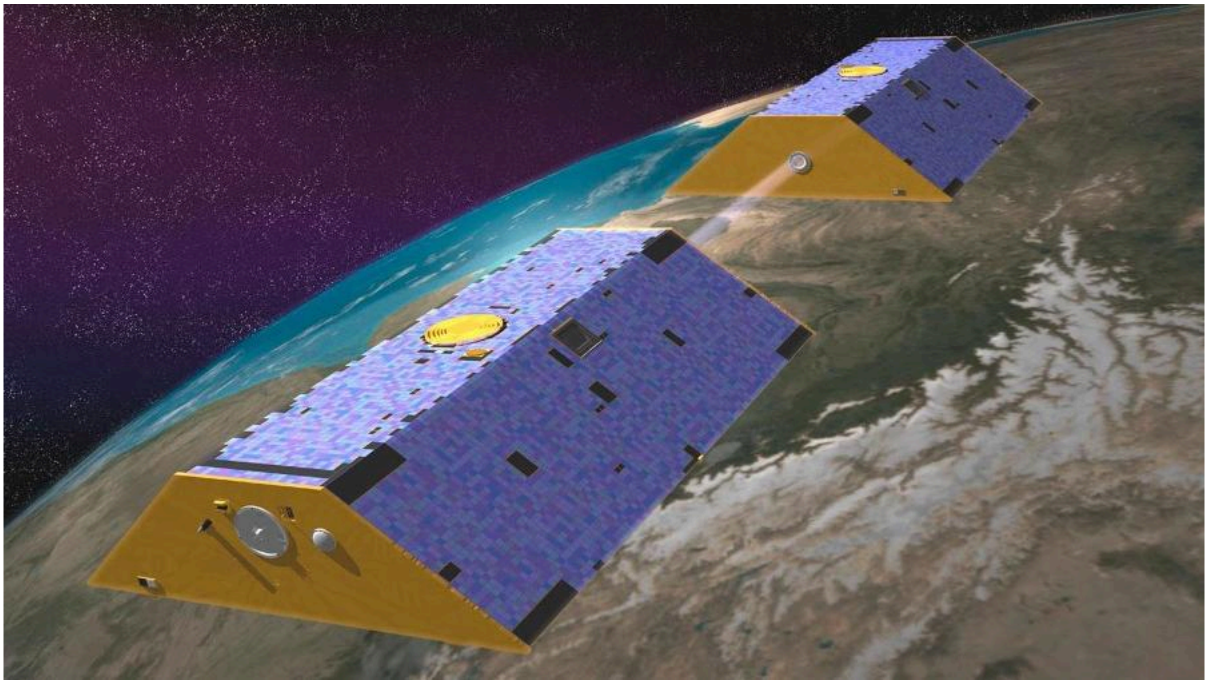

Space-based technologies and data complementing GRACE datasets for groundwater assessments and monitoring

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With increasing populations, groundwater abstraction (https://www.space4water.org/s4w/web/taxonomy/term/1419) also increased as about half of the global urban population access their water through aquifers (https://www.space4water.org/taxonomy/term/1560) (Foster et al., 2020). With 74% of the world population depending on it for safe drinking water services and sanitation (WHO and UNICEF, 2021), groundwater (https://www.space4water.org/taxonomy/term/1568) plays a vital role in health. According to the Food and Agriculture Organization of the United Nations (FAO), 70% of groundwater abstraction can the attributed to irrigated agriculture (https://www.space4water.org/taxonomy/term/820) (FAO, 2020). Thus, freshwater resources monitoring is crucial, especially in arid and semi-arid regions which have historically suffered and continue to suffer from depleting freshwater resources amplified by droughts and thus highly dependent on groundwater resources (Haq et al., 2022). Globally, groundwater-dependent ecosystems (https://www.space4water.org/water/groundwater-dependent-ecosystems) (GDEs) are at risk due to unsustainable groundwater extraction and climate change (Guirado, et al., 2017). In drylands, vegetation can be affected by changes in the quantity, quality, and distribution of groundwater due to overexploitation and fragmentation caused by agricultural and urban sprawl.

A hidden resource: the value of groundwater

> "…groundwater is our biggest source of liquid freshwater … Yet, some 20% of the world's aquifers are being overexploited. In many places, we simply do not know how much of this precious resource might exist. We need to improve our exploration, monitoring and analysis of groundwater resources to protect and better manage them and help achieve the Sustainable Development Goals." - António Guterres, UN Secretary-General, World Water Day 2022

Aquifers are underground reservoirs that store far more water than the capacity of all surface reservoirs. They are continually recharged by rainwater and snowmelt, or from leaks in the bottom of lakes and rivers (Figure 1) (BGR and UNESCO, 2008). Due to the huge volumes of groundwater, aquifers can serve as a buffer in times of water scarcity, enabling people to survive in even the driest of climates (UN WWDR, 2022). In addition, groundwater indirectly contributes to urban poverty reduction by allowing water utilities to develop sources at much lower cost and allow lower connection charges (UN WWDR, 2022).

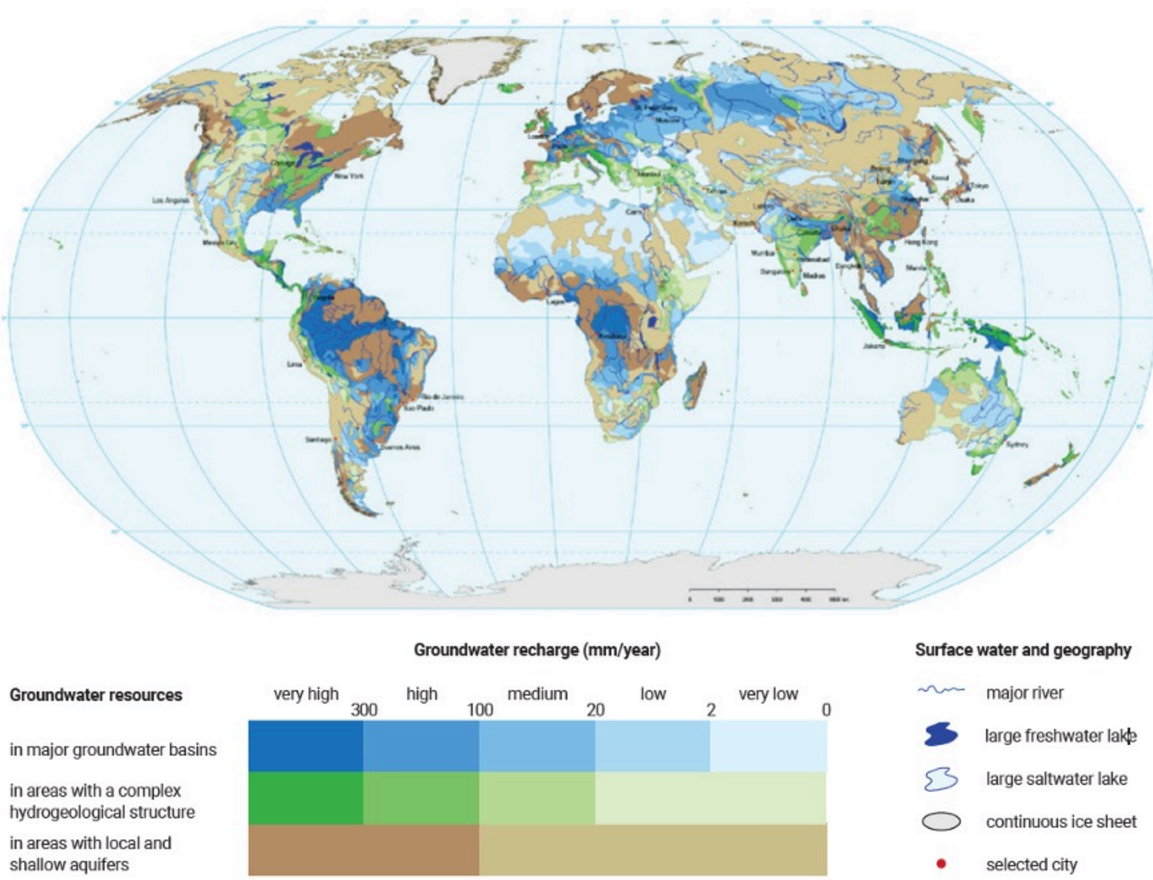

Figure 1 Global groundwater resources (BGR and UNESCO, 2008)

Despite all this, groundwater is still overlooked in high-level discussions about climate change and water and in sustainable development policy (UN WWDR, 2022). Consequently, all major water events and conferences for 2022 including the 9th World Water Forum (https://www.worldwaterforum.org/en), World Water Day (https://www.worldwaterday.org/) and the upcoming UN-Water Summit on Groundwater (https://www.space4water.org/s4w/web/events/groundwater-summit) are drawing attention to the topic of groundwater through the campaign “Groundwater: making the invisible visible”. The aim of the campaign is to unify statements and define actions towards more responsible and sustainable use and protection of groundwater resources.

In recent decades, some aquifers have been permanently losing their essential storage capacity due to the combination of extreme droughts and increased groundwater withdrawals (Smith et al., 2017). The World Water Development Report 2022 states that the long-term sustainability of global aquifers depends on precise and comprehensive groundwater assessing and monitoring which is essential in informing national water and sustainable development policies for 2030 and beyond (UN WWDR, 2022). However, data for water resources studies are often limited which makes it challenging to assess, monitor and manage groundwater resources.

Therefore, to provide better tools for monitoring and management to water resources managers, the latest space technology including hydrology missions (e.g., European Space Agency’s (ESA) Soil Moisture and Ocean Salinity (SMOS) satellite) and space gravity missions (e.g., NASA-DLR’s GRACE) provide estimates of the spatial and temporal variations of terrestrial water storage in soils, lakes, reservoirs, and groundwater (ESA, 2007).

GRACE datasets for groundwater assessments and monitoring

Space technologie (https://www.space4water.org/s4w/web/taxonomy/term/811)s have played an increasingly important role in groundwater monitoring since the 1970s (Figure 2) through their contributions in collecting information on groundwater influencing factors (Huang et al., 2018; Ritchie, 2021). They gather data which provides fast and valuable baseline information on geology, geomorphology, drainage patterns and/or density, vegetation, land use and/or land coverage (LULC), soil moisture, water table depth, land surface temperature, slope of the terrain, and hydraulic conductivity that can be used as basis from which to monitor change in the area of interest (Ritchie, 2021). This information directly or indirectly relates to the existence and movement of groundwater (Huang et al., 2018).

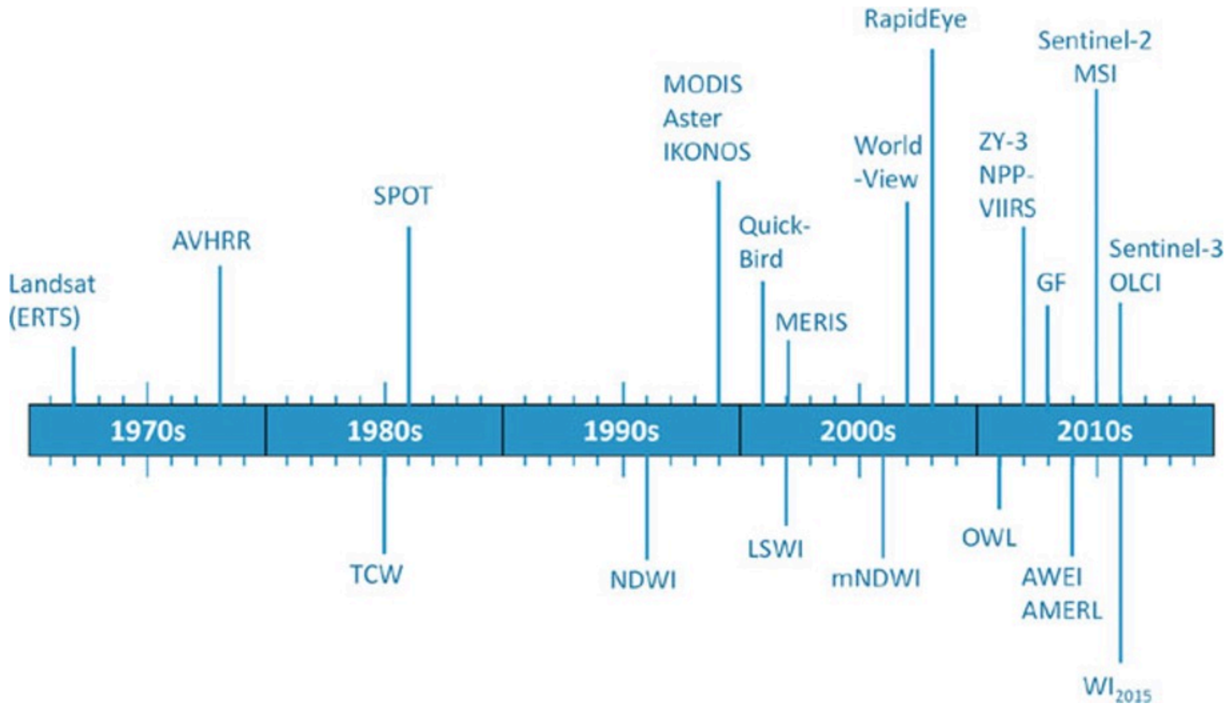

Figure 2 Timeline diagram of various applied water indices and satellite sensors. (Huang et al., 2018)

Gravity Recovery and Climate Experiment (https://www.space4water.org/s4w/web/space/grace) (GRACE) satellite missions provide an excellent opportunity to monitor large-scale climatic and anthropogenic impacts on water resources including terrestrial water storage (TWS) and groundwater storage (https://www.space4water.org/s4w/web/water/groundwater-storage) (Werth et al., 2017; Haq et al,. 2022). The data collected by these satellites is used to determine changes in surface mass (https://www.space4water.org/environmental-terms/surface-mass), total water storage, (https://www.space4water.org/space/total-water-storage) and derived variables.

GRACE datasets have been used successfully to estimate groundwater storage change across Africa (Gido et al., 2020; Nigatu et al., 2021), USA (Massoud et al., 2021), and in the Middle East (Pradipta et al., 2018; Massoud et al., 2021). The analysis of GRACE datasets from 2002-2016 in Saudi Arabia revealed the depletion of groundwater resources which suggests that influences of climate variability and water extraction have exceeded the natural recharge rates thus indicating water resource exploitation (Haq et al., 2022). A study estimating groundwater storage change Gangetic Plain, India showed that the analysis of GRACE data coupled with available recorded groundwater data can be used as a regional-scale groundwater assessment tool to understand the regional groundwater hydrologic regime (Dasgupta et al. 2014). This makes GRACE a unique tool to study the development of deficits and surpluses of all water present in a defined region and period (Werth et al., 2017).

However, there are some challenges in GRACE applications which include a leakage bias due to the coarse spatial resolution (300 km) of GRACE, difficulties in uncertainty assessments and independent validations due to lack of adequate independent observations at scales comparable to GRACE observations (Chen et al., 2022).

In spite of that, other space technologies can be used to complement GRACE datasets to reduce bias and uncertainties. As such, GRACE satellite mission, altimetry satellites (e.g., Sentinel-3), hydrology missions (e.g., SMOS), and numerical groundwater modelling are recommended to be used conjunctively to assess the groundwater resources more efficiently (ESA, 2007; Masood et al., 2022). This combination generates various outputs, such as glacial response to climate change, total precipitable water, cloud formation, atmospheric profiles, land cover, evapotranspiration, water mask, snow, and soil moisture, which affect groundwater recharge (Masood et al., 2022).

Furthermore, machine learning frameworks can be used to integrate in-situ datasets and satellite data to effectively simulate and analyse groundwater dynamics under changeable conditions (Chen et al., 2020; Martinsen et al., 2022).

Space-based technologies and data complementing GRACE datasets

Scientific knowledge, methods and tools available in hydrogeology are sufficient to address most groundwater management issues. The challenge lies more with the scarcity of reliable data for area-specific groundwater assessments (https://www.space4water.org/water/groundwater-assessment)and scenario analyses. Space technologies, particularly remote sensing (https://www.space4water.org/taxonomy/term/835) and Geographic Information Systems (https://www.space4water.org/s4w/web/space/geographic-information-system-gis) (GIS) are widely used to study and predict spatial and temporal changes in hydrological processes including groundwater (Ritchie, 2021). Remote Sensing techniques have been used by the scientific community to improve the monitoring and estimation of groundwater resources through the use of proxy data and information collected on groundwater influencing factors.

The commonly used satellite images for groundwater assessments are from IKONOS, Spot, Aster, Landsat 7 and Moderate Resolution Imaging Spectroradiometer (MODIS) (Figure 2; Table 1), with a spatial resolution of 1 m, 5 m, 15 m, 30 m and 250 m, respectively (Masood et al., 2022). The images are processed by using special software, most commonly ERDAS Imagine, ENVI and PCI Geomatica.

Satellite	Launched by	Start	Sensors	Spatial Resolution	Temporal Resolution	Outputs
Landsat	NASA and USGS	1972	Return Beam Vidicon (RBV) and the Multispectral Scanner System (MSS)	30 m	18 days	Agriculture, land use, water resources, forestry
Terra	NASA	1999	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Clouds and Earth's Radiant Energy System (CERES), Multi-angle Imaging Spectroradiometer (MISR), Measurements of Pollution in the Troposphere (MOPITT), Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m, 500 m, 1 km	16 days	Precipitable water, cloud, atmospheric profiles, land cover, evapotranspiration, water mask, ocean products, and snow, glaciers, and sea ice cover
SRTM DEM	NASA	2000	InterferometricSynthetic Aperture Radar (InSAR) (C-band and X-band)	90 m, 30 m	Multi days	Elevation data of an area
Aqua	NASA	2002	Atmospheric Infrared Sounder (AIRS), Advanced Microwave Scanning Radiometer for EOS (AMSR-E), Advanced Microwave Sounding (AMSU-A), Clouds and Earth's Radiant Energy System (CERES), Humidity Sounder for Brazil (HSB), Moderate Resolution Imaging Spectroradiometer (MODIS)	250 m, 500 m, 1 km	16 days	Cloud formation, precipitation, and radiative properties, air-sea fluxes of energy, carbon, and moisture
GRACE	DLR, ESA,GFZ, NASA	2002	GRACE instruments (K-band Ranging System (KBR), Ultra Stable Oscillator (USO), SuperSTAR Accelorometers (ACC), Star Camera Assembly (SCA), Coarse Earth Sun and Sensor (CES), Center of Mass Trim Assembly (MTA), BlackJack GPS Receiver and Instrument Processing Unit (GPS))	300 km	30 days	Terrestrial water storage that includes groundwater, soil moisture, surface water, canopy water, snow, and ice water
IRS-P6	ISRO and USGS	2003	Advanced Wide Field Sensor (AWiFS), Linear Imaging Self Scanner - III (Resourcesat) and IV	24 m	24 days	Data for integrated land and water resource management, snow cover, vegetation, landscape topography
Copernicus: Sentinel-2	ESA	2015	MultiSpectral Instrument (MSI)	10 - 20 m	5 days	Soil, water, and vegetation cover for land, inland waterways, and coastal areas

Table 1 Satellites at varying resolutions and their outputs used for groundwater assessments and monitoring (ESA, 2022; Masood et al., 2022).

MODIS sensors promote the continuity of data collection essential for understanding both long- and short-term changes in the global environment by extending data sets collected by sensors such as the Advanced Very High-Resolution Radiometer (AVHRR), used for meteorology and monitoring sea surface temperature, sea ice, and vegetation; Landsat, used to monitor terrestrial conditions; and High-Resolution Infrared Radiation Sounder (HIRS), used to observe atmospheric conditions (NASA, 2022). They help with improving different model inputs for groundwater modelling (https://www.space4water.org/water/groundwater-modelling). This has been done in a New Zealand national mapping of groundwater recharge where actual evapotranspiration and leaf area index estimates from the MODIS sensor in combination with climate and other land surface data were used to develop the Nation-wide Groundwater Recharge Model (NGRM) (Martinsen et al., 2022).

Satellite data at higher spatial resolution (i.e., 900m to 10 m) (see Table 1) have been used for groundwater recharge estimation in a so called "water budget (https://www.space4water.org/water/water-budget) approach" which utilises both, in-situ data and satellite remote sensing data. As groundwater occurrence is restricted to the deep-seated fracture zones only, high-resolution satellite data has the potential to infer buried pediment plains (https://www.space4water.org/environmental-terms/pediplain) and interconnected fracture zones for the selection of groundwater exploration and artificial recharge sites (Mukherjee, 2008). IRS-LISS-3 data has better capability to infer these landform units in comparison to the IRS-P6-AWIFS data of limited spatial and spectral resolution (Mukherjee, 2008). A comparison of the two shows, only LISS-3 data can provide detailed hydrogeological information for groundwater / water resource management (Figure 3).

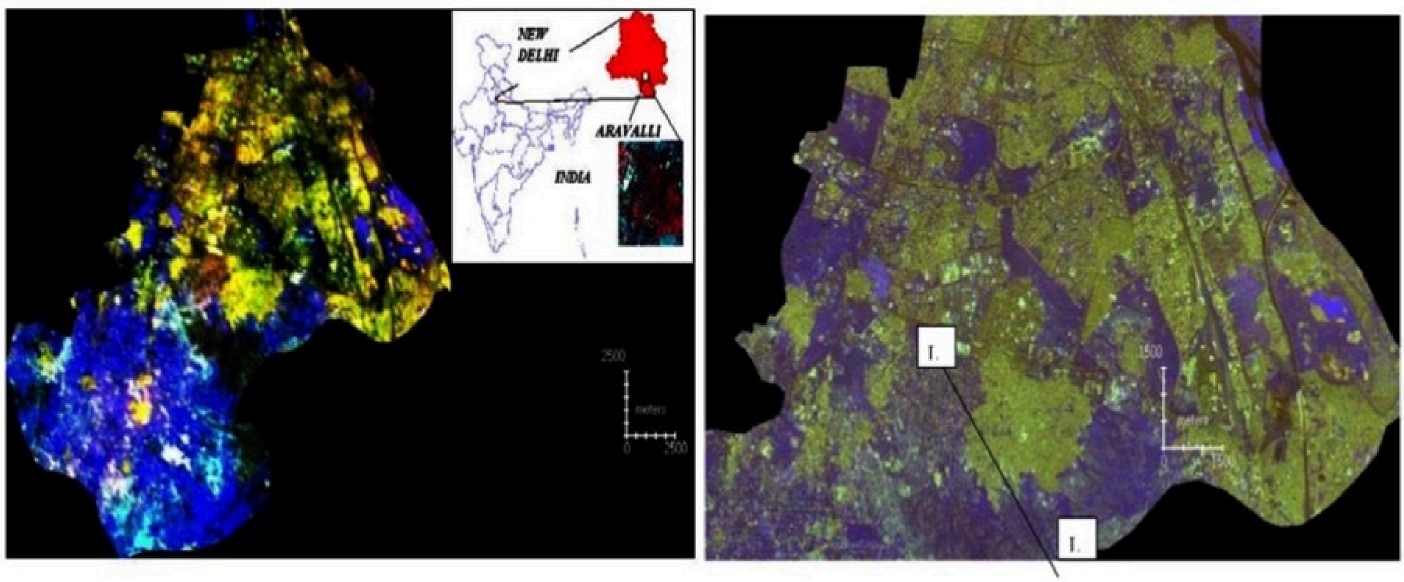

Figure 3 AWIFS sensor showing lineaments (L) in south Delhi without detailed information of hydrogeology (left) and IRS-1D LISS-III sensor data analysed with ERDAS software showing details of lineaments (L) and detailed hydrogeological information of whole Delhi, for ground water management.

High-resolution, multi-spectral imaging missions such as Sentinel-2 MSI support Copernicus Land Monitoring studies with the monitoring of vegetation, soil and water cover, as well as observation of inland waterways and coastal areas (Table 1). Sentinel-2 data has been used to indirectly estimate groundwater withdrawals by investigating irrigation requirements to sustain agricultural production (Masood et al., 2022). Vanino et al. (2018) in showed that satellite observations can accurately infer potential crop evapotranspiration (ETp) and irrigation water requirements by estimating crop parameters such as leaf area index and surface albedo which influence the dynamics of ETp. In previous studies, crop coefficient (Kc) models based on Sentinel-2 imagery were developed to estimate estimating cotton crop water consumption, demonstrating the potential of developing Kc prediction for field crops using Sentinel-2 (Rozenstein et al., 2019).

Depth to the water table is an important factor affecting vegetation cover (Figure 4). Hence, satellite-based vegetation indices may be used as suitable indicators of groundwater depth, storage and quality in areas where 1) vegetation is natural, 2) the water table is shallow, and 3) in-situ groundwater observations are not available (Banja et al., 2019; Huang et al., 2019). Satellite data (for example, Sentinel-2 data) together with vegetation indices are used to confirm the dependence of vegetation on groundwater by comparing the seasonal dynamics of the photosynthetic activity of the selected plant species, with their surrounding non-phreatophytic vegetation (Guirado, et al., 2017). The vegetation cover and its temporal pattern can be extracted from several spectral indicators, such as ratio vegetation index (RVI), vegetation index number (VIN), difference vegetation index (DVI), and normalized difference vegetation index (https://www.space4water.org/taxonomy/term/1239) (NDVI) (Merola et al., 2006; Ayanlade, 2017; Solymosi et al., 2019; Fabre et al., 2020).

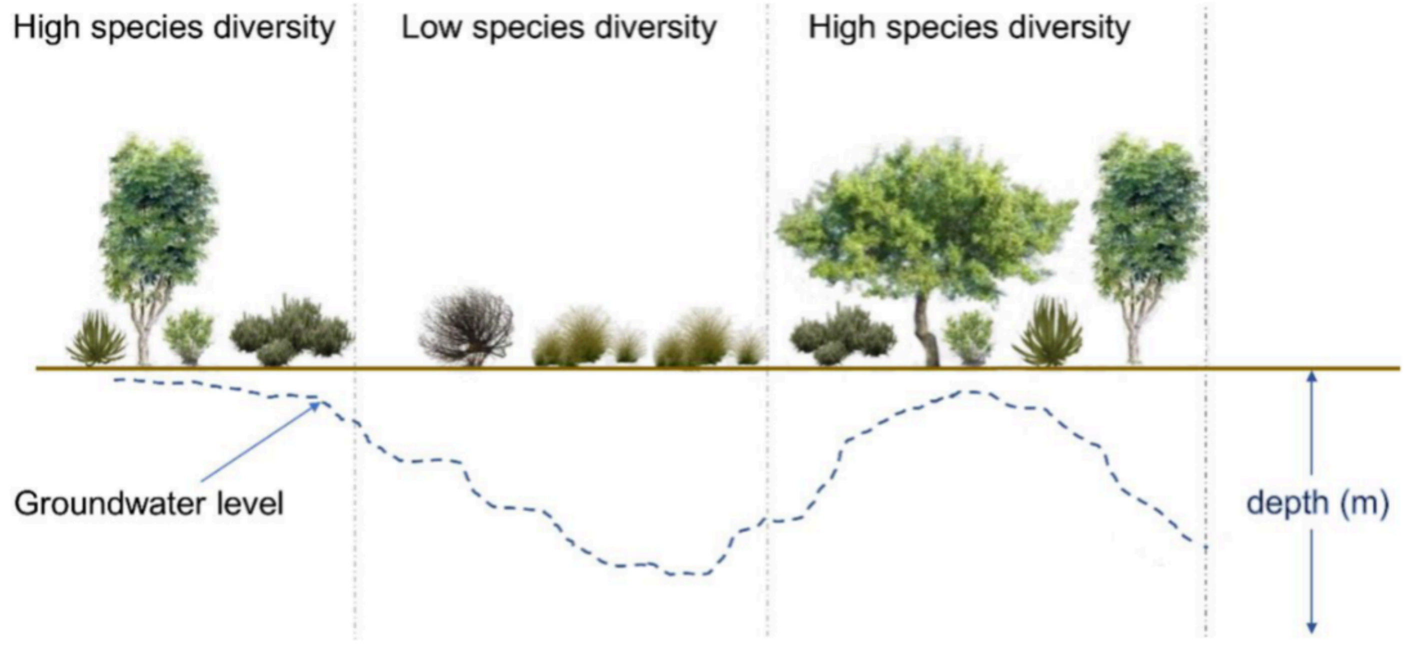

Figure 4 Interactions between groundwater levels and vegetation diversity in arid environments (Mpakairi et al., 2022).

Microwave remote sensing techniques including active (Synthetic Aperture Radar (https://www.space4water.org/taxonomy/term/1219) (SAR), ground penetrating radar, scatterometers, etc.) and passive (radiometers (https://www.space4water.org/space/imaging-multi-spectral-radiometers-passive-microwave)) have shown a high potential to provide valuable information at various spatial and temporal scales. They are used to map the spatial domain of surface soil moisture and to monitor its temporal dynamics (Jackson, 2002). Both, passive and active microwave sensors (e.g., AMSR, AMSU, ASTER, SAR) can be used for the estimation of ground water recharge as they provide quantitative measurements of depth to water table (Becker, 2005) (Table1). On a continuous soil profile, surface soil moisture contents can reflect the depth to water table (Jackson, 2002).

Excessive groundwater withdrawals resulting in lowered groundwater levels are the leading cause of land subsidence (Smith et al., 2017). Interferometric Synthetic Aperture Radar (InSAR) may be used to accurately measure subtle changes in land elevation. The strength of InSAR is that it offers greater spatial extent and resolution of land subsidence than can be obtained through ground-based measurements (Smith, 2002). Satellite-based Sentinel-1 InSAR is currently the most widely used technique for monitoring surface deformation associated with groundwater variations. InSAR line-of-sight displacements are likely to be the most sensitive to fluid pressure and corresponding effective stress changes within the confined aquifer while GRACE gravity observations are influenced by water mass changes (Vasco et al., 2022). As such, it is impossible to distinguish between the overlying unconfined aquifer and the confined aquifer below using GRACE (Figure 5). The Tulare Basin study has shown that the conjunctive use of Sentinel and GRACE satellite data can indeed monitor hydrological variations over time scales of a month or more (Vasco et al., 2022).

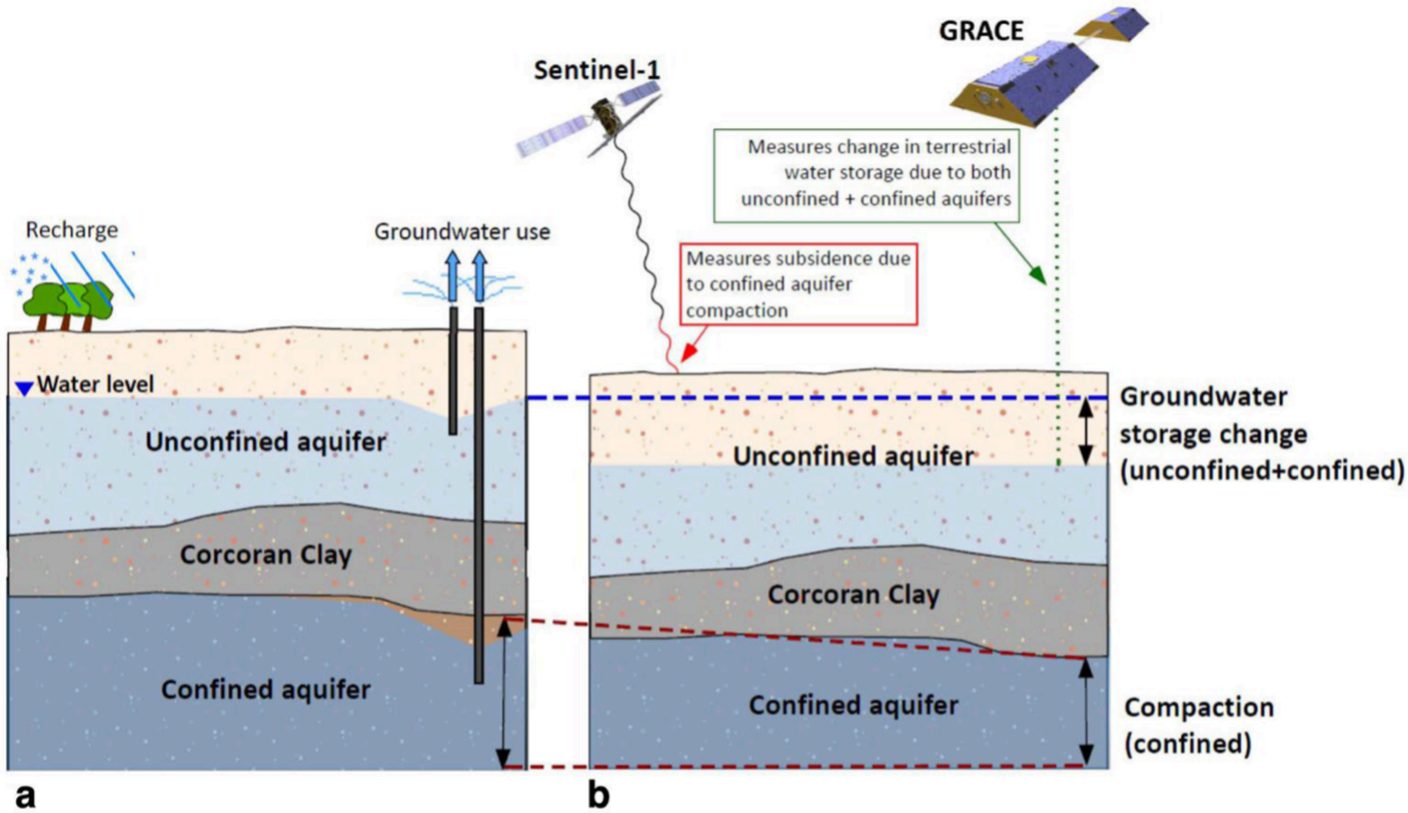

Figure 5 a) A conceptual model of the Tulare basin where Corcoran Clay separates unconfined aquifer from confined aquifer. b) Subsidence is measured by Sentinel-1 Synthetic Aperture Radar (SAR) satellites and changes in TWS are measured by GRACE satellites (Vasco et al., 2022).

Groundwater flow models, terrestrial modelling systems and hydrological models

Satellite data which is not backed by in-situ observation is not sufficient to fully define the groundwater system without the help of models. On the other hand, in-situ observations from wells are unable to provide direct information on storage or fluxes unless they are put in the context of a 3D groundwater model which will account for the hydrodynamic interplay between shallow and deep portions of the groundwater systems (Condon et al., 2021). A groundwater flow model is a numerical platform used to simulate hydrologic fluxes in the subsurface and may accommodate simulation of the entire terrestrial hydrologic cycle using integrated or coupled modelling approaches (Condon, et al., 2021).

Decision makers use models to predict the behaviour of a groundwater system and to support a management decision regarding groundwater quantity or quality. Commonly used modelling software packages using space-based data for performing groundwater flow simulations to predict groundwater recharge include Modular Three-Dimensional Finite-Difference Groundwater Flow modelling program (MODFLOW), HYDRUS, Finite Element subsurface FLOW system (FEFLOW), HydroGeoSphere (HGS), and MIKE-SHE (Fouad et al., 2018).

- MIKE-SHE can be used to simulate all the processes in the land phase of the hydrologic cycle. In MIKE-SHE, the saturated zone interacts with all the other components – evapotranspiration, overland flow, channel flow, and groundwater flow in the unsaturated zone (DHI, 2017).
- MODFLOW is restricted to simulating flow only in the saturated groundwater zone. It thus disregards all other components in the unsaturated zone or just has them set as boundary conditions for the saturated zone (DHI, 2017).
- HGS dynamically integrates key components of the hydrologic cycles and can incorporate land surface processes such as evaporation from bare soil, transpiration with evolving vegetation, unsaturated flow, flow in porous and/or discrete fractured media, and reactive solute and thermal energy transport within surface and subsurface hydrologic systems (Aquanty Inc., 2015). The most important feature of HGS is its ability to simulate water flow in a fully integrated mode, thus allowing precipitation to partition into overland and streamflow evaporation, transpiration, groundwater recharge or sub-surface discharge into surface water bodies such as rivers or lakes (Aquanty Inc., 2015).
- FEFLOW simulates a multitude of groundwater processes involving flow, contaminants, groundwater age and heat transport under fully or variably saturated conditions (DHI, 2022). It enables users to 1) predict potential water quality issues in groundwater and assess groundwater remediation (https://www.space4water.org/water/groundwater-remediation) strategies, 2) investigate

groundwater-surface water interaction, and 3) estimate ground subsidence and predict pumping rates and stability issues in geotechnical projects (DHI, 2022).

- Like FEFLOW, the HYDRUS software packages numerically solve the Richards equation for variably saturated water flow and advection-dispersion equations for both heat and solute transport (Šimůnek et al., 2016). They are therefore used to simulate one- and two- or three-dimensional movement of water, heat, and multiple solutes in variably saturated media (Šimůnek et al., 2016).

In addition, terrestrial modelling systems (https://www.space4water.org/environmental-terms/terrestrial-land-surface-modelling-systems) such as the Global Land Data Assimilation System (https://www.space4water.org/environmental-terms/global-land-data-assimilation-system-gldas)(GLDAS) and the WaterGAP Global Hydrological Model (https://www.space4water.org/water/watergap-global-hydrological-model-wghm) (WGHM) have been used in combination with GRACE datasets (Figure 6). GLDAS integrates satellite and ground-based observations to produce data on land surface conditions such as soil moisture and surface temperature in near-real time (Masood et al., 2022). On the other hand, WGHM can quantify both, surface and groundwater resources as it computes timeseries of surface and subsurface runoff, groundwater recharge, and river flows along with water storage variations from water bodies (Masood et al., 2022). The integration of GRACE with GLDAS and GRACE with WGHM provides precise and reliable datasets that are used to describe the variations of groundwater storage regionally.

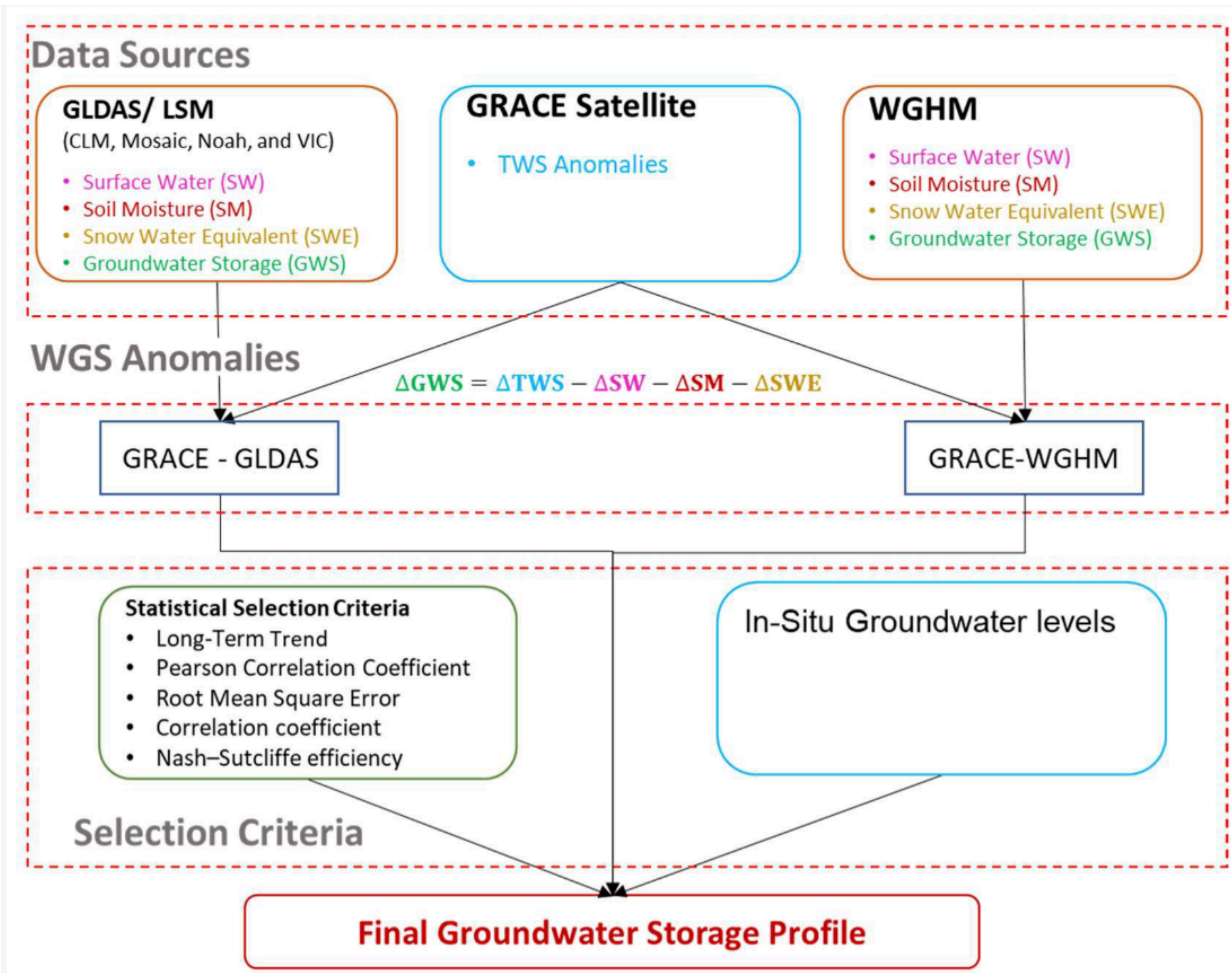

Figure 6 Approaches to obtain groundwater shortage profiles through the interaction of GRACE with GLDAS and GRACE with WGHM (Masood et al., 2022).

Conclusion

GRACE provides a unique opportunity for groundwater storage assessments at a continuous and large spatial scale. However, there are associated limitations due to its coarse resolution such as limited ability to investigate the water storage change at a small spatial scale. Therefore, a need arises to improve the resolution of GRACE data at a spatial scale applicable for regional-level studies.

GRACE satellite mission datasets for groundwater assessments and monitoring can be and have been complemented by using a combination of data from satellite altimetry and optical imaging missions, conventional in-situ observations and hydrological modelling. In addition, the integration GRACE data with models such as GLDAS and WGHM has proven to be efficient as these models help with upgrading GRACE resolution. This has the potential to significantly improve our understanding of hydrological processes affecting groundwater resources in response to climate variability and change.

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Groundwater Flow Model (/water/groundwater-flow-model) Groundwater (/taxonomy/term/1568) GRACE (/space/grace)

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Groundwater modelling (/water/groundwater-modelling) Total water storage (/space/total-water-storage)

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