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Satellite Remote Sensing of Terrestrial Hydrology

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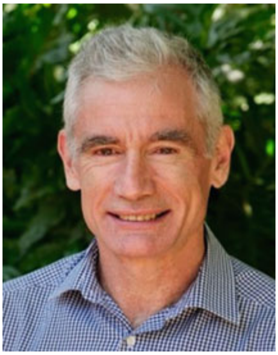
Foreword

Remote sensing using satellites with optical detection capability has been possible for some decades now, since the first Landsat missions of the 1970s. However, the uptake and use of satellite remote sensing for environmental applications has not been commensurate with emerging technological improvements in sensor spectral, spatial, radiometric, and geometric capability. Additionally, some of the potential of satellite remote sensing for environmental monitoring is only now starting to be realized with the development of coordinated strategies to support data acquisition, processing (e.g., using 'artificial intelligence') and visualization products. This book on Satellite Remote Sensing of Terrestrial Hydrology by Dr. Christopher Ndehedehe is timely and relevant because it provides a state-of-the-art synthesis of the field of remote sensing hydrology. It should be essential reading for many interested students, educationalists, and practitioners; from undergraduate students who seek fundamental knowledge about how remote sensing can improve their understanding of hydrological systems, to advanced practitioners who wish to update their technological, analytical, and/or hydrological skills. In between is a large and diverse group who will benefit from the many components of remote sensing hydrology described in this book, with application for hydrologists, graduate students studying in the area, and environmental managers who are interested in utilizing the potential of remote sensing to assist with improved decision-making for water management.

Changes in global surface water storage in the 'Era of the Anthropocene' is an area that is reiterated throughout this book, including impacts on vegetation cover, climate change and relationships to floods and droughts, and the impact of large surface water reservoirs. A series of case studies from across the globe reinforces the seriousness of the rate of change in our hydrological systems. These case studies have been selected as global hotspots to demonstrate the speed of hydrological change, issues of water scarcity and drought, and the geopolitical context that influences the quality of decision-making for water management.

Satellite Remote Sensing of Terrestrial Hydrology presents exciting new opportunities from satellite technological advances and analytical platforms. For example, the book provides background information and case studies related to the Gravity Recovery and Climate Experiment satellite observations. The resulting geospatial data can provide regional-scale assessments of groundwater storage that can be linked to surface water availability and vegetation cover. The Google Earth Engine and other cloud-based platforms discussed in the book are making satellite data increasingly accessible and are being used to perform critical pre-processing steps to ease the barrier to entry in the exploration of satellite data. The book also includes a forward-looking perspective in the discussion of new satellite hydrology missions like the Surface Water Ocean Topography mission scheduled for launch in 2022. The combination of theoretical understanding, synthesis of technological advances and case studies makes this book especially useful.

Dr. Christopher Ndehedehe is an academic in the Australian Rivers Institute at Griffith University who, despite being in the early stages of his career, has established himself as a global leader in hydrological remote sensing and environmental geoscience. He is pioneering the development of new geospatial tools to support assessments of tropical floodplain hydrology and the impacts of climate change on surface water, groundwater, and ecological resources. Dr. Ndehedehe is a prolific writer who has bridged multiple scientific disciplines in compiling chapters in Satellite Remote Sensing of Terrestrial Hydrology. The book provides all the tools required to successfully apply remote sensing in terrestrial hydrological assessments and should be essential reading for anyone with an interest in this subject.



March 2021

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Preface

The use of multi-mission optical satellite systems in environmental monitoring, including applications in hydrology and water resources has been the focuse in the last few decades. These satellite technologies provided a continuous and systematic stream of geospatial information across different time scales that underpinned an improved understanding of environmental processes and systems. Without any doubt, the application of satellite technologies in global environmental monitoring has contributed to new directions in policy, creating innovative opportunities to address several socio-economic and environmental issues confronting society. However, the potential of recent technological advances in satellite remote sensing, be it optical or geodetic systems, is still not well articulated and not fully understood. Dedicated satellite hydrology missions for direct monitoring of terrestrial water storage and fluxes have only recently emerged and others are scheduled to be launched in the coming months. But the opportunities that exist through the use of existing innovative satellite methods and frameworks to improve understanding, management, and monitoring of natural systems and key Earth resources are yet to be fully explored. The concept of satellite hydrology only became more pronounced after the launch of the Gravity Recovery and Climate Experiment (GRACE) in 2002. Satellite hydrology missions like GRACE and its successor (GRACE-Follow On) and radar altimetry missions as well as the anticipated Surface Water Ocean Topography mission, among other existing missions lead to a new satellite hydrology concept called remote sensing hydrology. This concept as further advocated in this book encapsulates the cross-disciplinary aspects of environmental geoscience and remote sensing of the environment, as well as integrating several geospatial tools and methods, including relevant cognate disciplines to provide quantitative evaluation of terrestrial hydrology. The growing need to understand hydrological processes and impacts of climate change as well as human actions (e.g., dams, water diversion projects, land-use change, intensive groundwater extraction, deforestation, surface water resources schemes, etc.) on global freshwater systems necessitated the discussion on GRACE observations in this book. Being an important tool in the box to navigate the challenges posed by lack of or limited observational data for freshwater monitoring (including groundwater, lakes, and reservoirs), its processing chains and hydrological applications are also detailed in this book.

As discussed in this book, the rise in improved sensor capabilities in satellite missions resulted in big remote sensing data. On the one hand, innovative pattern recognition and machine learning algorithms are now increasingly being used to improve key information extraction from the plenitude of big geospatial data. On the other hand, cloud computing platforms, have facilitated the use of data from these satellite systems, contributing to the growing applications of remote sensing observations in environmental monitoring in recent times. These cloud-based platforms are now easy pathways to remote sensing data retrieval and processing as well as geospatial analyses. In this day and age, large earth observation datasets are not only available and freely accessible from global repositories but can also be quickly processed to generate timely information that underpins important organizational decisions. These opportunities have facilitated informed decisions by government institutions, scientists, and the public on the environment. This book discusses, explores, and demonstrates key applications of various earth observations and earth resources satellites ranging from optical remote sensing systems to satellite geodetic systems (e.g., gravity and radar missions) in advancing our fundamental understanding of environmental systems (e.g., vegetation, freshwater ecosystems, droughts, groundwater, lakes, agriculture, etc.). The complexities of hydrological systems and global environmental change in this era of the Anthropocene due to human activities and the impact emanating from variability in natural systems are discussed using a suite of quantitative and empirical region-specific case studies. The book has 20 chapters covering several multidisciplinary aspects of remote sensing hydrology and environmental monitoring. The focus on satellite-based environmental monitoring in this book ensures that opportunities through investments in innovative satellite programmes to optimize key environmental decisions and policies are maximized.

Brisbane, QLD, Australia
March 2021

Christopher Ndehedehe

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I am very grateful to the Almighty God who through His Son, Jesus Christ, my Redeemer and personal Saviour, gave me abundant life and preserved me to see this day. I'm highly appreciative of Griffith University's Areas of Strategic Investment fund, which provided a career pathway for me at the Australian Rivers Institute (ARI) and School of Environment and Science at Griffith University, Queensland. My sincere gratitude also goes to Prof. David Hamilton, Deputy Director, ARI, for his great support as well as his strong leadership and mentorship. Prof. Stuart Bunn, Director of ARI, and the entire ARI family are acknowledged for the conducive and enabling research environment and support that led to my notable accomplishments since joining the institute in June 2018. I also thank Prof. Mark Kennard for his guidance and mentorship as well as the numerous support and help he has offered on several occasions. My work on the National Environmental Science Programme (NESP) projects undertaken in Northern Australia (Mitchel, Gilbert, and Flinders catchments) led to great collaborations with great team leaders and experts in freshwater ecology like Ben Stewart-Koster and Prof Stuart Bunn. The NESP project and international collaborations with Prof. Vagner G. Ferreira of Hohai University, Dr. Onuwa Okwuashi, and Dr. Nathan Agutu, among others, and other freshwater-based consultancies funded by the Asian Development Bank and Australian Water Partnership provided a platform and opportunity that underpinned my pioneering effort in developing the science of remote sensing hydrology. Moreover, working with A/Prof Brian McIntosh, the Education Director for the Master of Catchment Science programme (MCS), International Water Center, Griffith University, on capacity building projects was also very valuable. My postgraduate students (Masters and Ph.D.s) here at Griffith University and the pioneer MCS master's students I taught were also the key motivation for me on the need for an academic textbook and literature that simplifies the concept and provides easy-to-use resources in the field of environmental remote sensing and satellite hydrology. Special thanks to all my collaborators around the world in, the USA, Canada, Australia, Asia, Africa, Europe, and South America, you are all indeed an amazing team of diligent researchers. Collaborating with these excellent brands and teams of academics, which are too numerous to mention here is one of the best things that happened to me in the last 5 years. Their novel and ground-breaking contributions in the fields of water resources, hydro-geodesy, environmental geoscience, climate change, machine learning applications, and remote sensing hydrology also strengthened the concept advocated in this book.

My deepest appreciation goes to my beloved family. To my wife and special love, Mmayen Ndehedehe, her understanding, patience, and support are invaluable. To my three adorable, amazing, and beautiful kids; Koabasi, Kendarabasi, and Kereseabsi, I say thanks for your understanding and patience and God bless you. I'm also grateful to Ms. Enobong Akpan for reading the draft of this book (Chap. 1) just to ensure a non-remote sensing expert can also understand and get the message in the book. Mr. Ikechukwu Kalu is also acknowledged for his similar role among other things, having assisted with reading the draft of this book to ensure undergraduates and postgraduate students will find it an interesting read. I thank my late dad, Mr. Edet John Ndehedehe, who went to be with the Lord in 2018 shortly after I joined ARI. The foundation he laid and his numerous encouragement and prayers contributed immensely to the career path I forged and my success over the years. You are always remembered and may your soul continue to rest in peace. I also appreciate my mum for her consistent and patient love, and to all my siblings for their love and prayers.

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Part I
Global Terrestrial Hydrology

Chapter 1
Remote Sensing Hydrology

Abstract The emergence of new optical sensors provides unique capability in comprehensive monitoring of the environment. As opposed to well-known optical satellite Earth observation systems such as the Landsat and Sentinel missions, there are now satellite systems dedicated to hydrological applications. The combination of geospatial science with these systems provides an innovative satellite hydrology framework that underpins our capability to directly monitor and assess changes in terrestrial stored water and how they are impacted by human actions and climate change. In this chapter, the concept of *remote sensing hydrology* has an emerging discipline is discussed. A distinction between *remote sensing hydrology* and *application of remote sensing in hydrology* is articulated. The latter has been the focus in the last few decades, leveraging several methods to aid the processing of Earth resources satellite for hydrological applications. However, new investments in satellite geodetic programmes (e.g., Gravity Recovery and Climate Experiment mission) and the scheduled launch of the Surface Water and Ocean Topography mission in November 2022 gave birth to the former. These satellite geodetic systems are discipline-specific and dedicated hydrology missions, providing level 1 information on the quantitative aspects of freshwater resources. Together with novel computing technologies for big Earth observation data, they provide improved monitoring capabilities of the earth system that underpins our understanding of environmental processes and changes in hydrological systems.

1.1 Introduction

Several improvements in remote sensing optical systems have occurred in recent years. The use of these technologies in environmental monitoring and impact analysis from extreme events such as droughts, floods, and wildfires has been widely documented. New satellite technologies with capabilities to monitor changes in terrestrial water storage have emerged, complementing the well-known optical systems in baseline studies and freshwater ecosystem assessment. With the large amounts of geospatial data generated from satellite Earth observation systems, cloud computing platforms for big Earth observation data management and analysis such as Google

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Earth Engine, Sentinel Hub, Open Data Cube, and pipsCloud, among several others emerged (e.g., Gomes et al. 2020; Wang et al. 2018; Gorelick et al. 2017) to facilitate timely access and ease the application of these observations for decision support system. These novel computing technologies for big Earth observation data, though with varied levels of sophistication, have since enhanced access to archived petabytes of publicly available Earth observation data, as well as simplifying processing chains of satellite remote sensing observations. The fundamental objective of Earth observation systems in providing a continuous and systematic stream of geospatial information across different time scales to improve understanding of environmental processes and systems has been fostered by the emergence of cloud-based computing platforms. Additionally, these platforms have emerged as excellent alternatives to conventional infrastructures for spatial data sharing and processing. The dissemination of a new generation of digital infrastructure for planetary-scale computing is now today's reality, creating opportunities to address the diverse socio-economic and environmental issues confronting society. The efficacy, sophistication, and innovation behind these technologies and systems are apparently evidenced in the rise of satellite remote sensing applications in global environmental monitoring based on data retrieved and processed with these platforms. This engagement and enthusiasm reaffirm these cutting-edge platforms have been well received by the larger community of experts, students, researchers, and relevant stakeholders who rely on Earth observation for key decisions and regulations.

The application of these satellite technologies as well as cloud-based platforms in monitoring as a key foundation for planning and supervision, as well as for the systematic development of targeted water service delivery and policies, underpin their value as valuable tools in freshwater accounting and management. State-of-the-art satellite hydrology missions such as the Gravity Recovery and Climate Experiment (GRACE, Landerer et al. 2020; Tapley et al. 2004) are such technologies that have enabled the monitoring of freshwater changes and water accounting, including assessment of important contributions to improve our understanding of global water cycle and its responses to changes in climate and anthropogenic actions (Ndehedehe and Ferreira 2020; Tapley et al. 2019; Thomas and Famiglietti 2019; Rodell et al. 2018; Famiglietti and Rodell 2013). Several of these human influence or activities, including the construction of dams and river impoundments, water transfer projects, land-use change, and extensive groundwater extraction for irrigation and industrial applications have been quantified by combining multi-satellite hydrology missions with novel computational models (e.g., Ndehedehe et al. 2021; Getirana et al. 2020; Long et al. 2020; Zarfl et al. 2015). In the light of this recent advances, it is therefore important to facilitate the dialogue between knowledge providers and stakeholders through the use of this technology and geospatial tools. Existing opportunities in the use of satellite Earth observations continue to grow, ensuring that the advancement in space science and human capacity to fully utilize these data and information in directing policy and environmental analysis, and implementation of action plans is actualized.

Therefore, the use of sophisticated space-based observations depicting the biophysical and human dimensions of freshwater across the globe can expand our knowledge base on the causes and cascading impacts of climate change and the human actions that drive environmental and hydrological processes. Satellite data has been used to fill some of the existing data gaps, especially in emerging and some advanced economies where such observations are increasingly lacking. In addition to this, several data obtained from the model and by combining ground observations with simulations (reanalysis products) have shown great potential in environmental monitoring. The expectation of science at least by stakeholders and the end-users of scientific products is that it must take the lead in providing new information and evidence that advance human societies and improves relevant conditions. Earth resources satellites and the innovative capabilities behind them and satellite geodetic missions like GRACE and radar remote sensing techniques make this achievable. With this in mind, this book aims to provide an understanding of this emerging and novel field of study, called *remote sensing hydrology*. This concept and its practical applications in terrestrial hydrology as well as remote sensing of the environment and impact analysis are also detailed in this book.

The overarching goal of this book is to lay bare the concepts of *remote sensing hydrology* as it relates to the applications of optical (e.g., Sentinel, Landsat, SPOT, MODIS, etc.) and satellite geodetic (e.g., satellite gravity observations, radar altimetry, etc.) systems in quantitative and multidisciplinary aspects of land water storage (e.g., rivers, lakes, soil moisture, groundwater, floodplain wetlands, etc.) and assessing the impacts of climate change on freshwater ecosystems. The use of observations from these sensors, either independently or in combination with other data (e.g., reanalysis and model outputs) in remote sensing hydrology and impact assessment from extreme climate events such as droughts, floods, and wildfires is highlighted and demonstrated. With water being a key challenge in the twenty-first century, improving our contemporary understanding of global terrestrial hydrology, through the use of these observations and space-borne measurements is crucial. Another important aspect of this book is that it details the broad range of geospatial and relevant statistical methods and tools that are valuable in the analyses of hydrological time series and multi-mission satellite observations. With the growing applications of GRACE observations by Earth scientists, the book details practical utility of GRACE observations, including processing chains and demonstrating the contribution of climate change to the increased acceleration of global water cycle. In this regard, issues associated with freshwater changes and availability in the Anthropocene are highlighted and discussed using a plethora of region-specific case studies across the globe. Together, this book provides a range of opportunities for practitioners and relevant agencies to benefit from satellite-based information.

1.2 What is Remote Sensing Hydrology?

The emergence of new remote sensing platforms and sensors (Fig. 1.1) has revolutionized the applications of remote sensing in general. In the context of quantitative hydrology, new satellite systems like the European Space Agency state-of-art Sen-

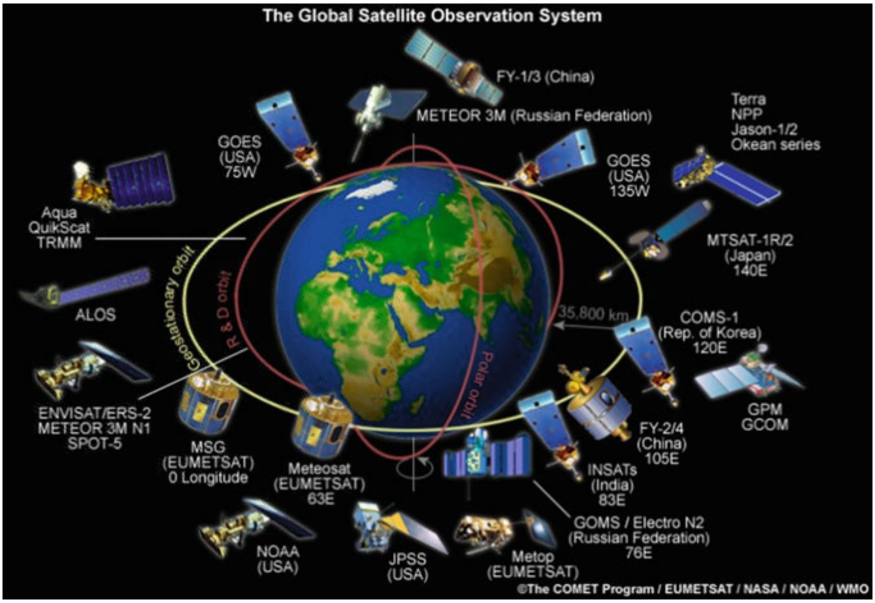

Fig. 1.1 Global satellite observation systems

tinel products, CryoSat-2, Ice, Cloud, and land Elevation Satellite (ICESat)-2 and Soil Moisture and Ocean Salinity, among other satellite missions provide unique and improved capability in comprehensive monitoring of the environment ranging from surface water in lakes, rivers, and floodplains to land surface conditions (evapotranspiration, temperature, etc.), land cover states (e.g., vegetation, urban settlements), soil moisture conditions, and extreme climate conditions such as floods, droughts, and wildfires. As opposed to previous optical satellite Earth observation systems such as the Landsat missions, there are now remote sensing systems dedicated to hydrological and meteorological applications. Satellites such as the Tropical Rainfall Measuring Mission (TRMM) provided extensive spatial coverage of rainfall across the globe on a relatively higher temporal (hourly, daily, monthly) and spatial resolution (0.25°). TRMM's operation commenced in 1997, providing critical inputs to tropical cyclone forecasting, numerical weather prediction, and precipitation climatologies, among several other contributions and societal applications. NASA's CloudSat mission also provides information on the Earth's atmosphere, oceans, land surface, polar ice regions, and solid Earth. This satellite sends out pulses of microwave energy through the clouds, and some of the energy in the pulses is reflected back to the spacecraft (https://cloudsat.atmos.colostate.edu/overview). The phase difference or time lag between when the pulse is sent and when the reflected energy is received back at the spacecraft is the basis for quantifying how much water or ice is contained in the cloud. Observations from CloudSat have been used to improve understanding of the Earth's water budget, climatology, land surface processes, tropical cyclones, among other atmospheric circulation patterns, which drive the global water cycle. In addition to these measurements, other advanced satellite systems such as GRACE enabled the assessment of changes in global terrestrial water storage (sum of soil moisture, groundwater, canopy water storage, ice/snow, and surface water storage in rivers, reservoirs, lakes and wetlands/floodplains, etc).

1.2.1 Satellite Hydrology

With the opportunity of combining satellite hydrology missions such as altimetry and GRACE missions with other Earth resource satellites (e.g., Landsat), direct monitoring of surface water hydrology (e.g., changes of lake water levels and volumes) and fluxes are gradually emerging. The combination of the second generation of Ice, Cloud, and Land Elevation Satellite (ICESat-2) and Lidar (Light detection and ranging) datasets with Landsat imagery in long-term monitoring of annual changes in lake water levels and volumes (Fig. 1.2) is a good example of satellite hydrology applications. One of the recent satellite hydrology missions is the ICESat, which measures ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics (https://icesat.gsfc.nasa.gov/). The first generation of ICESat was launched in January 2003, and it collected multi-year data on the elevation of the Earth's ice sheets, clouds, vegetation, and the thickness of sea ice off and on until October 2009. Its precise observation of the surface elevation of the Arctic sea ice enabled the measurement of ice thickness and volume. Figure 1.3a–d illustrate the sea ice thickness in the Northern Hemisphere, excluding the Baltic Sea and the Pacific for the months of February 2021 (3 and 25) and March 2021 (23 and 25). The insert on the upper right corner of Fig. 1.3a–d show the Arctic Sea Ice volumes from January to December. The maps in Fig. 1.3 show fluctuations in the thickness of ice. Sea ice is frozen seawater that floats on the ocean surface. It forms in both the Arctic and the Antarctic during winter periods. They retreat during summer but do not completely disappear. This floating ice has a profound influence on the polar environment, influencing ocean circulation, weather, and regional climate (https://earthobservatory.nasa.gov/features/SeaIce). As illustrated in Fig. 1.3, their observation and monitoring are possible and can be achieved using the ICESat-2 mission.

However, future space agency missions such as Surface Water and Ocean Topography (SWOT) mission, which is currently under development (www.jpl.nasa.gov/missions/surface-water-and-ocean-topography-swot) will directly provide this capability, serving as another dedicated satellite hydrology mission and tool in box for *remote sensing hydrology*, in addition to GRACE. The SWOT mission (see more details in Sect. 1.3.2) is expected to provide detailed measurements of surface water storage variations (i.e., wetlands, lakes, or reservoirs), complementing the GRACE mission. As indicated in the SWOT mission document (https://swot.jpl.nasa.gov/files/swot/SWOT_MSD_1202012.pdf), the scientific rationale for the development of SWOT is twofold. Firstly, to make high-resolution, wide-swath altimetric

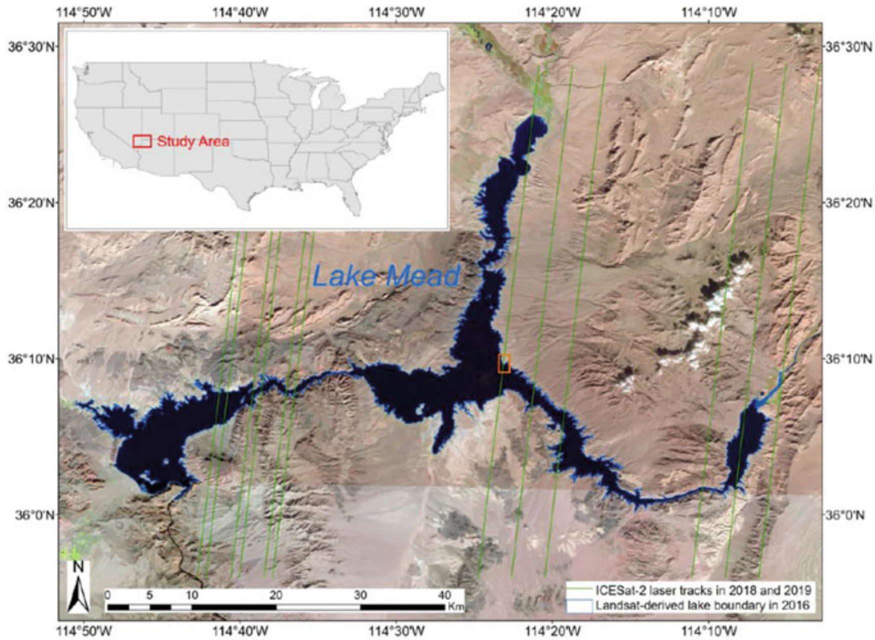

Fig. 1.2 Satellite monitoring of annual changes of lake water levels and volumes using Ice, Cloud, and land Elevation Satellite (ICESat)-2 and Landsat. Source Xu et al. (2020)

measurements of the ocean surface topography will advance the understanding of the oceanic mesoscale and sub-mesoscale processes. Secondly, the quest for a mission that will measure the elevation of water on land that will boost fundamental advances in the knowledge of the spatio-temporal distribution of storage and discharge of terrestrial water. Nevertheless, some other space agency missions relevant to hydrology and water resources have also been flagged for deployment in the coming years. They include, the Copernicus Sentinel-6, and Water Cycle Observation Mission, which is aimed at measuring snow water equivalent, soil moisture, precipitation, atmospheric water vapour, and other state variables. ICESat-2 is another sophisticated hydrology mission primarily designed to map ice sheet and in addition monitor surface water elevations (e.g., Ndehedehe 2019; McCabe et al. 2017). ICESat-2 mentioned earlier is second-generation of the laser altimeter ICESat mission and is optimized to use a micro-pulse multi-beam approach. It is designed to determine ice sheet mass balance as well as cloud property information, provide topography and vegetation data around the globe, as well as the polar-specific coverage over the Greenland and Antarctic ice sheets (https://icesat.gsfc.nasa.gov/). All these missions and others provide substantial context to what is now known as *remote sensing hydrology*.

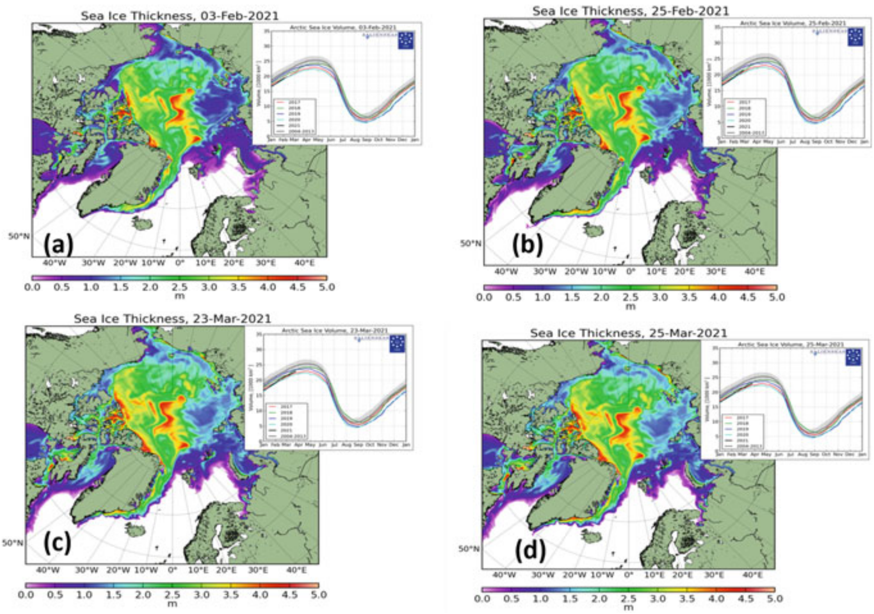

Fig. 1.3 Sea Ice thickness and volume observed by the Ice, Cloud, and Land Elevation Satellite (ICESat). Source, Polar Portal (http://polarportal.dk/en/home/)

1.2.2 The Concept of Remote Sensing Hydrology

Remote sensing hydrology is therefore the science that relies on space technology to monitor the occurrence, distribution, changes, and the characteristics of terrestrial stored water in all its forms (snow, ice, lakes, rivers, groundwater, canopy water, etc.) and their relationship with the environment and the Earth's climate system. This concept encapsulates the multidisciplinary aspects of environmental geoscience, and remote sensing of the environment, integrating several geospatial tools and methods, including allied sciences (e.g., statistics) to provide quantitative evaluation of terrestrial hydrology. Within this context, statistical and geospatial methods, using remote sensing and reanalysis data (a synthesis of satellite and ground observations), or even the use of platforms for big data analysis (e.g., Google Earth Engine) to support decision-making and management of water resources are integral aspects of remote sensing hydrology. Apparently, the application of satellite products in water resources and hydrology, including soil moisture and groundwater has been reported (e.g., Rango 1994). Over the years, these products have arguably been useful in understanding land surface hydrology and key state variables like soil moisture, especially in regions where in situ networks are sparse or lacking. However, the combination of geoinformation systems with new remotely sensed observations provides an innovative remote sensing hydrology framework that underpins improved water-related decisions. For example, with different digital image processing techniques, including image enhancement and directional Sobel filters, accurate fracture maps, and derived products (fracture density, coincidence map, and cross-points) have been generated using Landsat 8 (visible and infrared bands) in combination with advanced digital elevation models (Oussou et al. 2020). These fractured maps of aquifers are critical to improving drinking water access and can directly feed into water resources planning on a broad or local scale. While remote sensing has facilitated the successful location of important groundwater resources (Waters et al. 1990), the advent of space science in the last two decades contributed immensely to the progress in Earth system science, making it possible for frequent observations of large-scale, key water budget quantities such as rainfall, evapotranspiration, and terrestrial stored water from space. However, as discussed further in Sect. 1.3, some new remote sensing technologies are discipline-specific, providing measurements on surface water elevation and changes in freshwater bodies.

1.3 Remote Sensing Hydrology Systems

The revolution in space technology ushered in a new era of sophisticated satellite measurements of these quantities on several temporal (weekly, bimonthly, monthly, etc.) and spatial scales (high, medium, and low resolution). Dedicated remote sensing systems or platforms that will or can measure changes in surface water hydrology or provide the capability to directly monitor terrestrial stored water fall into the categories of what is here described as *remote sensing hydrology systems*. Apparently, the Landsat systems, SPOT, and some European Space Agency-based Sentinel products (e.g., Sentinel-2) are Earth resources satellites that can be used to monitor changes in surface water, among several other quantities such as vegetation and land surface conditions. But they are not dedicated systems that directly measure changes in surface water. Monitoring changes in surface water from these optical satellite systems require the use of indicators and metrics, especially to help with quantifying surface water extents, floods, water quality, etc. As global freshwater is undergoing substantial changes because of the impacts of climate change, measurements from remote sensing hydrology systems provide an increased opportunity to monitor such impacts. Satellite observations of freshwater (groundwater, surface water in lake, rivers, and floodplains) from new advanced satellite geodetic missions like the Gravity Recovery and Climate Experiment (GRACE) is therefore important to keep track of its variability. This mission has been providing an unparalleled perspective on global freshwater changes through quantitative estimates of variations in land water storage since its launch in 2002. The GRACE mission and its Follow-On are discussed in detail in Chap. 4. In this chapter, examples of remote sensing hydrology missions, like those in satellite radar family, which are dedicated satellite hydrology missions are highlighted.

With the anticipated launch of a key satellite hydrology program, the Surface Water Ocean Topography (SWOT) mission, the concept of *remote sensing hydrology* will be even more pronounced. The mission objectives of the SWOT program detailed