The Potential of Hydrogeodesy to Address Water-related Problems and Sustainability Challenges

Fernando Jaramillo, Saeid Aminjafari, Pascal Castellazzi, Ayan Fleischmann, Etienne Fluet-Chouinard, Hossein Hashemi, Clara Hubinger, Hilary R Martens, Fabrice Papa, Tilo Schöne, Angelica Tarpanelli, Vili Virki, Lan Wang-Erlandsson, Rodrigo Abarca Del Rio, Adrian Borsa, Georgia Destouni, Giuliano Di Baldassarre, Michele-Lee Moore, José Andrés Posada-Marín, Shimon Wdowinski, George Allen, Donald Argus, Omid Elm, Luciana Fenoglio, Frédéric Frappart, Xander Huggins, Zahra Kalantari, Simon Munier, Sebastián Palomino-Ángel, Abigail Robinson, Kristian Rubiano, Gabriela Siles, Marc Simard, Chunqiao Song, Christopher Spence, Mohammad J Tourian, Yoshitake Wada, Chao Wang, Jida Wang, Fangfang Yao, W R Berghuijs, Jean-François Cretaux, Jay Famiglietti, Alice Fassoni-Andrade, Jessica V Fayne, Félix Girard, Matti Kummu, Kristine M Larson, Martin Maranon, Daniel M Moreira, Karina Nielsen, Tanlin Pavelsky, Francisco Pena, J T Reager, Maria Cristina Rulli, and Juan F Salazar

1Department of Physical Geography/ Bolin Centre for Climate Research, Stockholm University
2Commonwealth Scientific and Industrial Research Organisation (CSIRO)
3Mamirauá Institute for Sustainable Development, Mamirauá Institute for Sustainable Development
4Earth Systems Science Division, Pacific Northwest National Laboratory
5Department of Water Resources Engineering, Lund University
6Department of Geosciences, The University of Montana
7Université de Toulouse, LEGOS (CNES/CNRS, IRD/UT3)
8Department Geodesy, GeoForschungsZentrum Potsdam
9Research Institute for the Geo-hydrological Protection, National Research Council
10Water and Development Research Group, Aalto University
11Stockholm Resilience Centre, Stockholm University
12Potsdam Institute for Climate Impact Research
13Anthropocene Laboratory, Royal Swedish Academy of Sciences, Stockholm University
14Departamento de Geofísica, Universidad de Concepción
15Scripps Institution of Oceanography, University of California San Diego
16Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology
17Affiliation not available
18Department of Earth Sciences, Uppsala University
19Dept of Geography and Centre for Global Studies, University of Victoria
20Grupo de Investigación INDEES, IU Digital de Antioquia
21Institute of Environment, Department of Earth and Environment, Florida International
The Potential of Hydrogeodesy to Address Water-related Problems and Sustainability Challenges


Corresponding author: Fernando Jaramillo (fenando.jaramillo@natgeo.su.se)
17. Department of Earth Sciences, Uppsala University, Sweden
18. Dept of Geography and Centre for Global Studies, University of Victoria, Australia
19. Grupo de Investigación INDEES, IU Digital de Antioquia, Colombia
20. Institute of Environment, Department of Earth and Environment, Florida International University, United States
21. Department of Geosciences, Virginia Polytechnic Institute and State University, United States
22. Jet Propulsion Laboratory, California Institute of Technology, United States
23. Institute of Geodesy, University of Stuttgart, Germany
24. Institute of Geodesy and Geoinformation, University of Bonn, Germany
25. ISPA, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE), France
26. Department of Civil Engineering, University of Victoria, Australia
27. Météo-France, Centre National de Recherches Météorologiques, France
28. Department of Biology, Faculty of Natural Sciences, Universidad del Rosario, Colombia
29. Département des sciences géomatiques, Université Laval, Canada
30. Radar Science and Engineering Section, Jet Propulsion Laboratory, California Institute of Technology, United States
31. Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, 210008, China
32. China University of Chinese Academy of Sciences, Nanjing (UCASNJ), Nanjing, 211135, China
33. Environment and Climate Change Canada, Water Science and Technology Directorate, Canada
34. Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Saudi Arabia
35. Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, United States
36. Department of Geography and Geographic Information Science, University of Illinois Urbana-Champaign, United States
37. Environmental Institute, University of Virginia, United States
38. Faculty of Science, Vrije Universiteit Amsterdam, The Netherlands
39. LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS, Toulouse, France
40. School of Sustainability Faculty, Arizona State University, United States
41. Institute of Geosciences, University of Brasília, Brazil
42. Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, United States
43. Géosciences Environnement Toulouse, Université de Toulouse, France
Abstract

Increasing climatic and human pressures are changing the world’s water resources and hydrological processes at unprecedented rates. These changes require monitoring water resources from ground and space at different temporal and spatial scales. This monitoring can be achieved with Hydrogeodesy, the science that measures the Earth’s solid and aquatic surfaces, gravity field, and their changes over time. Hydrogeodesy encompasses geodetic technologies such as Altimetry, Interferometric Synthetic Aperture Radar (InSAR), Mass gravimetry, and Global Navigation Satellite Systems (GNSS). During the last thirty years, these technologies have contributed to quantifying changes in surface and groundwater resources locally, regionally, and globally. Yet, to our knowledge, the evolution and combination of these technologies and their role within current hydrological, sustainability science, and management frameworks remain unaddressed. Here, we first perform a meta-analysis of over 3,000 articles to understand the range, trends, and applications of hydrogeodetic technologies. Second, we discuss the potential of Hydrogeodesy to significantly advance hydrology, water-related sustainability, and water management. For this, we focus on the 23 Unsolved Questions of the International Association of Hydrological Sciences and the Planetary Boundaries framework (meant as guidance towards a safe operating space for humanity). We find a growing body of literature relating to the advancements in methods, accuracy, precision, and measurements of these technologies and support of hydrological modeling. Hydrogeodesy is also largely published in multidisciplinary and remote sensing journals, which points to considerable potential for integration with water-related sciences, especially regarding terrestrial water features such as wetlands, permafrost, lakes, and rivers. We call for a coordinated way forward for hydrogeodesists to increase interdisciplinary collaboration and broader and deeper application of Hydrogeodesy for understanding and managing water resources and to provide guidance for a safe operating space for humans regarding water resources.

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; Jaramillo & Destouni, 2015b; Konikow & Kendy, 2005; Porkka et al., 2022; Yao et al., 2023). For example, global terrestrial water storage has decreased considerably in some regions due to freshwater consumption for energy and agriculture (M. Rodell et al., 2018). Around four 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 boundaries describing a safe operating space for humanity (Destouni et al., 2013; Jaramillo & Destouni, 2015a; Porkka et al., 2022; Richardson et al., 2023; Wang-Erlandsson et al., 2022).

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 are uniquely able to 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 depth, 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” (Shimon 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 i) Nadir-looking Altimetry (hereafter “Altimetry”), ii) Interferometric Synthetic Aperture Radar (InSAR), iii) Mass Gravimetry (hereafter “Gravimetry”), and iv) Global Navigation Satellite Systems (GNSS) (Fig. 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, which combines both nadir-looking Altimetry and a wide-swath Ka-band Interferometric Synthetic Aperture Radar (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; H. Lee et al., 2020; J. Lee, 2017; Papa & Frappart, 2021; White et al., 2022). However, how the use of these technologies has recently evolved, and their role within current water-related science and water management are questions that, to our knowledge, remain overlooked and, thus, are the focus of this review.
This study addresses two main research questions: (1) How has the field of Hydrogeodesy developed throughout the last three decades? and (2) 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 use insights from hydrogeodetic researchers to discuss the potential of Hydrogeodesy to address key water-related science and management frameworks, including the 23 Unsolved Problems of the Hydrological Community (Günter Blöschl et al., 2019) and the Planetary Boundaries Framework for guidance towards a safe operating space for humanity (Rockström et al., 2009).

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 most hydrological observations are point measurements of hydrological variables, such as water level or soil moisture, hydrogeodetic observations are obtained indirectly from geodetic data. These data are then translated to hydrological quantities, such as terrestrial water storage, snow depth, and surface water level (Fig. 1). The main advantages of spaceborne hydrogeodetic observations are their wide spatial coverage, low costs to the end user, relatively high spatial and temporal
resolution, and continuity and standardization of measurements, which enable comparison between multiple freshwater bodies across regions. For example, InSAR observations can achieve a spatial resolution of 1 to 100 meters, depending on acquisition parameters; GNSS-IR (interferometric reflectometry) integrates observations of soil moisture and snow depth over an area of roughly 100 m²; and GNSS- and GRACE-inferred estimates of terrestrial water storage cover wide areas, often on the order of tens to hundreds of square kilometers. The dimensions of an observed area vary depending on the measurement techniques, from ten to one hundred meters, in the case of GNSS-IR, to thousands of kilometers in GRACE measurements (Fig. 2).

Figure 2. Temporal and spatial scales of hydrological processes (diagonal and horizontal ellipses with grey 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 & Sivapalan (1995).

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 heights by considering the two-way travel time of radar or laser pulses between the satellite and Earth and applying specific corrections (Benveniste, 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; G. 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 or 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 (Guneriusser et al., 2001; Molan et al., 2018; Oveisghar & Zeberk, 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 (e.g., Hong & Wdowinski, 2014; S.-W. Kim et al., 2013; Liao et al., 2020; Siles et al., 2020; Shimon Wdowinski & Hong, n.d.; 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, its potential for inferring lake water levels is also gaining some attention (Palomino-Ángel et al., 2022).

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 terrestrial water storage (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 melting of the ice caps 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; Wang et al., 2021). Although satellite gravity’s low spatiotemporal resolution makes it difficult for usage in smaller aquifers (Melati et al., 2019), and although 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 (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 position changes (e.g., East, North, and Up). 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 et al., 2014; 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 that are 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 (C. C. Chew & Small, 2018a; Eroglu et al., 2019) and to monitor 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 (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 (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 the Clarivate Web of Science for English-language articles on Hydrogeodesy in, published 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, i.e., Gravimetry, InSAR, 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.

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 be able 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 3,657 articles (See Supplementary Materials for query).

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 (UASs) or Ground Penetrating Radar (GPR) 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 did this as we considered it essential to determine the scientific audience targeted by the articles’ authors, especially the difference between water-related and remote-sensing journals. 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, i.e. 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 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 datasets.

- **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 (Modelling)** – 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 to 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.

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 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. 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).

**Table 1.** Space geodetic technologies relevant to hydrology and the study of water resources, modified and updated after Wdowinski & Eriksson (2009). 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.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Acronym/Type</th>
<th>Agency</th>
<th>Time</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Navigation Satellite Systems (GNSS)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
<td>DoD</td>
<td>1980-present</td>
<td>Solid Earth, Hydrology, Glaciology, atmosphere, Ionosphere, Natural hazards</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Global Positioning System</td>
<td>USSR, Russia</td>
<td>1982-present</td>
<td></td>
</tr>
<tr>
<td>Galileo</td>
<td>Global Positioning System</td>
<td>ESA</td>
<td>2002-present</td>
<td></td>
</tr>
<tr>
<td>BeiDou-1/2/3</td>
<td>Global Navigation Sat. System</td>
<td>CNSA</td>
<td>2000-present</td>
<td></td>
</tr>
<tr>
<td><strong>IRNSS</strong></td>
<td>Regional Navigation Sat. System</td>
<td>ISRO</td>
<td>2013-present</td>
<td></td>
</tr>
<tr>
<td>QZSS</td>
<td>Quasi-Zenith Satellite System</td>
<td>JAXA</td>
<td>2018-present</td>
<td></td>
</tr>
<tr>
<td><strong>Altimetry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SeaSAT</td>
<td>Radar Altimetry</td>
<td>DoD</td>
<td>1978</td>
<td>Oceanography</td>
</tr>
<tr>
<td>GeoSAT</td>
<td>Radar Altimetry</td>
<td>DoD</td>
<td>1985-1989</td>
<td>Oceanography, Hydrology, Glaciology, Geoid determination</td>
</tr>
<tr>
<td>GeoSAT-Follow</td>
<td>Radar Altimetry</td>
<td>NASA</td>
<td>1998-2008</td>
<td></td>
</tr>
<tr>
<td>ERS-1</td>
<td>Radar Altimetry</td>
<td>ESA</td>
<td>1991-1996</td>
<td></td>
</tr>
<tr>
<td>TOPEX/Poseidon</td>
<td>Radar Altimetry</td>
<td>NASA/CNES</td>
<td>1992-2005</td>
<td></td>
</tr>
<tr>
<td>Jason-1/2/3</td>
<td>Radar Altimetry</td>
<td>NASA/CNES</td>
<td>2002-present</td>
<td></td>
</tr>
<tr>
<td>ERS-2 (RA-1)</td>
<td>Radar Altimetry</td>
<td>ESA</td>
<td>1995-2011</td>
<td></td>
</tr>
<tr>
<td>ENVISAT (RA-2)</td>
<td>Radar Altimetry</td>
<td>ESA</td>
<td>2002-2012</td>
<td></td>
</tr>
<tr>
<td>ICESat</td>
<td>Laser Altimetry</td>
<td>NASA</td>
<td>2003-2009</td>
<td></td>
</tr>
<tr>
<td>ICESat-2</td>
<td>Laser Altimetry</td>
<td>NASA</td>
<td>2018-present</td>
<td></td>
</tr>
<tr>
<td>CryoSAT-2</td>
<td>SAR, Interfer. Radar Altimeter</td>
<td>ESA</td>
<td>2010-present</td>
<td></td>
</tr>
<tr>
<td>Sentinel-3</td>
<td>SAR Altimetry</td>
<td>ESA</td>
<td>2016-present</td>
<td></td>
</tr>
<tr>
<td>SWOT</td>
<td>Radar interferometer / Altimeter</td>
<td>NASA/CNES</td>
<td>2022-present</td>
<td></td>
</tr>
<tr>
<td>Sentinel-6/MF</td>
<td>Radar Altimetry</td>
<td>ESA/NASA/CNES</td>
<td>2020-present</td>
<td></td>
</tr>
<tr>
<td>SARAL/AlRiKa</td>
<td>Radar Altimetry</td>
<td>CNES / ISRO</td>
<td>2013-present</td>
<td></td>
</tr>
<tr>
<td>GEDI</td>
<td>Laser Altimetry</td>
<td>NASA</td>
<td>2018-present</td>
<td></td>
</tr>
<tr>
<td><strong>(InSAR) Interferometric Synthetic Aperture Radar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SeaSAT</td>
<td>L-band, HH polarization (pol)</td>
<td>DoD</td>
<td>1978</td>
<td>Oceanography</td>
</tr>
<tr>
<td>ERS-1</td>
<td>C-band, VV pol</td>
<td>ESA</td>
<td>1991-1996</td>
<td>Solid Earth, Hydrology, Glaciology, Oceanography, Geotechnical, Natural hazards</td>
</tr>
<tr>
<td>ERS-2 (SAR)</td>
<td>C-band, VV pol</td>
<td>ESA</td>
<td>1996-2012</td>
<td></td>
</tr>
<tr>
<td>JERS-1</td>
<td>L-band, HH pol</td>
<td>JAXA</td>
<td>1992-1998</td>
<td></td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>C-band, HH pol</td>
<td>CSA</td>
<td>1995-2013</td>
<td></td>
</tr>
<tr>
<td>ENVISAT (ASAR)</td>
<td>C-band, VV+VH, HH+HV pol</td>
<td>ESA</td>
<td>2002-2012</td>
<td></td>
</tr>
<tr>
<td>ALOS (PALSAR)</td>
<td>L-band, quad-pol</td>
<td>JAXA</td>
<td>2006-2011</td>
<td></td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>C-band, quad-pol</td>
<td>CSA</td>
<td>2007-present</td>
<td></td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>X-band, quad-pol</td>
<td>DLR</td>
<td>2007-present</td>
<td></td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>X-band, quad-pol</td>
<td>DLR</td>
<td>2010-present</td>
<td></td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>X-band, quad-pol</td>
<td>ASI</td>
<td>2007-present</td>
<td></td>
</tr>
<tr>
<td>Rast-1</td>
<td>C-band, quad-pol</td>
<td>ISRO</td>
<td>2012-2017</td>
<td></td>
</tr>
<tr>
<td>KOMPAS-5</td>
<td>X-band, quad-pol</td>
<td>KARI</td>
<td>2013-present</td>
<td></td>
</tr>
<tr>
<td>ALOS-2</td>
<td>L-band, quad-pol</td>
<td>JAXA</td>
<td>2014-present</td>
<td></td>
</tr>
<tr>
<td>Sentinel-1 A</td>
<td>C-band, dual-pol</td>
<td>ESA</td>
<td>2014-present</td>
<td></td>
</tr>
<tr>
<td>Sentinel-1 B</td>
<td>C-band, dual-pol</td>
<td>ESA</td>
<td>2016-present</td>
<td></td>
</tr>
<tr>
<td>PAZ</td>
<td>X-band, quad-pol</td>
<td>PNOTS</td>
<td>2018-present</td>
<td></td>
</tr>
<tr>
<td>SAOCOM-1</td>
<td>L-band, quad-pol</td>
<td>CONAE</td>
<td>2018-present</td>
<td></td>
</tr>
<tr>
<td>RadaSat Constell.</td>
<td>C-band, dual-pol</td>
<td>CSA</td>
<td>2019-present</td>
<td></td>
</tr>
<tr>
<td>NISAR</td>
<td>L-band</td>
<td>NASA</td>
<td>2024</td>
<td></td>
</tr>
</tbody>
</table>

**Gravity missions**

| Technology | | | | |
| LAGEOS-1/2 | Laser Geodynamics Satellites | NASA | 1976-present | |
| Ajisai | Experimental Geodetic Satellite | JAXA | 1986-present | |
| CHAMP | Challenging Minisat. Payload | DLR | 2000-2010 | |
| GRACE | The Gravity Recovery and Climate Experiment | NASA/DLR | 2002-2017 | |
| GRACE-FO | Gravity field and steady-state Ocean Circulation Explorer | ESA | 2009-2013 | |

**Global geodetic constellations**

| Technology | | | | |
| LAGEOS-1/2 | Laser Geodynamics Satellites | NASA | 1976-present | |
| Ajisai | Experimental Geodetic Satellite | JAXA | 1986-present | |
| CHAMP | Challenging Minisat. Payload | DLR | 2000-2010 | |
| GRACE | The Gravity Recovery and Climate Experiment | NASA/DLR | 2002-2017 | |
| GRACE-FO | Gravity field and steady-state Ocean Circulation Explorer | ESA | 2009-2013 | |
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 (Fig. 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 (Fig. 3a). Its six-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.

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), GNSS (739), InSAR (626), Altimetry (547), and their combination (561). 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.

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 (Fig. 3b). A smaller number of studies combine up to three technologies (n=44), such as Yuan 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 (Fig. 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 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 processing required by the user is low, with monthly gridded datasets for land water storage already available, reducing data processing costs for the user and being 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 datasets have global coverage and are available at no cost to end users. The first such dataset 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.difi.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; Fig. 4). Regarding InSAR (20%), although datasets 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 dataset of InSAR products to study changes in water levels in lakes, reservoirs, and wetlands. This is difficult due to the intense processing and the specialized (and sometimes costly) software required for interferometry. Still, the availability of InSAR processing tools for hydrologists is increasing, with the spread of open-source software and services such as Hyp3 (K. Hogenson et al., 2016) and OpenSARLab at the Alaska Satellite Facility enable 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 (EGMS) (Crosetto et al., 2021), and the NISAR mission will publish interferogram of all imaged areas as a standard and freely available data product. Finally, the NASA-CNES SWOT mission
launched in December 2022 will soon provide surface water levels and storage changes (in pixel-cloud and raster products) with ~100 m spatial resolution and a repeat cycle of 21 days for most open waters worldwide during its time in orbit (Papa & Frappart, 2021). This is crucial for tracking rapid changes in water bodies and offering timely data for effective water management. Furthermore, the mission's synergy its combination with NISAR will expand such quantification to the vegetated waters of wetlands areas., providing vital insights into the interconnected nature of global water systems.

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.

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 (Fig. 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 and reservoirs worldwide due to their improved spatial coverage and along-track resolution. While earlier applications focused on larger water bodies only, advances in retracking algorithms minimize the impact of non-water reflections and allow now to track lakes of only a few hectares, under the condition that the satellite track covers the lakes (Boy et al., 2022; Egido & Smith, 2017). Regarding laser altimeters, they can mostly monitor small water bodies sporadically regarding water levels (Cooley et al., 2021; Sulistioadi et al., 2015), yet for ground height products measuring the banks of the lakes, combination with optical or radar imagery can increase temporal resolution (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 that can occur across a study area (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 (P. Castellazzi et al., 2019) and large impounded reservoirs such as the Grand Renaissance Dam in Ethiopia (Kansara et al., 2021) or the Three Gorges Dam in China (Huang et al., 2015). This, 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., 2002; Rodell et al., 2007; Scanlon et al., 2012), which represents one of many interdisciplinary applications of Gravimetry at the interface of water science and sustainability.

InSAR follows Gravimetry as the technology most used to track groundwater changes, using ground surface deformation as a proxy of groundwater storage change (4%). InSAR studies can relate ground and infrastructure subsidence to human groundwater withdrawal. For instance, InSAR can track the poroelastic deformation of the sub-surface related to changes in groundwater pressure, which propagates into changes in ground elevation at the surface. If elastic, once the aquifers are recharged, water content and pressure change, and the ground will later rise (Adams et al., 2022). InSAR has been used to identify poroelastic deformation in aquifers such as that of the San Joaquin Valley in California and Mexico City, which can be used to determine water use/withdrawal rates (Khorrami et al., 2020; Levy et al., 2020; Pardo et al., 2013; Smith et al., 2017). The InSAR method can also be combined with groundwater level data to calculate storage coefficients and groundwater heads (e.g., Chen et al., 2016). One limitation of InSAR for groundwater studies is dense vegetation cover, which reduces the coherence in time of the SAR signal. This explains why most InSAR studies studying groundwater changes focus on urban or agricultural areas with features such as infrastructure that enable a coherent signal. This also challenges large-scale InSAR applications, which inherently cover a wide range of land covers and, consequently, spatially variable InSAR noise levels (Castellazzi et al., 2021; Du et al., 2023). Recently, improvements in InSAR processing (Castellazzi & Schmid, 2021; Zebker & Chen, 2023) and machine learning have been proven useful to address this challenge (Naghibi et al., 2022). Another frequent challenge in InSAR applications for groundwater studies is the separation of deformation signals from different, spatially coinciding sources, such as stacked aquifers and clayey soils occurring in large alluvial fans (Castellazzi et al., 2021).

In locations with continuously operating GNSS networks, regional (i.e., watershed to basin-scale) TWS or groundwater storage can be inferred from the corresponding elastic Earth deformation response to surface and near-surface water loads (Fig. 5; 3% for groundwater and TWS). This is done using known Green’s functions for load displacements at individual GNSS stations (e.g., Farrell, 1972) to invert observed GNSS positions for the gridded load changes that best explain deformation across the network. The spatial resolution of this method is theoretically dependent on the spacing of the stations, but with a lower limit of ~50 km. Temporal resolution is limited by short-period non-loading signals and other noise in the daily
GNSS positions, but is at least 7 days (e.g., Adusumilli et al., 2019). Terrestrial water storage changes estimated from GNSS include water cycling through the Himalayas (Fu & Freymueller, 2012), seasonal water changes in the western USA (Argus et al., 2014; Fu et al., 2015), multiannual cycles of drought and recovery (Adusumilli et al., 2019; Argus et al., 2017; Borsa et al., 2014), and the impact of individual storms (Milliner et al., 2018).

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

GNSS applications 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. Regarding soil moisture (6%), GNSS-R, which consists of analyzing the GNSS signals reflected by the Earth’s surface, is now increasingly used to retrieve soil moisture variations from ground-based receivers. The launch of the first spaceborne GNSS-R missions, and especially the Cyclone Global Navigation Satellite 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 (Fig. 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 related to measuring water levels in these ecosystems; vegetation covering wetlands and peatlands limits certain technologies, and their inaccessibility limits the ground-truthing of the hydrogeodetic measurements. InSAR is probably the best technology for solving this issue. It is generally agreed that a SAR signal with a longer wavelength and lower frequency, such as L-band sensors, better penetrates 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 (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).

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 (70%), either aiming to improve methods/technologies (Fig. 6, Technical category, 49%), to estimate a specific hydrological variable and its variation in time and space (Fig. 6; Hydrovariable category, 28%), or as an aid for hydrological, geomorphological or hydraulic modelling (Fig. 6; Modelling category, 7%). The first is the most recurrent category of type of objective, 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; Wang et al., 2022; Wang & Morton, 2022). Gravimetry studies have the smallest proportion of studies falling under this category.

Regarding the second category (Fig. 6; Hydrovariable), many of the articles also aim to quantify the direct hydrological or geological variables that the technology can track (see Fig. 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 (M. 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 (ENSO) events (Bolanos et al., 2021).

Hydrogeodetic studies that address hydrological problems beyond technical developments, such as those aiming to understand hydrological and geomorphological processes or human impacts, are less numerous (Fig. 6; 38%, 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 and lake ice patterns (e.g., Kouraev et al., 2007; Siles & Leconte, 2023), providing evidence of the impacts of climate change on these freshwater ecosystems. Nevertheless, hydrogeodetic techniques are 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, when water mass increases, the additional weight depresses the ground surface, resulting in subsidence. If the deformation is inelastic, the permanent change to poor pressure will not be reversed once the force from the water mass load is removed. A particular case study of this effect is Lake Mead, United States, where drought and related water storage changes in the reservoir have resulted in an uplift in the surrounding areas, as well as displacements in Hoover Dam (Cavalić 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).

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. Grey numbers on the right represent the number of articles of each technology addressing a specific category of article objective.

4.6 The potential of Hydrogeodesy to help solve key hydrological problems

The International Association of Hydrological Studies (IAHS) has outlined the main focus topics for the Hydrological Community during the last three decades. The first decade (2003–2012) was termed the Decade on Predictions in Ungauged Basins (PUB), 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 observation of thousands of rivers, lakes, reservoirs, and glaciers to synthesize their changes and implications for society (Fig. 3-5). As part of this initiative, the IAHS has also proposed the Twenty-Three 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). The problems regarding Hydrology Interfaces with Society (UPHs 21-23) rank high among hydrogeodesists, especially the UPH related to the role of socio-hydrology and focusing on the role of water in migration, urbanization and human dynamics, and the implications for water management (UPH 23). Sociohydrology studies the interplay between water, infrastructure, and society (Di Baldassarre et al., 2013; Di Baldassarre et al., 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; 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 datasets of change in water resources from multiple places around the world, Hydrogeodesy can help i) unravel generic patterns and trends in the way that societies extract and transport energy sources, produce and convert energy, irrigate crops for biofuel production, and produce water-intensive renewable energy, ii) advance our understanding of the relationship between economic growth and water flows, iii) develop a complete picture of changes in global water resources by reducing the bias in in-situ monitoring towards the Global North, and iv) uncover the interconnected nature of food-energy-water systems and potentially enhance our ability to address all Sustainable Development Goals (SDGs) (Di Baldassarre et al., 2019).

Addressing the UPHs related to Measurements and data (UPHs 16-18) and Modelling 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 from hydrogeodesists to support hydrological modeling, either for its parametrization, calibration, validation, or assimilation (Fig 6; Modelling). It is worth noting the case of Gravimetry, where due to the many water components included in TWS observations, terrestrial water storage changes are usually validated with hydrological models and reanalysis products to obtain specific fluxes and stocks on the surface or below (Niu & Yang, 2006; Ramillien et al., 2021; Velicogna & Wahr, 2002). To give some examples, GRACE has been used to evaluate TWS with the World Climate Research Programme’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).
Table 2. How hydrogeodetic technologies could help answer the unsolved problems in hydrology of the IAHS. 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, green). 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.

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 storage during drought periods and conveying 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. With respect to water resource management, monitoring reservoirs by measuring water height by 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 National Water Agency has started incorporating hydrogeodetic technologies for the operational monitoring of
reservoirs and provisions of services to many communities and economic sectors across the country.

Addressing the agenda set out by IAHS and the UPs 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). The use of 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). 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 these technologies to detect signals and changes in near real-time could shorten these lags, leading to more responsive and effective management.

4.7 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 PBs framework has emerged as highly influential in the global sustainability agenda, and researchers and practitioners are increasingly attempting to operationalize it to translate planetary boundaries into actionable insights for local management and business strategies. Operationalising implies translating or downscaling planetary boundaries 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 provide accurate assessments of freshwater dynamics, essential for managing Earth's water resources sustainably and bridging global environmental goals with localized water management strategies. A widely known application used for operationalizing is the Doughnut 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. 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 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 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 (Fig. 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), and soil moisture (Porkka et al., 2022; 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 (Fig. 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 not explored yet 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. 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 (Fig. 7, right) and the other PBs representing other earth system processes or domains (Fig. 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, 2018b; Clarizia et al., 2019). Gravimetry and InSAR can enhance our ability to accurately monitor water changes, particularly in regions where ground-based data are scarce. 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; Matthew 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.

**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 grey circle). The sub-boundaries 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.

5 Conclusions and Call to Action

We have found an exponential increase in the number of publications using Hydrogeodesy to
study water resources (Fig. 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, underscores hydrogeodesy's growing value in addressing
complex water-related challenges and expanding the frontiers of hydrological research. We
expect this trend to continue due to the recent and near-future launch of hydrogeodetic missions
with spatial and temporal resolution and coverage beyond those currently in orbit. 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 (Fig 4) and could permeate the water
science community more thoroughly. This may be achieved by making datasets, tools and
methods more easily accessible, allowing for more resources to be focused on the
understanding of 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). 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 pertaining to 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.

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. The novel Earth System Boundaries framework
also aims to integrate the planetary safe operating space with justice aspects of this framework
and to present quantitative sub-global safe and just Earth System boundaries – including
surface water and groundwater. 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.

Acknowledgements

We thank the various space agencies (NASA, ESA, JAXA, CSA, DLR, CNES) for providing data to all the hydrogeodetic studies mentioned in this article and which have permitted all the possible ways that water resources can be studied with hydrogeodesy. The contributions of F.J., S.A., C.H., A.R., F.P., M.M., K.R., were funded with resources from the Swedish National Space Agency (180/18), Projects 2022-02148 and 2022-01570 of the Swedish Research Council for sustainable development and Project 2021-05774 of the Swedish Research Council (VR). M.K. and V.V. thank the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (SOS.aquaterra; grant agreement No. 819202). F.F. acknowledges CNES TOSCA grants: SWOT Wetlands Hydrology Monitoring (SWHYM) and Suivi des surfaces COntinentales par Mesures Aéroportée et satellites GNSS-R (SCOMAG). L.W.-E. is supported by funding from Formas (2019-01220, 2022-02089, 2023-0310 and 2023-00321), the IKEA Foundation, the Marianne and Marcus Wallenberg Foundation, and the Marcus and Amalia Wallenberg Foundation, Horizon Europe (101081661), and the European Research Council (ERC) (ERC-2016-ADG-743080).

Open Research

The list of publications include in the metanalaysis, their categorization and grouping, as well as the code used to retrieve and organize the data, will be freely available through the Bolin Centre Database (https://bolin.su.se/data/) at Stockholm University. Please refer to the title “Metanalaysis of Hydrogeodesy” to retrieve the data.

References


Castellazzi, Pascal, Garfias, J., & Martel, R. (2021). Assessing the efficiency of mitigation measures to reduce groundwater depletion and related land subsidence in Querétaro (Central Mexico) from decadal InSAR observations. *International Journal of...*


Oliver-Cabrera, T., & Wdowinski, S. (2016). InSAR-Based Mapping of Tidal Inundation Extent and Amplitude in Louisiana Coastal Wetlands. *REMOTE SENSING, 8*(5), 393. https://doi.org/10.3390/rs8050393


37


of the American Meteorological Society, 97(3), 385–395. https://doi.org/10.1175/BAMS-D-14-00218.1


