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Hydrogeodesy: Understanding changes in water resources using space geodetic observations

# The Potential of Hydrogeodesy to Address Water-Related and Sustainability Challenges

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**Key Points:**

- This is a community view on hydrogeodesy, the science that measures the Earth's solid and aquatic surfaces, gravity field, and their changes
- Hydrogeodesy encompasses geodetic technologies such as Altimetry, Interferometric Synthetic Aperture Radar, Mass gravimetry, and Global Navigation Satellite Systems
- We study the evolution of hydrogeodesy and its role within current hydrological, sustainability science, and management frameworks

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**Abstract** Increasing climatic and human pressures are changing the world's water resources and hydrological processes at unprecedented rates. Understanding these changes requires comprehensive monitoring of water resources. Hydrogeodesy, the science that measures the Earth's solid and aquatic surfaces, gravity field, and their changes over time, delivers a range of novel monitoring tools that are complementary to traditional hydrological methods. It encompasses geodetic technologies such as Altimetry, Interferometric Synthetic Aperture Radar (InSAR), Gravimetry, and Global Navigation Satellite Systems (GNSS). Beyond quantifying these changes, there is a need to understand how hydrogeodesy can contribute to more ambitious goals dealing with water-related and sustainability sciences. Addressing this need, we combine a meta-analysis of over 3,000 articles to chart the range, trends, and applications of satellite-based hydrogeodesy with an expert elicitation that systematically assesses the potential of hydrogeodesy. We find a growing body of literature relating to the advancements in hydrogeodetic methods, their accuracy and precision, and their inclusion in hydrological modeling, with a considerably smaller portion related to understanding hydrological processes, water management, and sustainability sciences. The meta-analysis also shows that while lakes, groundwater and glaciers are commonly monitored by these technologies, wetlands or permafrost could benefit from a wider range of applications. In turn, the expert elicitation envisages the potential of hydrogeodesy to help solve the 23 Unsolved Questions of the International Association of Hydrological Sciences and advance knowledge as guidance toward a safe operating space for humanity. It also highlights how this potential can be maximized by combining hydrogeodetic technologies simultaneously, exploiting artificial intelligence, and accurately integrating other Earth science disciplines. Finally, we call for a coordinated way forward to include hydrogeodesy in tertiary education and broaden its application to water-related and sustainability sciences in order to exploit its full potential.

**Plain Language Summary** Increasing climatic and human pressures are changing the world's water resources and hydrological processes at unprecedented rates. Understanding these changes requires comprehensive monitoring of water resources. Hydrogeodesy, the science that measures the Earth's solid and aquatic surfaces, gravity field, and their changes over time, delivers a range of novel monitoring tools complementary to traditional hydrological methods. It encompasses technologies such as Altimetry, Interferometric Synthetic Aperture Radar (InSAR), Gravimetry, and Global Navigation Satellite Systems (GNSS). Beyond quantifying these changes, we need to understand the potential of hydrogeodesy to contribute to more ambitious goals of water-related and sustainability sciences. Addressing this need, we combine a meta-analysis of over 3,000 articles to chart the range, trends, and applications of hydrogeodesy with an expert elicitation that systematically assesses this potential. We find a growing body of literature relating to advancements in hydrogeodetic methods, their accuracy and precision, and their inclusion in hydrological modeling. The expert elicitation envisages the large potential to solve hydrological problems and sustainability challenges. It also highlights how this potential can be maximized by combining several hydrogeodetic technologies, exploiting artificial intelligence, and accurately integrating other Earth science disciplines.

## 1. Introduction

The water cycle and associated surface and subsurface flows and storages are changing at unprecedented rates via complex and interconnected processes that increasingly challenge humanity (Bierkens & Wada, 2019; Konikow & Kendy, 2005; Porkka et al., 2024; Yao et al., 2023). For example, global terrestrial water storage (TWS) has decreased considerably in some regions due to freshwater consumption for energy and agriculture (Rodell et al., 2018). Around 4 billion people have inadequate access to water during one or more months per year (Mekonnen & Hoekstra, 2016), and ∼2.2 billion people live in regions facing both water stress and storage depletion (Huggins et al., 2022). In turn, water consumption and flow regulations have impacted freshwater ecosystems, with 59% of the world's largest river systems estimated to be either moderately or strongly affected by fragmentation (Grill et al., 2019) and 65% of riverine freshwater habitats already under threat (Vörösmarty et al., 2010). Overall, water scarcity is driven by water use, land use, and changing hydroclimatic conditions (Rijsberman, 2006; Schewe et al., 2014; Schmidt, 2019; Seckler et al., 1999; Singh & Kumar, 2019) and can further be exacerbated by climate change (X. Li et al., 2022). Global water use and climate change already impair essential functions of the water cycle and, at the global scale, may have already transgressed specific water-related thresholds describing a safe operating space for humanity (Destouni et al., 2013; Jaramillo & Destouni, 2015; Porkka et al., 2024; Richardson et al., 2023).

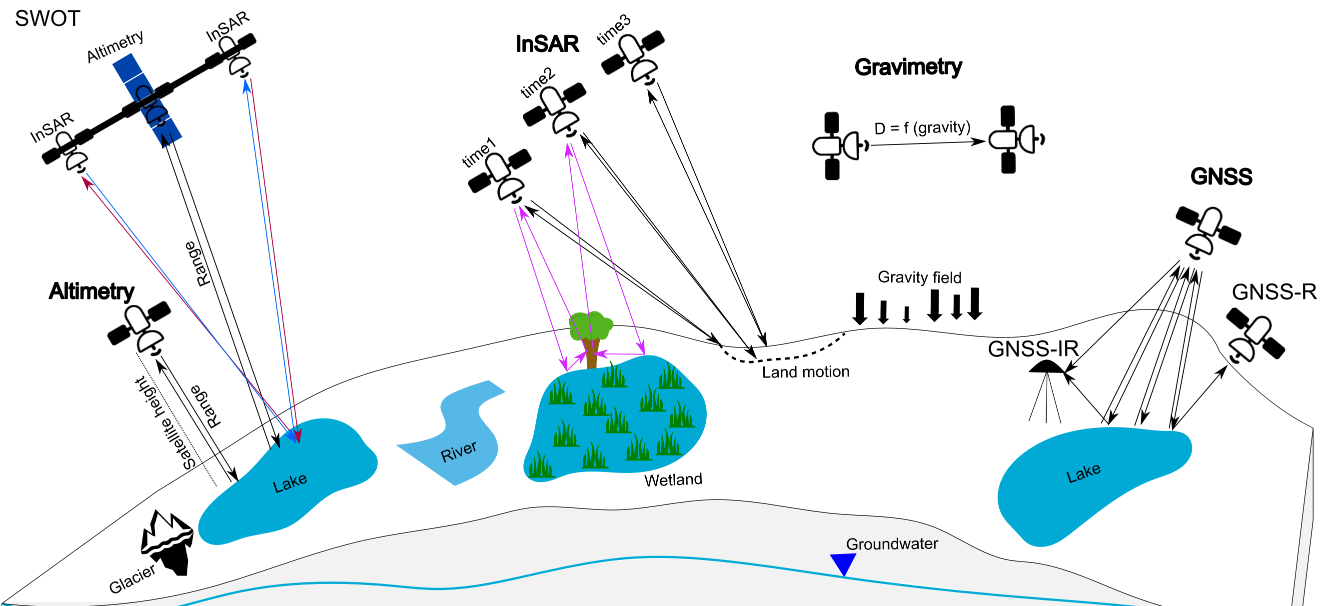
Only a limited fraction of global freshwater is considered an accessible resource (0.76%; Shiklomanov & Rodda, 2003), and freshwater resources are fragmented and fractioned across the landscape. For instance, millions of inland water bodies exist, many dispersed across remote or inaccessible regions (Hegerl et al., 2015; Pekel et al., 2016; Verpoorter et al., 2014). The distribution of these water bodies is unequal across Earth's land area, implying an even smaller percentage of freshwater per unit area in many regions. Consistent monitoring is required for understanding and managing the functioning and evolution of such a large number of fragmented freshwater bodies, especially under a rapidly changing global water cycle, and considering the need to prepare for extreme water-related events such as floods and droughts (Yang et al., 2021). Spaceborne remote sensing approaches can provide such comprehensive surveillance of surface water bodies and groundwater across our planet's land area.

Satellite-based geodetic observations can help track freshwater availability by measuring the temporal variation of geometry and gravity over Earth's landscapes in 3D (e.g., Adams et al., 2022; Jin & Feng, 2013; Singh et al., 2013; Tourian et al., 2022). Geodetic techniques have not only complemented the use of optical sensors to understand changes in surface water extent but have additionally and considerably increased our understanding of other characteristics of water availability, such as changes in water level, storage volume, and connectivity of water bodies. The use of satellite-based geodetic observations to understand changes in water availability, distribution, and movement can be termed "Hydrogeodesy" (Wdowinski & Eriksson, 2009). The term is the combination of Geodesy—which studies Earth's size, shape, orientation, gravitational field, and the variations of these quantities over time—and Hydrology, which studies the occurrence, distribution, fluxes, movement, and properties of water on Earth. Although the term Hydrogeodesy has been used to highlight the potential of specific geodetic technologies to study water resources (e.g., White et al., 2022), it scopes a wider range of technologies.

The main technologies related to Hydrogeodesy include (a) Nadir-looking Altimetry (hereafter "Altimetry"), (b) InSAR, (c) Mass Gravimetry (hereafter "Gravimetry"), and (d) GNSS (Figure 1). Combining the principles behind these techniques has led to technical advances in the study of water from space, as embodied in the recently launched Surface Water and Ocean Topography (SWOT) satellite (L.-L. Fu et al., 2024), which combines both nadir-looking Altimetry and a wide-swath Ka-band InSAR.

Comprehensive scientific reviews of these technologies already exist in the literature, highlighting each technology's limitations, requirements, and applications with respect to tracking water resources (e.g., Adams et al., 2022; Chawla et al., 2020; Fassoni-Andrade et al., 2021; J. Lee, 2017; H. Lee et al., 2020; Papa & Frappart, 2021; White et al., 2022). However, (a) how the use of these technologies has recently evolved, and (b) what their role within current water-related science and water management is, are questions that, to our knowledge, remain overlooked and, thus, are the focus of this review.

This study addresses two main research questions: (a) How has the field of Hydrogeodesy developed throughout the last three decades? and (b) How can Hydrogeodesy contribute to addressing the goals of key hydrological and sustainability science frameworks and water management? To answer the first question, we introduce the four main technologies of Hydrogeodesy and study the coevolution of their application for water resources with a comprehensive meta-analysis covering more than 3000 articles. The meta-analysis evaluates the use of these hydrogeodetic technologies and identifies their trends of use, combinations, main applications, and the water resources of interest for their usage. For the second, we conduct an expert knowledge elicitation on the potential of Hydrogeodesy to address key water-related and sustainability science questions, including the 23 Unsolved Problems of the Hydrological Community (Blöschl et al., 2019) and the Planetary Boundaries Framework for guidance towards a safe operating space for humanity (Rockström et al., 2009). Finally, we discuss how the potential can be maximized by combining different technologies and even by addressing the challenges of teaching and learning hydrogeodesy.




| | Altimetry | InSAR: Repeat pass | InSAR: Single pass (SWOT) | Gravimetry | GNSS: GNSS | GNSS: GNSS-IR | GNSS: GNSS-R |
|---|---|---|---|---|---|---|---|
| **Hydrologic parameter** | Surface water level | Surface water level and water storage change | Surface water level | Water storage change | Water storage change | Surface water level change | Surface elevation, soil moisture |
| **Measuring principle** | 2-way travel time of radar/laser | Difference in 2-way radar travel time between multiple acquisitions | Difference in 2-way radar travel time between simultaneous acquisitions | Precise orbit determination | Correlation of satellite and receiver signals | Difference in signal-to-noise ratio from 2 GNSS signal paths | Reflected GNSS's signal travel time and backscatter |
| **Temporal, spatial Resolution** | ~10- 35 days, 50-300 m (along-track) | ≥6 days, 10-100 m | ≤21 days, 95% of all water bodies | monthly, >300 km) | Daily, Point measurements | Seconds, 100m-100km | Seconds, 100m-100km |

**Figure 1.** Illustration of the various technologies of Hydrogeodesy and their applications. The table includes the hydrological parameters most commonly measured in the context of Hydrogeodesy, the principle behind such measurement, and the usual temporal and spatial resolution. Icons are under the Creative Commons License and used from https://uxwing.com.

## 2. Hydrogeodesy in a Nutshell

By using geodetic methods to measure or infer hydrological quantities and their changes over time, Hydrogeodesy supports hydrological monitoring, management, and research via measurements that standard hydrological observations cannot obtain. While hydrological observations are usually direct measurements of hydrological variables collected on-site or from space, hydrogeodetic observations are obtained indirectly from geodetic data. These data are then translated to hydrological quantities, such as TWS, snow depth, and surface water level (Figure 1) via translating concepts or geophysical models. The main advantages of spaceborne hydrogeodetic observations are their wide spatial coverage, low costs to the end user, and relatively high spatial and temporal resolution, which enable comparison between multiple freshwater bodies across regions. For example, InSAR observations can achieve a spatial resolution of 1–100 m, depending on acquisition parameters; GNSS-IR (interferometric reflectometry) integrates observations of soil moisture and snow depth over an area of roughly 100 $m^2$; and GNSS- and GRACE-inferred estimates of TWS do so over tens to hundreds of kilometers (e.g., the spatial resolution of GRACE is more than 150,000 $km^2$). The dimensions of an observed area vary depending on the measurement techniques, from 10 to 100 m, in the case of GNSS-IR, to thousands of kilometers in GRACE measurements (Figure 2). The main disadvantages include fairly short series of data as hydrogeodetic missions are relatively new (i.e., earliest 1978, Table 1), and the corresponding need to standardize data across the time span of different missions with the same technology, which can be challenging.

While satellite altimetry was initially designed for oceanography in the 1970s, it is now used also to monitor inland water and ice sheet surface elevation by measuring the range (distance inferred from a signal's travel time) between the satellite and continental water surfaces (Abdalla et al., 2021). Satellite altimeters measure surface

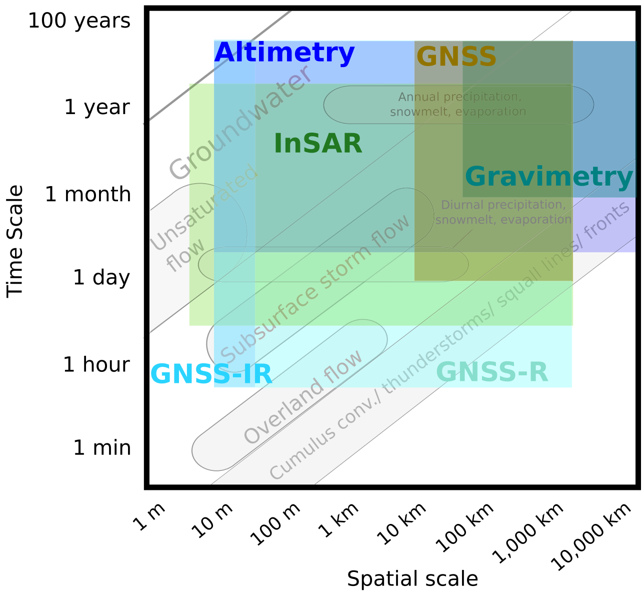



**Figure 2.** Temporal and spatial scales of hydrological processes (diagonal and horizontal ellipses with gray text) and the capacity of hydrogeodetic technologies (colored shaded rectangles and text) to observe such processes. The combination of missions and technologies in time could also lead to longer temporal scales—water components taken from Blöschl and Sivapalan (1995). The boxes for each hydrogeodetic technology encompass, in the lower limit, the spatial and temporal resolution provided by the technologies, and in the upper limit, the available record length obtained by combining several missions (Table 1). For example, regarding the temporal scale, altimetry generally provides information on water levels in a range of every ∼10–35 days (depending on the mission), but combining various missions can give lake water level data every three days in some cases (An et al., 2022). Integrating data on various altimetry missions can result in a data series of ∼30 years (e.g., Aminjafari, Brown, Mayamey, & Jaramillo, 2024). Regarding the spatial resolution, altimetry synthesizes spatial information from 50 to 200 m for a water level data point. When several altimetric missions are combined, maps of water level for an entire basin, such as the Amazon (Birkett et al., 2002; Fassoni-Andrade et al., 2021) or the Congo (Kitambo et al., 2022) can be obtained. Large-swath altimetry (Surface Water and Ocean Topography) now offers a quasi-global coverage of rivers, wetlands, and lakes with a resolution of ∼100 m (L.-L. Fu et al., 2024).

heights by considering the two-way travel time of radar or laser pulses between the satellite and Earth and applying specific corrections (Cretaux et al., 2017; Cretaux et al., 2023). Altimetry has been used to track water levels in rivers and large lakes (Crétaux et al., 2011, 2016; Yao et al., 2023), reservoirs (Birkett et al., 2011; Y. Li et al., 2023; Schöne et al., 2018), wetlands (Enguehard et al., 2023; J.-W. Kim et al., 2009; Kitambo et al., 2022), and increasingly used over smaller lakes (Brasseur et al., 2022; Cooley et al., 2021; Luo et al., 2022). Such measurements are used to calibrate (Sun et al., 2012; Zhong et al., 2020), validate (Finsen et al., 2014; Velpuri et al., 2012) or parametrize hydrological (Durand et al., 2008; Emery et al., 2020; Michailovsky et al., 2013; Paiva et al., 2013) and hydraulic models (Coppo Frias et al., 2023), to estimate stage-discharge relationships in rivers (Papa et al., 2012; Paris et al., 2016; Tourian et al., 2013) or to reference water level stations (Calmant et al., 2013). They can also be used to estimate the snow height, changes in ice thickness on the sea or the ground surface (Liang et al., 2021; Moholdt et al., 2010; Siles et al., 2022) or to estimate the bathymetry (Armon et al., 2020; Fassoni-Andrade et al., 2020) and local geoid variations of lakes (Jiang et al., 2019).

InSAR can form spatially continuous maps of surface elevation (i.e., digital elevation models; DEMs) and surface elevation changes with time (e.g., subsidence). To create a DEM, InSAR employs two or more radar acquisitions collected from slightly different viewing geometries—either from antennas separated by a boom (e.g., Farr et al., 2007) or by shifting the platform's orbit (e.g., Krieger et al., 2007). Changes in surface elevation, commonly called ground deformation in the geomorphology literature, can be retrieved with up to millimetric accuracy (Wdowinski et al., 2004). These changes have been related to changes in soil moisture (Mira et al., 2022; Ranjbar et al., 2021), groundwater changes (Levy et al., 2020; Wu et al., 2022), fluvial sediment (Higgins et al., 2014), water mass changes in lakes or reservoirs (Cavalié et al., 2007; Darvishi et al., 2021; Doin et al., 2015), snow topography (Guneriussen et al., 2001; Molan et al., 2018; Oveisgharan & Zebker, 2007), permafrost thaw (Chen et al., 2020; Short et al., 2014; C. Wang et al., 2018), and ice flow (Fatland & Lingle, 2002; Forster et al., 2003; Palmer et al., 2009). InSAR applications to surface hydrology have been mostly used to measure water level changes in wetlands due to the double bounce of the SAR sensor on vegetation and the surface of the water, which yields a coherent signal that can be translated to water level changes (e.g., Hong & Wdowinski, 2014; S.-W. Kim et al., 2013; Liao et al., 2020; Siles et al., 2020; C. Xie et al., 2013) but are now increasingly used to assess changes in water extent and hydrologic connectivity (Jaramillo et al., 2018; D. Liu et al., 2020; Oliver-Cabrera & Wdowinski, 2016; Palomino-Angel et al., 2019). Furthermore, although with limitations, its potential for inferring lake water levels is also gaining some attention (Palomino-Ángel et al., 2022); the SAR signal can also bounce on vegetation on the shores of the lakes or emerging vegetation on the water surface, also guaranteeing a coherent signal (Aminjafari, Brown, Mayamey, & Jaramillo, 2024).

Time-variable mass gravimetry, especially from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO), measures temporal variations of Earth's gravity field to estimate changes in water mass (Tapley et al., 2004). GRACE and GRACE-FO are identical satellites orbiting together and separated by ∼220 km along their track (Landerer et al., 2020; Tapley et al., 2004). The missions measure and track the changes in the distance between the satellites, which correlate to changes in the gravity field and, thus, mass anomalies (Swenson et al., 2003). Once the effects of the atmosphere and oceans are accounted for, the remaining signal is generally associated with monthly to interannual changes in TWS (Landerer & Swenson, 2012). Most of these changes are related to large-scale surface and subsurface water resource variations and can elucidate regional hydrological changes (Rodell & Reager, 2023). These changes may be climate-driven, such as the

**Table 1**
*Space Geodetic Technologies Relevant to Hydrology and the Study of Water Resources, as Modified and Updated After Wdowinski and Eriksson (2009)*

| Technology | Acronym/type | Agency | Time | Applications |
|---|---|---|---|---|
| *Global Navigation Satellite Systems (GNSS)* | | | | |
| GPS | Global Positioning System | DoD | 1980-present | Solid Earth, Hydrology, Glaciology, atmosphere, Ionosphere, Natural hazards |
| GLONASS | Global Positioning System | USSR/Russia | 1982-present | |
| Galileo | Global Positioning System | ESA | 2005-present | |
| Beidou-1/2/3 | Global Navigation Sat. System | CNSA | 2000-present | |
| IRNSS | Regional Navigation Sat. System | ISRO | 2013-present | |
| QZSS | Quasi-Zenith Satellite System | JAXA | 2018-present | |
| *Altimetry* | | | | |
| SeaSAT | Radar Altimetry | DoD | 1978 | Oceanography |
| GeoSAT | Radar Altimetry | DoD | 1985–1989 | Oceanography, Hydrology, Glaciology, Geoid determination |
| GeoSAT-Follow | Radar Altimetry | NASA | 1998–2008 | |
| ERS-1 | Radar Altimetry | ESA | 1991–1996 | |
| TOPEX/Poseidon | Radar Altimetry | NASA/CNES | 1992–2005 | |
| Jason-1/2/3 | Radar Altimetry | NASA/CNES | 2002-present | |
| ERS-2 (RA-1) | Radar Altimetry | ESA | 1995–2011 | |
| ENVISAT (RA-2) | Radar Altimetry | ESA | 2002–2012 | |
| ICESat | Laser Altimetry | NASA | 2003–2009 | |
| ICESat-2 | Laser Altimetry | NASA | 2018-present | |
| CryoSAT-2 | SAR/Interfer. Radar Altimeter | ESA | 2010-present | |
| Sentinel-3 | SAR Altimetry | ESA | 2016-present | |
| SWOT | Radar interferometer/Altimeter | NASA/CNES | 2022-present | |
| Sentinel-6MF | Radar Altimetry | ESA/NASA/CNES | 2020-present | |
| SARAL/AltiKa | Radar Altimetry | CNES/ISRO | 2013-present | |
| GEDI | Laser Altimetry | NASA | 2018-present | |
| *(InSAR) Interferometric Synthetic Aperture Radar* | | | | |
| SeaSAT | L-band, HH polarization (pol) | DoD | 1978 | Oceanography |
| ERS-1 | C-band, VV pol | ESA | 1991–1996 | Solid Earth, Hydrology, Glaciology, Oceanography, Geotechnical, Natural hazards |
| ERS-2 (SAR) | C-band, VV pol | ESA | 1996–2012 | |
| JERS-1 | L-band, HH pol | JAXA | 1992–1998 | |
| RADARSAT-1 | C-band, HH pol | CSA | 1995–2013 | |
| ENVISAT (ASAR) | C-band, VV + VH, HH + HV pol | ESA | 2002–2012 | |
| ALOS (PALSAR) | L-band, quad-pol | JAXA | 2006–2011 | |
| RADARSAT-2 | C-band, quad-pol | CSA | 2007-present | |
| TerraSAR-X | X-band, quad-pol | DLR | 2007-present | |
| TanDEM-X | X-band, quad-pol | DLR | 2010-present | |
| COSMO-SkyMed | X-band, quad-pol | ASI | 2007-present | |
| Risat-1 | C-band, quad-pol | ISRO | 2012–2017 | |
| KOMPSAT-5 | X-band, quad-pol | KARI | 2013-present | |
| ALOS-2 | L-band, quad-pol | JAXA | 2014-present | |
| Sentinel-1 A | C-band, dual-pol | ESA | 2014-present | |
| Sentinel 1-B | C-band, dual-pol | ESA | 2016-present | |
| PAZ | X-band, quad-pol | PNOTS | 2018-present | |

**Table 1**
*Continued*

| Technology | Acronym/type | Agency | Time | Applications |
|---|---|---|---|---|
| SAOCOM-1 | L-band, quad-pol | CONAE | 2018-present | |
| Radarsat Constell. | C-band, dual-pol | CSA | 2019-present | |
| NISAR | L-band | NASA | Expected 2024 | |
| *Gravimetry* | | | | |
| LAGEOS-1/2 | Laser Geodynamics Satellites | NASA | 1976-present | Geoid determination, Oceanography, Hydrology, Glaciology |
| Ajisai | Experimental Geodetic Satellite | JAXA | 1986-present | |
| CHAMP | Challenging Minisat. Payload | DLR | 2000–2010 | |
| GRACE | The Gravity Recovery and | NASA/DLR | 2002–2017 | |
| GRACE-FO | Climate Experiment | NASA/DLR | 2018-present | |
| GOCE | Gravity field and steady-state Ocean Circulation Explorer | ESA | 2009–2013 | |

*Note.* The names of the missions were used to perform the meta-analysis of articles in Hydrogeodesy (see Methods). Time starts with the launch of the mission.

melting of the ice caps (Velicogna et al., 2020) or long-term droughts (Tapley et al., 2019), or man-made, such as groundwater withdrawal (Adams et al., 2022; Richey et al., 2015; Rodell et al., 2018; W. Wang et al., 2021). Although satellite gravity's low spatiotemporal resolution makes it difficult for usage in smaller aquifers (Melati et al., 2019), and there are still some discrepancies among gravimetric products (Jing et al., 2019), gravity-determined water mass changes are commonly combined with hydrological modeling to obtain water mass variations at the higher resolution needed for water management applications (B. Li et al., 2019; Zaitchik et al., 2008).

Lastly, precise ground-based GNSS monitoring systems reside on the Earth's surface and are primarily used for measuring 3-D positions (e.g., East, North, and Up) and their changes. The positions are based on advanced modeling (orbits, clocks, and the atmosphere) and simultaneous observations from multiple satellites (Blewitt, 2007). Networks of GNSS stations can track changes at larger spatial scales, and different GNSS applications can even be used to track changes in soil and plant moisture content, snow, and ice (White et al., 2022). Hence, changes in the position of the ground or water surfaces obtained by GNSS can elucidate the effect of changes in sea level, glaciers, and ice caps (e.g., Hugonnet et al., 2021; Khan et al., 2022), snow depth, groundwater storage, or storage in rivers, lakes, and soils. Specifically, for hydrology, techniques have been created to measure crustal loading and deformation across a Global Positioning System (GPS) station network to infer a hydrologic load at the Earth's surface. Pioneering papers (Argus et al., 2014, 2017; Borsa, Agnew, & Cayan, 2014; Borsa, Moholdt, et al., 2014; Y. Fu et al., 2015) introduced the viability of this approach to detect long-period signals in total water storage for hydrologic science.

Reflected GNSS signals can be observed in space and potentially be considered to fall in the category of hydrogeodetic techniques after applying the loosest constraints on the definition and accepting that other reflectometric techniques, such as radar and radiometry, can be included by that standard. The technology known as GNSS-R uses scattered signals reflected from the surface captured by receivers on low Earth-orbiting satellites (Cardellach & Rius, 2008). The receiver processes information about the time delay, phase shift, amplitude, and polarization of the reflected signals to infer the properties and elevation of the reflected surface. For instance, spaceborne acquisitions from CYGNSS have been used to retrieve soil moisture variations (Chew & Small, 2018; Eroglu et al., 2019) and for flood mapping and monitoring inundation extent (Chew et al., 2023; Zeiger et al., 2023). Another hydrogeodetic technique based on GNSS signals is called GNSS interferometric reflectometry (GNSS-IR). It has been used to measure soil moisture (Larson et al., 2008), permafrost melt (L. Liu & Larson, 2018), tides (Larson et al., 2013; Löfgren et al., 2014), lake and river levels (Holden & Larson, 2021; Zeiger et al., 2021), freeboard ice (S. Xie, 2022), and snow/ice surfaces (Larson & Nievinski, 2013; Siegfried et al., 2017). These environmental products use the interference between the direct and reflected GNSS signals to calculate the height difference between the GNSS antenna and the reflecting surface.

## 3. Materials and Methods

We searched for English-language articles on hydrogeodesy published on the Clarivate Web of Science through November 2023 (https://www.webofscience.com/wos/woscc/basic-search). The query to retrieve these scientific articles focused on the names of the hydrogeodetic technologies introduced in Figure 1, that is, Gravimetry, Altimetry, GNSS, and InSAR. Optical and SAR satellite imagery have also been utilized in different Hydrogeodesy-related applications (Elmi et al., 2016). However, they generally encompass a broad spectrum of Earth system monitoring, and for water resources, their utility is focused on the spatial depiction of surface waters. Given that most applications of these two geodetic techniques fall outside the scope of Hydrogeodesy, we have excluded them from the query. Likewise, hydrogeodetic technologies can be used in either space-borne or air-borne missions. Air-borne hydrogeodetic missions, such as AirSWOT (Altenau et al., 2019; Atimetric and InSAR) or UAVSAR (Jones et al., 2016; enabling InSAR), are important for experimental purposes and focused assessments but have shorter periods of operation and smaller spatial extents of application, resulting in limited data availability. Space-borne missions usually have a longer life span and a larger spatial extent of application than air-borne missions, leading to more studies and corresponding publications. Hence, we decided to limit the meta-analysis to space-borne missions.

As these technologies are often referred to in the context of specific sensors, missions, or constellations (e.g., ICESat for Altimetry, GRACE for Gravimetry, or GPS for GNSS), in our preliminary search, we also included the names of the most common hydrogeodetic sensors (See Table 1). We used the root of the words rather than the complete word to avoid omitting relevant manuscripts. For instance, instead of searching for the word "Altimetry," we searched for "Altimet," which is the root of the words "Altimeter," "Altimetric" and "Altimetry." We initially searched for any of these words in the abstract or keywords, as sometimes these technologies are not mentioned in the article's title. However, due to the large number of false positive articles (over 10,000), and since many of the studies using these technologies are not necessarily focused on water resources, we decided to also look for specific words pertaining to water resources. Hence, the initial general query looked for the simultaneous occurrence of (at least) one word associated with Hydrogeodesy in the abstract and (at least) one word associated with water resources in the title or the keywords. This combination removed most unrelated articles, for instance, those using GNSS for positioning rather than to assess properties or changes in water resources or those using of hydrogeodetic techniques for seismological, volcanic, and geological studies. We decided to include studies related to glaciology to compare the use of hydrogeodesy on ice surfaces with that of water in liquid form. We looked in total for 24 words related to water resources and grouped them as follows: "lake," "lagoon," and "reservoir" we tagged as Lake; "wetland," "floodplain," "estuary" as Wetland; "watershed," "catchment," "hydrological basin" as Watershed; "river," "discharge," "stream" as River; "groundwater," "ground water," "aquifer" as Groundwater; "ice," "glacier," "Antarctic," "Arctic" as Ice; "total water storage," "terrestrial water storage" as Total Water; "snow" as Snow; "soil moisture," "soil humidity" as Soil Moisture; and "permafrost," "active layer" as Permafrost. The initial query yielded 3,279 articles.

We sorted the articles into five technology categories based on the hydrogeodetic words found (i.e., Altimetry, InSAR, Gravity, GNSS, Combined). The last category "Combined" was used when two or more of the four hydrogeodetic technologies were mentioned in the abstract. In addition, we manually classified missions carrying both an altimeter and a SAR sensor (e.g., Envisat, ERS-2) and discarded studies using just SAR backscatter data rather than interferometry (i.e., InSAR). It is worth noting that studies using SAR or optical data not involving altimetry and interferometry (e.g., SAR studies to classify wetlands or optical studies determining soil moisture, among others) were deliberately not accounted for in the list of articles. This deliberate scope refinement allows for a more targeted examination of articles that specifically integrate altimetry and interferometry. Articles that appeared in the search dealing specifically with landslides, earthquakes, and volcanoes or using primarily techniques such as drones, airborne missions (e.g., Uninhabited Aerial Vehicle SAR (UAVSAR)), unmanned aerial systems or Ground Penetrating Radar were also manually removed from the list.

Since we considered it essential to know the scientific audiences targeted by the articles' authors, and especially the split between water resources and remote sensing, we determined how articles were distributed between journals related to Water Resources, Glaciology, Remote Sensing, and Multidisciplinary studies. We used categories from the Science Citation Index Expanded (SCIE; https://mjl.clarivate.com/collection-list-downloads) of the Web of Science Core Collection based on the journal title. This categorization is based on the type of journal publishing the article. If the journal is classified under "Water Resources" among other categories, we tagged the journal as "Water Resources." We did likewise for the category "Remote Sensing," also including all journals focusing on Geodesy. The "Multidisciplinary" category includes all journal categories with the words "multidisciplinary," "geoscience" or "engineering." To make a broad differentiation between glaciology and studies of water resources, that is, hydrology, we generated an additional category called "Glaciology." When several of these four categories were listed for a journal, we chose the category highest on the prioritized order: Water Resources, Glaciology, Remote Sensing, and Multidisciplinary. These categories also helped remove articles from the initial list that were not targeting any of these categories based on the journals where they are published.

We also used meta-analysis of these studies to understand the authors' scientific motivations and their use cases for hydrogeodetic technologies. Each study's objective was categorized manually, as automatization proved difficult. We randomly selected approximately 120 articles for each of the five technology categories (∼20% of the number of articles in the initial query) and manually inspected the wording in the abstracts. We searched for the main objective in the article's abstract, specifically in the sentences describing the study's main goal, aim, objective, research question, or hypothesis. If this was not explicitly mentioned in the abstract, we performed an overall assessment based on the metadata available. The main categories selected to categorize the objective of the study (and the way we refer to them in parenthesis) were the following:

- *Technical advances (Technical)*—Studies seeking to advance coding, algorithms, procedures (such as generating digital elevation models), schemes, and theory of geodetic tools with applications focused on water resources. We also include studies comparing results from different missions or technologies, and studies reporting on the development of public access data sets.
- *Determination of key hydrological variables (Hydrovariable)*—Studies aiming to determine a hydrological parameter or variable, such as water level, water table, water storage, soil moisture, ice elevation, and their temporal change, without pursuing a case application (to separate this category from the effects of water management, for example) or attempting to understand the hydrological or geomorphological system. In addition, it includes studies determining the accuracy, precision, performance, and potential of a specific mission or technology to track changes in the hydrological parameter or variable.
- *Model development (Modeling)*—Studies using hydrogeodetic technologies to assimilate into, parametrize, calibrate, or validate a hydrological, hydraulic, or hydrogeological model.
- *Effects of water management (Management)*—Studies focusing on the geomorphological effects of irrigation, water impoundment for regulation, river diversion, groundwater abstraction, or water consumption. Also, studies focus on impacts on channels, dams, pipelines, aqueducts, and urban infrastructure regarding ground subsidence and uplift.
- *Geomorphological and surface water processes (Processes)*—Studies of processes not related to direct human activities but to natural variability, aiming to understand a hydro or geomorphological process beyond the sole calculation of the typical hydrological variables estimated by the technologies. Such processes include glacier growth and mass balance, melting and movement, permafrost thaw, iceberg movement, ground seepage, and infiltration. Regarding water in liquid form, studies focusing on sheet flow, hydroperiod, hydrological connectivity, seasonality of water availability, estimating discharge, or quantifying components by water mass balance. Studies focusing on landslides with no relationship to water resources were excluded from the selection.

It is worth noting that although an article may address several of these aspects, we selected the most prominent and relevant objective based on its importance, as stated in the abstract. For instance, studies implementing a novel algorithm to quantify a hydrologic variable would fit both the "technical" and "hydro variable" categories. It was then our task to assign the objective to select the one weighing more in the overall outcome of the article and, if needed, refer to the general manuscript beyond the abstract. These special cases also, once flagged, if needed, would receive a second opinion from another researcher to make a final decision.

To assess how Hydrogeodesy can contribute to significant advancements in hydrological science, we focused on the 23 Unsolved Problems in Hydrology (UPH) proposed by Blöschl et al. (2019). We asked all coauthors of this study to rate how each of the four technologies could benefit the research towards each UPH, taking advantage of

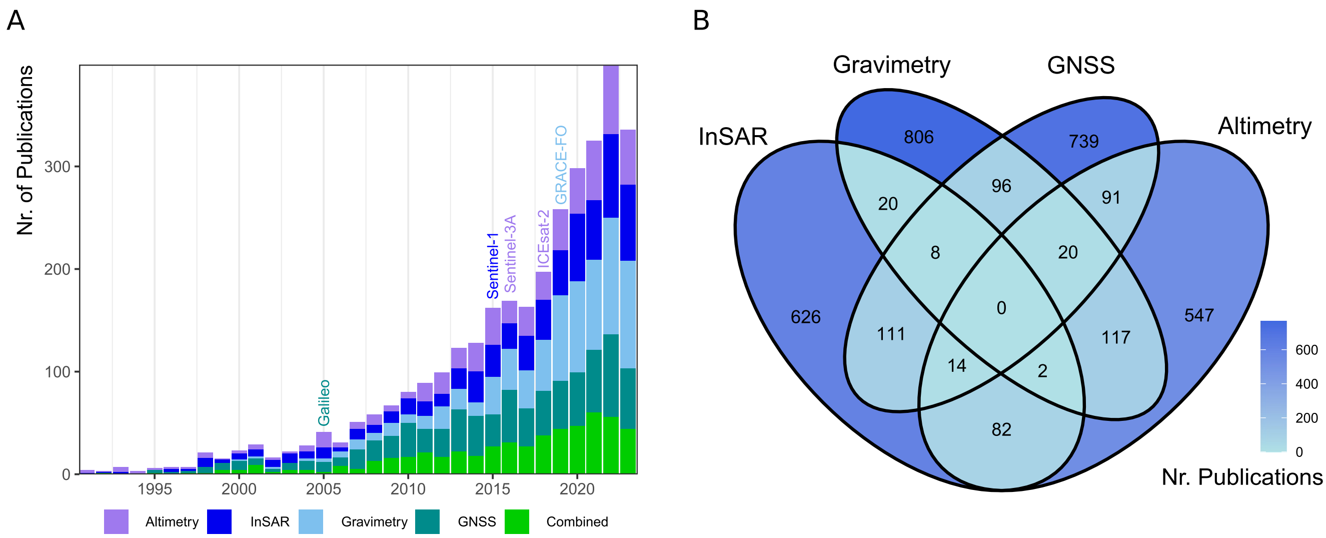



**Figure 3.** Development of Hydrogeodesy (a) Annual number of scientific peer-reviewed publications in the Web of Science in the field of Hydrogeodesy ($n$ = 3278), differentiated by technology: Gravimetry (806), Global Navigation Satellite Systems (739), Interferometric Synthetic Aperture Radar (626), Altimetry (547), and their combination (561). Publications from December 2023 are excluded due to the time of writing. (b) Venn diagram showing the total number of publications up to November 2023 for each technology and for publications that combine more than one technology.

the various areas of expertise among coauthors concerning the four technologies and a wide range of related space missions. The rating ranged from scores 1 (low) to 5 (high) for the potential of Hydrogeodesy to contribute to resolving each UPH. Depending on their areas of expertise, the coauthors also elucidated the potential of hydrogeodetic technologies to help advance the science to help solve the 23 UPH and the limitations that would need to be overcome to do so. Finally, we discussed the potential of Hydrogeodesy in relation to global sustainability frameworks, with special emphasis on the Planetary Boundaries framework that aims to delimit a biophysically safe operating space for humanity (Rockström et al., 2009).

## 4. Results and Discussion

### 4.1. An Increasing Trend of Publications Involving Hydrogeodetic Technologies

The number of publications using hydrogeodetic technologies to understand changes in water resources has been increasing at an accelerating pace, with 3278 articles published from January 1990 to November 2023 in peer-reviewed journals indexed in the Web of Science (Figure 3a). There are more than 800 articles involving Gravimetry (806), followed by studies using GNSS (739), InSAR (626), Altimetry (547), and their combination (561). This acceleration coincides with the increasing availability of hydrogeodetic missions and sensors in orbit and the extended period available for observations when several missions are combined. The four technologies analyzed here show a substantial increase in published articles following the launch of specific space missions for each technology (Table 1). For instance, the launch of the Sentinel-1 satellite constellation in 2014 by the European Space Agency (ESA) substantially increased the annual publications of InSAR studies using C-band SAR data to perform ground deformation analysis related to groundwater changes (Figure 3a). Its 6-day revisit time (for the A and B satellites together) and its global coverage now allow a high temporal resolution of the ground surface changes worldwide. Likewise, the launch of the Sentinel-3A radar altimeter in 2016 and the ICESat-2 laser altimeter in 2018 by the National Aeronautics and Space Administration (NASA) can also explain the gain in publications using Altimetry to determine water levels in lakes and ice changes in glaciers. Additionally, (the launches of GRACE-FO Gravimetry) and Galileo (GNSS) have been followed by an increasing number of publications per year.

Moreover, the number of studies combining two or more technologies has steadily increased. Around 16% ($n$ = 561) of all publications in Hydrogeodesy used two or more technologies, with the use of Altimetry in combination with Gravimetry ($n$ = 117) and GNSS with InSAR ($n$ = 111) the most frequent combinations among publications (Figure 3b). A smaller number of studies combine up to three technologies ($n$ = 44), such as T. Yuan

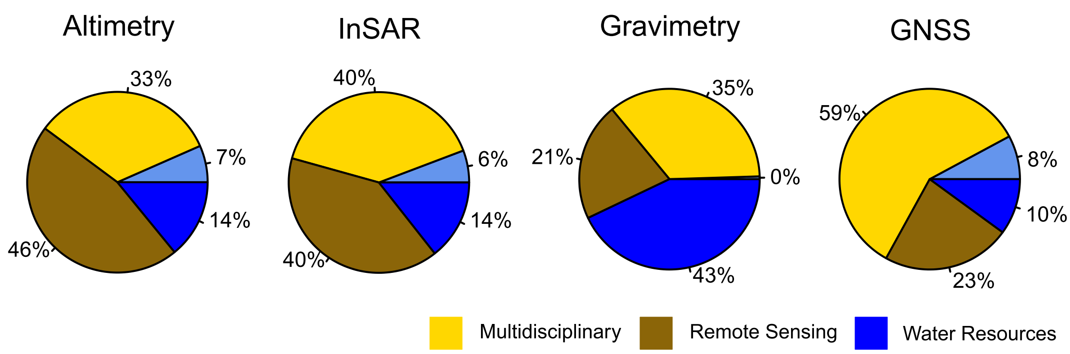



**Figure 4.** Percentage of publications featuring each of the four main hydrogeodetic technologies or their combination grouped by "Multidisciplinary," "Remote Sensing," "Water Resources," and "Glaciology" categories, according to the Science Citation Index Expanded (SCIE) of the Web of Science Core Collection.

et al. (2017), who estimated absolute water storage in the Congo River floodplains by computing water depths and storage volumes by integrating InSAR and Altimetry. They later compared it with large-scale estimates of total water storage as obtained from gravimetric measurements of the GRACE satellite.

### 4.2. Hydrogeodesy Is Published Mostly in Remote Sensing and Multidisciplinary Journals

Regarding the journals hosting these publications, 33%–59% of articles are published in Multidisciplinary journals, depending on the technology, and thus are not necessarily solely directed to the Hydrological or Remote Sensing audiences (Figure 4). This is evident across all four technologies. It is worth noting that Gravimetry is the technology that has permeated the hydrological community the most, with 43% of all publications in water resource-related journals, while Altimetry, InSAR and GNSS studies are more prevalent in journals of Remote Sensing and Multidisciplinary categories (only 18%–21% in water-related journals). Finally, water resources journals have a larger share of publications than Glaciology journals across all four technologies. The wider spread of Gravimetric studies in water-resource journals may stem from the fact that gravimetric missions (GRACE/GRACE-FO) have hydrology as their primary application, whereas Altimetry, GNSS and InSAR have a broader range of applications across other disciplines. It may also be related to the long-standing public availability and accessibility of GRACE and GRACE-FO data, which reduces the skill and knowledge barriers required to process and generate the data. For instance, NASA has open and processed gravimetric data for the GRACE/GRACE-FO satellites, provided on 0.5-degree global grids and updated monthly (e.g., https://grace.jpl.nasa.gov/data/get-data/). The user's processing requirements are low. Monthly gridded data sets for land water storage are already available, reducing data processing costs for the user and making them ready for hydrologic analysis.

Yet, the small share of altimetric studies published in water-related journals (21%) is not explained by limited data availability and accessibility, as several altimetric data sets have global coverage and are available at no cost to end users. The first such data set was River and Lake launched by ESA https://altimetry.esa.int/riverlake/shared/main.html. Now, there are several altimetric databases that track many lakes worldwide, such as the Global Reservoirs and Lakes Monitor (G-REALM; https://blueice.gsfc.nasa.gov/gwm/lake/Index) via the NASA and USDA/FAS Water Measurements web portal; the Hydroweb next (https://hydroweb.next.theia-land.fr/) of CNES and LEGOS; DAHITI (https://dahiti.dgfi.tum.de/en/) from the German Geodetic Research Institute at the Technical University of Munich (DGFI-TUM) delivering rivers and lake level data for 10,676 targets; and HydroSat (http://hydrosat.gis.uni-stuttgart.de) by the Institute of Geodesy, University of Stuttgart, featuring time series of water levels in the rivers and lakes worldwide through almost 25,000 virtual stations.

GNSS and InSAR studies also have relatively low penetration in water-related journals (18%), in comparison to journals more related to Geodesy (under the Remote Sensing category; Figure 4). Regarding InSAR (20%), although data sets of ground deformation and water level changes are becoming more open and accessible at the regional level, the hydrogeodetic community still needs a centralized global data set of InSAR products to study changes in water levels in lakes, reservoirs, and wetlands (Wdowinski & Hong, 2015). This is difficult due to the intense processing and the specialized (and sometimes costly) software required for interferometry. Still, the

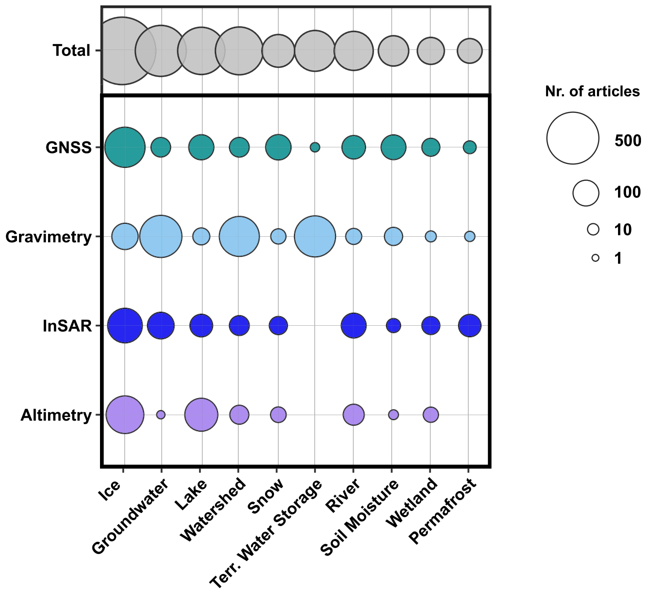



**Figure 5.** Number of publications grouped by type of water resource investigated (see Methods for grouping and assigning of water resource names).

availability of InSAR processing tools for hydrologists is increasing, with the spread of open-source software and services such as Hyp3 (Hogenson et al., 2016) and OpenSARLab at the Alaska Satellite Facility enabling cloud-based interferometric processing (Hogenson et al., 2021), reducing both local processing costs and time. Additionally, the interferometric ground deformation analysis results for the entire European continent since 2015 are openly accessible through online services such as the Copernicus European Ground Motion Service (Crosetto et al., 2021), and NASA plans to publish an interferogram of all imaged areas by the NISAR mission as a standard and freely available data product.

### 4.3. Ice, Lakes, and Groundwater Are Widely Investigated With Hydrogeodesy

The four hydrogeodetic technologies target different surface or below-ground water resources. Glaciers and lakes are the most studied water resources (Figure 5; Ice, 32%), especially by GNSS and Altimetric studies. Ice sheets/caps and glaciers have been monitored mainly by Altimetry since the 1980s, with the first studies focusing on the Antarctic and Greenland ice sheets and sea ice in the Baltic Sea (Scott et al., 1994). Many altimetric missions track ice topography, determine ice surface elevations, map the boundaries of ice shelves, and identify icebergs and ice-surface features (Mcintyre, 1991).

In ice-free regions, the water-related words most targeted by Hydrogeodesy are lakes (15%) and watersheds (15%). Regarding the first, although radar altimeters were designed to measure the global sea level, altimetric sensors now track water level changes in numerous lakes, reservoirs, and ponds worldwide due to their improved spatial coverage and along-track resolution. While most applications focused on large water bodies only (Birkett et al., 2011; Crétaux et al., 2011, 2016; Y. Li et al., 2023; Schöne et al., 2018; Yao et al., 2023), advances in retracking algorithms minimize the impact of non-water reflections and allow now to track smaller ones of only a few hectares, under the condition that the satellite track covers the water bodies (Boy et al., 2022; Egido & Smith, 2017). Laser altimeters can be applied to sporadically monitor water levels of small water bodies (Cooley et al., 2021; Sulistioadi et al., 2015). Additionally, they can be combined with optical or radar imagery to increase temporal resolution and reconstruct water levels over a longer period (Yao et al., 2024), which can also produce ground height products for measuring the banks of the lakes (Arsen et al., 2014).

Regarding watersheds, the focus of hydrogeodetic studies at these larger spatial scales is mostly related to gravimetric studies aiming to study TWS changes. This is because changes in groundwater storage are determined by time-variable gravity data from GRACE (10% of all studies) after isolating the groundwater storage contributions within the TWS observations. The groundwater storage change is typically considered the residual after all non-groundwater contributions are subtracted from the GRACE TWS in a process referred to as decomposition. This requires model output or observations of soil moisture, snow water equivalent, surface water storage, and canopy water. It also requires a good conceptualization of the dominant water stores and all potential non-water mass changes across a study area (i.e., glacial isostatic adjustment, large earthquakes, mining exports). For typical large-scale applications in which diffuse water storage contributors (soil moisture) dominate the signal or where signal leakages in or out of the study area can be important, the challenges of separating contributors of TWS and the inherent low resolution of the GRACE observations (~300 km, Luthcke et al., 2013) forces hydrologists to synthesize data on water storage changes at the watershed scale.

For regional scale applications, Gravimetry can also be used to distinguish temporal variations of TWS arising from focused, spatially discrete masses such as lakes (e.g., Urmia Lake; Saemian et al., 2020), glaciers (Castellazzi et al., 2019) and large impounded reservoirs such as the Grand Ethiopian Renaissance Dam (Kansara et al., 2021) or the Three Gorges Dam in China (Huang et al., 2015). Such approaches are feasible if the spatial distribution of the expected mass change can be inferred via auxiliary data (Longuevergne et al., 2013). Furthermore, downscaling GRACE data can relate mass changes to human groundwater use and consumption (Argus et al., 2022; Castle et al., 2014; Famiglietti et al., 2011; Rodell et al., 2007; Rodell & Famiglietti, 2002;

Scanlon et al., 2012), which represents one of many interdisciplinary applications of Gravimetry at the interface of water science and sustainability.

Earth surface deformation sensors like InSAR and GNSS follow Gravimetry as the technology most used to track groundwater changes. Deformation data can be used to track aquifer mechanical responses due to changes in groundwater pressure, causing poroelastic compaction or deflation of sub-surface layers, which is experienced as changes in ground elevation at the surface. If the deformation is elastic, once the aquifers are recharged, water content, pressure, and the ground will again rise (Adams et al., 2022). While GNSS and InSAR sensors are sensitive to poroelastic deformation signals, especially high-resolution deformation maps of InSAR are useful to resolve aquifer-related deformation accurately and have served as a proxy of groundwater storage change (4%; e.g., Motagh et al., 2008). Such studies can relate ground and infrastructure subsidence to human groundwater withdrawal. For example, poroelastic deformation in aquifers has been used to determine water use/withdrawal rates in the San Joaquin Valley in California and Mexico City using InSAR data (Khorrami et al., 2023; Levy et al., 2020; Manuel Pardo et al., 2013; Ojha et al., 2018; Smith et al., 2017), and to a lesser extent using GNSS observations. However, in most regions worldwide, GNSS data do not provide sufficient spatial coverage for the deformation signal to resolve water use/withdrawal rates accurately. High-resolution deformation data can be combined with groundwater level data to calculate storage coefficients and groundwater heads in compacting aquifer layers (e.g., Chen et al., 2016). The major limitation of using deformation data for groundwater studies is the intricate relationship between surface deformation and water volume change, particularly immediately after drought when residual or delayed compaction coincides with groundwater pressure increase (Lees et al., 2022; Murray & Lohman, 2018; Shirzaei et al., 2019). In addition, most groundwater studies applying InSAR deformation data focus on urban or agricultural areas with features such as infrastructure that enable a coherent signal. This also challenges large-scale applications of high-resolution InSAR data, which inherently cover a wide range of land covers and spatially variable InSAR noise levels (Castellazzi et al., 2021; Du et al., 2023). However, recent improvements in InSAR processing (Ao et al., 2024; Castellazzi & Schmid, 2021; Ohenhen et al., 2024; Ojha et al., 2018; Zebker & Chen, 2023) and machine learning have been proven useful to address this challenge (Naghibi et al., 2022). Another frequent challenge in groundwater studies applying deformation data is the separation of the groundwater-related signal from other, spatially coinciding sources, such as stacked aquifers and clayey soils occurring in large alluvial fans (Castellazzi et al., 2021), tectonic deformation, sediment compaction, and elastic loading (Kang & Knight, 2023; Larochelle et al., 2022).

Regional TWS changes, including groundwater storage, can be inferred from the elastic deformation response of the Earth's crust to surface and near-surface water loads (Figure 5; 3% for groundwater and TWS). Green's functions for crustal load displacements (e.g., Farrell, 1972) are applied to invert for gridded mass changes that best explain the observed deformation. So far, most loading studies have relied on GNSS observations because the amplitude of the loading signal is relatively small compared to other deformation processes, that is, a few mm up to 1 cm for annual deformation (Argus et al., 2014), and the signal includes large spatial wavelengths that were difficult to resolve with InSAR until recently. Hence, this approach is mostly applied in locations with continuously and densely operating GNSS networks, as the temporal and spatial resolution of resulting TWS change maps depends on the sampling rate and spacing of the GNSS stations. Up to ∼50 km spatial resolution has been achieved in a few densely monitored regions, like the US west coast (Borsa, Agnew, & Cayan, 2014; Borsa, Moholdt, et al., 2014; Carlson et al., 2022). The temporal resolution of this approach is limited by short-period non-loading signals and other noise in the deformation data, but it is at least 7 days for daily GNSS positions (e.g., Adusumilli et al., 2019). Terrestrial water storage changes estimated from GNSS include water cycling through the Himalayas (Y. Fu & Freymueller, 2012), seasonal water changes in the western USA (Argus et al., 2014; Y. Fu et al., 2015), multiannual cycles of drought and recovery (Adusumilli et al., 2019; Argus et al., 2017; Borsa, Agnew, & Cayan, 2014; Borsa, Moholdt, et al., 2014), and the impact of individual storms (Milliner et al., 2018). Recent progress in InSAR processing for yielding large-scale deformation maps in global reference frames that are combined and validated with GNSS observations can provide high-resolution maps of the loading response as recently achieved in Mexico City (Khorrami et al., 2023) and are promising for further applications of this approach in regions worldwide where GNSS networks are sparse or absent.

GNSS observations are also used to measure water levels of rivers and lakes and inundation dynamics (Holden & Larson, 2021; Zeiger et al., 2021), especially in the tropics. To retrieve soil moisture variations (6%) from ground-based receivers, GNSS-R, which consists of analyzing the GNSS signals reflected by the Earth's surface, is used increasingly. The launch of the first spaceborne GNSS-R missions, and the Cyclone Global Navigation Satellite

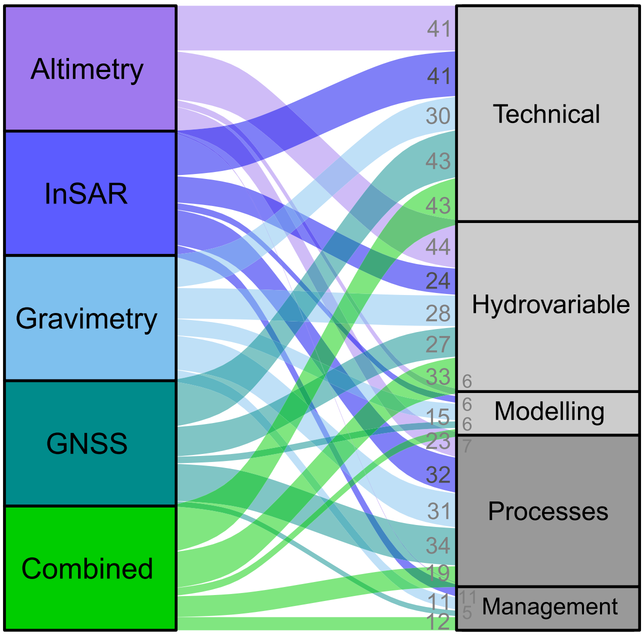



**Figure 6.** Sankey diagram of the main objective behind hydrogeodetic studies. The article objectives were tagged based on random samples of articles for each technology or their combination ($n = 120$). See Methods for a description of the categories of primary objectives. Gray numbers on the right represent the number of articles of each technology addressing a specific category of article objective. Light-gray boxes are the objectives of technical nature while the dark-gray boxes are those going beyond technical (into hydrological processes, water management and sustainability).

System (CYGNSS) (Ruf et al., 2016), have offered new opportunities to monitor surface soil moisture variations (Chew & Small, 2018).

### 4.4. Wetlands Are Understudied With Hydrogeodetic Technologies

Few hydrogeodetic studies focus on wetlands as compared to other water resources (Figure 5; ∼4%), despite the growing importance of these ecosystems for climate mitigation, biodiversity conservation, and sustainable development (Jaramillo et al., 2019; Thorslund et al., 2017). A possible explanation may be the challenge of measuring water levels in these ecosystems; the vegetation covering wetlands and peatlands limits certain technologies, and their inaccessibility limits the ground-truthing of the hydrogeodetic measurements. InSAR and GNSS are probably the best technologies for solving this issue (Zeiger et al., 2022). It is generally agreed that SAR and GNSS-R with a longer wavelength and lower frequency, such as L-band sensors, better penetrate vegetation canopy than the higher frequencies of C-band sensors (Freeman & Durden, 1998; Hess et al., 1990). These characteristics help distinguish water below vegetation and, thus, determine corresponding water level changes in wetlands. Drawbacks of InSAR for wetlands study include difficulties in obtaining a coherent radar signal and the fact that it can only resolve relative water levels in time and space (H. Lee et al., 2020). This change in time is "relative" to other points on the water surface, requiring Altimetry or in-situ observations to determine absolute water level changes. Nevertheless, the maps of water level change are useful due to non-uniform changes across wetlands from sheet flow, contributions from different river inflows and groundwater, and hydrological barriers of flow between water bodies (Gondwe et al., 2010; Jaramillo et al., 2018; D. Liu et al., 2020; Lu & Kwoun, 2008). In recent years, InSAR has been effectively used to study peatland evolution and carbon emissions. Hoyt et al. (2020) and Khodaei et al. (2023) have used InSAR to map peatland ground deformation in tropical and temperate regions, respectively, to calculate the contribution of peatlands to carbon emission/sink at both regional and local scales.

### 4.5. A Large Portion of Hydrogeodetic Studies Have a Technical Focus

In agreement with recent studies (Fassoni-Andrade et al., 2021; Topp et al., 2020), we find that a large fraction of Hydrogeodesy articles can be considered of a technical nature (71%), either aiming to improve methods/technologies (Figure 6, Technical category, 36%), to estimate a specific hydrological variable and its variation in time and space (Figure 6; Hydrovariable category, 28%), or as an aid for hydrological, geomorphological or hydraulic modeling (Figure 6; Modeling category, 7%). The first is the most recurrent type of objective of the studies, involving new algorithms, remote sensing methodologies, and statistical methods and refinements to improve the quality, precision, and accuracy of the data, decrease uncertainty, and remove the noise of the various signals of the sensors (e.g., Canisius et al., 2019; Seo et al., 2020; T. Wang et al., 2022; Y. Wang & Morton, 2022). Gravimetry studies have the smallest proportion of studies falling under this category.

Regarding the second category (Figure 6; Hydrovariable), many of the articles also aim to quantify the direct hydrological or geological variables that the technology can track (see Figure 1). The quantification of these variables is crucial for regions or water resources where it is important to understand regional and temporal patterns of change and to assess and track water availability. These regions include Greenland, Patagonia, West Antarctica and the Antarctic Peninsula, where ice-cap and glacier loss are accelerating; and California (United States), Northern India, the Middle East, Caspian and Aral Sea regions, and Eastern China, where drought and groundwater depletion are reducing water availability for human use (Rodell et al., 2018); or for instance, northwestern South America, where water availability is decreasing due to an increasing frequency of El Niño Southern Oscillation events (Bolanos et al., 2021).

Hydrogeodetic studies addressing hydrological problems beyond technical developments, such as those aiming to understand hydrological and geomorphological processes or attribute changes to human or climatic impacts, are less numerous (Figure 6; 29%, which is the sum of Processes (23%) and Management (6%)). Processes analyzed by hydrogeodetic techniques often relate more to the cryosphere than liquid water, involving ice-cap dynamics, changes in ice thickness, iceberg movement, or dynamics of river and lake ice. Indeed, satellite techniques such as InSAR and altimetry, along with auxiliary derived information from sources like climate models, have revealed notable changes in river/lake ice patterns (e.g., Kouraev et al., 2007; Siles & Leconte, 2023) and attributed to climate change. These impacts are also discernible in liquid water resources. Rodell et al. (2018) quantified freshwater mass trends observed by GRACE satellites and attributed them to natural interannual variability, unsustainable groundwater consumption, climate change, or combinations thereof. More recently, Yao et al. (2023) combined altimetry missions with satellite images, hydroclimate models, and field surveys to quantify and attribute global lake water storage trends. They found that more than water levels in half of the world's largest lakes have declined over the past three decades, with human water consumption, warming climate, and sedimentation largely responsible for these water losses. Additionally, hydrogeodetic techniques have been used on a much smaller scale to understand surface water processes, such as dynamics in estuaries and coastal wetlands, and determine river water surface slopes.

Anthropogenic effects of management of water resources focus on groundwater depletion for agricultural or urban consumptive use, at large spatial scales with Gravimetry and small scales by InSAR and GNSS. The effects of fragmentation and regulation on water seasonality and connectivity are, to some degree, studied with Altimetry. InSAR and GNSS are also used to determine the geomorphological changes occurring by water storage changes in managed reservoirs. For instance, ground deformation around Lake Mead and vertical displacements of the Hoover Dam (United States) have been found to relate to water storage changes in the reservoir (Cavalié et al., 2007; Darvishi et al., 2021). InSAR and GNSS technologies are usually combined with geomorphological modeling to understand the dynamics of elastic deformation necessary to guarantee the stability of water-related infrastructure such as dams and ancillary structures (e.g., Neelmeijer et al., 2018).

### 4.6. The Potential of Hydrogeodesy to Help Solving Key Hydrological Problems

The International Association of Hydrological Studies (IAHS) has outlined the main topics of focus for the Hydrological Community during the last three decades. The first decade (2003–2012) was termed the Decade on Predictions in Ungauged Basins, aiming to develop and improve methods and techniques for estimating hydrological and hydraulic parameters in ungauged basins where little or no hydrological data is available. The decade's goals aligned with the relevance of using hydrogeodetic applications to make accurate predictions and assessments of water resources and flood risk, where traditional hydrological data collection was limited or absent.

The second decade (2013–2023) was termed Panta Rhei ("everything flows") and highlighted the challenges imposed by global changes on traditional assumptions, such as hydrological stationarity, setting the pathway for socio-hydrology. During this decade, the challenges of global environmental change, including issues related to water resources management, extreme events, and climate change, were prioritized to quantify changes in the global hydrological system and their impact on society. The hydrogeodetic community has supported this initiative by spaceborne gauging and observing thousands of rivers, lakes, reservoirs, and glaciers to synthesize their changes and societal implications (Figures 3–5). As part of this initiative, the IAHS has also proposed the 23 Unsolved Problems in Hydrology (UPH; Blöschl et al., 2019). These UPHs represent major challenges faced by the hydrology field that, if solved, could potentially transform the management of water resources worldwide and considerably increase the understanding of hydrological processes.

Our insights on the potential of Hydrogeodesy to target these UPHs—through a survey among co-authors ranking the applicability of the four technologies to solve each of them—highlight the convenience of using hydrogeodetic techniques for such an endeavor (Table 2). Addressing the UPHs related to Measurements and data (UPHs 16–18) and Modeling Methods (UPHs 19–20) could also largely benefit from Hydrogeodesy. Hydrogeodetic technologies have revolutionized water resource monitoring by increasing the temporal and spatial resolution and record lengths of hydrological observations worldwide, mostly regarding unmonitored water resources. Furthermore, there is a growing interest of hydrogeodesists to support hydrological modeling, either for its parametrization, calibration, validation, or assimilation (Figure 6; Modeling). It is worth noting the case of Gravimetry, where due to the many water components included in TWS observations, TWS changes are usually validated with hydrological models and reanalysis products to obtain specific fluxes and stocks on the surface or below (Niu &

**Table 2**
*How Hydrogeodetic Technologies Could Help Answer the Unsolved Problems in Hydrology of the International Association of Hydrological Studies*

| Unsolved problem in hydrology (UPH) | Altimetry | InSAR | Gravimetry | GNSS | Total |
|---|---|---|---|---|---|
| Time variability and change | | | | | |
| 1. Is the hydrological cycle regionally accelerating/decelerating, and are there tipping points (irreversible changes)? | 3.6 | 3.5 | 4.1 | 3.1 | 3.6 |
| 2. How will cold region runoff and groundwater change in warmer climates ? | 2.9 | 4.1 | 4.1 | 2.9 | 3.5 |
| 3. How does climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions? | 2.7 | 3.2 | 3.2 | 3.3 | 3.1 |
| 4. How do land cover change and soil disturbances impact water and energy fluxes on land and groundwater recharge? | 2.1 | 3.2 | 3.4 | 2.6 | 2.8 |
| Space variability and scaling | | | | | |
| 5. What causes spatial heterogeneity/homogeneity/sensitivity to controls in hydrological and material fluxes? | 2.4 | 3.4 | 2.7 | 3.4 | 3.0 |
| 6. What are the hydrologic laws at the catchment scale, and how do they change with scale? | 2.7 | 3.1 | 2.9 | 3.3 | 3.0 |
| 7. Why is most flow preferential across multiple scales, and how does such behaviour co-evolve with the critical zone? | 1.9 | 2.1 | 2.1 | 2.3 | 2.1 |
| 8. Why do streams respond so quickly to precipitation inputs when stormflow is so old, and what is the transit time distribution of water in the terrestrial water cycle? | 2.5 | 2.9 | 2.7 | 3.6 | 2.9 |
| Variability of extremes | | | | | |
| 9. How do flood-rich and drought-rich periods arise, are they changing? | 3.5 | 3.3 | 4.0 | 3.8 | 3.7 |
| 10. Why are runoff extremes in some catchments more sensitive to land use/cover and geomorphic change? | 2.7 | 3.4 | 2.2 | 3.0 | 2.8 |
| 11. Why, how and when do rain-on-snow events produce exceptional runoff? | 2.0 | 3.1 | 2.1 | 4.1 | 2.8 |
| Interfaces in hydrology | | | | | |
| 12. What processes control hillslope–riparian–stream–groundwater interactions, and how do they connect? | 2.2 | 3.1 | 2.7 | 2.9 | 2.7 |
| 13. What processes control groundwater fluxes across boundaries ? | 1.7 | 3.0 | 3.3 | 2.3 | 2.6 |
| 14. What factors contribute to the long-term persistence of sources responsible for water quality degradation? | 1.8 | 2.2 | 1.7 | 1.1 | 1.7 |
| 15. What are the extent, fate and impacts of contaminants? How are subsurface microbial pathogens removed/inactivated? | 1.3 | 1.2 | 1.5 | 1.1 | 1.3 |
| Measurements and data | | | | | |
| 16. How can we use innovative technologies to measure surface and subsurface properties, states and fluxes? | 4.2 | 4.6 | 4.6 | 3.5 | 4.2 |
| 17. What is the value of traditional hydrological observations vs. qualitative observations from lay persons, data mining? Under what conditions can we substitute space for time? | 3.7 | 3.8 | 3.5 | 4.1 | 3.8 |
| 18. How can we extract information from available human and water systems data to inform the building process of socio-hydrological models and conceptualizations? | 3.4 | 4.1 | 3.5 | 3.7 | 3.7 |
| Modeling methods | | | | | |
| 19. How can hydrological models be adapted to extrapolate to changing conditions? | 3.5 | 4.1 | 3.6 | 4.1 | 3.8 |
| 20. How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction? | 3.8 | 4.0 | 4.1 | 3.4 | 3.8 |
| Interfaces with Society | | | | | |
| 21. How can the (un)certainty in hydrological predictions be communicated to decision makers/ general public? | 3.1 | 3.2 | 3.1 | 2.9 | 3.1 |
| 22. What are the synergies and tradeoffs between societal goals related to water management ? | 2.7 | 3.4 | 3.2 | 2.7 | 3.0 |
| 23. What is the role of water in migration, urbanization and the dynamics of human civilizations, and what are the implications for contemporary water management? | 3.6 | 3.8 | 3.1 | 2.9 | 3.4 |

*Note.* The survey results consist of answers from each co-author to the question: What is the potential of this hydrogeodetic technology to help solve this unresolved question (UPH)? The answers ranged from 1 (low potential for Hydrogeodesy to contribute, red) to 5 (high potential for Hydrogeodesy to contribute, blue). The numbers below each technology show the average score of all co-authors answering the survey for that specific technology. The column "Total" is the average of all scores from all answers.

Yang, 2006; Ramillien et al., 2021). To give some examples, GRACE has been used to evaluate TWS with the World Climate Research Program's Coupled Model Intercomparison Project Phase 5 (CMIP5) (Freedman et al., 2014) or regional-scale hydrologic modeling with the Soil and Water Assessment Tool (SWAT) in Sub-Saharan Africa (H. Xie et al., 2012). InSAR ground displacement and water level change outputs can calibrate and parameterize modeling of groundwater such as 1D compaction models (e.g., Lees et al., 2022) or 3D finite element groundwater flow and geomechanical model (Boni et al., 2020).

The problems regarding Hydrology Interfaces with Society (UPHs 21–23) also rank high among hydrogeodesists, especially the UPH related to the role of socio-hydrology and focusing on the role of water in migration (Wolde et al., 2023), urbanization and human dynamics (Sardo et al., 2023), and the implications for water management (UPH 23). Sociohydrology studies the interplay between water, infrastructure, and society (Di Baldassarre et al., 2013, 2015; Hall, 2019; Sivapalan et al., 2012). This interplay includes the water-energy-food nexus across all spatial scales of analysis (Cudennec et al., 2018; D'Odorico et al., 2018; Lant et al., 2019; J. Liu et al., 2017). We argue that Hydrogeodesy is essential to complement models and to go beyond the specific case studies constrained by data availability on changes to water resources. By exploring large data sets of change in water resources from multiple places around the world, Hydrogeodesy can help (a) unravel generic patterns and trends in the way that societies extract and transport energy sources, produce and convert energy, irrigate crops for biofuel production (Rulli et al., 2016), and produce water-intensive renewable energy, (b) advance our understanding of the relationship between economic growth and water flows, (c) develop a complete picture of changes in global water resources by reducing the bias in in-situ monitoring toward the Global North, and (d) uncover the interconnected nature of food-energy-water systems and potentially enhance our ability to address all Sustainable Development Goals (Di Baldassarre et al., 2019).

Regarding water levels, several altimeters (e.g., Jason-3 and Sentinel-3A/B) sensors have been used to calibrate hydraulic models (Malou et al., 2021; Schroeder et al., 2019). Special attention is paid to Cryosat-2, which can accurately monitor river profiles and slopes due to its short inter-track distances, benefiting hydraulic applications and river discharge estimation (Schneider et al., 2018). Given the role of surface water bodies and rivers in providing water storage during drought periods and conveying and storing water during flood events, their observation is critical, and the role of water elevation in this regard allows mitigation of the impacts of these hydrological extremes. Concerning water resource management, monitoring reservoirs by measuring water height with altimeters (and changing spatial extent from optical sensors) allows their volume to be quantified when combined with water extension changes obtained by optical and radar imagery (Tourian et al., 2022). For instance, in Brazil, the water and risk management agencies (ANA, SGB) have started incorporating hydrogeodetic technologies to monitor reservoirs and provide services to many communities and economic sectors across the country.

Addressing the agenda set out by IAHS and the UPHs requires consideration of both the changes that can be measured by these technologies and related research problems whose solutions are relevant to water management. While hydrogeodetic technologies may be able to better quantify reductions in water availability, there is still limited experience in applying this information in practice, such as in formal or informal water allocation decision-making (Curran et al., 2023). Hydrogeodetic observations could be particularly beneficial in areas with insufficient data coverage or for management practices that require, for example, estimating groundwater use when monitoring well data is restricted or otherwise unavailable (Molle & Closas, 2020). Moreover, these technologies could also be operationalized to inform a broader range of water management decision-making processes (Sheffield et al., 2018). For instance, clarifying the distinctions between changes that result from over-allocation (i.e., policy-only decisions that can be altered locally) versus biophysical changes resulting from broader climate change can be helpful for water managers (e.g., Grafton et al., 2013; Ricciardi et al., 2022). As another example, lags in decision-making often mean that responses to sudden or slower changes in water availability are too delayed to be effective (Barnett et al., 2015; Punzo & Arbabi, 2023). While some lag time may always remain, the ability of hydrogeodetic technologies to detect signals and changes in near real-time could shorten these lags, leading to more responsive and effective management.

### 4.7. Maximizing the Potential of Hydrogeodesy and Potential Limitations to Solve the Problems

The four hydrogeodesy technologies discussed here can be used to solve specific UPHs (Table 3; second column), although there are potential limitations the researcher/user will face in the process (Table 3; third column). The

**Table 3**
*Selected Extracts From the Expert Elicitation on How Hydrogeodesy Can Help Address the UPHs and the Limitations That Need to Be Overcome*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| Time variability and change | | |
| 1. Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)? | The occurrence of tipping points and determination of accelerating change in hydrological fluxes requires tracking in time. This can be done with many hydrogeodetic sensors. To name a few, the Ka-band Radar Interferometer (KaRIn) onboard SWOT can observe surface water fluxes in millions of lakes, reservoirs, and rivers at an unprecedented spatiotemporal scale (<100 m, sub-monthly). The ICESat-2 altimeter provides high-accuracy measurements of mass changes in global glaciers and ice sheets. The forthcoming NISAR satellite mission will collect radar images in both L- and S-bands and measure changes in ice masses and soil moisture at a spatial scale of farm fields every 6–12 days. Combining these data with hydrological models, we can determine if the changes are (irreversible or transient. | Each geodesy sensor has its tradeoffs between temporal and spatial coverages or resolutions. Many of the existing sensors are relatively young. For example, altimetry satellites have only been available since the early 1990s, implying that observed trends are sensitive to the short-term variability of the natural climate system, and additional mechanistic analyses and data are often needed to disentangle short-term signals from longer-term trends. |
| 2. How will cold region runoff and groundwater change in warmer climates (e.g., glacier melt and permafrost thaw)? | Groundwater change in warmer climates can be tracked with InSAR applications to determine rates of ground deformation once the relationship between groundwater change and ground deformation is established. We can combine data on several SAR missions to determine ground deformation and estimate groundwater volume change. Traditional monitoring methods, that is, observation wells, are insufficient for obtaining detailed spatial and temporal groundwater data to understand the dynamics of large-scale aquifer systems. InSAR, combined with the power of AI, can upscale the point measurements in the monitoring wells to the entire aquifer both in time and space. Hence, the integration of InSAR measurement and AI is emerging as a promising solution in the realm of groundwater monitoring and management. | Data availability limitations of SAR sensors in important regions where groundwater resources need to be monitored. Data on groundwater levels needed to establish the relationships between deformation and groundwater level may be scarce. Coherence of the signal in some locations may be low, limiting the application of InSAR. Lastly, although InSAR is becoming a common approach to detecting deformation in groundwater-induced subsidence in agricultural regions, vegetation decorrelation results in the partial spatial coverage of land deformation. |
| 3. What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions? | As with InSAR, Gravimetry can indeed monitor the magnitude of human water use or consumption over catchments by measuring the change in water mass and when combined with national statistics for socio-economic data (e.g., Solander et al., 2017). Furthermore, the combination of gravimetry with radar altimetry, optical and radar imagery, and microwave sensors, GNSS and InSAR allow the water balance to be closed at the basin scale, helping estimate evapotranspiration, whose change relates to human water consumption once the other change contributions are removed. In arid regions, basins are generally endorheic, so satellite data enables us to address this question. Discrimination between climate change and water use can be achievable by integrating satellite data into hydro-climatic models. | GRACE downscaling is feasible, but the uncertainty varies depending on the region. Spatial coverage of GNSS and InSAR data can also become a limitation. There is a need for standardized routines and accuracy controls for InSAR processing; more accurate and detailed knowledge of subsurface properties, including aquifer characteristics for poroelastic models as well as elastic and inelastic Earth properties for loading models, and separation of deformation signals from non-hydrological sources. The short-time availability of gravimetry data (and satellite altimetry over some areas) hampers a long-term understanding of (semi-) arid processes. |
| 4. What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface and the resulting groundwater recharge? | Altimetry provides precise measurements of terrain elevation, enabling monitoring of changes caused by deforestation, urbanization, and other human activities, controlling the partitioning of precipitation on the surface and groundwater recharge. Gravimetry can also detect changes in soil mass and | In-situ data concerning groundwater level changes is needed, and there is a need to standardize data across time and space for different missions. |

**Table 3**
*Continued*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| | underground water resources linked to deforestation, land cover changes, and corresponding water storage changes. GNSS offers accurate measurements of soil vertical and horizontal displacements, facilitating land subsidence monitoring due to activities like groundwater extraction or urbanization. InSAR can measure changes in land surface altitude, which, combined with groundwater withdrawals and runoff changes, can indicate groundwater recharge trends. Together, these techniques enhance our understanding of how land cover changes and soil disturbances impact water and energy fluxes on land and groundwater recharge. | |
| Space variability and scaling | | |
| 5. What causes spatial heterogeneity and homogeneity in the runoff, evaporation, subsurface water, and material fluxes (carbon and other nutrients, sediments) and their sensitivity to their controls (e.g., snowfall regime, aridity, reaction coefficients)? | Fluxes of water and water-borne elements between floodplains and main channels are hydrologically and ecologically important. A combination of L-band or C-band SAR (e.g., NISAR and Sentinel-1) and Ka-band SAR (SWOT) interferometry can provide spatially continuous data sets of water surface slope, which can constrain floodplain/channel water exchange, which is also relevant for hydrologic transport. Also, by incorporating geodetic data (e.g., GNSS observations of Earth-surface displacement) into hydrological models, we can assess how different watersheds and hydrogeological units respond to water fluxes. | SWOT and longer wavelength radar will not always be available simultaneously and technical challenges when combining interferometric products from sensors at multiple wavelengths. Groundwater systems can be highly heterogeneous and are difficult to observe and model. Geodetic data provide another empirical constraint on the models, complementing other hydrological observables; however, the observables have spatial and temporal limitations. |
| 6. What are the hydrologic laws at the catchment scale, and how do they change with scale? | Direct observations of water bodies (lakes, rivers) from InSAR or altimetry can be compared to other components of the hydrologic cycle (e.g., groundwater inferred from gravity, snowpack from InSAR, or subsidence from InSAR) across spatial scales to understand how hydrologic laws change with scale. | Satellite-based hydrogeodesy observations largely miss the smallest headwater catchments and many surface water bodies. SWOT will increase the monitoring of these bodies, yet the data availability is too short. |
| 7. Why is most flow preferential across multiple scales, and how does such behavior co-evolve with the critical zone? | The effects of topographic heterogeneity on hydrologic processes can be measured with high-resolution soil moisture (e.g., GNSS-reflections) and scaled to understand spatial process variability better. Data obtained from GNSS are sensitive to hydrological mass fluxes occurring across a wide range of spatial scales (from local to global). Therefore, GNSS can be used to advance understanding of how the hydrological cycle operates across scales and how it evolves with time. | Hydrogeodetic techniques are sometimes too coarse in resolution to resolve field-scale and catchment-scale processes. |
| 8. Why do streams respond so quickly to precipitation inputs when stormflow is so old, and what is the transit time distribution of water in the terrestrial water cycle? | By integrating geodetic data with hydrological modeling, researchers can estimate the transit time distribution of water, revealing the timescales over which water moves through the terrestrial water cycle. This comprehensive understanding is essential for effective water resource management and climate change adaptation strategies. InSAR can monitor changes in land surface elevation caused by precipitation events (i.e., landslides) and provide information on the timing and magnitude of runoff generation. Additionally, GNSS can track ground movement, aiding in identifying preferential flow paths and transit times of water through the landscape. | Studying how streams respond to precipitation inputs requires high-resolution data to characterize the process in the scale of minutes and meters. Techniques like gravimetry that measure basin water storage are limited to larger spatial scales and longer temporal sampling (e.g., ~monthly, 100 km), but future gravity constellations may improve these limitations significantly. |

**Table 3**
*Continued*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| Variability of extremes | | |
| 9. How do flood-rich and drought-rich periods arise, are they changing, and if so, why? | Flood-rich and drought-rich periods are associated with anomalous precipitation rates but reflect longer-term wetting and drying cycles of surface water, groundwater, and soil moisture storage. Regarding droughts, InSAR via SBAS and PS algorithms can derive long-term volumetric changes in groundwater storage and their links to other hydrological parameters to understand how they affect the occurrence of hydrological droughts. Regarding floods, InSAR can measure the water extent and water level in wetlands. Different SAR data sources can be combined to determine long-term changes in the water storage capacity of the wetland and link it to their ability to buffer flooding. Integrating GRACE data with other land use and physiographic data can help understand flood- and drought-rich environments/conditions. Decadal water variability obtained by hydrogeodesy at a local, regional, and global scale, combined with numerical analysis of time-series peaks and anomalies and hydroclimatic data, allows for addressing this question. | Capturing floods and droughts is feasible with satellite-based observations; however, thresholds of when floods and droughts will occur need to be better defined and improved so that the changes detected by the satellite observations are more meaningful with regional contexts considered. Furthermore, scale mismatches between GRACE and other higher-resolution data sets must be addressed. |
| 10. Why are runoff extremes in some catchments more sensitive to land use/cover and geomorphic change than in others? | InSAR and altimetric sensors can be used to map the change in land use (i.e., change in the height of vegetation or subsidence/uplift) and help understand sub-surface water storage by measuring flood precursors (i.e., how full the "bucket" is) and drought penetration into the soil column (i.e., how much water is "missing" during a drought). Gravimetry is the first technique to achieve those measurements with global coverage. | The main limitation of this application is related to the multiple processes and drivers existing in a catchment and related to runoff extremes. Intercomparison projects could overcome this by researching these particularities in different worldwide catchments. |
| 11. Why, how, and when do rain-on-snow events produce exceptional runoff? | Repeat altimetry observations can estimate snow depth and thus contribute to better snow-water equivalent (SWE) estimates when ground observations are unavailable. The use of GNSS can help trace snowpack dynamics under large rain-on-snow events. | Snow density cannot be accurately determined from spaceborne hydrogeodesy sensors. Wet snowpack conditions during and before rain-to-snow events limit the use of other alternative approaches (e.g., microwave sensors). |
| Interfaces in hydrology | | |
| 12. What processes control hillslope–riparian–stream–groundwater interactions, and when do the compartments connect? | Estimating water-induced ground deformation with InSAR and relating it to the water extent of near/related water bodies can help understand the relationship between groundwater levels and surface water elevation. Furthermore, InSAR can also identify hydrologic connectivity among water bodies by comparing water and land surface levels over time. | Lack of SAR data availability for some regions with important groundwater resources. Data on groundwater levels are needed to establish the relationships between deformation and groundwater levels. Coherence of the signal in some locations may be low, limiting the application of InSAR. |
| 13. What are the processes controlling the refluxes of groundwater across boundaries (e.g., groundwater recharge, inter-catchment fluxes, and discharge to oceans)? | Geodetic data (e.g., GNSS, InSAR, and gravity) could be used to track groundwater fluxes across horizontal (i.e., lateral) boundaries. In other words, mass transfers from one geographic region to another can be quantified. Gravimetry data have also proven useful for monitoring local-scale groundwater storage changes in hydrologically homogeneous areas (e.g., portions of the Brazilian semiarid), as validated with in situ wells. | Geodetic techniques are insensitive to vertical (i.e., radial) mass fluxes. For example, geodesy alone cannot be used to assess how groundwater moves between soil layers and deeper bedrock fractures. Furthermore, as stated above, the spatial resolutions of TWS changes from geodesy depend on network density (GNSS) and satellite orbital distance (GRACE missions). |

**Table 3**
*Continued*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| 14. What factors contribute to the long-term persistence of sources that are responsible for the degradation of water quality? | Although hydrogeodesy is more useful for estimating water quantity rather than quality, the estimate of pollutant loads in rivers or lakes needs quantification of flow. The loading of a pollutant is equal to the product of its concentration and the flow rate of the medium in which it is being transported. Hydrogeodesy is well known to quantify the latter. For instance, the SWOT is ready to provide discharge estimates for river sections wider than 100 m based on measurements of river water surface elevation, width, slope and other ancillary data (Durand et al., 2023). | The temporal variability of discharge captured by the SWOT may be too coarse when estimating loads of, for example, suspended sediment if the storm event moving much of the monthly sediment does not coincide with an acquisition of the SWOT. |
| 15. What are the extent, fate, and impact of contaminants of emerging concern | See discussion for UPH 14. | See discussion for UPH 14. |
| Measurements and data | | |
| 16. How can we use innovative technologies to measure surface and subsurface properties, states, and refluxes at a range of spatial and temporal scales? | Satellite radar altimetry is useable for measuring water height changes in time at large scales, one example for lakes is Aminjafari, Brown, Frappart, et al. (2024). Moreover, with the SWOT satellite, height extent and stock variations in millions of lakes, floodplains, and reservoirs are also measured globally and regionally. Discharges (fluxes) are measurable from SWOT too. In the case of SWOT, the novel KaRIN onboard offers synchronous, repeated (21 days or finer), and wide-swath (50 km) measurements of both surface water elevation and extents, which then allow us to derive water storage changes in millions of lakes and reservoirs and discharge in hundreds of thousands of rivers. NISAR will provide SAR data in both L- and S-bands, allowing the track of soil moisture at a spatial scale of farm fields every 6–12 days. GRACE-FO satellites measure the changes in Earth's gravity field, eventually leading to knowledge of groundwater dynamics. Combining these estimates with groundwater levels allows the prediction of aquifer storage parameters. Additionally, launched pairs of GRACE-like satellite missions or increased spatial coverage of InSAR for loading studies can enhance spatial resolution to relevant scales. Improved resolution of derived GWS would also allow for better spatial distinction of net GW recharge and discharge quantities. A combination of GRACE GWS with poroelastic models and well data allows for separating confined and unconfined aquifer storage changes. | -Measuring fluxes during flash floods in small rivers is not always possible at the required time resolution (hourly or daily) since the frequency of satellite data is, at most, weekly.<br>-The resolution of GRACE does not allow for the measurement of surface and subsurface small-scale properties. Future gravimetry missions (MAGIC) would allow for this to be improved. In addition, monitoring wetland extent and storage dynamics remains difficult due to the ambiguity of wetland boundaries and the mixture of vegetation and water characteristics. Regarding groundwater, more accurate and detailed knowledge of aquifer properties for poroelastic models and separation of deformation signals from non-hydrological sources is required.<br>-Regarding InSAR, increased spatial coverage of spatiotemporal deformation maps, for example, from NISAR, might improve the capabilities of elastic loading model output. |
| 17. What is the relative value of traditional hydrological observations versus soft data (qualitative observations from lay persons, data mining, etc.), and under what conditions can we substitute space for time? | Traditional GNSS-based measurements can provide precise and accurate hydrological data in flood-prone regions. Integrating these with qualitative data from laypersons (e.g., crowdsourced flood reports) and data mining from social media can enhance spatial coverage and situational awareness during hydrological events. For instance, crowdsourced and mined data can offer spatial distributed real-time updates on water extent and impacts during a flood. Combining disaggregated, local-scale citizen science observations of, for example, water table levels, could be used to understand the sub-grid variability | There are challenges in integrating and standardizing diverse data sources. Establishing reliable methods to substitute spatial observations for temporal changes requires robust validation—variability in the accuracy and reliability of qualitative observations, such as crowdsourced data. |

**Table 3**
*Continued*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| | of GRACE signals and how these vary across space and time. | |
| 18. How can we extract information from available data on humans and water systems to inform the building process of socio-hydrological models and conceptualizations? | In rapidly urbanizing areas such as the East Coast of China, InSAR, and GNSS can identify areas of subsidence related to groundwater extraction. Satellite altimetry can track changes in surface water bodies due to increased water usage. Integrating these data sources with socio-economic data, such as population density and land use patterns, allows for the support to develop socio-hydrological models that capture the interactions between human activities and water resources. | Integrating InSAR, GNSS, and satellite altimetry data requires sophisticated data fusion techniques to ensure coherence and accuracy and unify or deal with different spatiotemporal resolutions. |
| Modeling methods | | |
| 19. How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics? | Satellite altimetry and gravimetry are widely used for model validation, calibration, and assimilation, improving the model's representation of the water cycle in current and past conditions. See Section 4.5. Concerning the case of InSAR, wetlands are poorly captured by many hydrological models and are changing quickly due to climate and land-use changes. Inaccurate information on wetlands risk can, for example, cause errors in model simulations of flood attenuation and impacts. InSAR data can provide information on up-to-date wetland extent and dynamics for model incorporation. | Lack of in situ data to validate satellite-based estimates over poorly gauged catchments |
| 20. How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction? | A traditional watershed mass balance requires estimates of water fluxes into and out of the watershed (e.g., precipitation, runoff, evapotranspiration) to estimate total water-storage changes within the watershed. Geodesy complements this traditional mass-balance approach in providing a direct constraint on $\Delta S$. Depending on the hydrological parameter that the prediction or forecast aims to quantify, a direct constraint on $\Delta S$ from geodesy can potentially reduce the number of free parameters in the model and reduce the overall uncertainty in the model. | Limitations of spatial resolution and distinguishing between different contributions to the geodetic signal (e.g., GNSS estimates of site position contain information about water loading at local and regional scales, tectonics, volcanism, tides, etc.). |
| Interfaces with Society | | |
| 21. How can the (un)certainty in hydrological predictions be communicated to decision-makers and the general public? | Reaching the public where they are, with a technology they are familiar with from their everyday lives, might help kickstart a conversation on how geodesy can be used for water management and how it is both powerful and imperfect. For example, GRACE data have widely been used as a science communication tool in transdisciplinary settings and for high-level information on the groundwater crisis with regional, national, and international policymakers. | It is challenging to communicate the basics of hydrogeodesy to end users and stakeholders, as it requires previous technical knowledge. |
| 22. What are the synergies and tradeoffs between societal goals related to water management (e.g., water–environment–energy–food–health)? | -GNSS, InSAR, and satellite altimetry technologies can provide critical information on river water levels and reservoirs, such as the Three Gorges Dam, helping manage flood control while ensuring renewable energy production and water supply security. These technologies offer detailed and real-time data that can inform decision-making to balance competing societal water management goals.<br>-A great deal of water level data in the Global North allows us to test and train models of water surface | Satellite availability and financial resources can limit continuous and comprehensive data coverage, especially in remote or under-resourced areas. Communicating the tradeoffs and uncertainties associated with water management decisions to diverse stakeholders, including policymakers, the general public, and industry leaders, is essential for balanced decision-making. |

**Table 3**
*Continued*

| Unsolved problem in hydrology (UPH) | Examples on the potential of hydrogeodesy to contribute to the UPH | Limitations that need to be overcome |
|---|---|---|
| | elevation. These data are much scarcer in the Global South, so assessing uncertainty in predictions in many parts of the world is challenging. Altimetry (e.g., S-6MF, SWOT) can validate models that simulate water surface elevation in these environments, increasing understanding of their accuracy/uncertainty. | |
| 23. What is the role of water in migration, urbanization and the dynamics of human civilizations, and what are the implications for contemporary water management? | Example: Multiannual cycles of drought and recovery can be tracked from Gravity Recovery and Climate Experiment (GRACE) satellite gravity (e.g., Adusumilli et al., 2019) to explore potential relationships with patterns of human mobility. In particular, societal responses to drought might include migration from affected areas and accelerating urbanization rates (Ceola et al., 2023). Furthermore, linking GRACE data on TWS and GWS anomalies with recent human migration/movement patterns can provide a starting data integration to begin understanding the relative importance of freshwater availability (and especially in the subsurface) in driving the movement and settlement of populations. Using altimetry for monitoring, for example, reservoir, can help provide timely and accurate information for decision-making in a context of fast-changing water uses in areas with migration, urbanization, and dynamic changes in water use (e.g., tourism). | GRACE observations are monthly and include some occasional gaps. Thus, they cannot be used to assess water availability during and after short-duration events, such as flash droughts (X. Yuan et al., 2023). Uncertainties associated with the challenges of separating storage types can affect water availability estimates and affect decision-making. |

potential of hydrogeodesy application to UPHs increases when accounting for the new technologies that have been recently launched or will be in operation soon. For instance, the data of the new SAR altimetry satellite SWOT, launched in late 2022, is already available to the public. The SWOT is a joint mission developed by the National Aeronautics and Space Administration (NASA), the French Space Agency (CNES), the Canadian Space Agency (CSA), and the UK Space Agency (UKSA), providing weekly observations of water level in high latitudes and 21-day observations around the equator covering the majority of lakes. As SWOT now provides surface water levels and corresponding storage changes (in pixel-cloud and raster products) with ~100 m spatial resolution at least every 21 days (depending on its location) for most open waters worldwide during its time in orbit (Biancamaria et al., 2016; Papa & Frappart, 2021), it increases considerably the number of monitored lakes and rivers globally, complementing the data from older altimetry missions. This is crucial for tracking rapid changes in water bodies and offering timely data for effective water management. The SWOT mission is also equipped with a Ka-band sensor with the possibility of measuring water levels and water extent in wetlands with short vegetation types suitable for water storage estimation. Moreover, since SWOT provides cloud points of water elevations, it is possible to estimate river slope, which can be later translated to river discharge. Obtaining digital maps of water surfaces can also help to understand the connectivity of water in open water surfaces.

The coupling of SWOT with the upcoming long-wavelength satellite NISAR will be able to maximize the combined monitoring of vegetated and open water surfaces. The NISAR uses two radar frequencies (L-band and S-band) with long wavelengths of 24 and 10 cm, respectively, which can penetrate dense vegetation; very convenient for tropical wetlands as it enables the exploration of flooded areas, wetlands, and ground with dense and tall canopies. The NISAR swaths are 240 km long, and their resolution is 7 m along track and 2–8 m cross-track. NISAR is planned to be launched in 2024, and its data will be freely available to the public. Regarding GNSS, the future mission of HydroGNSS will be the second mission of the European Space Agency's (ESA) Scout Program, and it will measure key hydrologic variables such as soil moisture and flooded vegetation through the GNSS-R technique. This mission will improve the spatio-temporal resolution of older remote sensing satellites such as ESA's SMOS and Biomass, Copernicus Sentinel-1, and NASA's SMAP.

Broadly, we conclude that the satellite missions that we currently have enable us to begin to answer many of the UPHs, but that many of these systems are new or are short-lived with no firm plans for continuity. The lack of a long time series for these observing systems makes answering many UPH problems challenging. In addition, while the spatial, temporal, and radiometric sensitivities of these systems are theoretically capable of taking the necessary measurements, additional algorithm development is necessary to maximize the utility and compatibility of the diverse observations. Two major challenges rest in mission continuity and algorithm development.

A single hydrogeodetic data set alone is sometimes insufficient to provide accurate predictions at the resolution, coverage, or accuracy required to answer the UPHs. Another reason for combining different hydrogeodetic technologies is their different resolutions. While GRACE observations of TWS variations have provided unique insight into the budget of watersheds, the resolution is not high enough to utilize them for progress with certain UPHs (e.g., 3–6, 16, 20), requiring higher spatial or temporal scales. The already planned staged launch of a next-generation gravity mission with a self-aliasing bender-type double pair for the year 2028 will improve the spatial resolution by approximately a factor of 2, which is significant progress but remains low for many hydrological applications (Daras & Pail, 2017; Jensen et al., 2020; Pail et al., 2019). However, many of the hydrogeodetic methods have been established well enough that further progress could be made by a combination of multiple sensors. One route to take here is the combination of similar hydrological variables derived from different hydrogeodetic sensors. An example is the combination of GRACE TWS estimates with those derived from load models applying observations of vertical land motion. This combination can increase the accuracy and improve the spatial resolution of the data set from ∼400 km to a maximum of ∼50 km in regions with sufficient GNSS station density, or higher if InSAR data with sufficient accuracy to resolve the loading process are available (i.e., at the level of ∼1 mm/yr). A few regional works have progressed in this direction by applying GRACE either as a constraint or as a second observation in a joint inversion scheme for Southwest U.S. and China (Adusumilli et al., 2019; Carlson et al., 2022, 2024; Fok & Liu, 2019) and the resulting data sets are shown to be more accurate than GRACE or GNSS inversions alone. The availability of InSAR vertical land motion data with continental to global coverage could further boost the development of high-resolution TWS data independent from hydrological models. This independence is important for their application as input, calibration, or assimilation variables of hydrological models, resulting in specific progress with UPH 20.

A second route can be taken by combining different but related hydrogeodetic variables that require integrated geophysical modeling frameworks to generate more accurate hydrological data sets. A first example is the complex composition of different deformation signals surrounding aquifers. While TWS change in the entire region causes an overall crustal loading response, poromechanical deformation due to changes in groundwater storage (GWS) may be dominant above confined aquifers. Hence, the detected signal at the surface, for example, via GNSS or InSAR, combines both processes. Although studies often focus on one deformation process, leaving the other behind or excluding it (Argus et al., 2017, 2020; Carlson et al., 2022), separating the signals has been attempted recently. Nevertheless, the attempts use methods that are either not quantitative (Kang & Knight, 2023) or not validated for other regions (Larochelle et al., 2022). An ideal approach here would be a modeling framework that includes both deformation processes to gain an integrated estimate of TWS and GWS variations, as Carlson et al. (2024) recently conducted for Central Valley, California.

A second example of combining different but related hydrogeodetic variables is the effort to improve and validate GWS change estimates by comparing GRACE-based water balance approaches with poroelastic models quantifying groundwater loss during drought. Although both employed data sets (TWS change from GRACE and poroelastic aquifer deformation from GNSS or InSAR) are very different, the estimates from both approaches agree well within the margins of errors (Khorrami et al., 2023). In another study, Carlson et al. (2020) yielded better results for a combination of GRACE-based TWS change with elastic loading models when external constraints on GWS changes from poroelastic model output were introduced. A further advancement in this direction is the direct combination of GRACE and InSAR by Vasco et al. (2022), whose work emphasized that GWS estimates from poroelastic models detect water volume change in confined aquifers only, while GRACE-based GWS changes include those in confined and unconfined aquifers. These evolutions are encouraging for hydrological studies, as they result in further enhanced data sets that integrate detailed knowledge of the engaged physical processes, in some examples, specifically to address the limited spatial resolution and integrated nature of GRACE TWS data. These developments demonstrate how the hydrogeodesy community slowly gains the domain knowledge required to accurately combine hydrogeodetic observations with traditional hydrological data.

When various water cycle or TWS components need to be computed, hydrogeodesy can be combined with ensembles of hydrological and land surface models. An example of this approach is J. Wang et al. (2018), which disentangled TWS changes in the global endorheic system by separating TWS of global endorheic basins into changes in surface water (including lakes, reservoirs, glaciers, snow, and canopy water), soil moisture, and groundwater. Surface water storage changes in large lakes and reservoirs were estimated using a constellation of radar altimetry and optical sensors (for measuring lake WSE and area, respectively). Glacier mass changes were estimated using the time series of co-registered DEMs constructed from ASTER stereo-images. In J. Wang et al. (2018), mass changes in other surface water storage components (including snow and canopy water) and soil moisture were estimated using an ensemble of two global hydrological models (WaterGAP and PCR-GLOBWB) and five land surface models (GLDAS CLM, Mosaic, Noah, VIC, and CLSM) to constrain the uncertainties. Groundwater changes were then calculated as the residuals between the changes in the above-quantified water components and GRACE-observed TWS. Uncertainties are inevitable, but hydrogeodesy and modeling synergy will soon lead to improved accuracies with the proliferation of new-generation sensors such as SWOT and NISAR.

The potential of hydrogeodesy to solve hydrological and sustainability problems can also be maximized by its combination with Artificial Intelligence (AI). AI, including deep learning models, has facilitated and increased the efficiency of various tasks like image recognition, speech detection, self-driving, and machine translation (LeCun et al., 2015). In hydrogeodesy, AI models have proven effective for wetland delineation (Jamali et al., 2022), flood detection (Munawar et al., 2021), and drought monitoring (Shen et al., 2019). In recent years, AI has been integrated to hydrogeodesy, especially with InSAR, to improve the monitoring and quantification of water resources. Deep learning is now widely used for flood detection (Ghosh et al., 2022) or even for efficiently recognizing hydrological barriers to flow in wetlands (Hübinger et al., 2024). For the case of groundwater, since InSAR has spatial limitations in intense agricultural land, Naghibi et al. (2022) developed an InSAR-AI-based approach to accurately produce a full-coverage map of groundwater-induced land subsidence in an arid region. Hasan et al. (2023) also integrated machine learning and InSAR to predict groundwater storage loss at the global scale at the 2 km spatial resolution. They concluded that over 70% of mapped subsiding areas are located in croplands and built-up regions, suggesting the power of an integrated InSAR-AI approach to provide insight into the hydrologically disturbed basins at the global scale.

AI models work well using different types of data, including multispectral (K. Yuan et al., 2021) and SAR imagery (Dirscherl et al., 2021) or a combination of both (Hosseiny et al., 2022), showing a promising future for the use of artificial intelligence in hydrogeodesy. One of the biggest limitations of using deep learning models is the need for large quantities of annotated data to train, which is often costly and time-consuming to collect through fieldwork. This results in an entry barrier for their application in hydrogeodesy. However, self-supervised models (Caron et al., 2021), which learn from the data without annotated examples, have become more prominent. Recently, self-supervised models were applied for hydrogeodesy on the task of wetland delineation, showing a superior performance (Peña et al., 2024). These new advancements open the door for new possibilities for using AI in hydrogeodesy, though challenges remain, particularly regarding the limitations of sensor resolution, which limits the applicability of AI for detecting small bodies of water.

### 4.8. The Role of Hydrogeodesy in Assessing Local and Global Sustainability

The need for hydrogeodetic studies to address sustainability questions beyond water management is worth noting. The importance of freshwater as an integral part of the Earth System, concerns about its resilience to climate and other changes, and its centrality to social-ecological sustainability is acknowledged by the inclusion of freshwater in many leading global-scale sustainability-focused frameworks. For instance, freshwater constitutes one of the nine Planetary Boundaries (PBs) (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015), which identify nine Earth system processes or domains critical to maintaining a safe operating space for humanity. Among these domains, freshwater dynamics play a key role, directly impacting ecosystems, agriculture, and human settlements. In this context, hydrogeodesy's precise monitoring of water resources plays a vital role, offering essential data that inform global sustainability policies and practices, particularly under the pressures of climate change, where alterations in the water cycle are a primary concern.

The PB framework has emerged as highly influential in the global sustainability agenda, and researchers and practitioners are increasingly attempting to operationalize it to translate PBs into actionable insights for local

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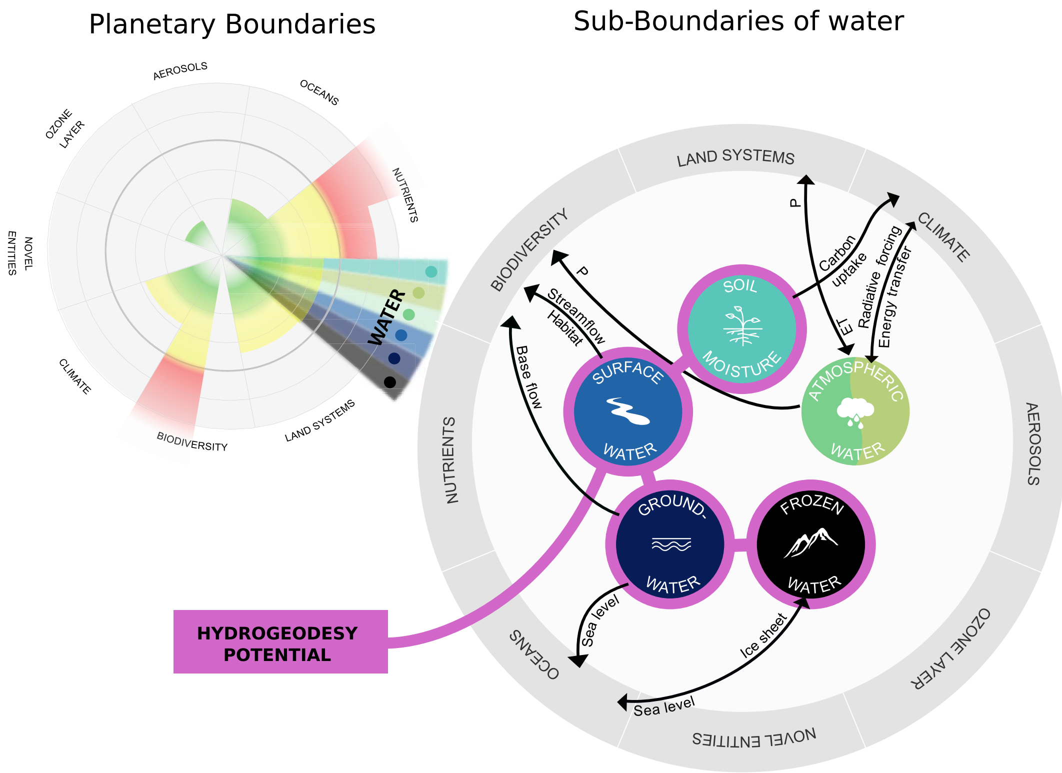


**Figure 7.** The Potential of Hydrogeodesy to observe and assess six planetary sub-boundaries as proposed by Gleeson et al. (2020), based on the functional relationship (arrows) between water stores (colored circles) and Earth system components (outer gray circle). The panel on the left represents the nine planetary boundaries suggested by Steffen et al. (2015) to comprise humanity's safe operating space. For each planetary boundary, the green zone represents the safe operating space, the yellow represents the zone of increasing risk and uncertainty in relation to the transgression of the planetary boundary, and the red zone is a high-risk zone, probably pointing to a transgression of the planetary boundary. The planetary boundary lies between the green and yellow zones. The right panel shows the sub-boundaries of the freshwater planetary boundary, which include: (1) atmospheric water for hydroclimatic regulation, (2) atmospheric water for hydro-ecological regulation, (3) soil moisture, (4) surface water, (5) groundwater and (6) frozen water. This categorization underscores the multidimensional nature of water in the Earth system, where each boundary reflects a unique aspect of water's role in ecological and climatic stability.

management and business strategies. Operationalizing implies translating or downscaling PBs to help local-scale actors assess the implications of their activities on the planetary safe operating space (Häyhä et al., 2016; Zipper et al., 2020). This operationalization increasingly relies on Earth observations to accurately assess freshwater dynamics, essential for sustainably managing Earth's water resources and bridging global environmental goals with localized water management strategies. A widely known application used for operationalizing is the Donut Economics framework (Raworth, 2012, https://doughnuteconomics.org/), which proposes an “ecological ceiling” based on the planetary boundaries and a “social foundation” based on basic human needs. More recently, the novel Earth System Boundaries framework also aims to integrate the planetary safe operating space with justice aspects and to present quantitative sub-global safe and just Earth System boundaries—including surface water and groundwater (Rockström et al., 2023; Stewart-Koster et al., 2024). Furthermore, the recent Planetary Guardians initiative aims to launch a Planetary Boundaries Health Check to monitor the state of the planet, which will be largely reliant on satellite-based data (https://planetaryguardians.com/).

As freshwater is recognized as one of the key elements in Earth system stability and in the concepts of safe and just operating spaces, there is an increasing need for the global-scale monitoring of freshwater resources. Such need is also evident in operationalizing the PB framework, allowing stakeholders, local authorities, and communities to detect and quantify changes in freshwater availability. This operationalization is vital for regions facing water scarcity, where precise surface water and groundwater data can inform sustainable water management practices. Hydrogeodesy can fill this need by guiding, monitoring, and analyzing water cycle variables, contributing to both global-scale assessments of sustainability and local-scale water management. Hydrogeodetic technologies can observe rates and ongoing directions of change in near real-time from local to the global scale, thereby contributing to applying and developing global and regional sustainability frameworks.

To date, the role of freshwater in the PB framework (Figure 7) has focused on estimating sustainability thresholds in the quantity of freshwater available or consumed based on hydrological variables such as evapotranspiration (Destouni et al., 2013; Rockström et al., 2009; Steffen et al., 2015), runoff (Gerten et al., 2013; Richardson et al., 2023; Steffen et al., 2015), groundwater storage (Rockström et al., 2023; Stewart-Koster et al., 2024), and soil moisture (Porkka et al., 2024; Richardson et al., 2023; Wang-Erlandsson et al., 2022). Yet, additional hydrological variables are available for indicating freshwater change in the Earth system and closely relate to local and global Earth system resilience in terms of coupled hydro-socioecological systems (Figure 7). These other variables include surface water levels in wetlands and lakes, groundwater flow and storage/level changes, and ice mass. In turn, these variables that have not yet been explored are also relevant for the quantification of other independent planetary boundaries relevant to water quality and pollution, such as the nutrients, land systems, biodiversity, and climate PBs (Ellis et al., 2024). For example, terrestrial ecosystems may depend on groundwater flow, level and quality conditions, and overlooking such relationships may risk severe ecosystem degradation (Huggins et al., 2023); greenhouse gas emissions may be emitted from, for instance, reservoir operation (Deemer et al., 2016) or wetland changes (Zou et al., 2022); and decline in lake water levels may compromise ecosystem services depending on lake water storage and flow buffering capabilities (Yao et al., 2023). Understanding these dynamics aids in developing strategies to mitigate adverse impacts on biodiversity and human communities reliant on these ecosystems.

Hence, hydrogeodesy has great potential to contribute to identifying and tracking these water-related sub-boundaries (Figure 7, right) and the other PBs representing other Earth system processes or domains (Figure 7, left). As one example, hydrogeodetic technologies used to study soil moisture at different spatial scales could elucidate the rate and magnitude of changes in soil moisture. For instance, Gravimetry can help track changes in soil moisture globally based on its relatively long temporal coverage and capability to detect regional patterns of soil moisture change. Integrating GRACE data with local climate models could provide a more dynamic understanding of the freshwater cycle under changing climatic conditions. This regional perspective is essential for understanding how local practices and climatic conditions contribute to broader hydrological shifts.

Additionally, research and refinement of the soil moisture sub-boundary to include carbon uptake and net primary productivity functions could benefit from local and regional assessments of soil moisture changes with GNSS-R (Chew & Small, 2018; Clarizia et al., 2019). Gravimetry and InSAR can enhance our ability to accurately monitor water changes, particularly in regions with scarce ground-based data. These technologies' ability to provide global coverage complements traditional ground-based observations, filling gaps in areas lacking extensive monitoring networks and enabling a deeper understanding of how local and global water cycle components interact.

To give another example, global studies of Gravimetry on the global state of fluxes and stocks of groundwater (e.g., Bhanja et al., 2020; Rodell & Reager, 2023; Tapley et al., 2019) are relevant or a safe and just Earth System Boundary (Rockström et al., 2023). Also, InSAR and GNSS can aid in delimiting safe operating spaces of specific groundwater and aquifer systems in zones under critical groundwater stress by human water depletion (Bai et al., 2022; Castellazzi et al., 2018; Cigna & Tapete, 2021; Haghighi & Motagh, 2019). Changes in water level in lakes and rivers monitored by the SWOT mission, with unprecedented spatial resolution and spatio-temporal coverage, can also help in assessing the contribution of water level changes to the surface water sub-boundary that is represented by streamflow (Richardson et al., 2023). Recent global studies on lake and reservoir water level changes in the context of climate variability and human activities such as regulation and irrigation (Cooley et al., 2021; Yao et al., 2023) can serve as further reinforcement. Finally, Altimetry or Gravimetry can capture relevant hydrological flow and storage changes that precede or relate to the nutrients PB through diffuse waterborne nutrient and carbon pollution and related ecosystem impacts (Basu et al., 2022; Cantoni et al., 2023), locally and for the whole Earth system.

### 4.9. Challenges in Teaching Hydrogeodesy

Many educators in tertiary education programs related to water resources and hydrology increasingly realize the importance of forming professionals with hydrogeodesy knowledge. The knowledge is relevant for engineering and sustainability, engineering and geodesy, and earth sciences and water resources. It is worth noting that the subdiscipline combines two different disciplines, geodesy and water-related sciences. Issues to be considered when teaching hydrogeodesy and that arise from its combination of two disciplines are (a) the prior knowledge of the student, (b) the requirements of time and resources to teach both geodesy and water sciences, (c) selection of the hydrogeodetic technology of focus in the teaching, due to actors of complexity, desired outcomes, and applicability, and (d) the nature of the water-related problems used in the teaching experience.

Regarding the first issue of prior knowledge, we can take the example of a typical Master's program in Hydrology or Water Resources. Most students who enroll in a master's of hydrology have, in most cases, only basic knowledge of remote sensing and almost none of geodesy. This lack of knowledge hinders the understanding of hydrogeodesy applications, forcing most students into additional learning time required to understand the processing schemes of the different hydrogeodetic sensors work and to feel comfortable processing and analyzing the data.

Regarding the time requirements, forming hydrogeodesists implies that students need knowledge of hydrological and geodetic principles or that the principles should be taught during tertiary education. This requires additional teaching and learning time. Choosing the most suitable technology for the learning experience and the nature of the water-related problems also depends on the priorities and learning outcomes desired by the learning institution. We have mentioned how the four main technologies of hydrogeodesy have advantages and limitations in terms of their capability and potential and how they facilitate the learning of tertiary education students. For instance, if time is a constraint, altimetry and gravimetry are probably the best alternative. Altimetry requires minimum data processing and has high applicability in various water resources such as lakes, wetlands, and glaciers. Gravimetry also requires minimum data handling and can be used to quantify water availability changes in various types of water resources at large spatial scales. There is a clear need to form students from the master level who can use hydrogeodesy for relevant water-related applications that go beyond the quantification of a specific hydrologic variable. We believe hydrogeodesy studies should focus more on hydrological processes, water management, and sustainability. Addressing this need is only possible by improving the level of knowledge of master students regarding hydrogeodesy.

There are few examples of hydrogeodetic tools in the scientific literature on teaching. For instance, Maggioni et al. (2020) built an online learning module for Satellite Remote Sensing Applications in the Hydrologic Sciences. Online modules are regarded as efficient in transferring key hydrological concepts to students, with the potential for meeting learning outcomes in hydrology and related educational needs (Habib et al., 2012; Joyce et al., 2014; Popescu et al., 2012). The module is based primarily on satellite gravimetry, one of the four techniques of hydrogeodesy, by applying two types of activities: simple "check-your-understanding" problems and quantitative authentic tasks.

Teaching hydrogeodesy is challenging. The necessity of gaining knowledge of hydrology and geodesy (or remote sensing) poses high demands regarding basic knowledge, time, and resources. Yet, it is currently the best way of understanding water resources and their changes at the global scale and also for local applications of water management. Although hydrogeodesy could have a wider presence in water-related science curriculums and remote sensing, it is understandable that it is just a sub-area of both disciplines. Learning the best equilibrium for teaching hydrogeodesy depends on the specific hydrological questions or problems that want to be addressed and the profile of the students taking the course, as their previous knowledge of hydrogeodetic concepts depends on this. Finding this equilibrium will imply a good combination of knowledge and skills for students to go into their working lives and apply hydrogeodetic concepts and tools in academia, consulting, water management, or environmental or water governing authorities.

## 5. Conclusions and Call to Action

We have found an exponential increase in the number of publications using Hydrogeodesy to study water resources (Figure 1). This surge in research interest, driven by recent and near-future launches of hydrogeodetic missions with enhanced spatial and temporal resolution capabilities and coverage beyond those in orbit,

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underscores hydrogeodesy's growing value in addressing complex water-related challenges and expanding the frontiers of hydrological research. Water scientists and practitioners need to be informed of these developments, know where to access the data, and know how to integrate new hydrogeodetic information to benefit from its application in water management decision-making and practices. This aligns with our finding of a high and yet unexplored (in some cases) potential application of hydrogeodetic technologies to many hydrological and water-related problems (Table 2). Besides Gravimetry, studies using other hydrogeodetic technologies (GNSS, Altimetry, and InSAR) are mostly published outside water-resources-related journals (Figure 4) and could permeate the water science community more thoroughly. This may be achieved by making data sets, tools, and methods more easily accessible, allowing for more resources to be focused on understanding hydrological processes and applications.

We also emphasize the importance of communication and collaboration between hydrogeodetic technology developers, water scientists, and practitioners. Improving channels for such communication will enhance the potential of hydrogeodetic technologies to aid in resolving key hydrological and sustainability questions. One possible mechanism is setting a timely Hydrogeodesy agenda in the new decade of the IAHS of Science for Water Solutions “Hydrology Engaging Local People In one Global World” (HELPING) (Arheimer et al., 2024). For instance, Theme 3 of HELPING aims to integrate new technologies with existing ones and co-create hydrological knowledge between people and disciplines. This Theme will leverage transdisciplinary research and could also integrate Hydrogeodesy (remote sensing, geodesy, and hydrology). The Hydrogeodesy community also needs to organize beyond common research collaborations within main problem niches and areas of expertise on each technology or space mission. This will ultimately set the way for a better understanding and usage of the full potential of Hydrogeodesy to contribute to addressing key hydrological and water-related sustainability questions and challenges.

We find a considerably large percentage of articles using hydrogeodesy and focusing on technical objectives. An explanation for such a percentage of technical manuscripts may be related to the know-how needed to master hydrogeodetic technologies, which becomes a scientific objective per se. Another explanation may be the considerable costs and know-how it entails to use hydrogeodesy to solve questions regarding water management, sustainability, or hydrological processes. Doing so requires double expertise, one in geodetic tools and the other in water-related sciences. Here, the community of Hydrogeodesy faces a crucial crossroads regarding whether to invest and focus research on their improvements as technologies or on their applications. This article points to the latter, giving an overall perspective on the undisclosed potential of hydrogeodesy in solving hydrological and sustainability questions. The road map to do so implies investment in the availability, retrieval, and management of hydrogeodetic data to give opportunities to water-related scientists to focus on the more fundamental scientific questions.

Hydrogeodesy also has an important role in aiding the development and operationalization of global sustainability frameworks, of which the Planetary Boundaries may be the closest related due to its predominantly biophysical focus. In providing nuanced monitoring of water resources, hydrogeodetic technologies could increase the anticipatory capacity for freshwater changes within water management decision-making and enrich the globally aggregated PB picture more towards applicable scales.

Finally, Hydrogeodesy is probably the best way to monitor global changes in freshwater quantity, which is needed to track and determine humanity's safe operating space. By providing comprehensive data on critical hydrological variables, hydrogeodesy stands as a crucial tool for defining but also actively managing Earth's freshwater resources within the planetary boundaries' framework, ensuring sustainable use and conservation for future generations. We believe that hydrogeodetic technologies have reached a satisfactory level of maturity and have the potential to play a central role in supporting key global water issues, increasing the understanding of hydrological processes, evaluating human impacts on freshwater resources, their sustainable consumption, and the resilience of socio-hydrologic systems to change.

## Data Availability Statement

The data archiving of the list of publications, including the meta-analysis, their categorization, and grouping, and the expert elicitation is found in the Bolin Centre Database (https://bolin.su.se/data/) at Stockholm University. Please refer to the title https://bolin.su.se/data/jaramillo-2024-hydrogeodesy-1 to retrieve the data.

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