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Interdisciplinary Perspectives on Remote Sensing for Monitoring and Predicting Water-Related Hazards

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ABSTRACT

Water-related hazards, including floods, droughts, rainfall-triggered landslides, water-scarcity-induced soil salinization, and other interconnected hazards related to water, have caused considerable loss of human life and damage to property and infrastructure throughout human history. As significant progress has been achieved in satellite technology in recent decades, remote sensing of water-related hazards has emerged as an effective tool for better monitoring of hazards and reducing our vulnerability to extreme events. This chapter presents an overview of this book, which reviews recent advances and presents new studies in remote sensing of floods, droughts, rainfall-triggered landslides, and their associated cascading hazards. The main objective is to offer an up-to-date perspective on remote sensing of water-related hazards across disciplines by presenting the work of scientists from different backgrounds.

1.1. BACKGROUND

Water-related hazards broadly include floods, droughts, rainfall-triggered landslides, water-scarcity-induced soil salinization, and many other interconnected hazards related to water. Floods and droughts, as the core types of water-related hazards, have caused numerous losses of human lives and properties throughout human history (Du et al., 2018; Paprotny et al., 2018). With rapid socio-economic development, population and industrial growth, and other anthropogenic activities over recent decades, many new water-related challenges have emerged and imposed increasing threats on the built and natural environment (Lehnert et al., 2017; Wear et al., 2021; Zhang et al., 2021). Moreover, climate change and variability have altered regional to global water cycles (Huntington, 2010; Zhang et al., 2018; Y. Q. Zhang et al., 2016), causing an overall increase in the frequency and intensity of drought and floods around the world (AghaKouchak et al., 2015; Gu et al., 2020). Importantly, climate change is projected to increase the frequency and intensity of drought and floods in the mid- to late 21st century (IPCC, 2013; Wu et al., 2020), and to combine with other anthropogenic activities (AghaKouchak et al., 2021; Zhang et al., 2015; Y. Q. Zhang et al., 2016), leading to a rising risk to humans (Kam et al., 2021; Roudier et al., 2016). The growing impacts of water hazards have spurred research into improving monitoring and prediction of water hazards (Khaing et al., 2019; Makinano-Santillan et al., 2019), understanding the underlying drivers (Gui et al., 2020), implementing various mitigation and adaptation strategies (Xu et al., 2020),

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and identifying other relevant factors such as climate change, population growth, exposure, and socioeconomic development.

Historically, water-related hazards have been monitored and studied using ground-based point observations or spatially interpolated grids (AghaKouchak et al., 2014; He et al., 2018; Sheffield et al., 2012). Globally, many areas are not well instrumented to provide sufficient ground-based observations of precipitation, near-surface air temperature, relative humidity, soil moisture, and atmospheric water vapor among other hydrometeorological variables that are necessary for monitoring and investigating the water-related hazards (AghaKouchak et al., 2015). In addition, ground-based gauges are often destroyed by water-related hazards such as flash floods, hurricanes, and landslides, making real-time observation and consistent analysis of water-related hazards challenging.

Remote sensing refers to the process of detecting and monitoring an object at a distance from sensors, often onboard platforms such as aircrafts, satellites, unmanned aerial vehicles (UAVs), and towers. Satellite remote sensing of the Earth's weather started in earnest with the Television and Infrared Observation Satellite (TIROS-1) mission 1960 (NASA, 1987). TIROS-1 became a very successful mission and led to a series of additional meteorological satellite missions such as the Nimbus series, the Environmental Science Services Administration Satellite Program (ESSA), the NOAA satellites, QuikScat, Landsat, and Tropical Rainfall Measuring Mission (TRMM). NASA launched the Earth Resources Technology Satellite, which was eventually renamed Landsat 1 in 1975, on 23 July 1972. The Landsat program is a joint NASA/USGS program that provides the longest continuous space-based record of Earth's land in existence. In 1997, NASA launched the Earth Observing System (EOS) program (https://eospso.nasa.gov) that is composed of a series of satellite missions and scientific instruments in Earth orbit, making it possible for long-term global observations of the land surface, biosphere, atmosphere, and oceans. There are mainly two common types of Earth-observing satellites, namely, geostationary satellites and sun-synchronous polar-orbiting satellites (Njoku, 2014). Geostationary satellites, at altitudes of approximately 36,000 kilometers, revolve at speeds that match the rotation of the Earth so they are stationary relative to the Earth's surface (Njoku, 2014). This allows the satellites to observe and collect information continuously over specific areas, which are particularly valuable for monitoring weather and forecasting water-related hazards (Njoku, 2014). In contrast, sun-synchronous polar-orbiting satellites are designed to follow a north-south orbit, allowing them to cover most of the Earth's surface over a certain period and collect data at the same local solar time, which are extremely valuable to observe the Earth's surface to a larger extent and monitor changes over a long time period (Njoku, 2014).

The emergence of remote sensing techniques has provided new avenues to study, monitor, and predict water-related hazards (AghaKouchak et al., 2015; Andreas et al., 2020; Argaz et al., 2019; Boni et al., 2020; Elsadek et al., 2019; Fu et al., 2009). Equipped with passive or active sensors in the optical, thermal, and/or microwave bands, remote sensing platforms can capture a wealth of information that can be used to measure and infer water-related hazards and their impacts, including precipitation (Prabhakara et al., 1998; Sorooshian et al., 2000), evapotranspiration (Mu et al., 2007; Zhang et al., 2010), soil moisture (Du et al., 2016; Entekhabi et al., 2010; Kerr et al., 2012; Lindell and Long, 2016; Parinussa et al., 2015; Reichle et al., 2016; Wigneron et al., 2017), vegetation health (Jones et al., 2011; Mitchard et al., 2011; Zhang et al., 2008), total water storage (Schmidt et al., 2006; Tapley et al., 2004), snow cover (Ehrler et al., 1997; Zhou et al., 2014), inundation (Islam et al., 2010; Kumar et al., 2008), and land deformation (Guo et al., 2010; Rosi et al., 2018). As a result, remote sensing of water-related hazards has become the cutting edge of the natural hazard studies.

1.2. ADVANCES IN REMOTE SENSING TECHNOLOGIES

Remote sensing is applicable to the detection, monitoring, and forecasting of water-related hazards because most hydrological and atmospheric variables and geologic phenomena can be observed or inferred from space (Njoku, 2014). Revealing the location/frequency of previous occurrences and/or distinguishing the conditions under which extreme events are likely to occur can improve not only our understanding of water-related hazards but also their detection and monitoring. A deep understanding of the underlying processes and key variables along monitoring capabilities is fundamental to prevent future natural hazards from becoming human disasters.

Remote sensing technologies have evolved considerably over the past four decades, resulting in a wide variety of instruments and platforms (Njoku, 2014; Weng, 2017). Aerial remote sensing using aircraft is useful for studying and verifying small-scale events or features that are too small for detection by satellite imagery. Aerial photography, airborne radars, lidar, hyperspectral imagery, and thermal infrared scanners are arguably the most useful and widely used tools for the assessment and monitoring of water-related hazards (Bech and Chau, 2012; Mätzler, 2006; Njoku, 2014; Weng, 2017). Additionally, new satellite and UAV photogrammetric sensors and cameras provide new solutions for generating data of large spatial coverage and very high resolution at the field scale with relatively low cost for water-related hazard monitoring and geotechnical engineering, leading to improved spatial resolution, enhanced image quality, increased variety of information, and reduced data latency. For example, the Global Precipitation Measurement (GPM) mission launched in 2014 provides observation of precipitation with a spatial resolution of 10 km and a latency of 4 hours for the latitudes of 60°N–60°S, which shows a large advance relative to its predecessor, the Tropical Rainfall Measuring Mission (TRMM) launched in 1997. The airborne polarimetric and interferometric SAR2 (Pi-SAR2) instrument provides high-resolution, X-band, polarimetric data with a resolution of up to 0.3 m, which is also a large improvement relative to its predecessors. The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) onboard the International Space Station, which was launched on June 29, 2018, measures the vegetation and land surface of the Earth at 30–70 m spatial resolution. Moreover, several recent commercial satellite sensors can provide unprecedented high-resolution imagery such as the WorldView-3, which can provide imagery at 31 cm panchromatic resolution, 1.24 m multispectral resolution, and 3.7 m shortwave infrared resolution.

Aerial photography provides the closest approximation of what the human eye sees (Njoku, 2014; Weng, 2017), and hence, it offers unique opportunities for rapid large scale assessment of hazards and their impacts. However, the available light and the weather (e.g., clouds and fog) often limit the use of aerial photography, especially during floods and severe storms. Airborne radars are active sensors that produce their own transmissions rather than reflected light from other sources, which can be used at any time and in nearly all weather conditions. Thermal infrared scanners use a semiconductor detector, which is sensitive to the thermal infrared part of the spectrum, producing information on the thermal pattern of Earth's surface. Combined with other sensors and information such as near-infrared remote sensing, passive and active microwave remote sensing, hyperspectral remote imaging, and multitemporal high-resolution synthetic aperture radar (SAR), our capabilities to monitor and assess water hazards have drastically improved especially in the past three decades (Du et al., 2016; Entekhabi et al., 2010; Huffman et al., 2007; Kerr et al., 2012; Mu et al., 2007; Njoku et al., 2003; Reichle et al., 2016; Wigneron et al., 2017; Zhang et al., 2010).

Remote sensing of hazards will be increasingly relied on to reduce our vulnerability and increase our resilience against extreme events. However, understanding the breadth of the available contributions in this area is challenging, because scientists from different fields have used satellite observations to address problems in their own disciplines. For this reason, many publications on remote sensing of hazards have appeared in disciplinary journals of many fields (e.g., hydrology, ecology, climatology, geography, agriculture, sensor design, physical remote sensing, forestry, geophysics, and social sciences) (e.g, AghaKouchak et al., 2015; Andaru et al., 2021; Andreas et al., 2020; Argaz et al., 2019; Casas et al., 2014; Dubovyk et al., 2019; Francesca Franci et al., 2015; Haemmig et al., 2014; Hong et al., 2017; Kirschbaum et al., 2019; Lissak et al., 2020; Meng et al., 2015; Sierra-Soler et al., 2016; Su et al., 2015; Wang et al., 2015; Xu et al., 2021; Zeng et al., 2016; K. Zhang et al., 2016). This can limit the visibility of disciplinary studies within the broader water hazards community. This monograph bridges a wide range of disciplines and provides an overview of the available data, sensors, models, and indicators developed for monitoring, assessment, and prediction of water hazards.

1.3. OBJECTIVES AND ORGANIZATION OF THE BOOK

This book reviews recent advances and presents new studies in remote sensing of floods, droughts, rainfall-triggered landslides, and their associated secondary or cascading hazards, including, but not limited to, progress in remote sensing of precipitation, improvements in the integration of remote sensing data within computational modeling, near-real-time observations of storms and tornados, multisensor integration, integrated approach for predicting flood and landslide cascading hazards, and multi-indicator and multisensor approaches for quantifying drought impacts. The main objective is to offer an up-to-date perspective on remote sensing of water-related hazards, drawing on contributions from scientists with different backgrounds. This book is organized into three parts, with each of the 13 chapters representing an independent but interconnected topic related to water hazards (Figure 1.1).

Part I: Remote Sensing of Precipitation and Storms

Precipitation is a key variable in global water and energy cycles, and a driver of many types of extreme events. Understanding the underlying mechanisms triggering water-related natural hazards and monitoring and predicting these hazards require accurate precipitation data. Remote sensing of precipitation provides a valuable source of quasi-global and near real-time information, widely used in hydrometeorological studies and hazard monitoring. In chapter 2, Tang et al. summarize recent progress in global satellite remote sensing of precipitation

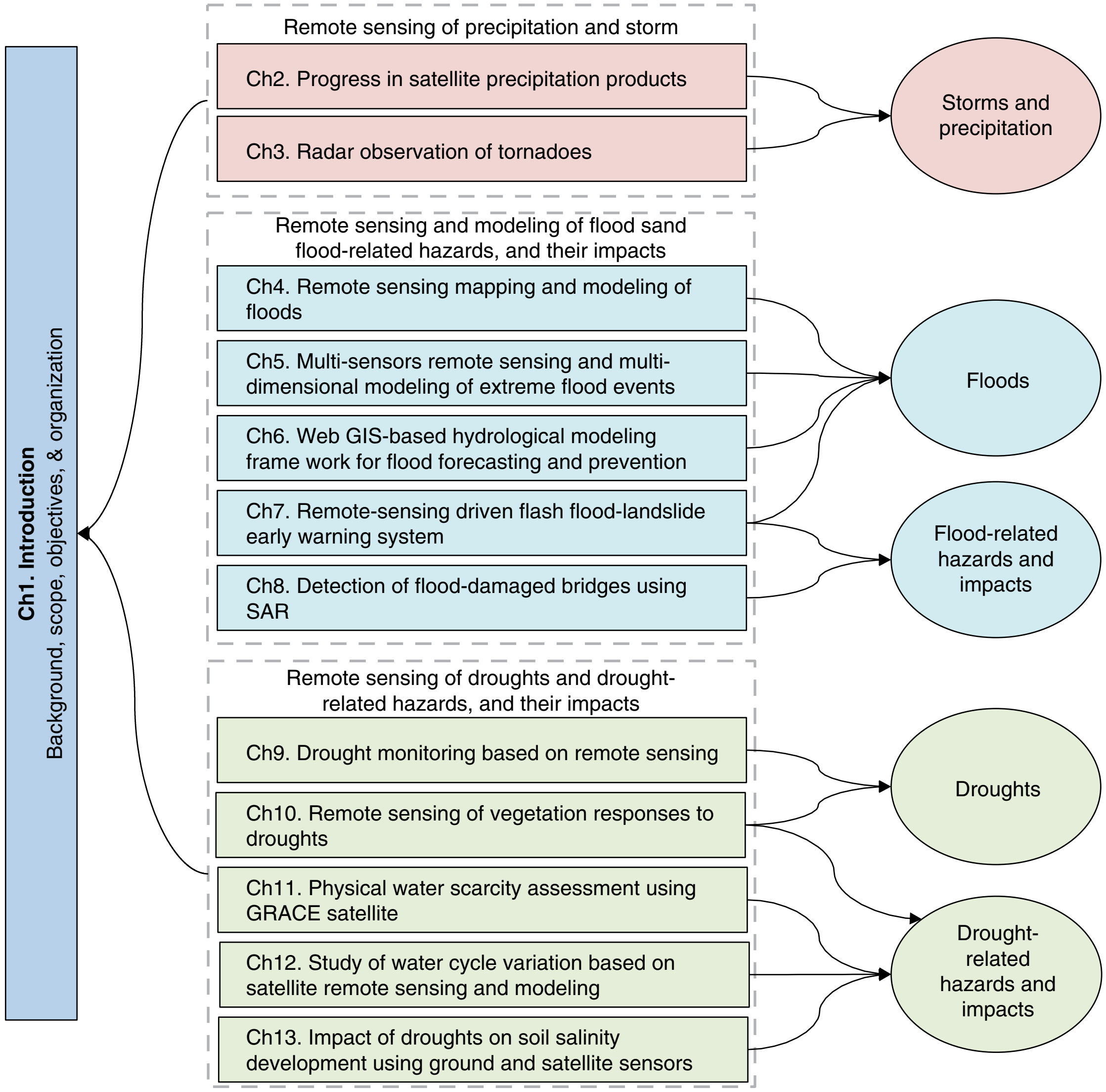

Figure 1.1 Structure and organization of this book.

and then focus on assessing the accuracy of the retrospective Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG). Comparing IMERG with the other mainstream satellite and reanalysis products, they discuss advantages and disadvantages of IMERG relative to the other products. This chapter provides a valuable reference for both users and developers who are interested in practical applications, model development (bias correction and uncertainty assessment), and algorithm development of satellite precipitation products.

Tornadoes, usually born during thunderstorms and accompanied by hail and/or heavy rainfall, are vertical funnels of rapidly spinning air and driven by extreme gradients in atmospheric pressure and temperature. Ground-based, mobile Doppler radar is one of the most effective and reliable tools for observing and monitoring tornadoes. In chapter 3, Bluestein starts with a brief history of the different types of mobile radars and their properties (e.g., wavelength, type of modulation, and polarization technique). The chapter then describes how to determine (a) the distribution of wind in tornadoes and their parent storms, (b) the development of pretornado vortex signature, and (c) the tornadic vortex signature itself using ground-based, mobile Doppler radars. Finally, this chapter discusses the potential new radar techniques for ground-based mobile radars to improve the ability to probe tornadoes.

Part II: Remote Sensing of Floods and Associated Hazards

As one of the deadliest natural hazards in the world, floods have historically received a great deal of attention in the remote sensing community. In chapter 4, Zhang et al. integrate remote sensing, hydrological-hydraulic modeling, and Geographic Information System (GIS) techniques to map inundation and quantify flood hazard risks. Their approach allows for filling the information and knowledge gap in data scarce regions. More specifically they combine a two-dimensional coupled hydrology-inundation model with satellite remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Phased Array Type L-band Synthetic Aperture Radar-2 onboard the Advanced Land Observing Satellite-2 (ALOS-2 ALOS2/PALSAR-2) to map flood hazards and their impacts in Nyaungdon Area, Myanmar.

In chapter 5, Chen et al. use a case study of remote sensing of floods triggered by Hurricane Harvey in Houston, Texas, USA. This chapter investigates the detectability of extreme rainfall through multisensor remote sensing and the simulation performance of the induced flooding via multidimensional modeling. It introduces a multidimensional modeling framework based on the Coupled Routing and Excess Storage (CREST) model family, designed to utilize multisensor remote sensing products for hydrologic applications. The chapter demonstrates that the integration of multisensor remote sensing precipitation and multidimensional modeling has a high potential to provide accurate and timely flood warning of the extreme events in a changing climate.

Hydrological modeling is a key tool for flood forecasting and early warning. Remote sensing datasets have allowed not only better parameterization of hydrological models but have also moved toward large-scale, near-real-time flood/inundation forecasting. However, configuring and executing stand-alone hydrologic models can be difficult, especially in regions with a lack of high-level modeling and data analysis expertise. In chapter 6, Wan et al. present a new web-accessible lumped hydrological modeling framework for researchers and practitioners to facilitate the organization of hydrological data, execution of hydrologic models, and analysis of results. The chapter shows how the efficiency of data processing and query can be improved through adopting the Hadoop Distributed File System (HDFS) and the Apache Hive concept. The authors integrate the lumped CREST and Hydrological Model (HyMOD) as a proof of concept in this framework.

Rainfall-triggered landslides are often associated with extreme precipitation events and floods, causing significant loss of life and property. Understanding the interactions between flood/rainfall events and landslides is fundamental to improve current landslide monitoring and prediction models. In chapter 7, Zhang et al. develop a coupled flood and landslide disaster early warning system for operational use by coupling two distributed hydrologic models, the Coupled Routing and Excess Storage (CREST) model and the Sacramento Soil Moisture Accounting (SAC-SMA) model, with two physically based landslide prediction models, the Slope-Infiltration-Distributed Equilibrium (SLIDE) model and the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) model. The Bayesian Model Averaging method is then applied to average the outputs of the ensemble members to produce an integrated outcome. This ensemble-based framework allows quantifying the uncertainty of the predictions and the probability distributions of anticipated events, enhancing disaster preparedness and prevention.

Advances in sensor technology make high-resolution SAR imagery data with a spatial resolution as fine as 0.3 meters available for distinguishing manmade objects in urban areas, such as bridges, roads, and drainage systems. In chapter 8, Liu et al. present an investigation to understand the backscattering characteristics of bridges over water using TerraSAR-X satellite images and Pi-SAR2 airborne images. The difference and correlation coefficient of the backscattering intensity between the SAR images before and after the hazard events were calculated to detect potential flood damages. Using both SAR and aerial photos, they demonstrate that high-resolution SAR images can provide a valuable and effective way to accurately detect collapsed bridges caused by extreme events.

Part III: Remote Sensing of Droughts and Associated Hazards

Drought poses signicant risks to ecosystems and human society. Effective drought monitoring tools are important for scientists to understand the underlying drives and mechanisms and for decision makers to develop operational strategies for drought management and mitigation.

In chapter 9, Li et al. review the current and emerging drought monitoring approaches based on remote sensing techniques. They present a case study on using remotely sensed precipitation and vegetation data for meteorological and agricultural drought monitoring in Jiangsu Province, China. This chapter also discusses the major gaps, challenges, and potential future research directions for remote sensing of drought.

In chapter 10, Zhang et al. review the definition and quantification of drought and mechanisms that control vegetation responses to it. They then introduce two methods to detect vegetation stress under drought disturbances based on remote sensing of vegetation and hydroclimatology. Yunnan Province, a key ecozone in China, is presented as a case study area to analyze drought dynamics and their impacts on ecosystem water use efficiency. This provides a valuable reference for studying and monitoring vegetation responses to drought using spaceborne optical and near-infrared sensors.

Physical water scarcity indicates the lack of sufficient water resources to meet human and environmental demands. In chapter 11, Hasan and Tarhule present a study on quantifying physical water scarcity based on the water scarcity indicator derived from the Gravity Recovery and Climate Experiment (GRACE) data. They introduce an approach for quantifying potentially available water through the integration of the GRACE data, reanalysis precipitation, and total evapotranspiration estimates using the Noah land surface model.

In chapter 12, Lv and Ma examine water cycle variation in the Yellow River Basin using both satellite remote sensing and numerical modeling. Considering that current evapotranspiration (ET) products have large uncertainties and irrigation effects on ET are not well represented, this chapter describes a method to reconstruct ET from the Global Land Data Assimilation System (GLDAS) land surface models using observation-based precipitation, streamflow, and irrigation water. The chapter then describes the attribution analyses of changes in streamflow and GRACE-derived terrestrial water storage in response to climate, watere cycle, and land use/cover changes. This line of research can provide guidance for the river basin water resource management and risk assessment.

Climate variability and change have dramatically influenced some agricultural areas, including the historic 5-year drought in California's San Joaquin Valley and 20-year drier-than-normal conditions in the Red River Valley of the midwestern USA. One impact of protracted droughts is increased soil salinity in the root zone of agricultural areas. Inventorying and monitoring soil salinity is crucial to evaluate the extent of the problem, recognize the trends, and formulate irrigation and crop management strategies for maintaining a sustainable agricultural productivity. In chapter 13, Corwin and Scudiero provide an overview of salinity assessment technologies, including proximal sensor and satellite remote sensing methodologies at multiple scales.

This collection of chapters provides an up-to-date overview of the available data, sensors, models, and indicators developed for monitoring and predicting various kinds of water hazards, with case studies drawn from different parts of the world. By presenting contributions from a diverse group of scientists, we hope to bridge some of the gaps between the various disciplines engaged in the remote sensing of hazards.

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