on monthly mass concentration (mascon) data from the Gravity Recovery and Climate Experiment (GRACE) satellites. Six significant TWS change regions have been identified, including negative trends in the northwest of China, the southeast Tibetan Plateau, and northern China, as well as positive trends in the west, the south, and the northeast of the country. Statistics show that urbanization's increased water demand was the main factor in the decrease of TWS, while glaciers melting brought on by human-caused climate change was a significant factor in the decline of TWS in northwest China and the southern Tibetan Plateau.

Hu et al. (2018) examined the spatio-temporal variation of TWS in Central Asia over ten years (2003-2013) using data from Gravity Recovery and Climate Experiment satellites. The findings showed that TWS exhibited a declining trend in Central Asia between 2003 and 2013 at a rate of 4.44 2.2 mm/a. The largest positive anomaly for TWS (46 mm) occurred in July 2005, while the minimum negative anomaly (32.5 mm) occurred in March 2008–August 2009. Decline in TWS could be associated with increased evapotranspiration, which typically drives soil moisture storage depletion.

A study focused on the estimating and analyzing of TWS variations over the Canadian landscape was carried out by (Fatolazadeh et al., 2022). GRACE data from April 2002 to June 2017 and GRACE-FO observations from June 2018 to December 2019 were used to produce the estimation. TWS fluctuations were at their highest between February and April. The study's findings showed that from 2002 to 2019, a positive TWS trend from -160 to 80 mm was seen in 78% of the nations.

2.2. Assessment of ground water storage using GRACE data

Numerous studies have proved the efficiency of GRACE and GRACE-FO for ground water assessment over larger areas. Nazari et al., (2023) conducted a study to quantify the changes in groundwater storage over a period of 18 years from 2003 to 2021 in the Helmand River basin. The study was conducted using observations from the Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) data. The information from observation wells was used to verify the outputs of GRACE and GLDAS. According to the findings, the average decline in groundwater storage between 2003 and 2021 was equivalent to (-98.6 226.84 mm or -1.9 4.38 km3/year). In the HRB, the groundwater table decreased by -2.6 m on average between 2003 and 2021. The study found a good correlation (0.75) between the direct in-situ measurements and the GRACE data. This study demonstrated how the GRACE-derived data can be used to estimate changes in groundwater storage in the HRB accurately and may help to manage groundwater resources sustainably in the area.

In the study conducted by Guo et al., (2022) monthly GWS variations in Haile River Basin from 2003 to 2020 were estimated using the Gravity Recovery and Climate Experiment and GRACE Follow-On (GRACE-FO) data in combination with three land surface models from the Global Land Data Assimilation System (GLDAS). The results showed that HRB suffered extensive GWS depletion from 2003 to 2020, which has been aggravated since 2014, with a mean rate of 1.88 $cm\cdot yr^{-1}$, which is equivalent to a volume of 6 billion $m^3\cdot yr^{-1}$. The GWS depletion is more severe in the plain zone $-2.36\ cm\cdot yr^{-1}$than in the mountainous zone which is approximately $-1.63\ cm\cdot yr^{-1}$. In addition, GWS changes showed a low correlation with meteorological factors. It has been established that the two main causes of GWS depletion in HRB are groundwater use for irrigation and changes in land use. Therefore, to ensure the sustainability of groundwater resources in HRB, groundwater exploitation must be controlled, and a more cost-effective agricultural irrigation system must be developed.

Salam et al., (2020). conducted a study to estimate groundwater storage change over Indus River basin from 2010 to 2017 utilizing Gravity Recovery and Climate Experiment (GRACE) data. Net change in storage of groundwater was estimated from the change in TWS by including the additional components such as Soil Moisture, Surface water storage (Qs) and snow equivalent water. For the estimation of these components Global Land Data Assimilation system (GLDAS) Land Surface Models were used. The monitoring well water-level records from the Scarp Monitoring Organization and the Punjab Irrigation and Drainage Authority from April 2009 to December 2016 were also used. Study revealed a significant decline in Ground water storage, and it was estimated that net loss in groundwater storage is at mean rate of 85.01 mm per year and 118,668.16 Km3 in the 7 year of study period were also used from April 2009 to December 2016. Study indicated that the GRACE based estimation of groundwater storage changes are accurate enough to provide monthly updates on the trend of the groundwater storage changes over the study area.

Ztürk et al. (2022) sought to evaluate estimated ground water storage variations in southeast Anatolia, Turkey, where hydro climatological research was few because of scant observation. The investigation of changes in ground water storage in the study area employed data from the Gravity

Recovery and Climate Experiment satellite mission and the Global Land Data Assimilation System. The findings showed that ground water storage decreased over time in all subareas, but was most pronounced in high-elevation locations. Additionally, ground water storage had been impacted by climatic changes in both the short- and long-term.

2.3. Assessment of water resources using different GRACE products

The significance of employing a range of GRACE (Gravity Recovery and Climate Experiment) products is profound in assessing water resources. Emerging satellites measurements provide an unparalleled perspective for comprehending and evaluating the intricate dynamics of Earth's water resources. Across the world, diverse researchers have employed a variety of GRACE products to evaluate water resources, yielding impactful findings.

The TWSA in the GB region was considered for a period of 13 years from January 2003 to December 2016 in a study by Hussain et al., (2021). The Global Land Data Assimilation System (GLDAS)-driven Noah model, in situ precipitation data from weather stations, and Gravity Recovery and Climate Experiment (GRACE) level 2 monthly data from three processing centers, namely Centre for Space Research (CSR), German Research Center for Geosciences (GFZ), and Jet Propulsion Laboratory (JPL), were used for the study investigation. According to the data, TWS has a declining trend as predicted by the GRACE (CSR, GFZ, and JPL) and GLDAS-Noah models. TWS achieves its highest in April and its minimum in October, according to the TWSA's mean monthly analysis.

Sediqi et al. (2019) conducted research across Afghanistan to assess the geographical changes in the availability and sustainability of water resources there. For this, 1° × 1° spatially resolved Terrestrial Water Storage (TWS) data from the Gravity Recovery and Climate Experiment

(GRACE) satellite collected from three institutions were employed. The findings showed that over the previous 15 years, the country's water availability had significantly decreased. Country's central area, where most of the population lives, was determined to have the largest decline. Overall, the northeast and southwest were determined to have the most sustainable water resources in the nation, while the south and the center were found to have the least.

Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO) Level-3 data from three products (JPL, GFZ, and CSR) were used in the study by Arora et al., (2022), to estimate monthly changes in water storage (TWS, terrestrial water storage, and GWS, groundwater storage) over a region of the Indus Basin, India, for the period from April 2002 to December 2021. To determine changes in the water storage changes over a portion of the Indus Basin, the GRACE data have been studied in three phases: (i) monthly variations; (ii) seasonal variations (pre-monsoon and post-monsoon); and (iii) annual variations. This study discovered completely negative trends after 2008 in the water storage from GRACE satellite missions, demonstrating a falling pattern of average TWS from + 17.4 to 28.8 cm and GWS from + 18.1 to 30.2 cm over the study area. The negative trends signified a TWS and GWS deficiency. In June 2021 and May 2021, respectively, the biggest peak deficits of TWS (28.8 cm) and GWS (30.2 cm) were recorded. The decreasing trends in water storage could be associated with intricate interactions between anthropogenic and natural factors. Most of the changes in the region were caused by changes in the groundwater level, the storage of soil moisture (SM), and the amount of water in the canopy.

Ahmed et al. (2021) conducted a study to investigate and comprehend patterns in Pakistan's groundwater storage's spatial variability. The Center for Space Research (CSR), the Jet Propulsion Laboratory (JPL), and the GeoforschungsZentrum Potsdam (GFZ) provided the three sets of GRACE data that were utilized. With a 1.0° 1.0° spatial resolution, these datasets span the years

2003 to 2016. Sen's slope was used to determine the rate of change in groundwater storage, and a modified Mann-Kendall (MK) test was used to determine the significance of the change. The findings demonstrated that different geographical areas had varied levels of groundwater storage change. With a range of 9.02 to 11.3 cm/year and being higher in the south of the country compared to other regions, the decline in groundwater storage was considerably larger in areas of intensive agriculture. According to the MK test, 35 grid cells in various regions of the country showed significant reductions.

2.4. Assessment of water resource sustainability through Reliability, Resilience and Vulnerability approach using GRACE data

Since anthropogenic activities and climate change make changes to a region's water storage unavoidable, understanding these changes is essential for planning and managing water resources. Analysis of sustainability utilizing the Reliability, Resilience, and Vulnerability (RRV) approach provides information on the use of water resources, efforts taken to restore water storage, and the sustainability of the water resources under the influence of climate change and human activity. Extensive data on various hydrological variables above, below, and on the earth's, surface is needed to assess the sustainability of water supplies in a location. However, it is difficult to get data which normally unavailable at all places for these hydrological variables. In this aspect, the Gravity Recovery and Climate Experiment (GRACE) Terrestrial Water Storage (TWS) data has certain advantages because it offers a column of integrated data for groundwater, soil moisture, surface runoff, and snowmelt (Zu etal. ,2023).

Researchers have extensively utilized these datasets worldwide to evaluate the sustainability of water resources. Using two Gravity Recovery and Climate Experiment (GRACE) satellite solutions, Bhere et al., 2022) conducted research to evaluate water sustainability in the Amu Darya basin. Integrating Reliability, resilience, and vulnerability allowed for estimating the spatial variability of water sustainability. Modified Mann-Kendall (MMK) test was also used to find significant water availability patterns. The basin's water supply was found to have significantly decreased, particularly after 2010. According to the study, the cold semi-arid regions and most of the cold desert regions have higher sustainable water supplies than the remainder of the basin. Overall, the findings showed that the study's methodology could be effectively utilized to analyze the availability of water resources in a vast basin with diverse climatic conditions.

The sustainability analysis of the TWS over the Indian River basins was reported by (Sacchin et al. ,2022). Combining the Reliability, Resiliency, and Vulnerability of TWS allowed for an analysis of the regional distribution of sustainability. The study showed how the GRACE's TWS data could be used to analyze the sustainability of water resources across different river basins in India and discovered a declining trend in groundwater storage, especially in Punjab and Haryana, as well as a general decline in water availability across the nation.

The reliability, resiliency, and vulnerability concepts have been used in research by (Ali et al. ,2022) to ascertain the geographical distribution of sustainability in groundwater resources throughout the heavily irrigated region of South Asia and China. Groundwater storage data from the satellite-based Global Land Data Assimilation System (GLDAS) was collected and utilized for this. The results indicated groundwater storage has decreased in Northern China, Western India, and Eastern Pakistan, with Western India seeing the greatest decline rates of -50 to -200 mm per decade. In several areas of the research area, groundwater dependability, resilience, and vulnerability were decreasing, with west India experiencing the worst decline -0.2 to -0.3 per decade.

Using data from the Gravity Recovery and Climate Experiment (GRACE) for 2002 to 2019, the regional and temporal changes of Iraq's Terrestrial water storage were assessed by Al-Mohammadi et al., (2022). Sen's slope estimator and the Mann-Kendall test were used to estimate change rate and significance in terrestrial water storage (TWS), which was generated from several GRACE solutions. The sustainability of water supplies was assessed using indices of reliability, resilience, and vulnerability. Results showed that water availability has significantly decreased, and it was also evaluated that Water resources had low levels of resilience (range 0.01-0.23) and reliability (0.22-0.30).

CHAPTER 3

MATERIALS AND METHODS

3.1. Study Area

The study area used for this research is the Indus River Basin (figure 3.1). The Indus River Basin spans 1120,000 km2 across Pakistan, India, China, and Afghanistan and is located between latitudes 240° and 370° N and 660° and 820° E. Indus Basin Share of Allied Countries has been shown in table 01. The Indus Basin extends from Pakistan's Sindh province's arid alluvial plains to the Himalayan Mountains in the north before ending at the Arabian Sea in the south. Elevations vary from 0 to 8600 meters above mean sea level. Indus Basin covers most of Pakistan, which benefits the four provinces of Sindh, Baluchistan, Khyber-Pakhtunkhwa, and Punjab. The Indus Basin's drainage affects India's Jammu and Kashmir, Punjab province, Rajasthan state, and Himachal Pradesh states. Around 65% of Pakistan's land is covered by the Indus River, which is a significant source of hydropower, irrigation, and water supply (Sambuddha et al., 2019). India likewise has a similar reliance on rivers. The Indus watershed has at least 300 million inhabitants (Pritchard et al., 2017). The Middle and Upper Indus Plain (18.28%) includes lowlands with well-developed industrial and agricultural infrastructure, whereas severe topography, glaciers, and snow characterize the Upper Indus Basin (17.82%).The Indus, Jhelum, Chenab, Ravi, Sutlej, and Bias Rivers are tributaries of IRB. The Chitral River, which rises in Pakistan, travels towards Afghanistan, and eventually empties into the Indus River in Pakistan, is the tributary that flows east. The climate of the basin varies from subtropical to semiarid to temperate to subhumid to alpine in the northern mountainous highlands. In the lowlands, the average annual precipitation ranges from 100 to 500 mm to around 2000 mm in mountainous areas.

3.1. Methodology

The research methodology's three distinct phases, as illustrated in Figure 3.2. The initial phase involves data acquisition, where the main dataset comprises GRACE TWS data from three sources: JPL, CSR, and GSFC, along with additional datasets listed in Table 02. The second stage, known as pre-processing, involves converting data into a geographic format and extracting information relevant to the study area from 2002 to 2022. This is followed by the elimination of duplicate entries, utilization of linear interpolation to address missing values, and the organization of the dataset to ready it for subsequent analysis. The third phase which is the most crucial one involves data processing. In the third phase, programs are executed on the pre-processed data to obtain required results. The final step involves result validation, achieved by comparing outcomes with LULC and population density data across the entire study area. This structured methodology ensures a systematic approach to data collection, processing, analysis, and validation, contributing to comprehensively exploring of the study's objectives.

3.1.1. Data acquisition

In the study's context, data's role is central, rendering its acquisition the foundational and essential step. The process of data acquisition needs the collection of significant information from reputable sources, a critical enabler for responding to research inquiries and attaining the primary study goals. Towards this end, a diverse array of datasets, specified in table 2, are consistently factored into the analytical framework. The selection of these datasets is supported by references originating from a spectrum of research papers, thereby ensuring alignment with the established literature review within the field, and further serving as guiding examples for incorporating distinct components within the datasets.

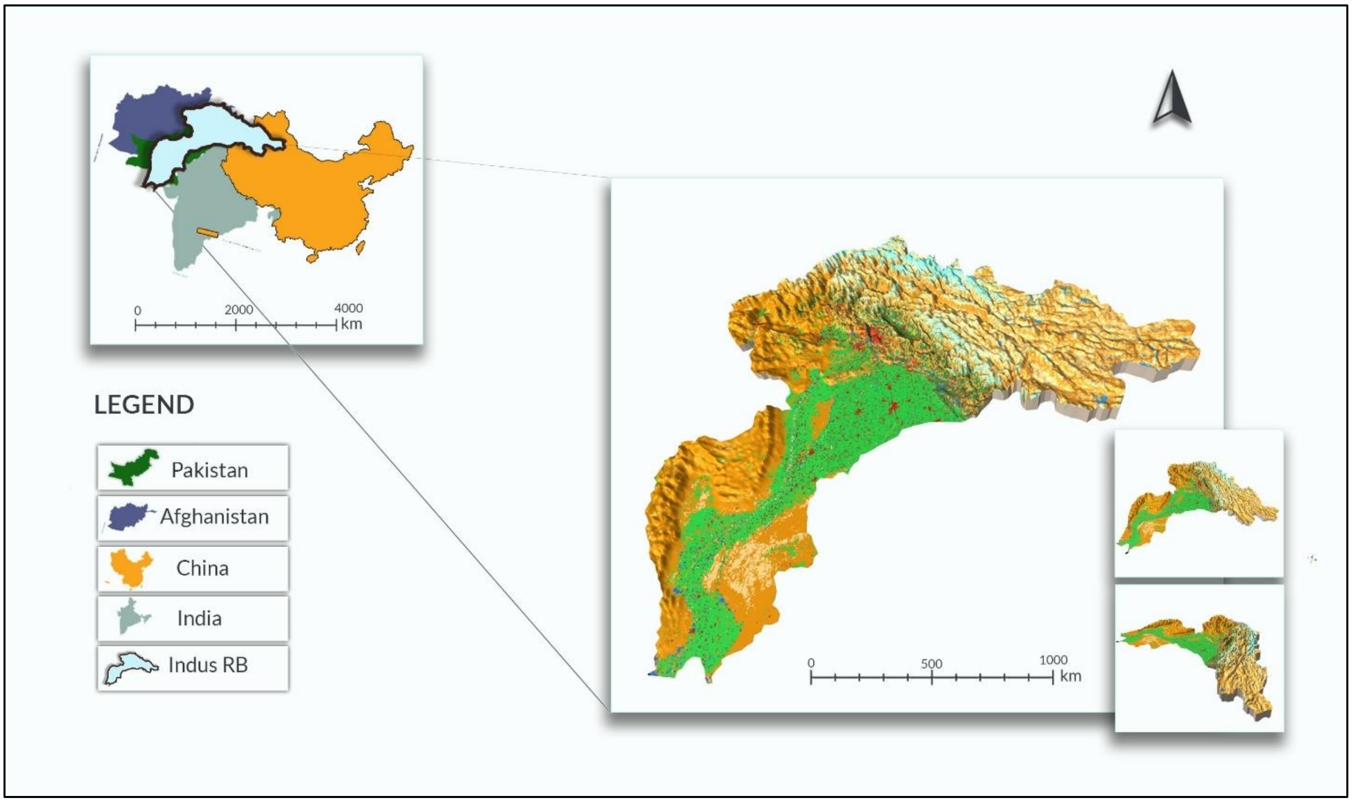

Figure 3.1. Study area map of the Indus River Basin.

Table 3.1. Showing Indus Basin share of allied countries.

Basin	Area		Countries Included	Area of country in basin (Km^2)	As % of total area of the basin	As % of total area of the country
Indus River Basin	Km^2	% of south east Asia	Pakistan	520000	47	65
			India	444000	39	14
	1120000	54	China	88000	8	1
			Afghanistan	72000	6	11

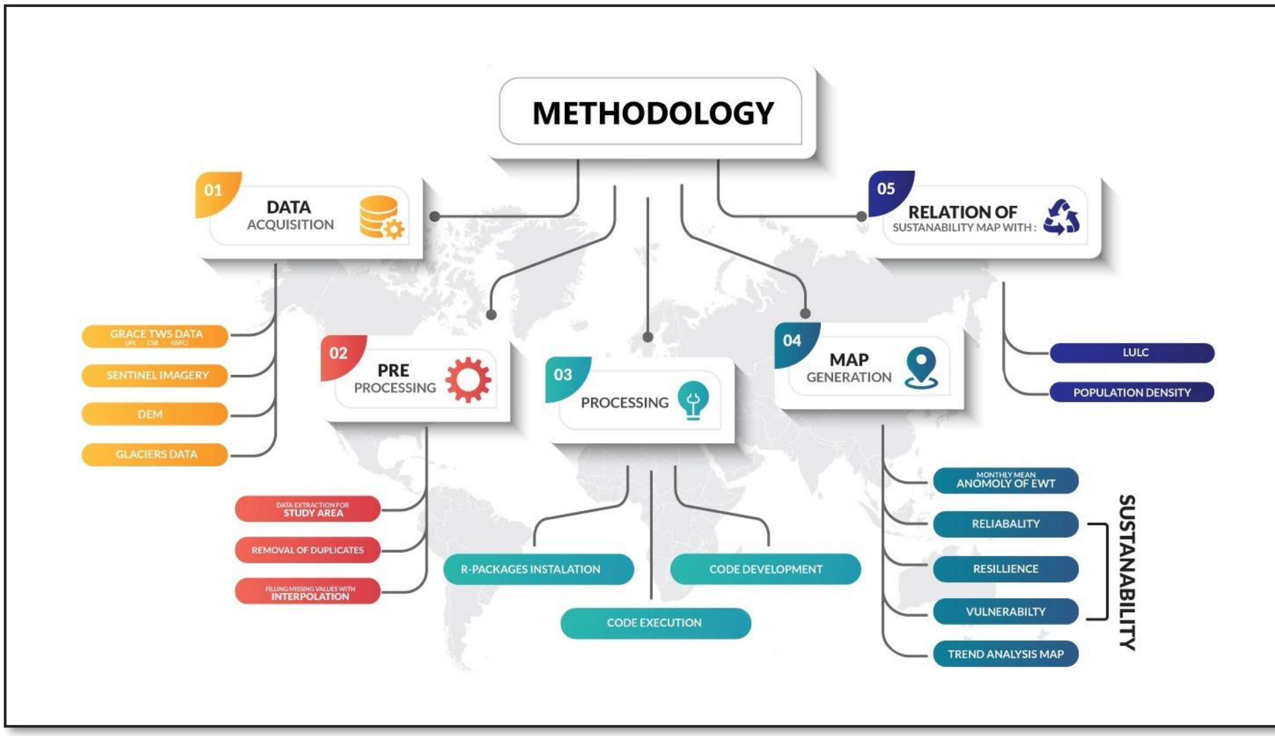

Figure 3.2. Flowchart of methodology.

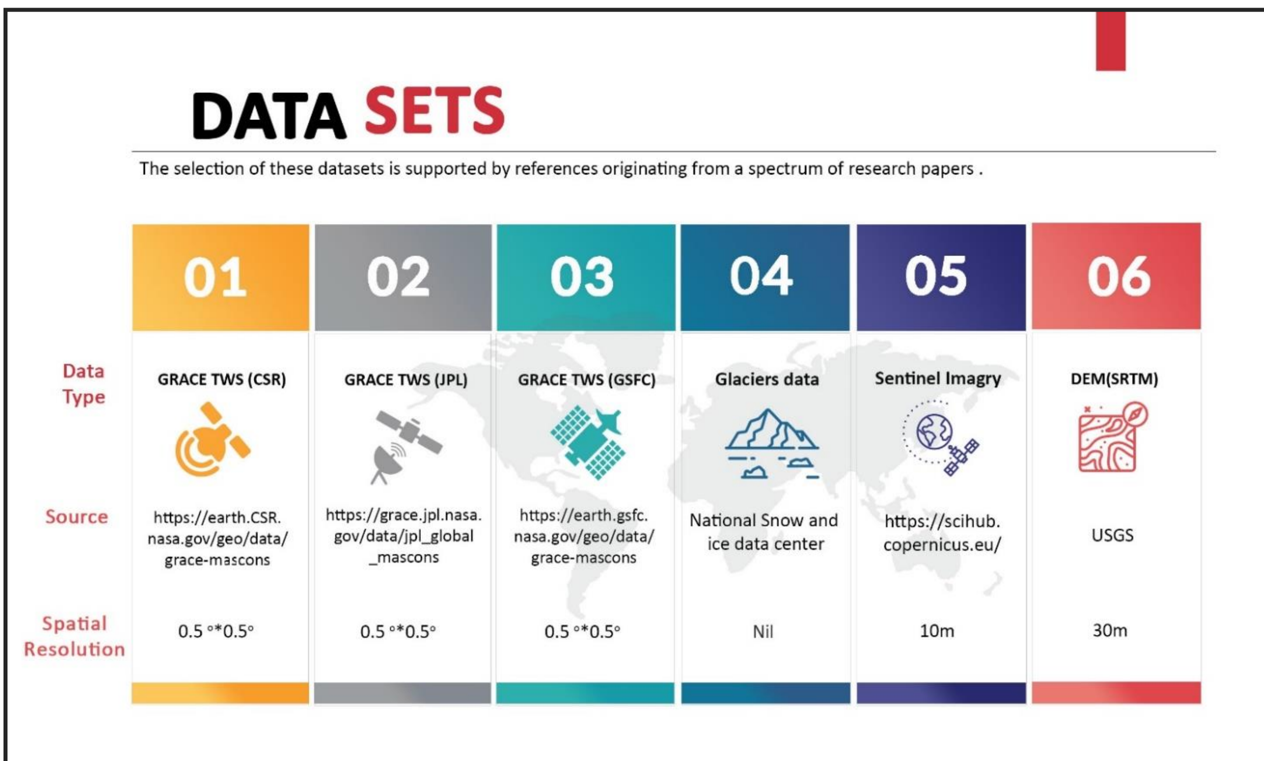

Figure 3.3. Data sets used for research.

3.1.1.1. GRACE's TWS data

The GRACE satellites measure the gravitational field of the Earth. The monthly change in observed gravity is mainly caused by the change in the Earth's surface mass which is indeed mainly caused by the change in water storage. GRACE and GRACE-FO have provided two approaches, the spherical harmonic and the mass concentration blocks (mascons) data versions. Three GRACE solutions are. There are three GRACE solutions generated from the conventional spherical harmonic technique (JPL, CSR, and GFZ) and three from the mascon approach (GSFC, JPL, and CSR). Studies showed a strong relationship between GRACE mascons and spherical harmonics solutions. The current analysis is restricted to three GRACE solutions (JPL, CSR, and GSFC) obtained from the mascon technique. The description of the data is provided in Table 2.

The GRACE TWS data with a 0.5-degree resolution for the period April 2002 to December 2022 have been used in the present study with some missing monthly values. Through linear interpolation, the missing data were calculated. Data from 392 grid points were used in the current study to cover the whole Indus River basin. Equation (1) illustrates how the TWS data provides a column of integrated values for all the hydrological parts of the water storage. The TWS is the aggregate of snow water equivalent, surface water, soil moisture and groundwater.

$$\Delta \mathrm{TWS} = \Delta \mathrm{GW} + \Delta \mathrm{SM} + \Delta \mathrm{SWE} + \Delta \mathrm{SW} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The terms "GW," "SM," "SWE," and "SW" refer, respectively, to changes in groundwater, soil moisture, snow water equivalent, and surface water. Three data centers from the University of Texas at Austin Centre for Space Research (CSR), NASA Goddard Space Flight Center (GSFC) and Jet Propulsion Laboratory (JPL) are employed to give the level 3 version 4 data of the GRACE's TWS. The information for monthly gravitational changes is employed which is translated into a change in TWS in terms of water equivalent thickness in cm. The error has been reduced using all three data sets from data centers therefore individual analysis is conducted on each dataset.

3.1.1.2. Ground Water level data

Groundwater data from Northwest India , Punjab and Pakistan (Punjab)has been obtained from the following source https://doi.org/10.5285/150c95f7-18bf880b8364b7257b26.Dataset contains groundwater level data in metres indicating the depth at which Ground water is found below the earth surface from 2028 individual site between 2002 and 2010.

3.1.1.3. Digital Elevation Model

A digital elevation model (DEM) is a representation of the topographical aspects of the Earth that uses precise elevation data to cover a specified geographic area. A variety of data sources and procedures are used in the development of DEMs. Notably, the United States Geological Survey (USGS) is a key player in creating and sharing high-fidelity DEM datasets, which are essential for a variety of applications including geographic analysis, mapping, environmental modeling, and infrastructure development. The Shuttle Radar Topography Mission (SRTM) DEM was used in the context of this study to explore the topography features of the targeted area carefully. The selected dataset, which has a spatial resolution of 10 meters, accurately represents the elevation of the study region. This SRTM DEM dataset is enhanced using void filling procedures, which is significant since it guarantees an accurate and thorough representation of the terrain characteristics. The study gets a solid foundation for terrain analysis by utilizing the SRTM DEM with careful evaluation of its spatial resolution and void-filling upgrades. Within the parameters of the research goals, this dataset acts as a cornerstone for clarifying landscape characteristics, enabling precise geographical interpretations, and supporting informed decision-making.

3.1.1.4. Sentinel imagery

Sentinel satellite imagery from the European Space Agency's Copernicus program served as the primary dataset for conducting the Land Use and Land Cover (LULC) classification in this study. The Sentinel 2 satellites, initially launched in mid-2015, were chosen as a suitable option for LULC mapping due to their remarkable spatial, spectral, and temporal resolution. The Sentinel program encompasses a constellation of satellite missions equipped with radar and multispectral sensors, thus providing a comprehensive range of Earth observation data. The decision to employ Sentinel imagery was driven by its capability to capture high-resolution images that are frequently updated, rendering it well-matched for tracking and analyzing shifts in land cover and land use patterns over extended periods. The spatial resolution of Sentinel-2 imagery, commonly at 10 meters for visible and near-infrared bands and 20 meters for shortwave infrared bands, facilitated the precise differentiation of diverse land cover categories. Sentinel imagery is conveniently accessible through resources such as the Copernicus Open Access Hub and authorized data portals. Researchers can readily access this imagery based on their study area and the desired temporal scope.

3.1.1.5. Population Data

Population data holds significant importance across a spectrum of research domains, returning vital insights into demographic patterns, urban evolution, and regional strategic planning. In the context of this specific study, the acquisition of population data was derived from the distinguished Global Land Scan dataset, renowned for its comprehensive and high-resolution portrayal of population distribution that spans diverse geographical expanses. The precise selection of the

Global Land Scan dataset as the primary source for population data was grounded in its firmly established repute for delivering exhaustive and contemporary insights into population distribution trends. Notably, this dataset employs a fusion of satellite imagery, land cover data, and census records, in a gridded representation that captures population figures with exceptional spatial accuracy. The process of accessing the Global Land Scan dataset was streamlined through authentic data repositories or dedicated platforms. Typically presented in a raster configuration, wherein individual pixels correspond to precise population counts. This gridded dataset, characterized by a spatial resolution of 250 meters, was procured from the Oak Ridge National Laboratory (ORNL) website, subjected to reprocessing, and subsequently extracted for the designated study area, employing the ArcMap software.

3.2.1. Data Preprocessing

The thesis's methodological section strongly emphasizes data preprocessing, which provides a critical framework for the following analysis. The integrity and quality of the dataset are ensured by completing numerous crucial processes during this crucial phase. The first step entails extracting data according to the study area, an essential step that helps to focus and make the analysis more relevant. The dataset is afterwards thoroughly cleaned up of duplicates, thus enhancing the knowledge pool and reducing the impact of redundancy. After that, filling in any missing numbers is accomplished by using linear interpolation methods. This ensures that the data is complete. In addition to maintaining the dataset's consistency, this complex method also makes it possible for numerical trends to continue smoothly. To achieve the goals of the research, these preprocessing procedures work together to prepare the data for a more consistent and reliable analysis.

3.2.2. Data Processing

3.2.2.1. Monthly mean anomaly of Terrestrial water storage (TWS)

GRACE TWS data from three distinct sources, JPL, CSR and GSFC has been used to evaluate the Monthly Mean Anomaly of Terrestrial water storage over the study area from 2002 to 2022. The Monthly mean anomaly of Terrestrial water storage analysis involves assessing the deviation of each month's TWS value from the expected or typical value for that specific month. This analysis facilitates the identifying and comprehending of variations or alterations in water storage patterns over time. It is given by the following equation:

$$\text{Monthly mean anomaly of } \mathrm{TWS} = \mathrm{TWS(i)} - \mathrm{TWS\ avg(i)} \ldots\ldots\ldots\ldots (2)$$

Whereas:

TWS(i) = Terrestrial water storage value for the individual month 'i'.

TWS avg(i)= monthly average Terrestrial water storage for month 'i'.

By examining these monthly mean anomalies, valuable insights can be gained regarding the trends, anomalies, and abnormal patterns in water storage. This information plays a critical role in monitoring and understanding changes in hydrological systems, groundwater levels, soil moisture, and even ice melting. Ultimately, it enhances our understanding of the dynamic behavior of water resources over time.

3.2.2.2. Trend Analysis of Water Availability

Sen's slope estimator and the MMK test are used to quantify the importance of trends and estimate EWT changes. Sen's slope is a nonparametric method for estimating the size of change in data from climatic time series. The rate of change between two subsequent data points is measured (Q):

$$Qi = \frac{xi-xk}{i-k} \quad for\ N = 1, 2, 3, \ldots, n \qquad \ldots\ldots\ldots\ldots. (3)$$

where there are two data points at periods i and k, xi and xk. The median of these n values of Qi is the Sen's estimator of the slope, as shown below:

$$Q = \begin{Bmatrix} \frac{Qn+1}{2} & \text{if n is odd} \\ \frac{1}{2}\left(\frac{Qn}{2} + \frac{Qn+2}{2}\right) & \text{if n is even} \end{Bmatrix} \qquad \ldots\ldots\ldots (4)$$

For a time, series of values x1, x2, x3, and xn, the MK test statistic (S) can be calculated as follows:

$$S = \sum_{k=0}^{n-1} \sum_{i=k+1}^{n} \text{sign}\ (xi - xk) \qquad \ldots\ldots\ldots (5)$$

$$\text{Where sign}\ (xi - xk) = \begin{Bmatrix} +1 \text{ if sign}(xi - xk) > 0 \\ 0 \text{ if sign}\ (xi - xk) = 0 \\ -1 \text{ if sign}(xi - xk) < 0 \end{Bmatrix}$$

where S is the total of positive or negative signs, n is the number of data points, and xk and xi are the time-series observations. To determine the importance of a trend, the Z statistic is estimated using the S variance.

$$Z = \begin{Bmatrix} \frac{s-1}{\sqrt{var(s)}} & \text{when } s > 0 \\ 0 \text{ when } s = 0 & \\ \frac{s+1}{\sqrt{var(s)}} & \text{when } s < 0 \end{Bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Z would be favorable for an ascending trend and unfavorable for a downward one. If |Z| > 1.96, the null hypothesis that there is no trend is rejected with a 95% confidence range. Hirsch and Slack proposed the MMK trend test to tackle the autocorrelation issues in time series data. The MMK test is run when the null hypothesis of no trend is rejected. The MK test is used to first evaluate the trend in the MMK process. Since the MMK test ranks the data (Ri) to estimate its equivalent normal variants (Zi) using the inverse standard normal distribution function (1) if the time series exhibits a significant The MMK test uses the inverse standard normal distribution function (1) to de-trend the series and rank the data (Ri) to estimate its equivalent normal variations (Zi).

$$Zi=\emptyset^{-1}\left(\left(\frac{Ri}{n+1}\right)\right) \text{ for } i = 1 : n \quad \ldots\ldots\ldots\ldots (7)$$

where n is the duration of the time series and 1 is the inverse standard normal distribution function. The Hurst coefficient (H) is calculated using the Z through the maximum log-likelihood function [70].

$$\text{Log L (H)} = -\frac{1}{2}\log\left|cn(H)\right| - \frac{Z\tau[C_{n(H)}]^{-1}Z}{2_{\gamma 0}} \quad \ldots\ldots\ldots\ldots (8)$$

The amount of H that produces the highest value of log L(H) is counted to show the presence of long-term dependency in the time series, and |Cn(H)| is the determinant of the correlation matrix of lag for a particular H; z denotes the transposition and variance of Z. For H = 0.5, the importance of H can be determined by utilizing the mean and standard deviation. The biased estimate of Var(S) H0 can be represented as follows when H is determined to be significant:

$$\text{Var}(s)^{H'} = \sum_{i<j}.\sum_{k<1}\frac{2}{\Pi}\sin^{-1}\left(\frac{\rho|j-i|-\rho|i-1|-\rho|j-k|+\rho|i-k|}{\sqrt{(2-2p|i-j|)}\sqrt{(2-2p|k-i|)}}\right) \ldots\ldots\ldots\ldots (9)$$

where ρl is the autocorrelation function for a given H.

3.2.2.3. Assessment of Water Resources Availability

The variation in the sustainability of water resources was assessed using the sustainability index, developed by Loucks, and refined by Sandoval-Solis et al., defines sustainability (S) as a function of Reliability, resilience, and vulnerability as follows:

Sustainability = [Reliability × Resilience× (1 - Dimensionless Vulnerability)]1/3……. (10)

Sustainability refers to the long-term management and responsible use of water sources to ensure the continuous availability of clean and adequate water for current and future generations while safeguarding the ecological health of aquatic ecosystems and considering social and economic needs.

The RRV metrics offer the best way to assess a structure's likelihood of success or failure and the speed at which it recovers from unsatisfactory conditions. The RRV outlined by Hashimoto et al. and Sandoval-Solis et al. has been used in this study which are as follows.

3.2.2.3.1. Reliability

Reliability indicates the frequency of satisfactory events or excess water availability at the specific location. It is given by following Equation:

$$\text{Reliability} = 1 - \sum_{j=1}^{M} \frac{dj}{T} \text{……….} \quad (11)$$

Whereas:

M= total number of negative events

J= serves as index spanning from 1 to M

dJ= duration of j^{th} event

T=total time being analyzed

To generate a reliability map, a customized code was developed using the R programming language based on the given equation. This code was designed to process and analyze the GRACE TWS (Gravity Recovery and Climate Experiment Terrestrial Water Storage) data obtained from the CSR (Center for Space Research) solution spanning the temporal range of 2002 to 2022. The code implemented a series of computational steps, including data preprocessing, reliability calculation, and spatial visualization. A reliability map was produced by executing the code depicting the spatial distribution of reliability values across the study area. This methodology facilitated the assessment of data consistency and accuracy, providing valuable insights into the reliability assessment of the study area in relation to water storage dynamics.

3.2.2.3.2. Resilience

Resilience assessment across the study area encompassing the years 2002 to 2022 involved the utilization of GRACE TWS data derived from the CSR (Center for Space Research) solution. Resilience represents the frequency of recovering from unsatisfactory events or replenishing water storage at a specific location. It is given by following Equation:

$$Resilience = ((\frac{1}{M}) - \sum_{j=1}^{M} dj)^{-1} \ldots\ldots\ldots \text{(12)}$$

Whereas:

M= total number of negative events
J= serves as index spanning from 1 to M
dJ= duration of j^{th} event

3.2.2.3.3 Vulnerability

Vulnerability represents the magnitude of extreme unsatisfactory events or the magnitude of water storage deficit at a specific location. It is given by following Equation:

$$Vulnerability = \frac{1}{M}\sum_{j=1}^{M} vj \text{..........(13)}$$

Whereas:

M= total number of negative events
J= serves as index spanning from 1 to M
vJ= extent of vulnerability for j^{th} event
A vulnerability map has been generated using GRACE TWS dataset from CSR solution by executing a code set in R programming language.

3.2.2.4. Ground water level data for validation of Sustainability Index

Tshe Inverse Distance Weighting (IDW) interpolation technique was applied to generate interpolated maps illustrating groundwater levels during two distinct time intervals: 2002-2005 and 2006-2010. Utilizing the same interpolation technique, an additional map (2006-2010) was produced for the latter period. Subsequently, a correlation analysis was conducted to establish the relationship between the sustainability map and the corresponding groundwater level data.

3.2.2.5. Land use land cover classification

In the present study the land use classification is performed on sentinel 2 imagery. The Sentinel 2 satellites, first launched in mid-2015, is an excellent candidate for LULC mapping due to its high spatial, spectral, and temporal resolution. 120 training samples have been used against each class and classified into seven classes using supervised classification. The classes are as follows: Trees, water bodies, snow, vegetation, barren land, built-up areas and range land. The quality of classification is checked and exported with the spatial resolution of 10 meters. The resultant raster output is transformed into universal transverse Mercator (UTM) projection zone 43N with the spatial resolution of 10 meters and the radiometric resolution of 32 bits. The error matrix is also run-on classification to check the accuracy and quality of classification results.

3.2.3.5 . Population density map

Many organizations are working on population data preparation by combining various sources. Land scans are one of them. It produced the population data by combining the census data along with spatial data and imagery analysis technologies on global scale to produce the gridded datasets. The population density data was acquired from Lands can global population database the industry standard for global population distribution with a spatial resolution of 250 meters. It can be downloaded from lands can website. This gridded dataset is downloaded with the spatial resolution of 250 meters, reprocessed and extract the study area in ArcMap.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1.1. Monthly mean Anomaly of Terrestrial Water Storage (TWS)

Figures 4.4,4.5, and 4.6 illustrate the anomalies in Terrestrial water storage (TWS) based on the GRACE data from the CSR, JPL, and GSFC solutions respectively for the Indus River basin throughout the study period of 2002-2022. The figure utilizes blue to represent positive TWS anomalies indicating higher water availability compared to the mean, and red to represent negative anomalies indicating lower water availability. The consistent seasonal variability patterns in TWS are observed across all GRACE solutions.

In the early years, the water availability was above the mean level particularly from May to September and at or somewhat below the mean level during September to December. Overall, it was above its mean level for a longer period (May to September) throughout the study area. In recent years, particularly after 2010, the EWT gradually declined except for 2011 and 2015. For example, it was generally above the mean level in May to September 2002 to 2010, but in recent years it did not even reach the mean level (Figure 4.4-4.6).

So, water availability has become less abundant in recent years, which is indicated by a reduction in the blue color in all GRACE products, signifying a decrease in TWS. These findings have been found consistent with the research conducted by (Sachin etal., 2022)

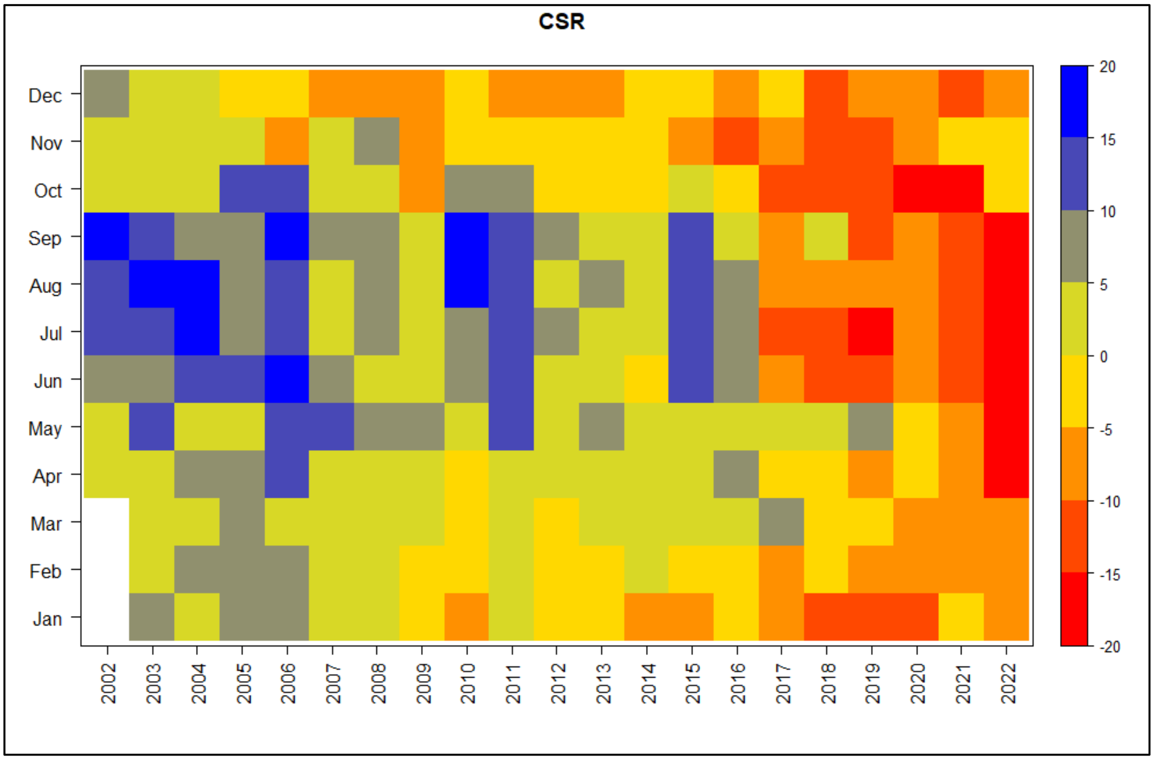

Figure 4.4. Mean monthly anomaly of terrestrial water storage in cm obtained by center for space research at university of Texas, Austin.

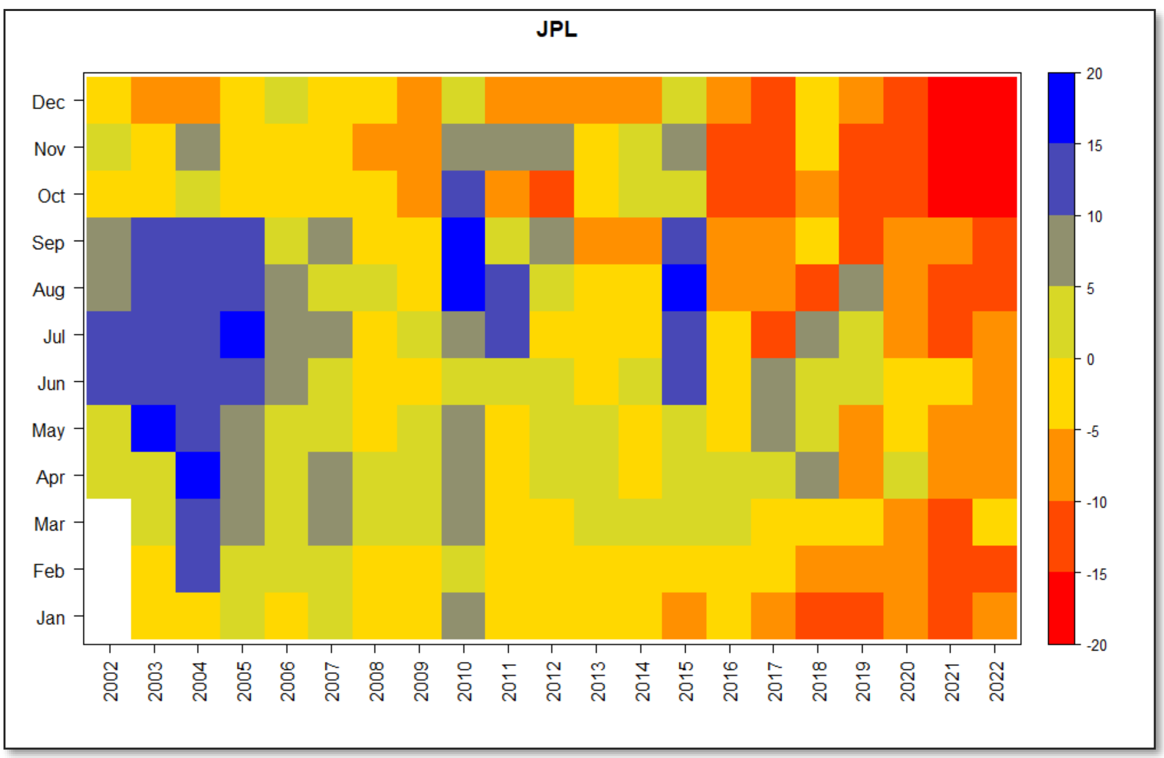

Figure 4.5. Mean monthly anomaly of terrestrial water storage in cm obtained by Jet propulsion laboratory.

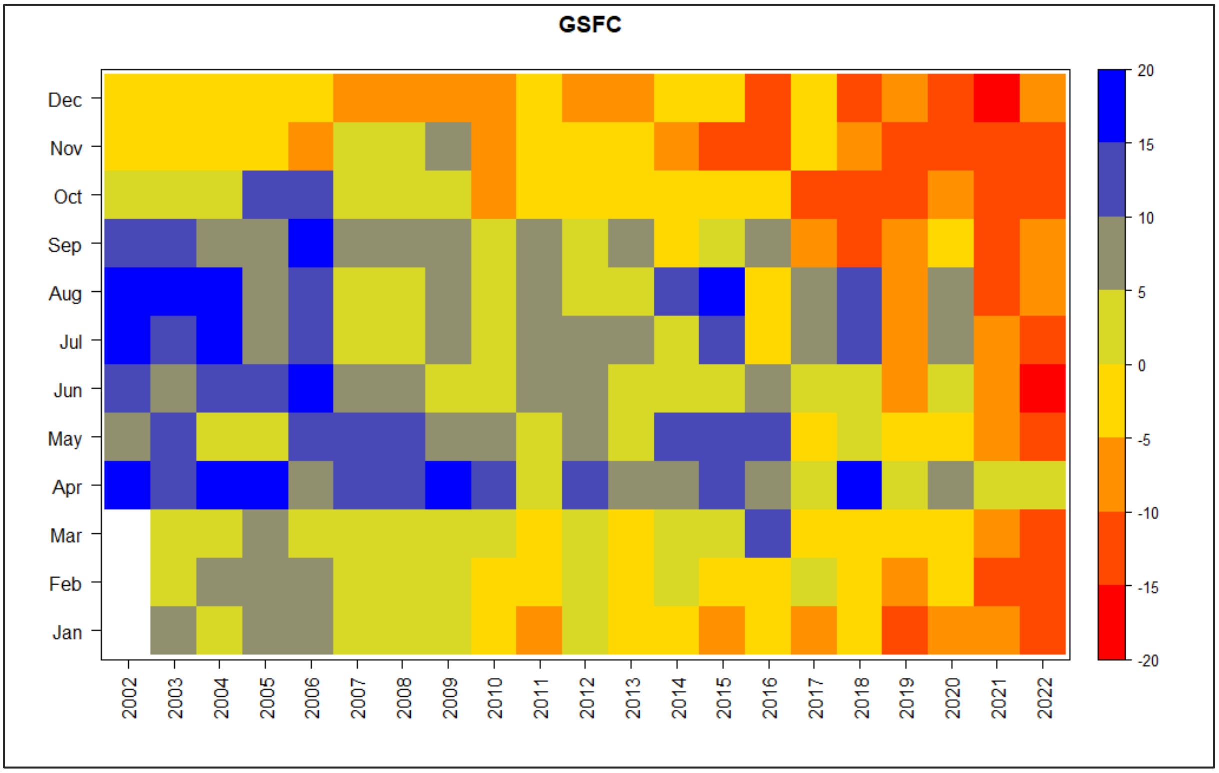

Figure 4.6. Mean monthly anomaly of terrestrial water storage in cm obtained by NASA Goddard space flight center.

4.1.2. Trend Analysis of Terrestrial Water Storage (TWS)

The spatial distributions of trends in annual average TWS for the CSR, JPL and GSFC solutions are shown in Figure 4.7, 4.8 , and 4.9. Modified-Mann Kendal test was performed to check the significance of trend. And the resultant p value obtained by Mann Kendal test were 0.00093, 0.00076 and 0.0042 for CSR, JPL and GSFC solution respectively, which ensured that a significant trend exists in TWS data. Using Sen's slope estimator, the rates of change in TWS over the study area for period 2022 to2022 were estimated.

The rate of change in TWS is presented using a color ramp which was in the range from 0.05 to −0.15 cm/year. The figures show that most of the study area has a negative change while a very small area in the northeast has a slight positive change. The figures show a significant decrease in water resources in most of the basins by all the three GRACE solutions. The highest significant decrease was found in the southern region at a rate of -0.10 to -0.15 cm/year. In contrast, a slight increase in the range of 0.05 to 0.10 cm/year in TWS was noticed over very small parts of the northern region. The central region of basin also shows a negative trend ranging from -0.10 to -0.05cm/year. These findings are consistent with that obtained through analysis of the monthly mean anomaly of TWS presented in Figure 2, 3 and 4.

4.1.3. Spatial distribution of Terrestrial Water Storage (TWS) Sustainability

The spatial distribution of water sustainability with its functions, reliability, resilience, and vulnerability obtained by CSR, JPL and GSFC solution is shown in Figures 4.10,4.11,4.12 and 4.13 respectively. The indexes were scaled in the range of 0.0–1.0 for presentation. The blue color in the map represents the higher values of the indexes.

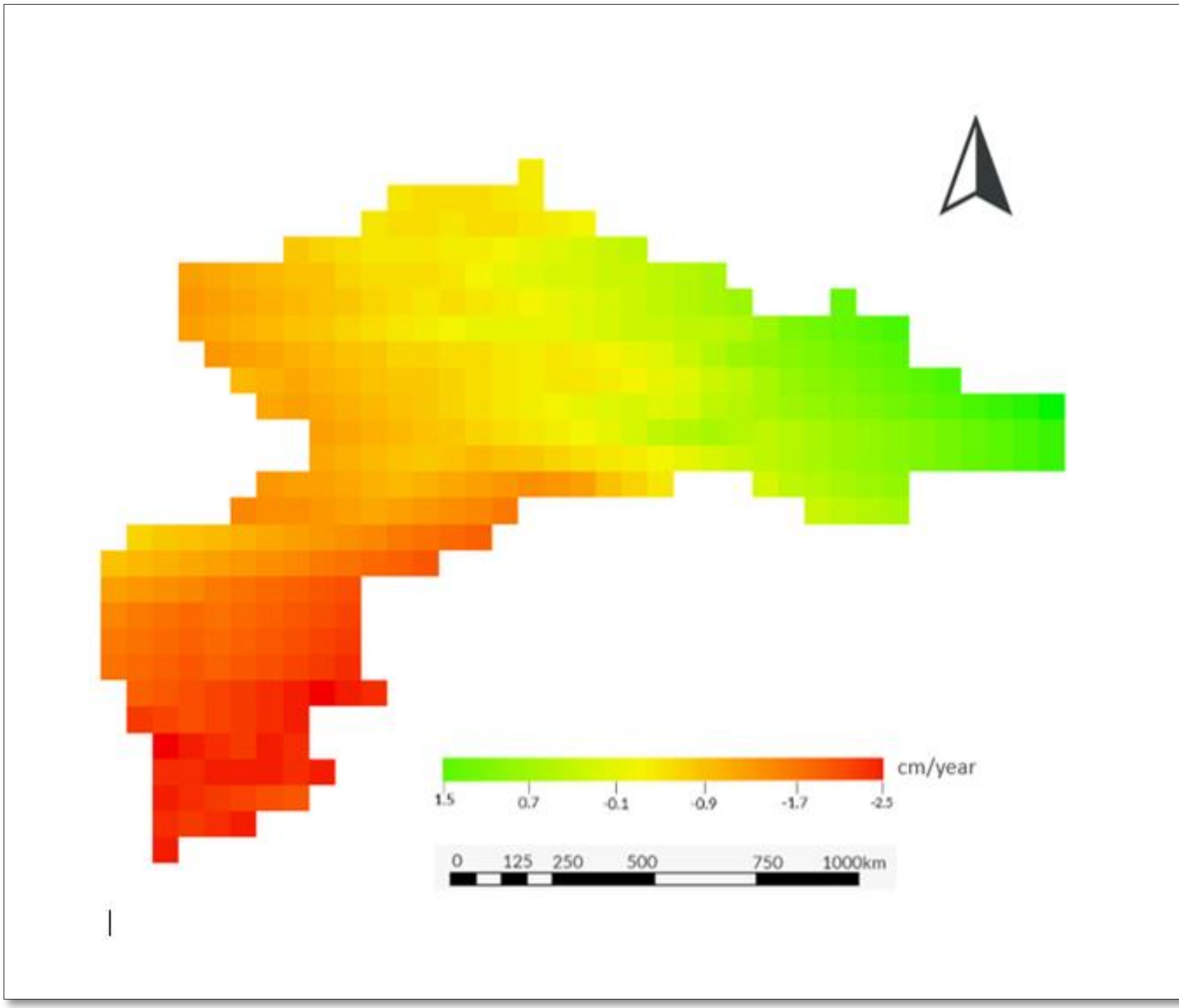

Figure 4.7. Spatial distribution of trend in terrestrial water storage obtained by center for space research at university of Texas, Austin.

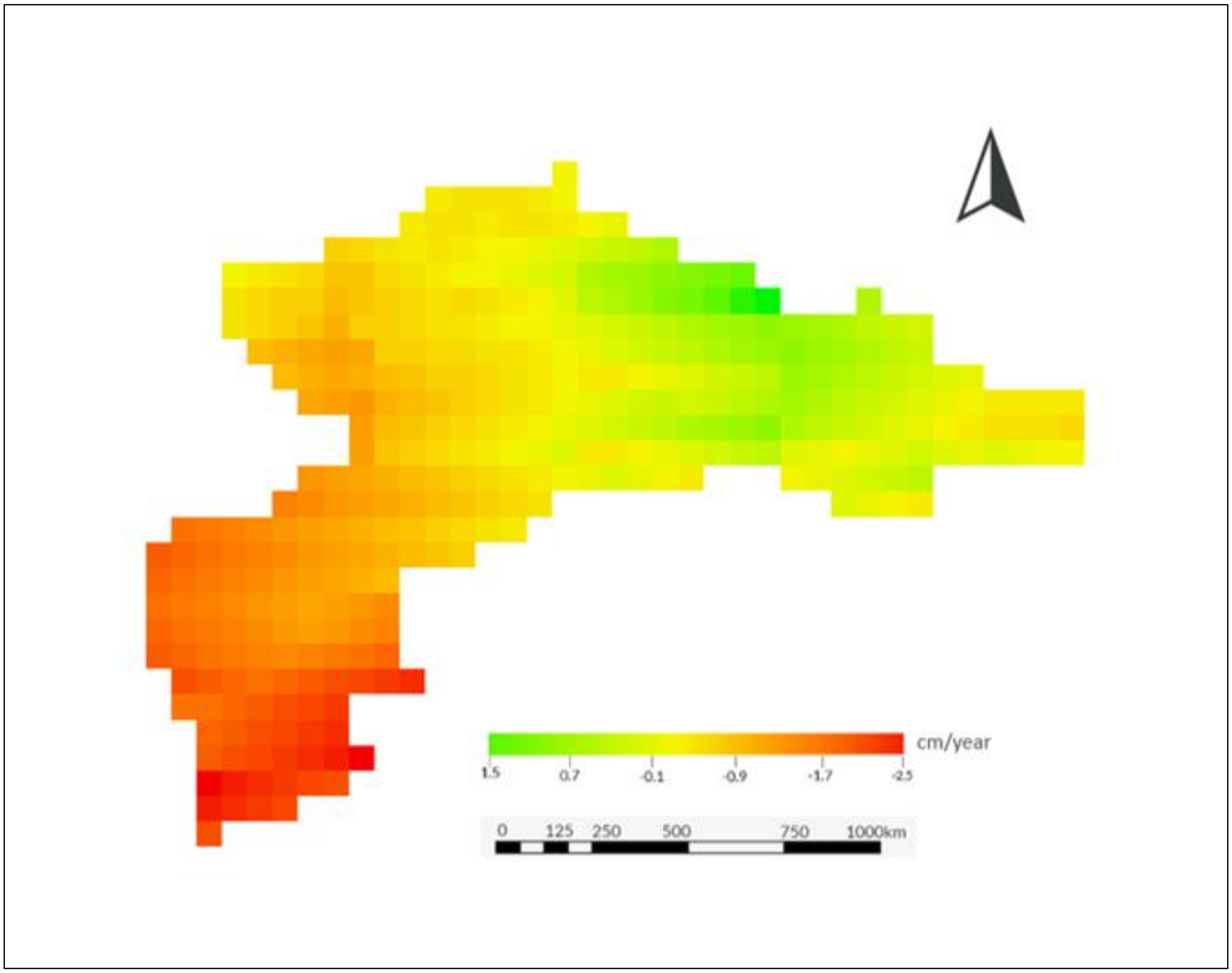

Figure 4.8. Spatial distribution of trend in terrestrial water storage obtained by Jet propulsion laboratory.

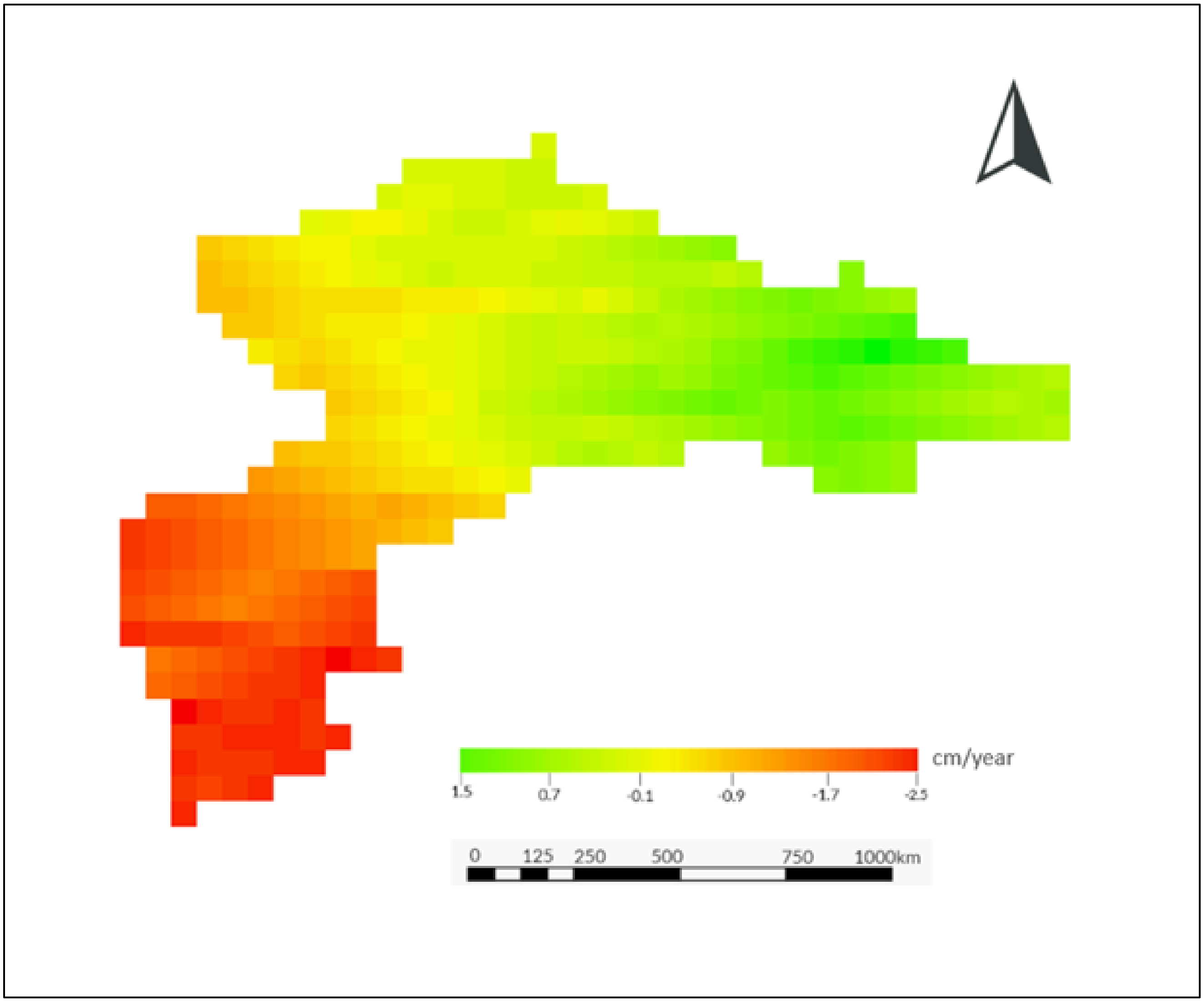

Figure 4.9. Spatial distribution of trend in terrestrial water storage obtained by NASA goddard space flight center.

The higher reliability in water was noticed in the north and northeast of the basin, covering most of the areas of GB, Niger in China, Kashmir, Himachal Pradesh, and some part of KPK of around 0.8-1.0. Low reliability is observed in Sindh, Baluchistan and Rajastan of around 0.2-0.4, which comes under the southwest zone.

Resiliency showed a similar pattern to reliability that is high in the north of the basin and low in the south and southwest except for some region in the center of basin covering most of the Punjab province in Pakistan and some part of the Indian Punjab shows highest resilience of the range 0.8 to 1. Results of vulnerability were contrary to reliability and resilience. Vulnerability was higher in some areas of the south and southwest covering Baluchistan, Sindh, and Rajasthan regions in the range of 0.8 to 1.0. least vulnerability was found in the northern and northeastern part of the basin. some parts of Punjab and Himachal Pradesh also indicated low vulnerability.The sustainability maps showed a spatial similar to reliability and resilience. The water resources in the northern and northeastern part of the basin were more sustainable than other regions of the catchment also covering a small part of Afghanistan, and KPK. Water resources in southern and southwestern zones of the basin encompassing a part of Baluchistan, Sindh and Rajastan are relatively less sustainable. These findings are in line with the research findings of Sidiqi et al. 2020.Overall, the estimated values of sustainability index by the three solutions were found in a range between 0.20 and 1.0 at most of the regions of the study area. The GFZ and JPL provided similar sustainable values while CSR showed a somewhat different pattern. However, all the solutions showed the highest sustainability (0.80–1.0) in the north and northeast of the country. The least sustainable regions having values of 0.0 to 0.40 were observed in the southwest by all solutions. Overall, it can be remarked that water resources in the northeast and southwest regions are more sustainable and in the south and southwest regions are less sustainable.

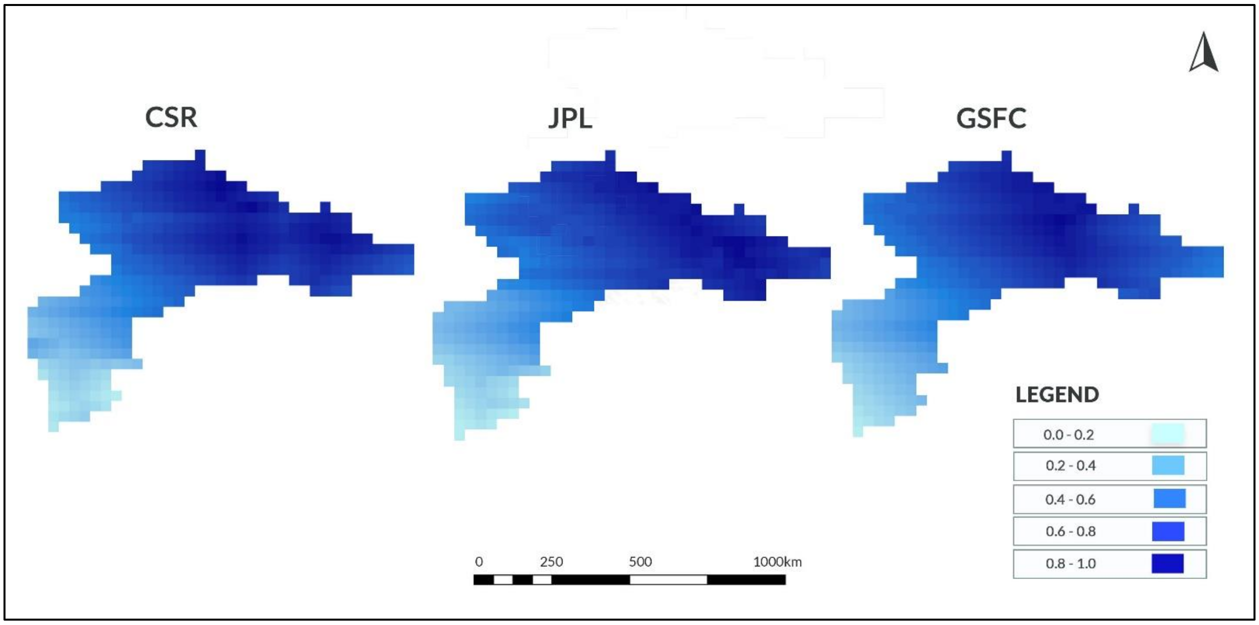

Figure 4.10. Spatial distribution of terrestrial water storage reliability using center for space research at university of Texas, Jet propulsion laboratory & NASA goddard space flight center solutions.

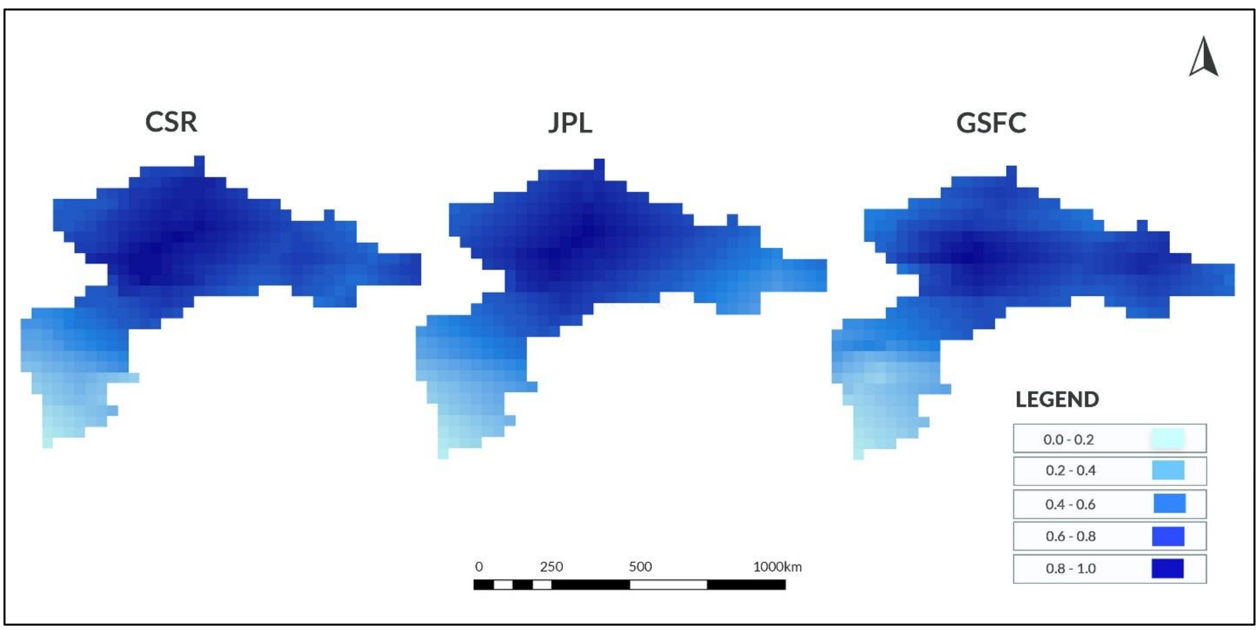

Figure 4.11. Spatial distribution of terrestrial water storage resilience using center for space research at university of Texas, Jet propulsion laboratory & NASA goddard space flight center solutions.

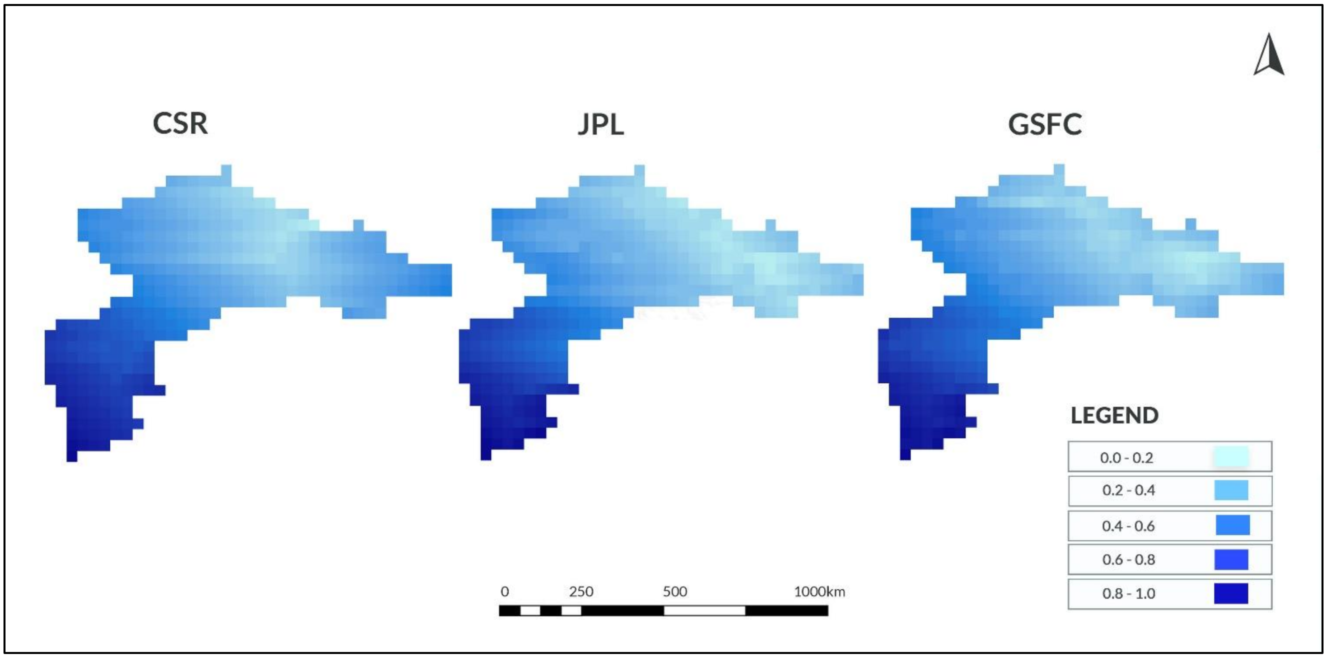

Figure 4.12. Spatial distribution of terrestrial water storage vulnerability using center for space research at university of Texas, Jet propulsion laboratory & NASA goddard space flight center solutions.

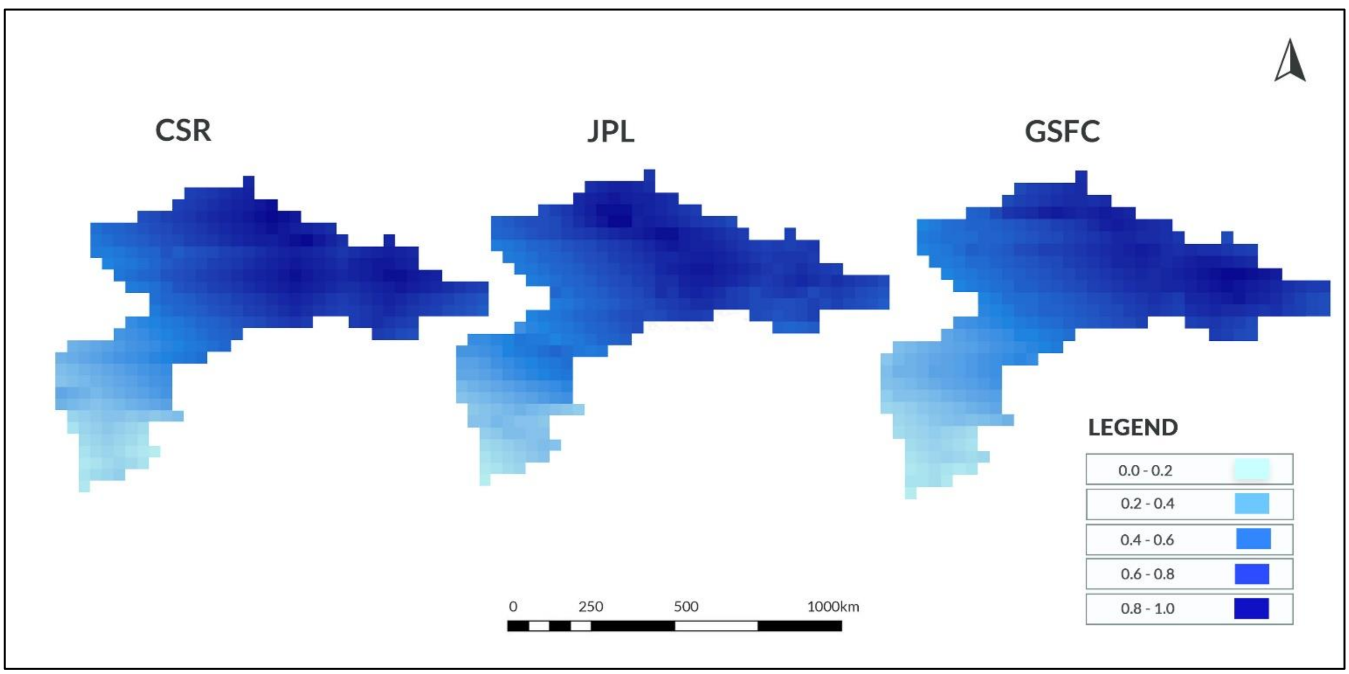

Figure 4.13. Spatial distribution of terrestrial water storage sustainability using center for space research at university of Texas, Jet propulsion laboratory & NASA goddard space flight center solutions.

4.1.4. Ground water level data for validation of Sustainability Index

The spatial distribution of groundwater data points (figure 4.14) and interpolated maps showing ground water depth (2002-2005) is visually presented in Figures 4.15 and maps showing ground water depth (2006-2010) is presented in figure 4.16. In Figure 4.15, a spatial analysis shows a noteworthy pattern of low groundwater levels in the north, northeast, and northwest, indicating shallower depths of groundwater in those areas. Conversely, there is an escalation in groundwater depth towards the center, south, and southwest, signifying greater depths in those directions. Notably, the spatial analysis of ground water depth map from 2006-2010 illustrates further increase in water levels over the specified timeframe in the south and southwestern region, suggesting a decline in groundwater availability.

These spatial observations align consistently with the sustainability map, which similarly portrays lower sustainability levels in the southern part of the area. Also ,a negative correlation is seen between groundwater levels and sustainability, with a correlation coefficient of -0.7. This implies that as groundwater levels increase (indicating decreased water availability), there is a corresponding decrease in sustainability. The southwestern region exhibits an increasing trend in groundwater levels, indicating a reduction in groundwater availability. Furthermore, sustainability in the southwestern region is lower compared to other parts of the basin. Thus, the decrease in groundwater availability points to a reduction in Total Water Storage (TWS) sustainability in the southwestern region.

Figure 4.16 presents a graph illustrating the average groundwater depth in meters from 2002 to 2010, revealing a consistent upward trend. This implies a continual decrease in groundwater availability over time. The decline in groundwater availability may contribute to the observed lower sustainability in TWS across the southwestern regions, as detailed by Bhere et al. (2022).

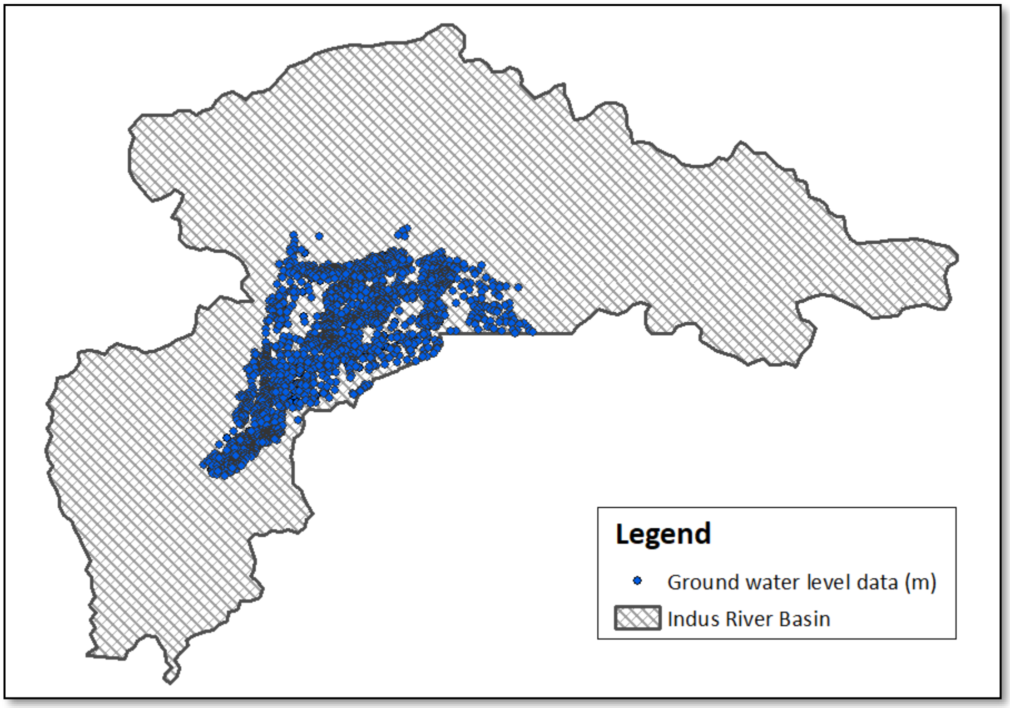

Figure 4.14: Groundwater data points depicting ground water depth in meters.

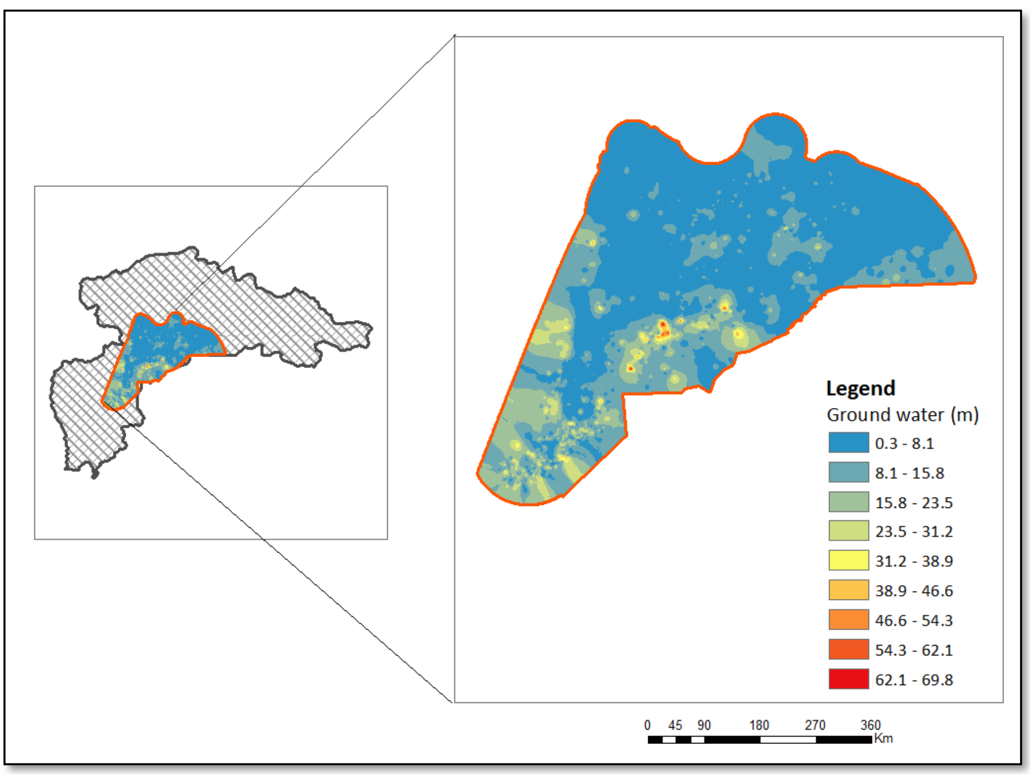

Figure 4.15: Ground water depth interpolated map (2006-2010).

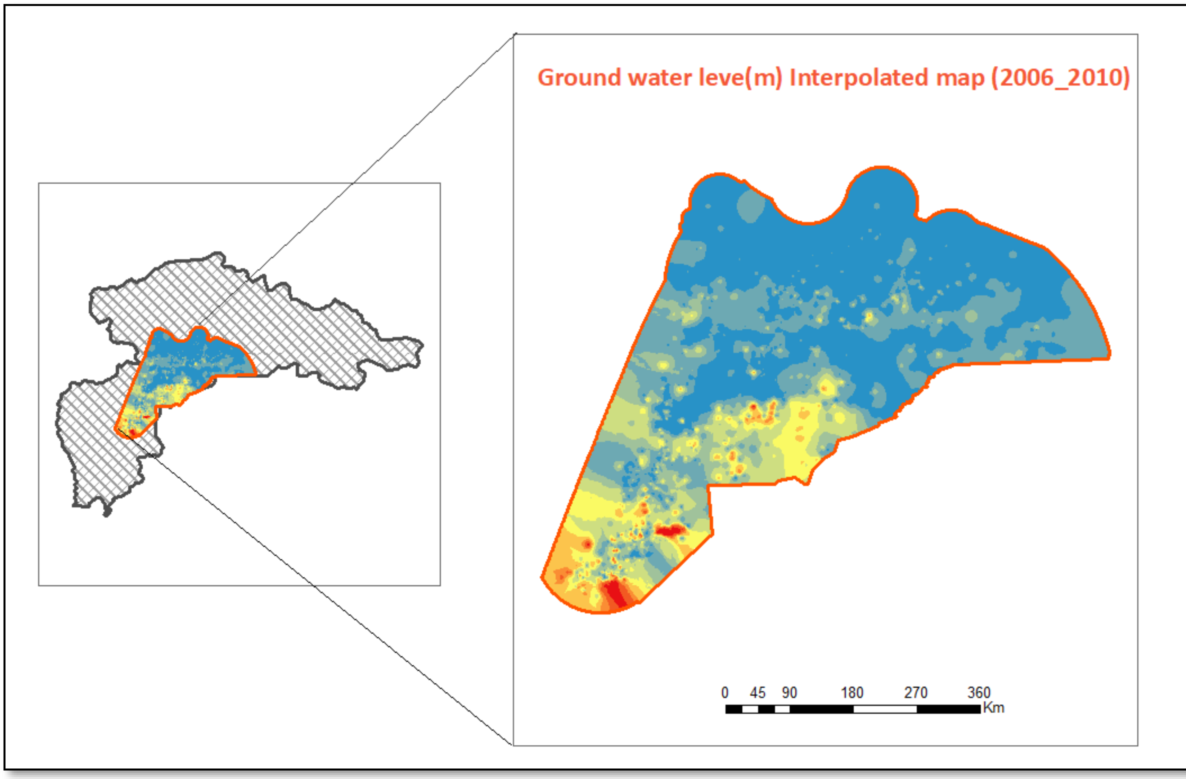

Figure 4.16: Ground water depth interpolated map (2006-2010).

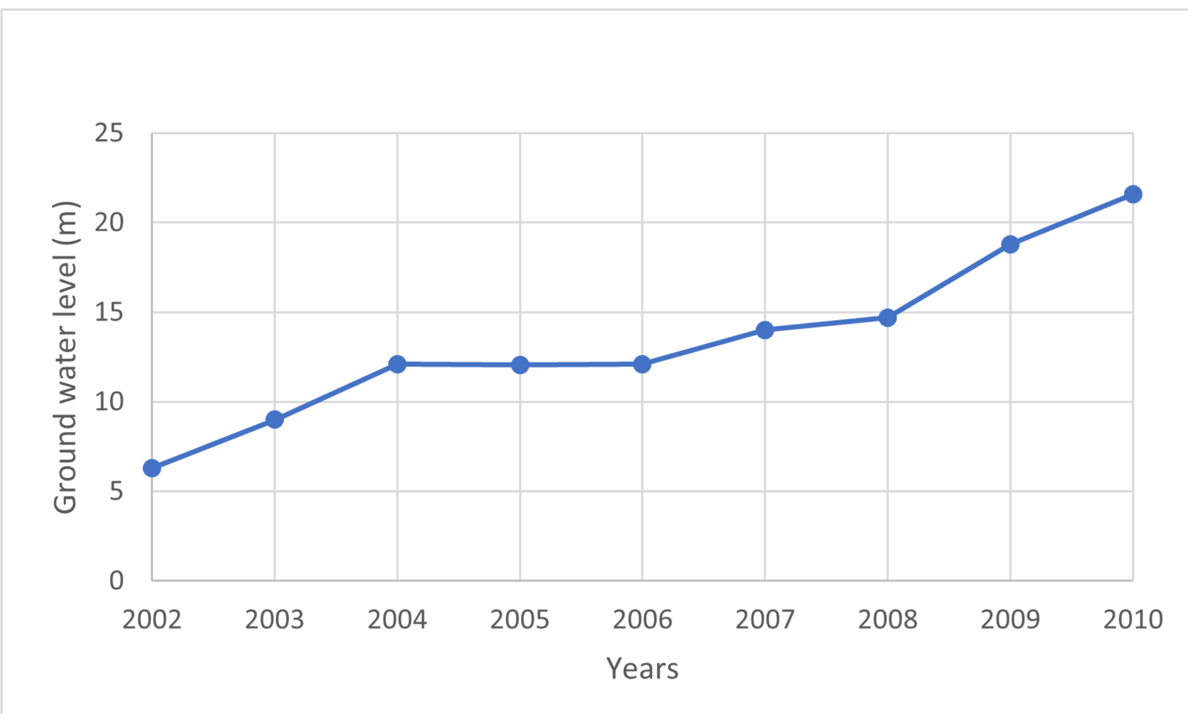

Figure 4.17: Temporal trend of Ground water level from 2002-2010.

4.1.5. Assessment of Terrestrial Water Storage Sustainability with respect to Land Use and Population density

Figure 4.14 shows the study area's land use and land cover map, generated using data from the Copernicus Global Land Service (CGLS). Croplands are the dominant feature in the basin's central, southern, and southwestern portions. Additionally, built-up areas are concentrated in the central and southern regions. The highest water consumption occurs in both agricultural and urban areas. This pattern contributes to lower water resource sustainability in the areas characterized by croplands and urban development, as depicted in Figure 5. This suggests that excessive water exploitation has rendered the southern and southwestern regions of the basin less environmentally viable in terms of water resources. The central area of the basin is also marked by extensive croplands and built-up regions, signifying increased water usage for agricultural and human-related activities. The central parts of the basin have witnessed the construction of multiple irrigation canals, notably the Indus Basin Irrigation canal System in Pakistan and the Bhakra-Nangal system in the Indian Punjab. These canal systems further underscore heightened water utilization in the middle regions of the basin.

Figure 4.15 shows the population density of the study area. The figure demonstrates that the central regions and some places in the south and southwest have a high population density, whereas the northern and northeastern parts of the basin have the lowest population. Higher water use is correlated with increased population density. Where there is a large population density particularly in the south and southwestern region of the basin (Figure 5), has the least water sustainability. High population density indicates a region's expanding urbanization and economic activity. Globally, there is a strong correlation between the water footprint and population density, which means that denser populations use more water.

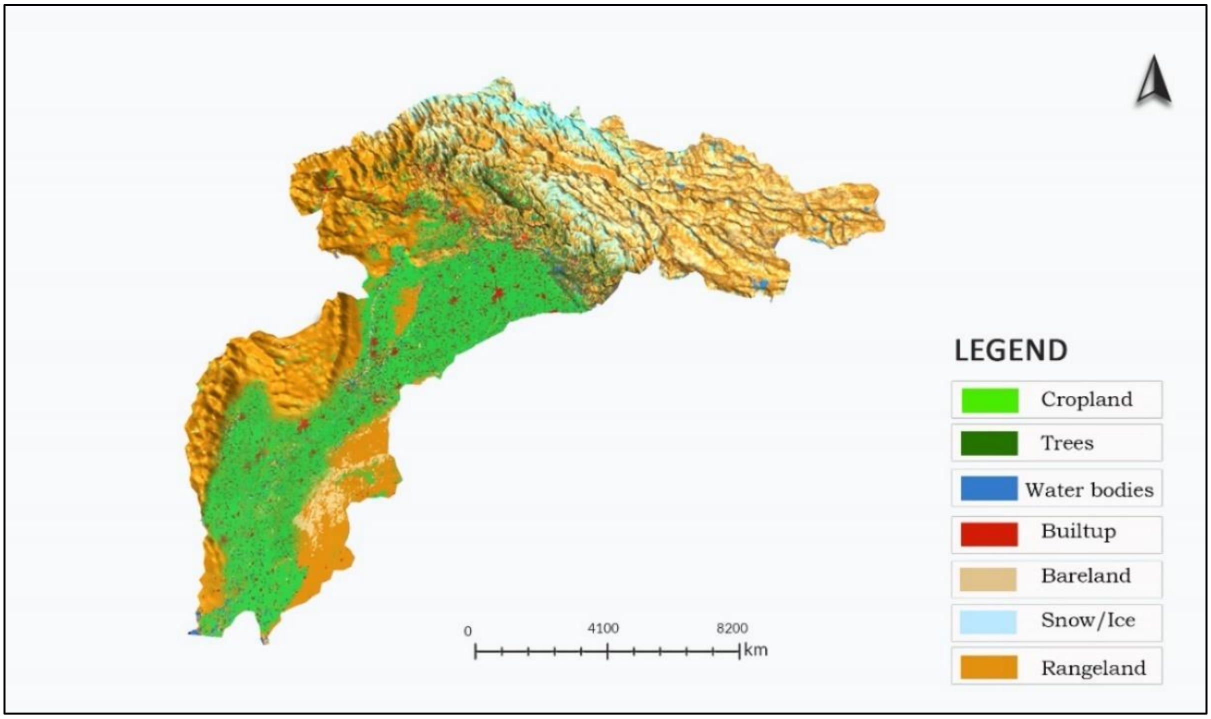

Figure 4.18. Land use and land cover map of the study area for 2022.

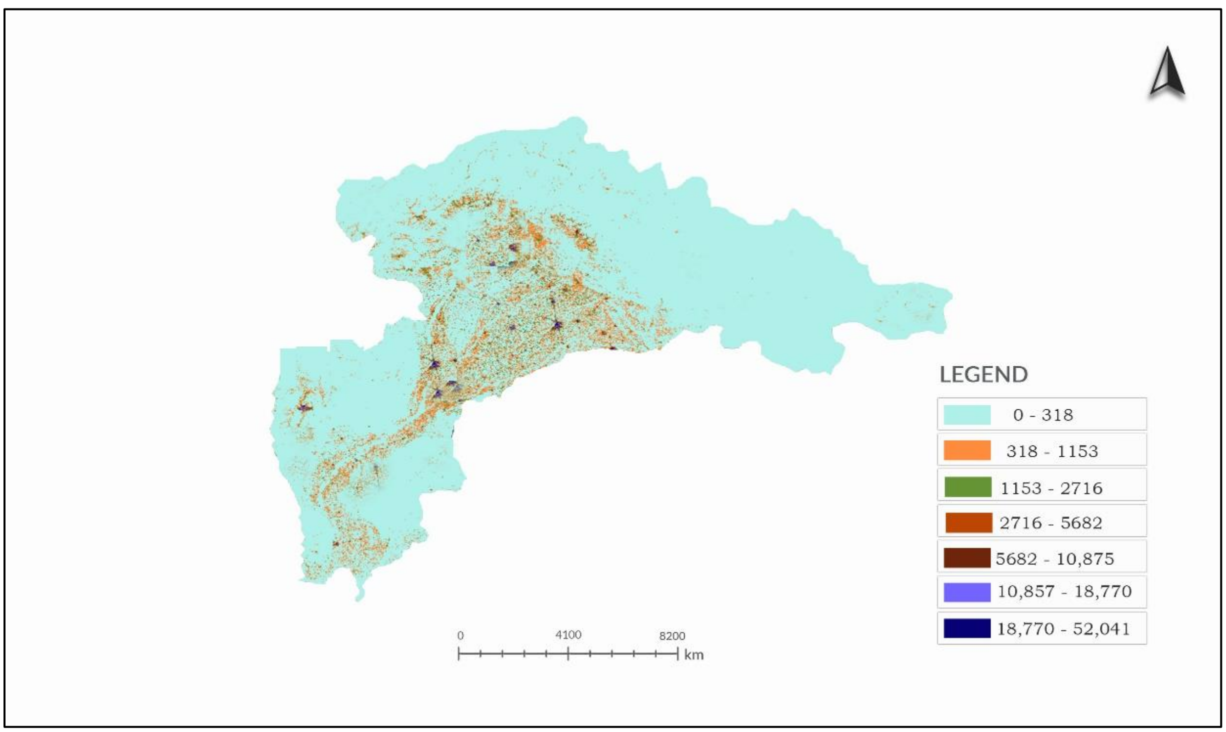

Figure 4.19. Population density map of the study area for 2022.

4.2. Discussions

4.2.1. Monthly mean Anomaly of Terrestrial Water Storage (TWS)

The monthly anomaly of GRACE solutions, including the CSR, GSFC and JPL, revealed that water availability exceeded the mean level in the early years particularly from May to September. This can be attributed to the substantial monsoon rainfall in Pakistan and India during this period. The monsoon season brings increased precipitation, resulting in heightened water availability. Consequently, the TWS values exhibit a significant increase during these months compared to other times of the year. In recent years, TWS gradually declined after 2010, except for 2011 and 2015 when Pakistan experienced massive floods. The floods in 2010 and 2015 had a severe impact, especially in the province of Sindh, due to unprecedented rains and inadequate drainage systems. In some recent years, TWS failed to reach the mean level, particularly after 2017. This decrease in TWS can be associated with increased water consumption due to population growth. In recent years, water availability has become less abundant, it indicated by a reduction in the blue color in all GRACE products, signifying a decrease in TWS. These findings have been consistent with the research conducted by (Sachin etal., 2022).

4.2.2. Trend Analysis of Terrestrial Water Storage (TWS)

The trend analysis (Figures 5,6 and 7) supported the TWS anomaly results. The results showed a decrease in water resources in the southern and southwestern regions of the basin. A generally negative trend in TWS anomaly was observed for the study period in the south and southwest of the basin for all the three solutions indicating that water storage generally decreased in the basin. In contrast, a small area of the north, water resources showed a 0.1 cm/year growth. In the southern part of the basin, where there is more urbanization and agricultural activity, TWS declination was greater. A significant decline in TWS may be attributed to increased water abstraction for industrial and commercial uses. Regions in the south of the basin have an arid to semi-arid climate, characterized by low rainfall. However, the decline in TWS in the area, might be related to the drop in rainfall. Despite the considerable water withdrawal for agricultural uses, there were no substantial changes in TWS in Punjab. This could be attributed to the fact that Punjab receives high precipitation relative to other regions and has a highly well-organized canal system for irrigation. These findings are similar to the findings of Ali et al., 2022 who conducted a similar study over Indus River basin. The results showed that TWS Anomaly experienced a significant decrease from 2002 to 2020, particularly in the lower Indus Basin.

4.2.3. Spatial distribution of Terrestrial Water Storage Sustainability

Results obtained using the sustainability index with reliability, resilience, and vulnerability of TWS, showed more reliability of water resources in the northern and northeastern part of the basin. High reliability could be due to substantial snow cover and glaciers acting as natural water reservoirs. In contrast, it was the opposite for the southern and southwestern regions. These regions are characterized by arid to semi-arid climates.

Resilience showed a similar pattern to reliability high in the north of the basin and low in the south and southwest except for some regions in the center of basin covering most of the Punjab province in Pakistan and some parts of the Indian Punjab. These regions show the highest resilience of TWS in the range of 0.8 to 1.0. GB, Himachal Pradesh, and Niger in China exhibit slightly lower resilience despite having high reliability. These regions are characterized by glaciated areas, where glaciers slowly accumulate snow and ice over time. However, the rapid melting of glaciers poses a challenge in replenishing the lost ice. As a result, glaciated regions face difficulties in restoring and returning to their original conditions resulting in less resilience (Kattel et al.,2023).

The spatial distribution of vulnerability was contrary to reliability and resilience, indicating that the southern and southwestern regions of the basin are more vulnerable than the rest of the study area. Sustainability analysis of TWS indicated the highest sustainability (0.8-1.0) in the northern and northeastern parts of the basin. Those regions cover a small part of kpk, a major part of GB, Himachal Pradesh, and most of Niger in China.

Increased rainfall in the northeast (600 t0 2000mm) and less urbanization made the region more sustainable in water resources as compared to southern region which is characterized by its arid climate with an annual precipitation of 600 to 100mm (Li etal., (2022). These findings are consistent with the results of the research conducted by Zhu et al., (2021) over the INDUS river basin using different statistical methods.

Overall, the study revealed that human activities such as the overexploitation of water for agriculture and for domestic purposes have caused a declination of TWS in the basin. Excessive use of water for irrigation has made the TWS highly variable and reduced sustainability in the water resources of the study area. Due to the lack of data on in situ water resources, it is impossible to assess the relative efficacy of the sustainability index calculated using various GRACE products. All products, however, offered the same spatial pattern of water sustainability. The findings can thus be relied upon to comprehend the basin's regional sustainability heterogeneity. Therefore, the results can be used with certainty to understand the spatial variability of sustainability in the study area.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1. Conclusion

The present study assessed sustainability and availability of water resources in Indus River basin using three GRACE solutions (CSR, GSFC, and JPL) from 2002 to 2022. The study of Monthly Mean Anomaly of TWS for the period April 2002–December 2022 revealed three temporal patterns throughout the basin. The first pattern extends from 2002 to 2008 showing a positive and very slight negative changes of TWS, followed by a cycle of positive and negative Anomalies from 2009 to 2016, and finally, a persistent negative trend for the rest of the time.

Trend analysis using Sen’s slope and Mann–Kendall tests showed that the southern and southwestern parts of basin have a significant decreasing change in the range of -0.9 to -2.5 cm/ year. Trend analysis also showed that the water shortage in southwestern region of the basin is more severe than that in the central and northwestern parts, probably because of agricultural activities and population growth. The Reliability of water resources was lowest in southwestern region and highest in the northern and northeastern part of the basin. Resilience was comparatively low in the north and northeast of the basin which indicates that water resources do not easily recover from stress. The lowest Resilience was observed for the west and southwest. Vulnerability was lowest in the north and highest in the south and southwest. Water resources were more Sustainable in northern and northeastern regions of basin than in central and southwestern regions which are more vulnerable to overexploitation of surface water and groundwater.

Overall, all GRACE solutions showed more or less similar results. Therefore, it can be concluded that water resources in the Indus River basin are decreasing with time. Although the information on the basin's water use activities is inaccessible, the low sustainability in water resources in intense agriculture and urban areas indicates that, overexploitation of water resources for agriculture and anthropogenic activities may be the main cause of water stress in the region. Overall, the results of water availability using GRACE data by applying the water sustainability method were able to provide a better understanding of water resources availability of the basin. The maps created as part of this study have the potential to be used for water resources planning and development of the basin. This study thus contributes to the broader understanding of water sustainability and has the potential to guide similar assessments in other river catchments facing similar challenges. Moreover, the study findings will benefit policy makers to conserve water resources for sustainable use in water deficit regions. The present study was limited to GRACE Mascon solutions. Further work can be conducted to calculate the uncertainties in the TWS sustainability using the GRACE spherical solutions.

5.2. Recommendations

5.2.1. Focused Interventions for Vulnerable Regions

Given the heightened vulnerability and lower resilience identified in the southern and southwestern regions regarding water availability, it is crucial to undertake specific interventions in these areas. Implementing efficient water management practices, such as rainwater harvesting and groundwater recharge, holds promise for alleviating water scarcity concerns in these regions.

5.2.2. Investment in Water Storage Infrastructure

Given the variations in water availability throughout the year, consider suggesting investments in water storage infrastructure, such as reservoirs or groundwater recharge systems. These could help capture excess water during positive TWS months and provide a buffer during water scarcity.

5.2.3. Localized Water Management Plans

Instead of a one-size-fits-all approach, tailored water management plans should be developed for different regions within the basin. This approach would account for the unique challenges and opportunities each area faces regarding water availability and usage.

5.2.4. Diversification of Water Sources

Propose exploring alternative water sources, especially in the more vulnerable southern and southwestern regions. This could involve promoting rainwater harvesting, treating and reusing wastewater, and exploring possibilities for desalination to reduce dependence on traditional water sources.

5.2.5. Community Education and Awareness Campaigns

Efforts are required for awareness campaigns stressing water conservation, sustainable usage, and the vital role of preserving water resources. These campaigns should target local communities and stakeholders, fostering a shared commitment to water sustainability. These initiatives hold the potential to raise broader societal awareness about the urgent matter of water sustainability.

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APPENDICES

Appendix-1. Code for Sustainability Analysis using three GRACE solutions.

```
rm(list = ls())
library(raster)
library(rgdal)
library (reshape)
setwd("D:\\Thesis\\Indus River system\\Extracted_data")
dat<-read.csv("JPL_Indus.csv") # The file contains all lat-long of the study area
zdat<-t(dat[,-(1:3)])
iloc<-round(dat[,2:3],2)
coln<-paste(iloc[,1],"x",iloc[,2],sep="")
colnames(zdat)<-c(coln)
pos<-iloc
yr<-as.numeric(substr(rownames((data)),2,5))
rel<-NULL; res<-NULL; vuln<-NULL
for(i in 1:ncol(zdat)) {
 gwss<-zdat[,i]
 gws<-(gwss-min(gwss))/(max(gwss)-min(gwss))  #new line
 mean1<-mean(gws)
 gws[which(gws>mean1)]<-0
 tt<-length(gws[which(gws<mean1 & gws>0)])
 dj<-sum(gws[which(gws<mean1)])
 mm<-gws
 mm[which(mm<mean1 & mm>0)]<-1
 mv<-length(rle(mm)$length[seq(2,length(rle(mm)$length),2)])
 tm<-length(gws)
 reli<-(tm-tt)/tm
 resi<-mv/tt
 vul<-(dj/tt)
 rel<-c(rel,reli)
 res<-c(res,resi)

vuln<-c(vuln,vul)
}
vuln<-abs(vuln)
#dvul<-(vuln-min(vuln))/(max(vuln)-min(vuln))
dvul<-vuln
rel<-abs(rel)
#drel<-(rel-min(rel))/(max(rel)-min(rel))
drel<-rel
res<-abs(res)
#dres<-(res-min(res))/(max(res)-min(res))
dres<-res
sus<-(rel*res*(vul))^(1/3)
#sus<-(drel*dres*(1-dvul))^(1/3)
result<-round(cbind(pos[,1:2],drel,dres,dvul,sus),2)
```

```
colnames(result)<-c("Lat","Long","Reliability","Resilience","Vulnerability","Sustainability")
```

Cont……….

```
setwd("D:\\Thesis\\Indus River system\\RRV_GRACE\\JPL")
write.csv(result,"Water Sustainability_CSR.csv")
R_Hist_CMIP5<-rasterFromXYZ(cbind(result[,1:2],result[,3]))
writeRaster(R_Hist_CMIP5, "Reliability_CSR.tif", options="INTERLEAVE=BAND", overwrite=TRUE)
R_Hist_CMIP5<-rasterFromXYZ(cbind(result[,1:2],result[,4]))
writeRaster(R_Hist_CMIP5, "Resiliance_CSR.tif", options="INTERLEAVE=BAND", overwrite=TRUE)
R_Hist_CMIP5<-rasterFromXYZ(cbind(result[,1:2],result[,5]))
writeRaster(R_Hist_CMIP5, "Vulnerability_CSR.tif", options="INTERLEAVE=BAND", overwrite=TRUE)
R_Hist_CMIP5<-rasterFromXYZ(cbind(result[,1:2],result[,6]))
writeRaster(R_Hist_CMIP5, "Sustainability_CSR.tif", options="INTERLEAVE=BAND", overwrite=TRUE)
```

Appendix-2. Code for TWS Trend Analysis using Sen's slope estimator.

```
library(raster)
library(rgdal)
library(reshape)
setwd("D:\\Thesis\\Indus River system\\Extracted_data")
dat <- read.csv("JPL_Indus.csv")
zdat <- t(dat[, -(1:3)])
iloc <- round(dat[, 2:3], 2)
coln <- paste(iloc[, 1], "x", iloc[, 2], sep="")
colnames(zdat) <- coln
pos <- iloc
yr <- as.numeric(substr(rownames(zdat), 2, 5))
# Function to calculate Mann-Kendall test statistic and p-value
mk_test_p_value <- function(x) {
  n <- length(x)
  s <- 0
  for (i in 1:(n - 1)) {
    for (j in (i + 1):n) {
      s <- s + sign(x[j] - x[i])
    }
  }

  # Calculate the variance of the Mann-Kendall test statistic under the null hypothesis
  var_s <- (n * (n - 1) * (2 * n + 5)) / 18
  # Calculate the standard normal distribution statistic
  z <- (s - 1) / sqrt(var_s)
  # Calculate the two-sided p-value
  p_value <- 2 * (1 - pnorm(abs(z)))

  # Determine if the p-value is significant
significance <- ifelse(p_value < 0.05, "Significant", "Not Significant")

  return(list(statistic = s, p_value = p_value, significance = significance))

}

# Function to calculate Sen's slope estimator

sen_slope_estimator <- function(x) {

  n <- length(x)

  slopes <- numeric(n * (n - 1) / 2)

  k <- 1

  for (i in 1:(n - 1)) {

    for (j in (i + 1):n) {

      slopes[k] <- (x[j] - x[i]) / (yr[j] - yr[i])
```

Cont……….

```
k <- k + 1
   }
  }
  return(median(slopes))
}
# Initialize vectors to store results
slope <- NULL
for (i in 1:ncol(zdat)) {
  gwss <- zdat[, i]
  gws <- (gwss - min(gwss)) / (max(gwss) - min(gwss))
  # Calculate Mann-Kendall test statistic, p-value, and significance
  mk_result <- mk_test_p_value(gws)
  # Print the results individually
  cat("Mann-Kendall Test Statistic:\n", mk_result$statistic, "\n")
  cat("P-value:\n", format(mk_result$p_value, scientific = FALSE), "\n")
  cat("Significance:\n", mk_result$significance, "\n")
  # ... (previous code)
# Function to calculate Mann-Kendall test statistic and p-value
# Initialize vectors to store results
slope <- NULL
confidence_intervals <- NULL
for (i in 1:ncol(zdat)) {
  gwss <- zdat[, i]
  gws <- (gwss - min(gwss)) / (max(gwss) - min(gwss))
  # Calculate Mann-Kendall test statistic, p-value, and significance
  mk_result <- mk_test_p_value(gws)
  # Calculate Sen's slope estimator
  sen_s <- sen_slope_estimator(gws)
  slope <- c(slope, sen_s)

  # Calculate the confidence interval (assuming normal distribution)
  n <- length(gws)
  se <- sqrt((n * (n - 1) * (2 * n + 5)) / 18)  # Standard error of the Mann-Kendall statistic
  z_critical <- qnorm(0.975)  # 95% confidence level, 2-tailed
  confidence_interval <- c(sen_s - z_critical * se, sen_s + z_critical * se)
  confidence_intervals <- rbind(confidence_intervals, confidence_interval)
}
  # Calculate Sen's slope estimator
  sen_s <- sen_slope_estimator(gws)
  slope <- c(slope, sen_s)
# ... (previous code)

# Function to calculate Mann-Kendall test statistic and p-value

# ...

# Initialize vectors to store results

slope <- NULL
```

Cont……….

```
confidence_intervals <- NULL
for (i in 1:ncol(zdat)) {
  gwss <- zdat[, i]
  gws <- (gwss - min(gwss)) / (max(gwss) - min(gwss))
  # Calculate Mann-Kendall test statistic, p-value, and significance
  mk_result <- mk_test_p_value(gws)
  # Calculate Sen's slope estimator
  sen_s <- sen_slope_estimator(gws)
  slope <- c(slope, sen_s)
  # Calculate the confidence interval (assuming normal distribution)
  n <- length(gws)
  se <- sqrt((n * (n - 1) * (2 * n + 5)) / 18)  # Standard error of the Mann-Kendall statistic
  z_critical <- qnorm(0.975)  # 95% confidence level, 2-tailed
  confidence_interval <- c(sen_s - z_critical * se, sen_s + z_critical * se)
  confidence_intervals <- rbind(confidence_intervals, confidence_interval)
  # Print Sen's slope estimator and 95% confidence interval
  cat("Sen's Slope Estimator:\n", sen_s, "\n")
  cat("95% Confidence Interval:\n", confidence_interval, "\n\n")
# Combine the Sen's slope estimator results into a data.frame
result <- data.frame(pos[, 1:2], slope)
# Set the working directory for raster files
setwd("D:\\Thesis\\Indus River system\\RRV_GRACE\\JPL")
# Write the result to a CSV file
write.csv(result, "SenSlope_CSR.csv", row.names = FALSE)
# Create a raster for Sen's Slope estimator
library(raster)
R_SenSlope <- rasterFromXYZ(cbind(result[, 1:2], result[, 3]))
writeRaster(R_SenSlope, "SenSlope_CSR.tif", options = "INTERLEAVE=BAND", overwrite = TRUE)
```