Groundwater Monitoring and Management for Indus Basin, Using Multi-sensor Data: A GIS and Remote Sensing Approach

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Abstract

Groundwater is a vibrant source of freshwater worldwide. With an increase in research on groundwater issues and monitoring, it is important to develop quantified conceptual models for monitoring and management of groundwater. Due to overexploitation, regular groundwater monitoring and management are critical for sustainable utilization. GIS and remote sensing play vital roles in monitoring and predicting groundwater on local, regional, and global levels. Multiple sensors are used to monitor groundwater in spatial and temporal domains to assist in developing and implementing its sustainable utilization. Groundwater relationship with land subsidence has been extracted and focused on the heterogeneous properties between them. High groundwater extraction for agriculture purposes has been used in the study area which further affects the infrastructure by land subsidence. GRACE data is used for groundwater storage change and its temporal variations help to analyze groundwater storage data using GIS. Using the Spatio-temporal regression model the heterogeneity has been evaluated with the groundwater extraction and land subsidence. Results indicate high storage capacity at different locations within the study area which gives input to areas where we have high extraction and also the land subsidence, occurring in the high storage depletion change areas. The northern area has a high groundwater storage of 967 mm and the highly stressed area has a groundwater storage of 141 mm in the study area. The annual cycle of groundwater extraction and recharge is imbalanced due to which the groundwater is depleting. Groundwater resource cycle balance is important for the area, as this balance will help to reduce the land subsidence occurrence in the area.

Keywords: Groundwater, Land subsidence, Spatiotemporal Regression, Spatial heterogeneity

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1. Introduction

Groundwater sustainability is important to ensure water availability in the future. Intensive pumping exceeds natural recharge in numerous semi-arid and arid areas of the world (FAO, 2011). Worldwide, the population is exclusively dependent on freshwater to fulfill domestic, agricultural and industrial utilization (Bhanja et al., 2016). The areas of land subsidence and sea-level rise are faced with more severe conditions (Vousdoukas et al., 2017). The land subsidence-affected areas are usually used for agricultural, overpopulated areas (i.e., towns and cities) and crossing of different infrastructures (roads, railway tracks) making them more vulnerable to land deformation (Khan et al., 2022; Ferrant et al., 2014; Raspini et al., 2013,). Efficient management of groundwater is essential to assist in ensuring the unhindered water supply. However, the situation is deteriorating largely due to the rapid extension of agricultural lands. Since the 1950s, there has been an increase of 174% in agricultural land increasing the utilization of freshwater at the rate of 90 % for agriculture (Scanlon et al., 2007). Globally, in densely populated areas, a sustainable supply of fresh water is a mounting challenge (Gorelick and Zheng, 2015). The evaluation of groundwater storage change requires a good knowledge of the hydrological properties of subsurface and in situ monitoring station data (Chen et al., 2016).

The groundwater-subsidence relation varies with time and space, however, the traditional regression models, e.g. linear regression, cannot adequately explain the spatio-temporal variations between groundwater variation and subsidence (Liu et al., 2018, Liu et al., 2019). Accordingly, this study proposes a reliable method incorporating both spatially and temporally varying relations using different techniques for land subsidence and groundwater prediction. A regression model that considers the Spatio-temporal variation, can sufficiently explain the spatial and temporal relation between groundwater and subsidence (Ali et al., 2020). Land subsidence owing to aquifer-system compaction is affected by groundwater drawdown, but its progression is characterized by the properties and subsequent response of the compressible fine-grained sediments of interbeds and confining units in the aquifer system (Li et al., 2017). The pumping history, intensity, duration and frequency of groundwater variation also affect the distribution of land subsidence. The model accounts for the spatiotemporal relation between groundwater variation and land subsidence under heterogeneous aquifer-system conditions. Geographically Weighted Regression (GWR) accounts for local effects in space based on the nearest neighbor weighing procedure (Chu et al., 2015). GTWR accounts for the local effects of groundwater and subsidence in both space and time and is becoming a practical approach to providing greater details on the spatial and temporal processes affecting the distribution of land subsidence (Fotheringham et al., 2015; Huang et al., 2010). The GTWR model can be readily applied to time-varying monitoring, however, it can only be utilized in a fixed temporally invariant monitoring system.

Multi-sensor data have been used by different researchers for groundwater monitoring and its impact on different groundwater variables. The groundwater can be monitored by multiple subsurface sensors such as piezometers and also the groundwater monitoring wells stations which show the groundwater table variations within the area. For land subsidence monitoring in-situ data can be used (like leveling, compaction wells and GPS vertical monitoring), and Synthetic Aperture Radar (SAR) data can be used for evaluating the vertical deformation of the area which can be further used for groundwater monitoring. Multiple linear regression has been used to find the relationship between groundwater and land subsidence. The relationship between land subsidence and groundwater is distributed spatially and, in some cases, linearly as well. However, the spatial heterogeneity between groundwater and land subsidence could be evaluated using the spatial regression model. Considering the spatial relationship between land subsidence and groundwater, spatial and temporal models are utilized for different datasets to find the spatial correlation between them. For local areas, the monitoring data can work using regardion models, but for regional areas remote sensing data has been used for groundwater storage change.

2. Materials & Methods

2.1. Study area

The Indus River Basin (IRB; Fig. 1) comprises a total area of 1.12 million km^2, distributed between 4 four countries with area coverage of: Pakistan 47 %, India at 39 %, China 8 %, and Afghanistan 6 %. The initial tributary in southwest Tibet, and flows through Ladakh, Gilgit- Baltistan, northern Pakistan, and the dry alluvial plains of Sindh in the south to finally enter the Arabian Sea. The IRB covers 65 % of the total area of Pakistan, comprising the Khyber Pakhtunkhwa and Punjab Provinces, the eastern part of Balochistan and most of Sindh. Due to its high coverage area, the climatic conditions display high variations. The precipitation level in the IRN varies considerably; the lower area gets annual rainfall of 100 to 500 mm and the upper region receives the maximum rainfall of 2000 mm annually. Much of the input to runoff water comes from snowfall in the upper region of the IRB.

Regional work (Pakistan, India, Bangladesh and Afghanistan) has been used as a case study to find the groundwater change. The data help to identify the groundwater change patterns and storage depletion in time intervals.

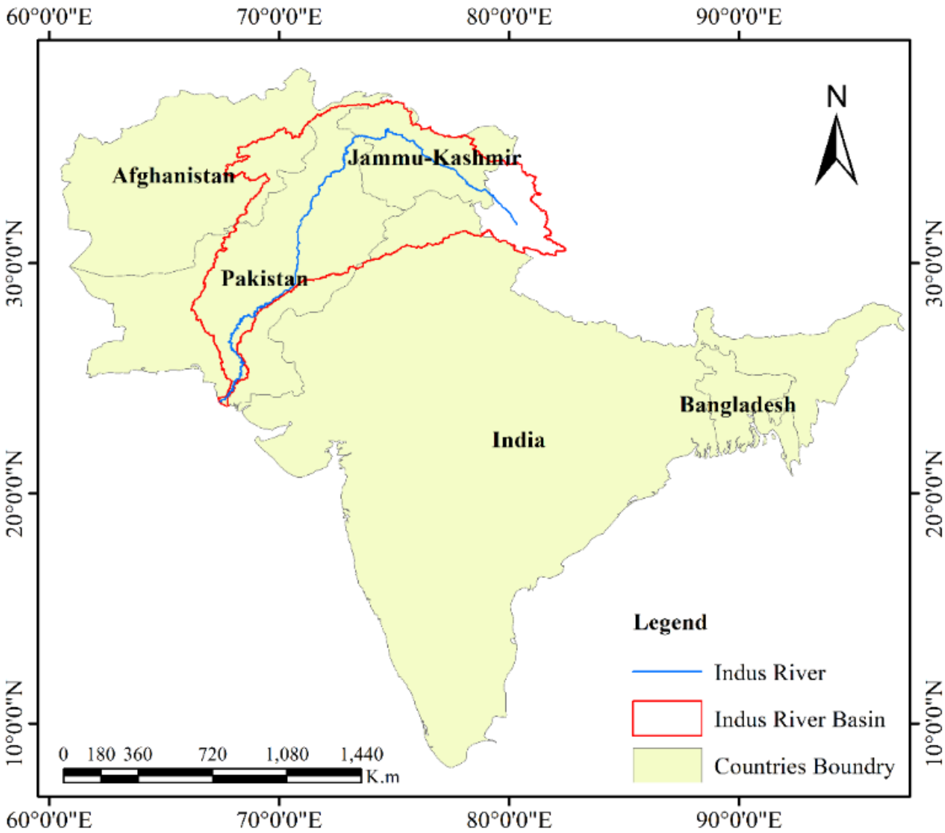

Figure 1. Study area location map, Showing the spatial extent of the Indus River and Indus Basin.

2.2. Datasets

2.2.1. Ground observation data. Different sensors are currently used for groundwater monitoring and their different characteristics in the form of sediments within the well and also the groundwater table and its storage by different datasets. For groundwater, piezometers have been used in case studies in different locations.

The groundwater monitoring station data are collected at a monthly level which shows the overall flow and temporal change of groundwater change (Fig. 2). For land subsidence monitoring, globally different types of data are used (Leveling, GPS and Monitoring Wells). Different monitoring data have different time intervals which help to evaluate land subsidence based on the groundwater extraction in the area.

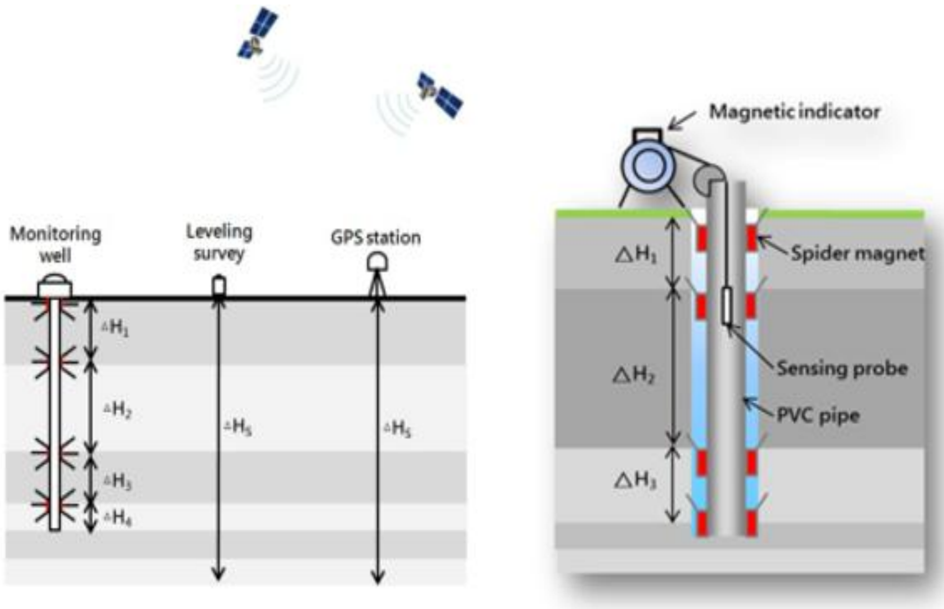

Figure 2. Groundwater monitoring station and land subsidence sensors (Hung et al., 2010).

2.2.2. Remote sensing data. The monitoring stations record the variation of groundwater at a local level, however, at the regional level, the remote sensing data can be effective. For groundwater storage monitoring, the GRACE satellite has been effectively and frequently used for the last few years to detect groundwater anomalies. By combining the GRACE data with the GLDAS, the groundwater storage data is monitored for long-term evaluations. For land subsidence, the SAR data is used for the deformation evaluation due to groundwater change

2.3. Methods

Multiple methods have been used by different researchers using ground observation data and remote sensing data. Some linear regression techniques have been used to correlate groundwater extraction with land subsidence in some areas. Béjar-Pizarro et al. (2017) have used linear regression to find the linear relationship between groundwater extraction and land subsidence:

$$Y_i = \beta_0 + \sum_k \beta_k X_{ik} + \varepsilon_i \quad (1)$$

Here the predictor and estimator have a linear relationship indicating groundwater extraction has a direct impact on land subsidence.

However, some case studies have highlighted the heterogeneity factor as well within those two variables, considering this relationship the Geographically Weighted regression (GWR) has been used by Ali et al. (2020) to target heterogeneity:

$$Y_{i,t} = \beta_{0,t}(u_i\ , v_i) + \sum_k \beta_{k,t}\ (u_i\ , v_i)\, X_{ik,t} +\ \varepsilon_{i,t} \quad (2)$$

Here the location is considered for every point and the relationship is based on the distance between one another. Where β_0 (u_i, v_i) is the intercept at location (u_i, v_i), βk (u_i, v_i) is the coefficient containing the location (latitude and longitude) of every data point i at variable k.

GWR has been used for spatial mapping of land subsidence based on groundwater extraction. The spatial coefficient shows the relationship between land subsidence and groundwater extraction. Furthermore, for temporal change spatiotemporal model has been used to find both the spatial and temporal variation using different datasets having different temporal resolutions. GPS-based monthly data has been used for the monthly groundwater change and its storage change.

Spatial mapping of groundwater storage change using remote sensing data is effectively implemented on a regional scale using GRACE and InSAR data to evaluate the relationship between land subsidence and groundwater storage extraction. The Indus Basin area groundwater change has been evaluated for spatial and temporal study. Time series data of the Indus River basin from GRACE and GLDAS has been evaluated and shown the trend of Groundwater storage change.

3. Results & Discussion – Remote Sensing Approach

3.1. Timeseries Groundwater Evaluation of Indus Basin

Groundwater monitoring and management is important globally due to their long-lasting impacts on societies. Groundwater temporal monitoring is usually based on ground-based sensors and the stored data is then further analyzed for its annual decreasing or increasing trends. Different research articles for different depleting zones show the graphical representation of groundwater trends.

A temporal study of the Indus River basin shows a high decreasing trend in groundwater storage over the last two decades. The results from different input components towards terrestrial water storage are shown in Fig. 3.

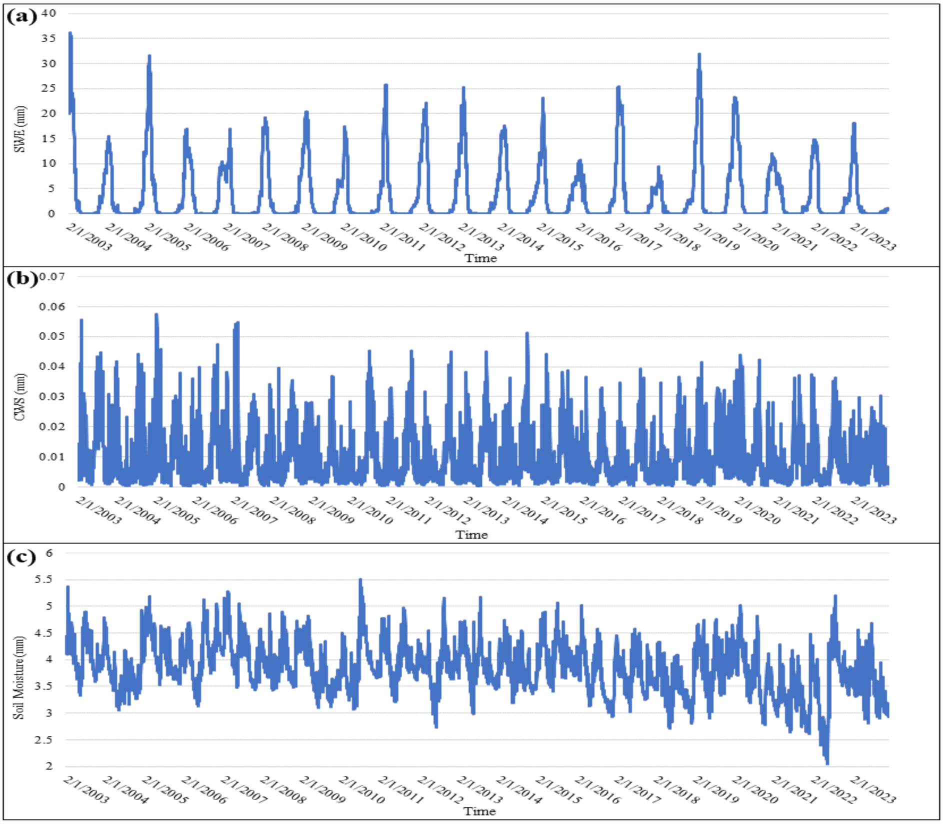

Figure 3. Variables of Indus River Basin; (a) Snow Water Equivalent, (b) Canopy Water Storage, and (c) Soil Moisture.

The IRB accumulated data is shown in a time series from February 2003 to February 2023. The Indus basin in the upper region is mostly covered by snow which is shown in Fig. 3 as the highest peak covering the water content in the Snow Water Equivalent (SWE), having 35 mm on the daily based data. The surface greenery area of water storage is very low, with a range of 0 to 0.06 mm. The soil moisture is shown in Fig. 3b with the highest value of 5.5 mm.

Those variables are important inputs for terrestrial water storage which is detected by the GRACE data which is further used to detect the groundwater storage change in the area. Fig. 4 shows the time series data of Terrestrial water storage.

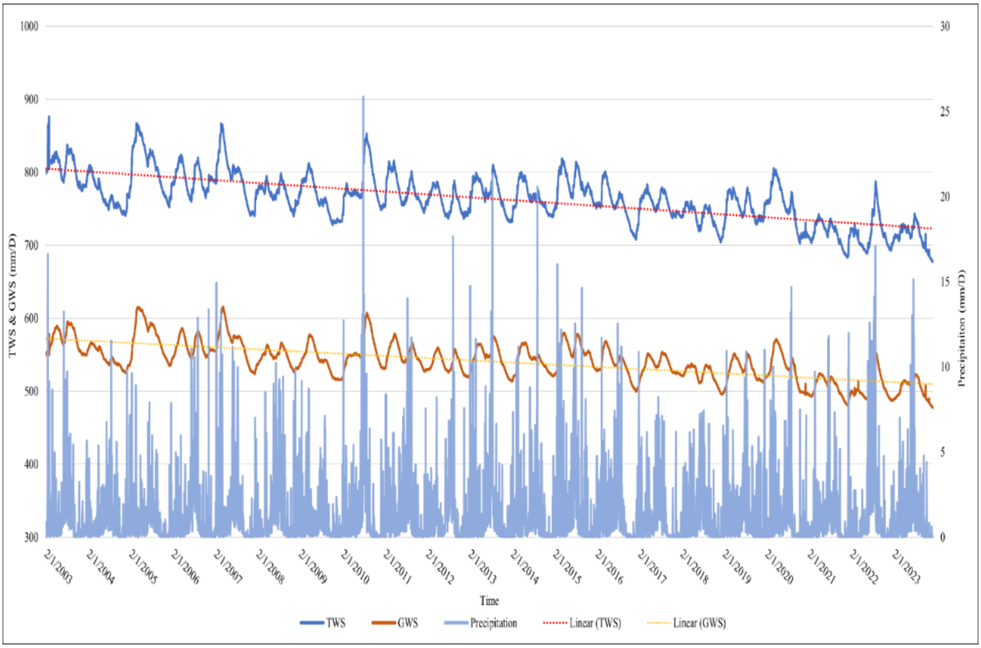

Figure 4. The 20 years of Time series variations of Terrestrial Water Storage (TWS), Groundwater Storage (GWS) and precipitation data.

The TWS of the Indus Basin accumulative area shows a decreasing trend in Fig. 4. The variations in TWS show the seasonality effect, including the monsoon recharge period. From 2003 the 800 mm of TWS storage of water decreased to less than 700 mm which shows a decreasing trend and after the subtraction of other variables (Snow Water Equivalent, Soil Moisture and canopy water storage) the remaining groundwater is shown. The GWS decreasing trend shows the long-term effect of high discharge with low recharge towards the groundwater. This imbalance affects the groundwater resources at high risk by decreasing the groundwater water in the Indus Basin.

3.2. Spatial Estimation of Groundwater Storage

Globally, for regional scale studies, remote sensing data has been used for groundwater monitoring from GRACE data (Bhanja et al., 2016: Billah et al., 2015; Chen et al., 2014). Further groundwater depletion impact on land subsidence is evaluated in different areas globally (Castellazzi et al., 2018; Ojha et al., 2020). The spatial-based groundwater storage for the accumulative period of 20 years has been shown in Fig. 5.

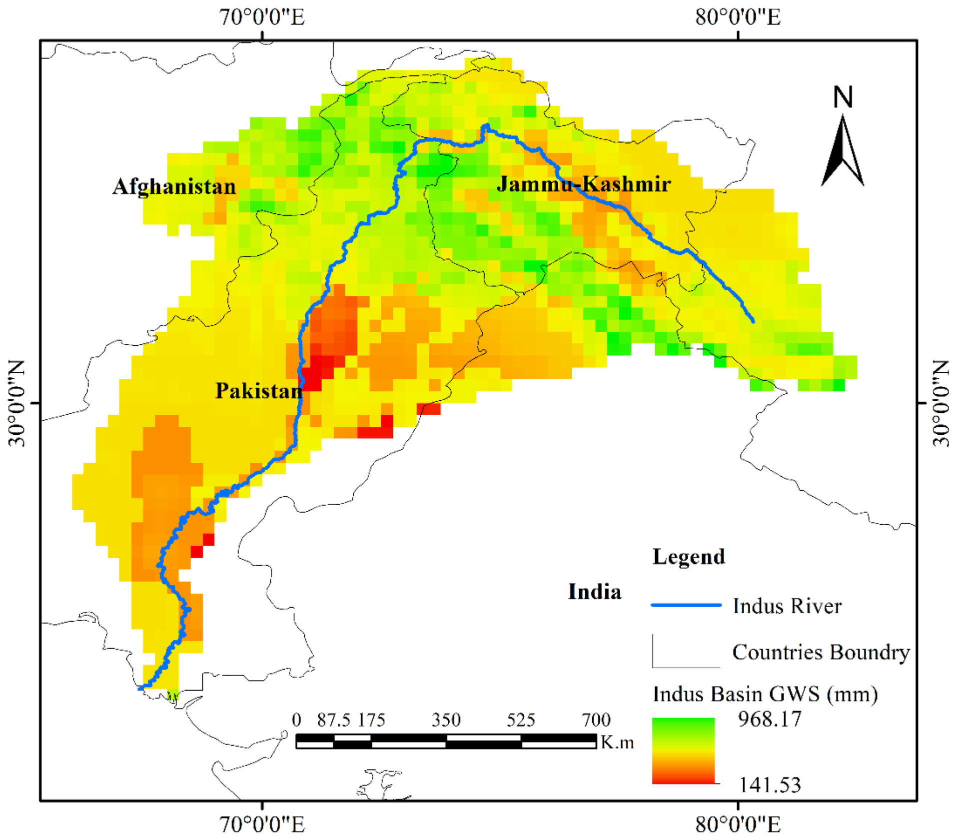

Figure 5. Spatial estimation of groundwater storage in the Indus Basin.

The Indus Basin groundwater shows the spatial variations within the Basin. The Himalayan region of the Indus Basin covers a high extent of groundwater with high values of 968 mm. This high coverage of groundwater shows the low discharge groundwater but the glacier coverage is extracted from here. In contrast, in plain areas, the groundwater faces high stress in central Pakistan where, due to high groundwater extraction for residential and agricultural purposes the imbalance between groundwater recharge and discharge is highlighted in Fig. 5.

The South Asia-based groundwater anomalies have been extracted to show the overall pattern of all countries covering the Indus Basin region. GRACE-based groundwater storage anomalies are extracted (for Pakistan, India, Afghanistan and Bangladesh). Fig. 6 shows the overall spatial map of the area to find the current situation of groundwater depletion in the area.

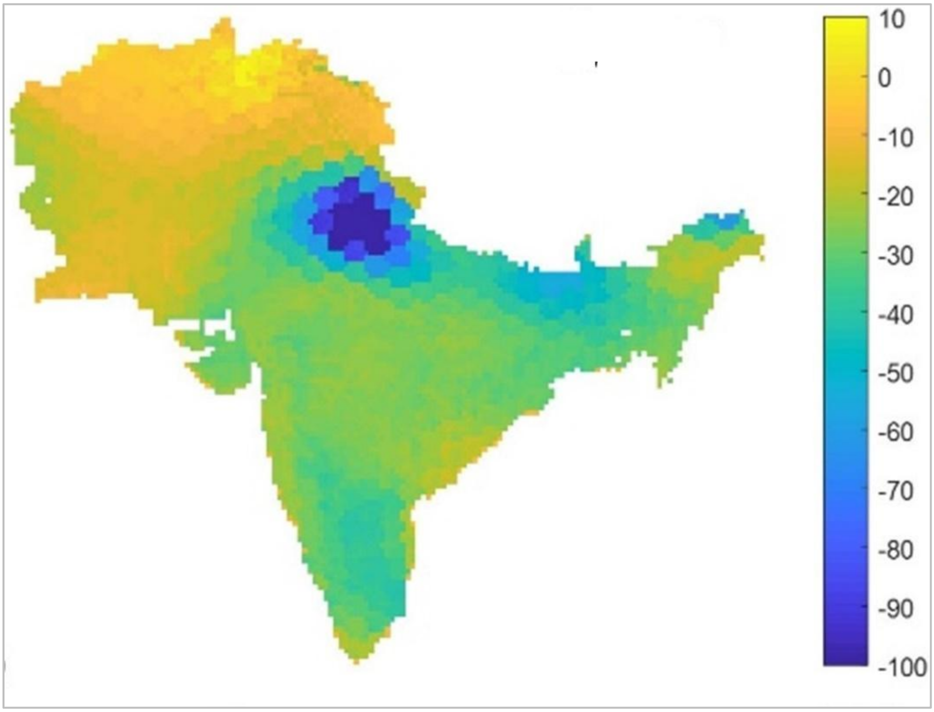

Figure 6. GRACE-based GWS anomalies for South Asia.

Fig. 6 shows the high depletion in northern India, specifically the Haryana and Punjab States, where the groundwater extraction rate is very high due to use in agriculture. Groundwater depletion in northern India is also reported by other case studies, whereas South India has a balanced situation regarding groundwater depletion (Asoka et al., 2017; Bhanja et al., 2016; Chinnasamy et al., 2013). Southern India is having a high recovery in the monsoonal season which is mostly in September and October, but extending to November in some years. Due to this, in pre-monsoon, the lowest GWS values are observed and after the monsoon, the GWS values are observed as the highest (Bhanja et al., 2016). Climatic variables like evapotranspiration and precipitation make a high variation in the groundwater storage and seasonality effect (Eltahir and Yeh, 1999). The long-term variations in precipitation may affect groundwater storage in North India due to high groundwater utilization and slow recharge.

4. Local-based Study of Taiwan

Different techniques are used for spatial mapping of groundwater depletion, such as the annual averaging technique for groundwater depletion.

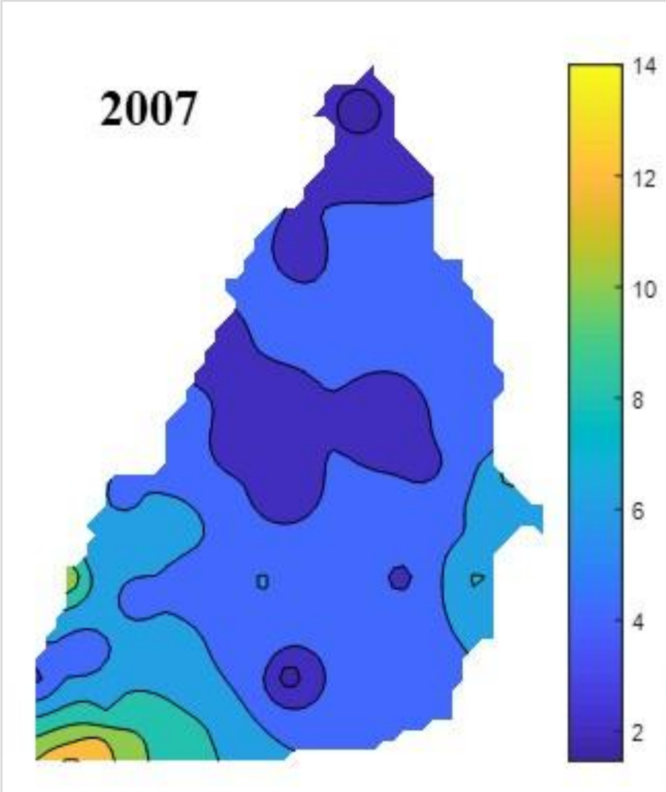

Figure 7. Groundwater annual depletion in 2007 in Taiwan county (Ali et al., 2020).

Fig. 7 shows the spatial distribution of groundwater depletion in Taiwan County using groundwater monitoring sensors. Monitoring stations are collecting monthly data which is averaged for annual representation.

Using this annual groundwater depletion map the land subsidence map has been developed (Fig. 8) through the use of the GWR model shown in Equation 2. The land subsidence map has some spatial differences according to the location, but such differences cannot be highlighted by linear regression. Ali et al. (2020) findings show that linear regression has a higher root mean square error as compared to GWR results, however, when the time “T” is included, the result is more refined because the overall pattern is highlighted.

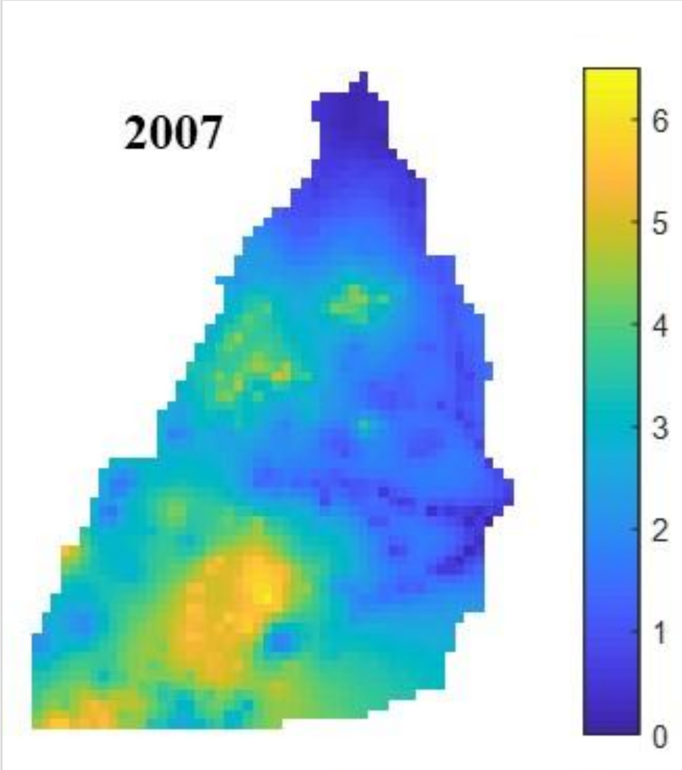

Figure 8. Land subsidence due to groundwater depletion, using the GWR model.

This area has high groundwater extraction for agricultural purposes, which ultimately leads to high subsidence in the area. Worldwide land subsidence issues occur due to high groundwater extraction for agriculture or due to high urbanization in the area (Khan et al., 2022; Galloway and Burbey, 2011).

From ground sensors, multiple pieces of information used for the extraction of groundwater storage variation have been analyzed by researchers (Argus et al., 2014; Ali et al., 2021). The hydraulic head and storage capacity quantification is very important for groundwater modeling, strategic management of groundwater resources and other environmental applications (Theodossiou and Latinopoulos, 2006; Varouchakis and Hristopulos, 2013). The most common deleterious effect of long-time groundwater extraction (and subsequent water-level declines) from unconsolidated aquifer systems in urban areas is land subsidence (Morris et al., 2003; Bell et al., 2008). In those conditions, the aquifer system gets high stress when the loss of groundwater storage is unstable due to the high difference between withdrawal and recharge in the area (Döll et al., 2012; Famiglietti, 2014).

For regional studies, remote sensing (RS) data has been used for groundwater monitoring from GRACE data, as said in 3,2. Further groundwater depletion impact on land subsidence is evaluated in different areas globally (Castellazzi et al., 2018; Ojha et al., 2020). RS-based data is used for land subsidence worldwide from different perspectives like fault slip detection, earthquake-based deformation or land subsidence due to groundwater extraction in an agricultural or urbanized area. In Fig. 9 the land subsidence is detected from synthetic aperture radar data using differential Interferometric SAR technique for the year 2017

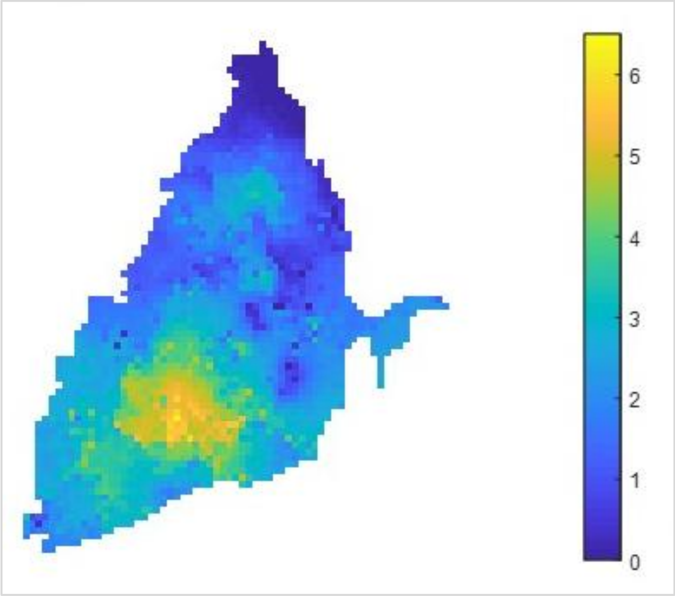

Figure 9. InSAR-based Land deformation map for 2017 using the D-InSAR technique (Ali et al., 2022).

Here the land subsidence is shown in the center of the county. This is a hotspot groundwater extraction area in Taiwan where we have high land subsidence (Ali et al., 2022). The area has land subsidence of 6.5 cm annually in the center, but in the northern part the land subsidence is lower. Furthermore, land subsidence output is used for the prediction of annual groundwater table variations.

5. Conclusion

Groundwater can be monitored using different ground-based and space-borne sensors. The ground-based monitoring stations can help ~~us~~ to monitor the different characteristics of the groundwater and groundwater table variations. Groundwater monitoring stations record the site-specific measurements, however, overlook the spatial heterogeneity of the groundwater. Therefore, remote sensing data is effective in evaluating the spatial and temporal variation of the groundwater from local, to regional and national scales. Integration of ground-based groundwater measurements with remote sensing data can derive high-resolution variations of groundwater monitoring and assist in water management. Considering–such problems, Rs data can help identify the areas better. By integrating the groundwater observation data with RS data, one can get high-resolution variations of groundwater monitoring and accordingly plan for management.

Due to the excessive extraction of groundwater, the compression of the subsurface, i.e., land subsidence problems, has been evaluated in many of the agricultural areas by different studies. Groundwater extraction in different areas should be monitored and policy should be formulated for the quantity of the groundwater extraction in different locations. The GRACE data effectively records the monthly global groundwater variations which can be used for the regional case studies where there is limitation of the groundwater monitoring stations.

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