From Deformation to Hydrology A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems

Khodaei, Behshid

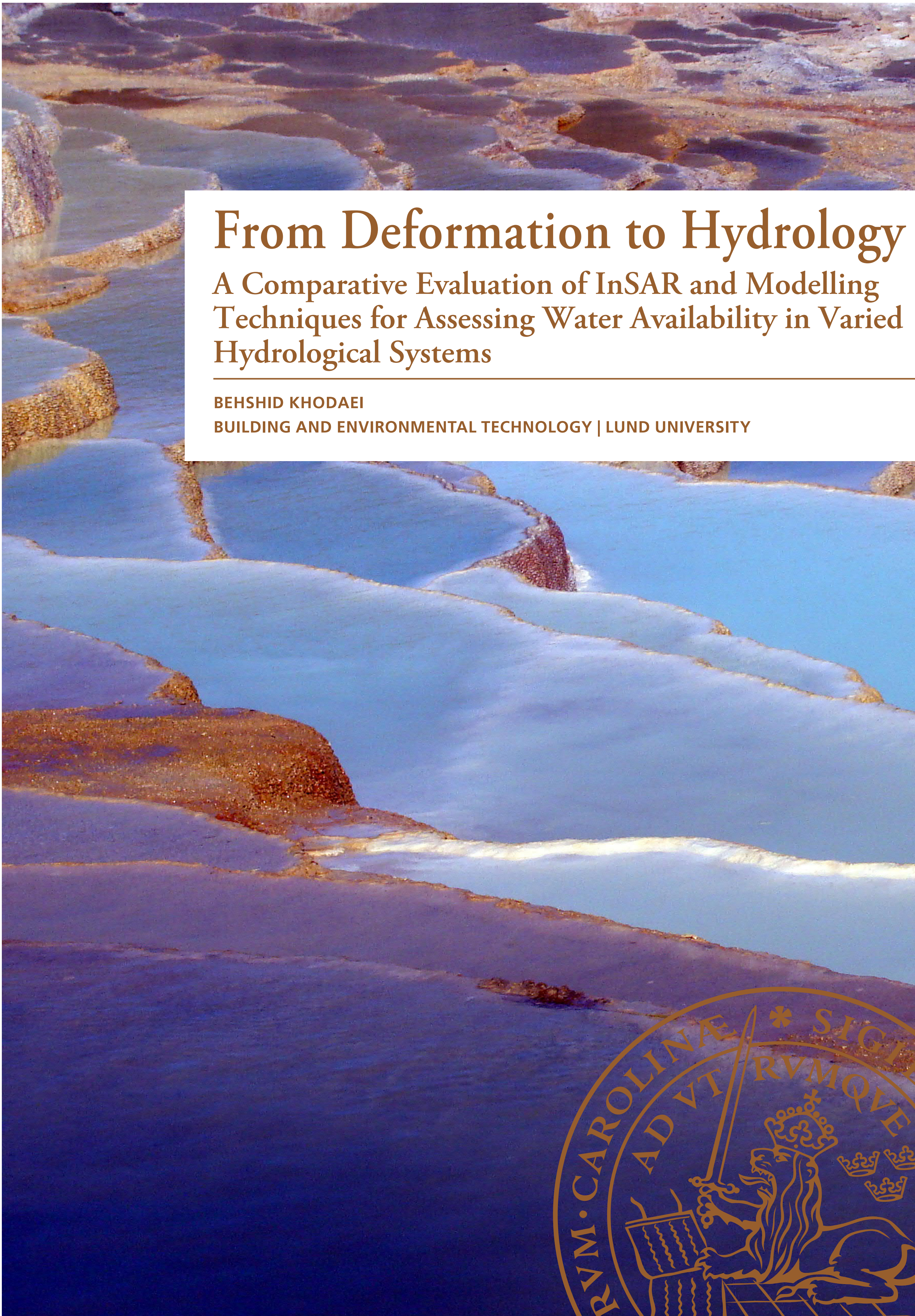
2025

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Khodaei, B. (2025). *From Deformation to Hydrology A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems*. Department of Building and Environmental Technology, Lund University.

Total number of authors:
1



From Deformation to Hydrology

A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems

BEHSHID KHODAEI
BUILDING AND ENVIRONMENTAL TECHNOLOGY | LUND UNIVERSITY

From Deformation to Hydrology

– A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems

From Deformation to Hydrology

A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems

Behshid Khodaei

LUND UNIVERSITY

DOCTORAL DISSERTATION

by due permission of the Faculty of Engineering, Lund University, Sweden.
To be defended at Faculty of Engineering, V-building, John Ericssons väg 1, Lund room V:A on October 31, 2025, at 10.00 a.m.

Faculty opponent

Prof. Dr. Mahdi Motagh

Organization: LUND UNIVERSITY

Document name: Doctoral Dissertation **Date of issue:** 2025-10-31

Author: Behshid Khodaei

Title and subtitle: From deformation to hydrology – A comparative evaluation of InSAR and modelling techniques for assessing water availability in varied hydrological systems

Abstract:

Water resources are under increasing pressure from population growth, climate change, and intensified human activity. Effective water management requires a clear understanding of both surface and subsurface hydrological systems, yet traditional monitoring methods often fall short in spatial and temporal coverage. Interferometric Synthetic Aperture Radar (InSAR), a satellite-based remote sensing technology, offers a powerful means to detect surface deformations linked to changes in groundwater storage. This dissertation explores the use of InSAR to monitor land subsidence, infer aquifer properties such as storativity, and enhance groundwater modelling in data-scarce, agriculturally intensive regions. By integrating InSAR with machine learning and physically-based models, the research enables improved estimation of groundwater levels and aquifer behaviour. It also examines the interactions between surface water and groundwater, emphasizing the importance of integrated management strategies. Overall, this work highlights InSAR's value in advancing scalable, data-driven approaches to sustainable water resource monitoring and decision-making.

Key words: water availability assessment, groundwater modelling, hydrological system interaction, InSAR

Classification system and/or index terms (if any) Supplementary bibliographical information

Language: English **ISSN and key title**: 1101-9824

ISBN: 978-91-8104-693-9 (print)
978-91-8104-694-6 (electronic)

Recipient’s notes **Number of pages**: 113

Price Security classification

Signature Date 2025-10-03

From Deformation to Hydrology

A Comparative Evaluation of InSAR and Modelling Techniques for Assessing Water Availability in Varied Hydrological Systems

Behshid Khodaei

LUND UNIVERSITY

Faculty of Engineering

Department for Building and Environmental Technology

ISBN 978-91-8104-693-9 (print)

ISBN 978-91-8104-694-6 (electronic)

ISSN 1101-9824

Report: TVVR 1104

Printed in Sweden V-huset, Lund University

Lund 2025

“Allting är mycket osäkert, och det är just det som lugnar mig.”

— Tove Jansson, Trollvinter (1957)

Table of Contents

Abstract

Water is essential for life, yet global water resources face increasing pressure from rapid population growth, climate change, and intensified human activities. Sustainable water management depends on a deep understanding of hydrological systems, both the visible surface water and the often-overlooked groundwater reserves. Traditional monitoring methods, however, are often too limited in coverage and frequency to capture the full complexity of water-system dynamics.

Interferometric Synthetic Aperture Radar (InSAR), a satellite-based remote sensing (RS) technology, is a powerful tool for detecting ground displacements as small as a few millimetres over wide areas. When combined with appropriate models and assumptions, these measurements can be used to infer variations in water storage driven by seasonal fluctuations, groundwater extraction, or ecological processes. Thanks to its high spatial and temporal resolution, InSAR has become an important tool in hydrological research.

A central theme of this dissertation is the use of InSAR to assess groundwater dynamics, particularly in arid and semi-arid regions where over-extraction often leads to land subsidence. By interpreting deformation patterns, it becomes possible to infer subsurface parameters such as aquifer storativity, which describes the capacity of geological formations to store and release water. When integrated with machine learning (ML), InSAR data support comprehensive mapping of land subsidence and the prediction of groundwater-related changes even in areas where direct measurements are sparse or unreliable. These models offer scalable solutions for groundwater monitoring in agriculturally intensive and data-scarce regions.

InSAR also complements physically based numerical and data-driven models that simulate groundwater flow. By calibrating such models with deformation data, it becomes feasible to estimate groundwater-level changes and characterize aquifer behaviour more accurately than with conventional observations alone, especially where monitoring networks are sparse. Moreover, combining satellite observations with environmental variables enables spatial extrapolation of key aquifer parameters, such as skeletal storage coefficients and characteristic lag times, to simulate subsurface dynamics across entire aquifer systems.

The dissertation also examines the interplay between groundwater and surface water, showing how interventions such as river regulation can have unintended consequences. Reductions or redirection of surface flows may increase reliance on groundwater, intensifying subsidence and threatening infrastructure and long-term availability. This underscores the importance of integrated water management that considers the coupled surface-subsurface system.

Beyond groundwater-focused applications, the research extends to wetland environments, particularly temperate peatlands that retain water, mitigate floods,

and act as carbon sinks. Using InSAR to track subtle surface elevation changes, often described as "peat breathing", the dissertation illustrates how these surface motions can correspond to water-table dynamics and, in turn, to carbon fluxes when interpreted with complementary hydrological and ecological information. This highlights the potential of InSAR to support ecological monitoring and climate-related assessments in vegetated landscapes.

Overall, this dissertation demonstrates how integrating Earth observation with diverse modelling strategies advances both the science and practice of water resource management. By applying InSAR across aquifers and ecosystems, the research highlights new ways to monitor subsurface and surface water dynamics, extends hydrological assessment to data-scarce regions, and underscores the broader ecological and climatic relevance of deformation monitoring.

Populärvetenskaplig sammanfattning

Vatten är avgörande för liv, men våra globala vattenresurser står inför ett ökande tryck till följd av snabb befolkningstillväxt, klimatförändringar och intensifierade mänskliga aktiviteter. Hållbar vattenförvaltning kräver en djup förståelse av hydrologiska system – både det synliga ytvatten och de ofta förbisedda grundvattenreserverna som döljer sig under våra fötter. Traditionella övervakningsmetoder är dock ofta för begränsade i täckning och frekvens för att kunna fånga den fulla komplexiteten i vattensystemens dynamik.

Interferometrisk syntetisk aperturradar (InSAR), en satellitbaserad fjärranalysteknik, har framträtt som ett kraftfullt verktyg för att observera små förändringar i jordytan – rörelser så små som några millimetre – över stora områden. Dessa ytförändringar speglar ofta variationer i vattenlagring under marken, oavsett om de orsakas av säsongsmässiga svängningar, grundvattenutvinning eller ekologiska processer. InSAR:s förmåga att fånga sådana deformationer med hög rumslig och tidsmässig upplösning har gjort tekniken banbrytande inom hydrologisk forskning.

Ett centralt tema i denna avhandling är användningen av InSAR för att analysera grundvattendynamik, särskilt i torra och halvtorra regioner där överuttag ofta leder till marksänkning. Genom att tolka deformationsmönster blir det möjligt att dra slutsatser om underjordiska parametrar som akviferers lagringsförmåga, vilket beskriver geologiska formationers kapacitet att lagra och släppa ifrån sig vatten. När InSAR-data kombineras med maskininlärningsmodeller kan man skapa omfattande kartor över marksänkning och förutsäga grundvattenrelaterade förändringar även i områden där direkta mätningar är glesa eller osäkra. Dessa modeller erbjuder skalbara lösningar för grundvattenövervakning i jordbruksintensiva och datafattiga regioner.

InSAR kompletterar också fysikaliskt baserade numeriska modeller som simulerar grundvattenflöde. Genom att kalibrera sådana modeller med deformationsdata blir det möjligt att uppskatta grundvattennivåer och karakterisera akviferbeteende mer exakt än med konventionella mätningar ensamma. Detta är särskilt värdefullt i regioner där täta övervakningsnätverk saknas. Dessutom gör kombinationen av satellitobservationer med miljövariabler och fjärranalysindex det möjligt att extrapolera viktiga hydrologiska parametrar – såsom elastiska lagringskoefficienter – över hela akvifersystem.

Avhandlingen utforskar även det komplexa samspelet mellan grundvatten och ytvatten, och visar hur åtgärder som reglering av floder kan få oavsiktliga konsekvenser. Till exempel kan omledning eller minskning av ytvattenflöden leda till ökad beroende av grundvatten, vilket i sin tur kan orsaka intensivare marksänkningar och hota både infrastruktur och långsiktig vattentillgång. Detta understryker vikten av integrerade vattenförvaltningsstrategier som beaktar det ömsesidiga beroendet mellan ytliga och underjordiska system.

Förutom grundvattenrelaterade tillämpningar omfattar forskningen även ytvattenförändringar i våtmarker, särskilt i tempererade torvmarker. Dessa ekosystem spelar inte bara en viktig roll i vattenhållning och översvämningsskydd, utan fungerar också som kolsänkor. Genom att använda InSAR för att spåra subtila förändringar i markytans höjd – ofta beskrivna som "torvandning" – visar avhandlingen hur dessa rörelser motsvarar förändringar i grundvattennivån och därigenom påverkar kolflöden. Detta belyser InSAR:s potential för ekologisk övervakning och klimatrelaterade bedömningar i vegetationsklädda landskap.

Genom att kombinera fjärranalys, numerisk modellering och maskininlärning presenterar denna forskning ett mångfacetterat ramverk för att förstå vattenresursers dynamik i olika hydrologiska miljöer. Den visar att moderna jordobservationsverktyg avsevärt kan förbättra vår förmåga att övervaka, förutsäga och förvalta både grundvatten- och ytvattenresurser. Genom dessa innovationer tar vi ett steg närmare hållbar vattenanvändning – från torkdrabbade akviferer till koldioxidrika våtmarker – och bidrar till att skydda denna livsviktiga resurs för kommande generationer.

کاربرد تداخل‌سنجی راداری روزنه مصنوعی و مدل‌سازی یکپارچه برای پایش و مدیریت پایدار منابع آب زیرزمینی و سطحی

آب، این عنصر حیاتی زندگی، امروزه تحت فشار شدید ناشی از رشد جمعیت، تغییرات آب‌وهوایی و فعالیت‌های انسانی قرار دارد. برای مدیریت پایدار این منبع ارزشمند، نیازمند درک عمیق از رفتار سامانه‌های آبی، از آب‌های جاری در سطح زمین تا منابع پنهان زیرزمینی هستیم. روش‌های مرسوم پایش آب به دلیل محدودیت‌های جغرافیایی و زمانی، اغلب قادر به ثبت کامل پیچیدگی‌های این سامانه‌ها نیستند. این پژوهش با بهره‌گیری از فناوری پیشرفته تداخل‌سنجی راداری روزنه مصنوعی و تلفیق آن با مدل‌های عددی و روش‌های هوشمند محاسباتی، راهکاری نوین برای رصد و مدیریت منابع آب ارائه می‌دهد.

هدف اصلی این مطالعه، توسعه چارچوبی جامع برای بررسی تغییرات منابع آبی با استفاده از قابلیت‌های منحصر به فرد تداخل‌سنجی راداری در اندازه‌گیری تغییرات میلی‌متری سطح زمین است. این پژوهش در سه حوزه اصلی متمرکز شده است: نخست، ارزیابی وضعیت آب‌های زیرزمینی در مناطق خشک و نیمه‌خشک که با مشکل فرونشست زمین به دلیل برداشت بی‌رویه مواجه هستند. دوم، بهبود مدل‌های شبیه‌سازی جریان آب زیرزمینی با استفاده از داده‌های تداخل‌سنجی. و سوم، بررسی ارتباط بین آب‌های سطحی و زیرزمینی و به طور خاص در بوم‌سازگان‌های حساسی مانند تالاب‌ها.

یافته‌های این تحقیق نشان می‌دهد که فناوری تداخل‌سنجی قادر است تغییرات ظریف سطح زمین ناشی از نوسانات ذخیره آب زیرزمینی را با دقت بالایی تشخیص دهد. این قابلیت، امکان پایش مستمر منابع آب را حتی در مناطق دورافتاده و فاقد شبکه‌های پایش فراهم می‌کند. همچنین، ترکیب این داده‌ها با روش‌های پیشرفته محاسباتی منجر به تولید نقشه‌های دقیق فرونشست زمین و پیش‌بینی تغییرات منابع آب شده است.

نتایج این مطالعه همچنین رابطه پیچیده بین منابع آب سطحی و زیرزمینی را آشکار ساخته است. به عنوان مثال، تغییر در جریان رودخانه‌ها می‌تواند وابستگی به منابع زیرزمینی را افزایش دهد که پیامدهایی مانند فرونشست زمین و آسیب به زیرساخت‌ها را در پی دارد. در مورد تالاب‌ها نیز، حرکات ظریف سطح زمین که به «تنفس تورب» معروف است، با نوسانات سطح آب و چرخه کربن در ارتباط مستقیم قرار دارد.

این پژوهش با ارائه چارچوبی نوین که در آن روش‌های سنجش از دور، مدل‌سازی عددی و محاسبات هوشمند به صورت یکپارچه به کار گرفته شده‌اند، گامی مهم در جهت مدیریت پایدار منابع آب برداشته است. دستاوردهای این تحقیق می‌تواند به سیاست‌گذاران و مدیران منابع آب کمک کند تا با اتکا به داده‌های دقیق و به‌روز، تصمیم‌های آگاهانه‌تری برای حفظ این سرمایه حیاتی بگیرند.

این مطالعه راه را برای پژوهش‌های آینده در زمینه پایش تغییرات اقلیمی، مدیریت خشکسالی و حفاظت از بوم‌سازگان‌های آبی هموار می‌سازد و نشان می‌دهد که چگونه فناوری‌های نوین می‌توانند درک ما از سامانه‌های پیچیده آبی را دگرگون کنند.

Acknowledgements

A PhD journey is often described as a lonely one. That is only half true. While there were indeed long nights, too much coffee, and the occasional existential conversation with my laptop, I was never truly alone. Behind every page of this work stand people who walked with me, mentors, colleagues, friends, and family, each offering their own unique kind of support, encouragement, or simply a smile at the right moment.

I want to express my deepest gratitude to my supervision team Hossein Hashemi, Ronny Berndtsson and Amir Naghibi. Hossein, my main supervisor, trusted me in every single step of this journey. That trust gave me the courage to take risks, the confidence to believe in my ideas, and the comfort of knowing that I was never walking this path alone. Ronny, you were like the sun behind the clouds, always there with your light and warmth even when not directly visible. The guidance and perspectives from the team as a whole have helped shape this work in invaluable ways. I am also grateful to Dr. Kompanizare for his valuable collaboration and guidance during our joint work.

I also want to thank my colleagues at TVRL who made everyday work both enjoyable and rewarding. Magnus Persson, I truly appreciate your support and encouragement in many ways. Carina, thank you for always being helpful and kind, and for your patience that made many things smoother. Cintia, Magnus Larson, Kenneth, Rolf, Johanna, Jing, Erik, Jonas, Peder, Elena, Babs, Sebastian, Björn, Caroline, Adriana, Linus, Catherine, Feifei, Raffaella, and Christoffer, thank you for contributing to a positive and friendly atmosphere with good discussions, support and many pleasant fika moments. Kourosh, I am especially grateful to you for always being available with advice and assistance.

Among the PhD students, I was lucky to find not only colleagues but also true companions. Anna Adell, Dimaghi, Clemens, my amazing officemate Iria who knows the true meaning of shared struggles and shared laughter, Alireza, Pablo, Kristofer, Fainaz, August, Leonard, Emmanuel, Joseph, Maria Jose, Adnan, Anna Söderman, Ellinor, Louise, and our newest good colleague Giuseppe. Thank you all for your encouragement, patience and solidarity.

Beyond these divisions, my appreciation extends to many others in the department. Special thanks to Oskar and Mohammad Kahangi for always being available with help and thoughtful discussions, and to Maryam, Marziyeh, Amirhossein, Bitte, Mohammad Gholampoor, Iman, Pouria, Hasan and many more whose names I cannot all list but whose kindness and support I will never forget.

At CMES, I owe special thanks to Karin whose kind leadership and open heart made me feel supported at every step. I also thank my colleagues Pinar, Lina, Linda, Sami, Mo, Hakim, Rafah, Lovisa, Wan Ni, Krishna, Filippo, Maria, Joel, Rami, Maira, Andrea, Lars, Adam, Purnendu and Malin who filled our events and meetings with smiles, warmth and genuine camaraderie.

My heartfelt gratitude also goes to my dear friends outside academia who have been a source of balance and joy. Naghmeh, Masoud, Iman, Masoud MJ, Shifteh, Thais, and Shokoufeh, your presence, love and endless patience reminded me that life exists beyond models, codes and late-night writing.

Some friends deserve their own spotlight. Khashayar, your unconditional support, encouragement and presence throughout this challenging journey have meant more to me than words can express. Your determination has always inspired me. Shakiba and Kavan, thank you for filling my heart with warmth; your love and friendship have been a true refuge.

And then, to the people who form the very foundation of who I am, my family. My dearest parents, Mitra and Ghobad, your love has been my guiding light. Without you, none of this would have been possible. My father, your expertise and passion for caring about the environment planted the very first seeds that eventually grew into this field of research. My mother, you are not only my heart but its very rhythm. You are the quiet strength that has carried me through silence and storm alike. Your boundless care and encouragement were the breath behind every step I took, and in every moment of doubt, it was your love that reminded me I was never alone. My beloved brother Behrang, you have been my role model in every step of my life. Your wisdom and kindness constantly remind me of the person I aspire to be.

Finally, to Baktash, my constant companion. No words will ever truly capture the depth of my gratitude and love. Your support, patience and faith in me made all of this possible. This thesis may carry my name, but it is as much yours as it is mine.

Behshid Khodaei

Lund, September 2025

Preface

This dissertation presents the research I have carried out during my time as a doctoral student at the Division of Water Resources Engineering at Lund University, with a dual affiliation to the Centre for Advanced Middle Eastern Studies (CMES). It is structured as a compilation of peer-reviewed papers, with the synthesis chapter providing a cohesive narrative that frames the collective contributions of the appended studies.

My journey into this research was shaped by a deep concern for the accelerating water crisis in arid and semi-arid regions, particularly in the Middle East, where groundwater depletion has reached alarming levels. In these regions, land subsidence is not merely a scientific concept but a lived reality, damaging infrastructure, displacing communities, and threatening long-term sustainability. This context has continually fueled my motivation and given a strong sense of purpose to my work. The challenge of bridging scientific rigor with real-world urgency has guided how I approach, design, and communicate my research.

Working across disciplines, from remote sensing and machine learning to hydrogeology and numerical modelling, has allowed me to explore the complexity of water resource systems in ways that no single method could achieve alone. My academic affiliations provided unique opportunities to engage with both technical experts and scholars in policy and regional studies, shaping a perspective that is both scientifically grounded and societally informed.

One of the most impactful aspects of this journey has been the chance to participate in international conferences, research schools, and collaborations that expanded not just my technical skills, but also my understanding of how interconnected global water challenges truly are. These experiences reaffirmed the importance of pushing research beyond academic boundaries, to inform policy, empower local stakeholders, and support sustainable development where it is needed most.

As I finalize this dissertation, I carry with me a strong conviction that research can and must be both innovative and responsible. I hope that the work presented here contributes not only to academic knowledge, but also to practical solutions in addressing one of the most pressing environmental issues of our time.

List of appended papers

Paper I

Naghibi, S. A., **Khodaei, B.,** & Hashemi, H., **An integrated InSAR-machine learning approach for ground deformation rate modelling in arid areas**, Journal of Hydrology, 2022, 608, 127627

Paper II

Khodaei, B., Hashemi, H., Kompanizare, M., Naghibi, M., & Berndtsson, R., **An Integrated InSAR-Numerical Approach for Accurate Groundwater Head Prediction**, Journal of Hydrology, 2025, 662, 134023

Paper III

Khodaei, B., Hashemi, H., Naghibi, M., Hosseini, H., & Berndtsson, R., **A Novel Technique for Space-Time Monitoring of Groundwater Head Using InSAR and Physics-Assisted AI**, Under review (2025)

Paper IV

Hashemi, H., Nazarieh, F, & **Khodaei, B., SIGH-Map: Space-time InSAR-based Groundwater Head Mapping: an integrated InSAR-MODFLOW framework for head calculation**, Under review (2025)

Paper V

Sharifi, A., **Khodaei, B.,** Ahrari, A., Hashemi, H., & Haghighi, A. T., **Can river flow prevent land subsidence in urban areas?**, Science of the Total Environment, 2024, 917, 170557

Paper VI

Khodaei, B., Hashemi, H., Salimi, S., & Berndtsson, R., **Substantial carbon sequestration by peatlands in temperate areas revealed by InSAR**, Environmental Research Letters, 2023, 18(4), 044012

Author’s contribution to the papers

Paper I

The author conducted the InSAR analysis for this research. The author also contributed to brainstorming, elaborating methodological concepts, and writing the relevant sections.

Paper II

The author led the efforts to carry out this study in collaboration with the co-authors. The author conducted data collection and preparation, formal analysis, modelling, and discussion, and was also responsible for writing the main body of the manuscript. The co-authors contributed to the discussion, assisted in conceptualizing the validation methodology, and provided a critical review of the manuscript.

Paper III

The author led the efforts to carry out this study in collaboration with the co-authors. The author conducted data collection and preparation, formal analysis, modelling, and discussion, and was also responsible for writing the main body of the manuscript. The co-authors contributed to the discussion, assisted in preparing some field-specific data, and provided a critical review of the manuscript.

Paper IV

The author conducted the InSAR analysis for this research. The author also contributed to conceptualizing the model, brainstorming, elaborating methodological and validation concepts, participating in critical discussions, preparing the main visual elements, and writing the relevant sections.

Paper V

The author conducted the InSAR analysis for this research. The author also contributed to conceptualizing the study, elaborating methodological and validation concepts, participating in critical discussions, and writing the relevant sections.

Paper VI

The author led the efforts to carry out this study in collaboration with the co-authors. The author conducted data collection and preparation, formal analysis, modelling, and discussion, and was also responsible for writing the main body of the manuscript. The co-authors contributed to the discussion, assisted in preparing field and lab-specific data, and provided a critical review of the manuscript.

Other publications

Shahnazi, S., Roushangar, K., **Khodaei, B.,** & Hashemi, H., Insights into the Interconnected Dynamics of Groundwater Drought and InSAR-Derived Subsidence in the Marand Plain, Northwestern Iran, Remote Sensing, 2025, 17(7), 1173

Salimi, S., **Khodaei, B.,** Laudon, H., Water Storage Capacity Dynamics in Drained Boreal Peatlands: Responses to Rewetting and Climate Change, Under review (2025)

Hashemi, H., Dehkordi, A., **Khodaei, B.,** Naghibi A., Ground Subsidence and Groundwater Dynamics: The Role of InSAR Analysis in Confined Aquifer Systems, Book chapter currently under publication in Elsevier (2025)

1 Introduction

Water resources globally face increasing pressure due to a combination of factors including population growth, climate change, and anthropogenic activities. Sustainable water management requires a comprehensive understanding of both surface water and groundwater availability, as well as the impacts of their depletion or alteration. Traditional methods of water resources monitoring can be limited in spatial and temporal coverage, making it challenging to effectively assess large-scale changes and complex interactions within hydrological systems.

Remote sensing technologies, particularly Interferometric Synthetic Aperture Radar (InSAR), have emerged as powerful tools for monitoring land surface deformation with high precision and over extensive areas. These deformation measurements provide valuable insights into hydrological processes such as aquifer storage changes and wetland dynamics.

This dissertation explores how InSAR can be combined with diverse modelling strategies, including physically assisted data-driven and numerical models, as well as machine learning approaches, to advance groundwater and ecosystem monitoring across varied hydrological settings.

1.1 Scope

This dissertation presents a comparative assessment of water availability and related environmental changes by leveraging remote sensing, primarily InSAR, in combination with complementary modelling approaches. The scope includes monitoring surface deformation as an indicator of water storage variations in groundwater aquifer systems as well as water-saturated ecosystems such as peatlands. In aquifers, the integration of InSAR with modelling frameworks is used to estimate key hydrological parameters and assess impacts of drought, groundwater extraction, and surface water regulation. In peatland environments, InSAR is applied to study ecosystem responses and carbon-related processes, without direct reference to groundwater behaviour. The dissertation draws upon findings from multiple studies across diverse geographical and environmental contexts.

The research begins with the development of an InSAR-ML framework (Paper I) that integrates sparse InSAR-derived deformation with geo-environmental factors to generate full-coverage maps of groundwater-induced land subsidence in agricultural areas. Using tree-based ensemble regression models, the approach overcomes the spatial discontinuity typical of InSAR data in an agricultural and highly vegetated areas, offering a scalable tool for subsidence modelling in data-scarce environments.

The second article (Paper II) introduces a deformation-driven head estimation (DHE) model that links InSAR-derived surface deformation with groundwater head variations by estimating seasonal and long-term skeletal storage coefficients. Rather than relying on dense monitoring networks, the method can reconstruct historical groundwater head changes and predict future head dynamics at monitoring well locations using deformation data, even in areas with limited in-situ measurements or incomplete records.

Building on this, the third article (Paper III) employs ML to spatially extrapolate storativity parameters, integrating remote sensing and ground-based data. This enables aquifer-wide groundwater head simulations, clarifying seasonal and long-term deformation behaviours.

Advancing the integration of InSAR with numerical modelling, the fourth article (Paper IV) introduces a framework, which calibrates skeletal storage coefficients using InSAR deformation within a MODFLOW-based numerical model. This novel approach enables future groundwater head estimations primarily from remote sensing data and estimated aquifer hydraulic parameters, and focuses on characterizing subsidence caused by over-pumping.

The fifth article (Paper V) examines the interaction between surface water regulation and groundwater depletion in an aquifer situated within a riparian zone. By combining satellite remote sensing and in-situ hydrological data, the study illustrates how river regulation reduces surface water availability, exacerbates groundwater overuse, and triggers significant land subsidence, posing threats to infrastructure.

Finally, the sixth article (Paper VI) explores surface water dynamics in temperate peatland ecosystems in southern Sweden. Using InSAR to measure peatland surface deformation, the study proposes a method to estimate carbon flux based on observed changes. The findings indicate significant surface uplift associated with carbon sequestration, highlighting InSAR's utility in monitoring ecological processes in vegetated landscapes.

Collectively, these studies highlight the value of InSAR in monitoring hydrological systems, from arid aquifers to temperate peatlands, and demonstrate how its integration with complementary modelling frameworks can enhance traditional groundwater assessments. The findings emphasize the interconnectedness of surface and subsurface water systems and their combined role in sustainable water resource management.

1.2 Aim and objectives

The overarching aim of this dissertation is to provide a comparative evaluation of the application of InSAR technology and its integration with modelling approaches for assessing water availability and related environmental changes in diverse hydrological settings.

To achieve this aim, the following objectives are addressed:

i. To evaluate the effectiveness of InSAR technology in monitoring environmental changes related to water in different hydrological systems.

ii. To assess the utility of integrating InSAR-derived deformation data with physics-based models for characterizing aquifer properties and predicting groundwater dynamics.

iii. To investigate the potential of machine learning techniques, in conjunction with InSAR data, for mapping and understanding spatial patterns of groundwater-related phenomena.

iv. To examine the impact of both natural climate variability and anthropogenic pressures on water availability and associated land surface deformation in the studied systems.

v. To highlight the strengths and limitations of the employed methodologies for water resource monitoring and management across different hydrological contexts

vi. To investigate peatland condition and surface dynamics through InSAR-based monitoring, with consideration of associated carbon sequestration processes as part of broader environmental change assessment.

1.3 Limitations

This dissertation is based on a comparative analysis of multiple case studies, and its findings should be interpreted within the constraints of data availability, InSAR measurement conditions, and model assumptions. The accuracy of deformation measurements may be influenced by atmospheric effects, vegetation cover, and satellite geometry, while the reliability of integrated modelling depends on the quality of in-situ observations and auxiliary datasets. Both physics-based and data-driven models remain sensitive to parameterization choices and training data. These aspects, along with associated uncertainties, are further discussed in the concluding chapter.

1.4 Brief overview of appended papers

[Paper I] This study presents an integrated InSAR-machine learning approach that combines InSAR deformation data with geoenvironmental variables to model groundwater-induced land subsidence in arid, agriculturally dominated regions. By addressing the spatial discontinuity inherent in InSAR measurements, particularly in vegetated areas, the approach enables the generation of continuous, high resolution subsidence maps. The methodology demonstrates the potential of ML-based, data-driven models to enhance deformation monitoring in data-scarce environments.

[Paper II] This paper introduces a deformation-driven head estimation (DHE) model to predict groundwater levels in arid and semi-arid regions using InSAR-derived land deformation and piezometric well data. By estimating seasonal and long-term skeletal storage coefficients, the model enables groundwater head simulation without requiring detailed aquifer characterization. It effectively captures both elastic and inelastic deformation responses, addresses time lags between head decline and surface displacement, and is validated against semi-logarithmic analytical methods. Applied to two hydrogeologically diverse aquifers in northeastern and northwestern Iran, the DHE model demonstrates strong predictive performance, providing a scalable and physically grounded approach for groundwater monitoring in data-scarce regions.

[Paper III] This study presents a physics-assisted, machine learning framework for spatiotemporal estimation of groundwater head dynamics in confined aquifers. By integrating InSAR-derived deformation data with groundwater observations, the framework first quantifies seasonal and long-term aquifer storativity parameters, and lag-time using DHE model (previous study). These parameters are then extrapolated across the aquifer using an eXtreme Gradient Boost (XGBoost) regressor trained on diverse environmental variables. Applied to the Shabestar aquifer in northwestern Iran, the model accurately simulates groundwater head variations across space and time while significantly reducing reliance on in-situ data. The approach highlights the potential of combining remote sensing, physics-based modelling, and AI for efficient groundwater monitoring in data-scarce regions.

[Paper IV] This paper introduces SIGH-Map, an integrated InSAR–MODFLOW framework for spatiotemporal groundwater head mapping in data-scarce aquifer systems. By combining InSAR-derived land deformation with a calibrated MODFLOW model, the framework infers aquifer skeletal storage coefficients and simulates groundwater behaviour under over-pumping conditions. Applied to the Neyshabour aquifer in northeastern Iran, the approach accurately reconstructs groundwater head variations across time and space, relying solely on InSAR data and storage parameters after initial calibration. SIGH-Map enables near real-time head estimation, offering a scalable, cost-effective solution for spatio-temporal monitoring of groundwater levels in subsidence-prone, confined aquifers.

[Paper V] This study examines how reduced surface water availability due to river regulation contributes to groundwater depletion and land subsidence in the Isfahan-Borkhar aquifer in central Iran. By integrating InSAR-based deformation measurements, remote sensing-derived surface indicators, and in-situ hydrological data, the research identifies a strong link between the loss of river flow and accelerated subsidence. The findings underscore the role of surface water in sustaining groundwater systems and highlight the infrastructure risks associated with unsustainable groundwater withdrawal in urban environments.

[Paper VI] This study demonstrates the use of InSAR to monitor surface deformation in temperate peatlands of southern Sweden, highlighting vertical motion as a key indicator of peatland hydrological and ecological health. The proposed approach links deformation patterns to subsurface dynamics, offering a non-invasive tools to assess peat condition across large spatial scales. While the study identifies substantial surface uplift that suggests peatland recovery, laboratory evidence supports a potential association with enhanced carbon sequestration, emphasizing the broader ecological implications of deformation monitoring.

Figure 1.1 presents an integrated conceptual framework that illustrates the coherence and progression of six interconnected research studies focused on advanced hydrological system monitoring using InSAR and complementary modelling techniques. It is structured in four main sections (Inputs, Modelling Approaches, Outputs, and Outcomes) to reflect the logical flow from raw data acquisition to scientific insight and practical application. Key datasets such as InSAR deformation measurements, piezometric well observations, and auxiliary environmental information serve as foundational inputs. These are processed through diverse modelling strategies, including numerical, data-driven, and machine learning approaches, aided by physical constraints and domain knowledge. The resulting outputs, such as groundwater head maps, deformation trends, and aquifer parameters, feed into broader hydrological insights. Ultimately, the framework contributes to enhanced understanding of groundwater dynamics, hydrological interconnectivity, climate-driven land deformation, and the development of scalable, data-efficient monitoring tools to inform sustainable water resources management.

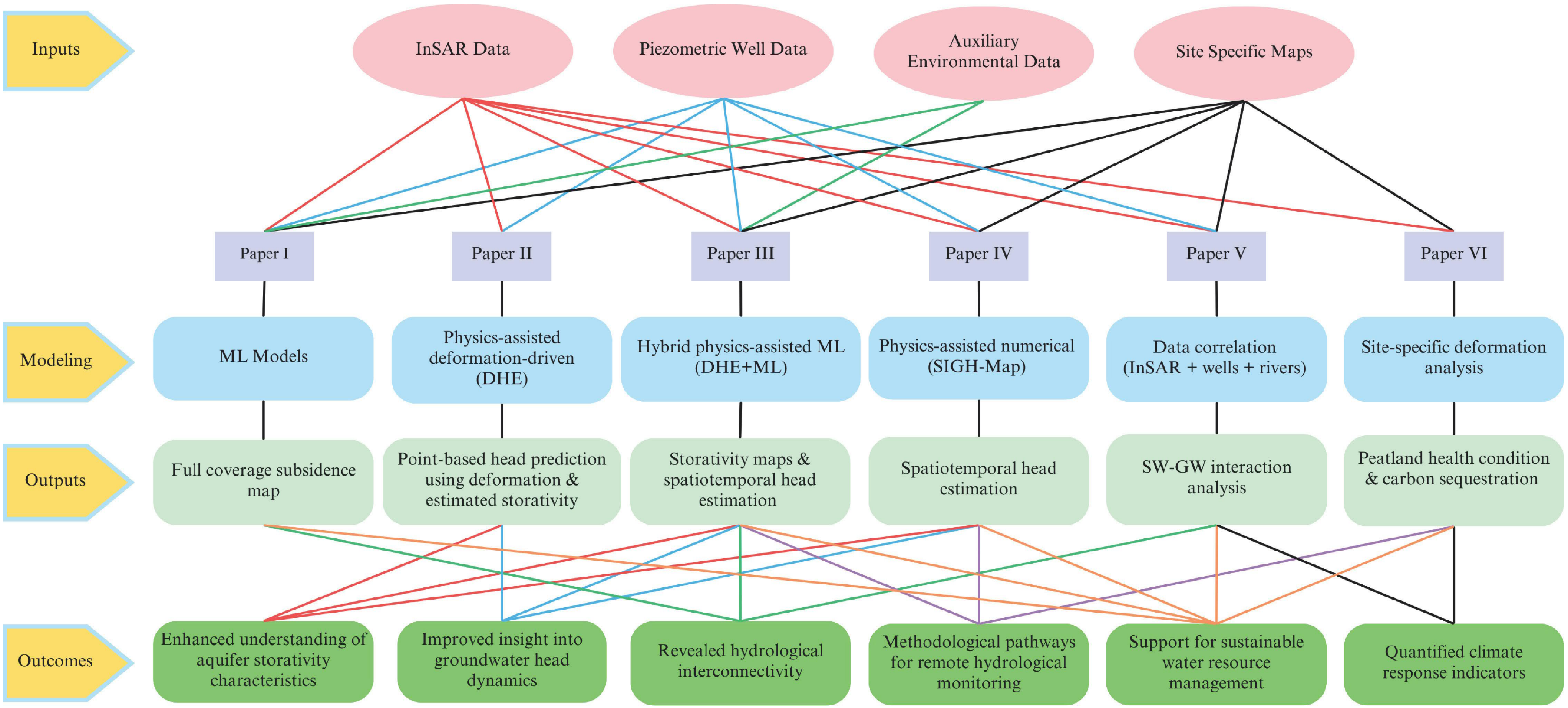


Figure 1.1: Conceptual diagram showing the integrated framework developed across six research studies for hydrological system monitoring. The framework links InSAR, piezometric, and environmental data to advanced modelling approaches, producing outputs such as groundwater head estimates and deformation maps, which lead to outcomes including improved aquifer characterization, spatiotemporal groundwater head dynamics, climate impact analysis, and support for sustainable water management.

1.5 Dissertation structure

Chapter 2 provides the theoretical background, outlining the key concepts, processes, and tools relevant to groundwater systems, surface water interactions, ecosystem dynamics, and remote sensing with a focus on InSAR.

Chapter 3 presents the materials and methods, describing the study areas, datasets, and modelling frameworks that form the basis of the appended articles.

Chapter 4 discusses the results, offering a comparative synthesis of findings on groundwater dynamics, aquifer properties, surface water interactions, and ecosystem responses, along with validation, uncertainties, and broader implications.

Chapter 5 concludes the dissertation by summarizing the main contributions, highlighting their significance for water resource management, and pointing to future research directions.

2 Theoretical background

Groundwater is a foundational component of the Earth's hydrological cycle, contributing substantially to freshwater availability for ecosystems, agriculture, and human use. Beyond its individual importance, groundwater interacts continuously with surface water bodies, soil moisture, and atmospheric processes, shaping watershed-scale water balances and sustaining flows in rivers, wetlands, and lakes (Winter et al., 1998). These interactions influence ecohydrological functions, regulate land surface stability, and provide critical buffers against climatic extremes such as droughts and floods. In human-modified environments, increasing pressures from population growth, agricultural intensification, land use change, and climate variability are placing unprecedented stress on groundwater resources (Famiglietti, 2014). This highlights the importance of integrated water resources assessments that consider groundwater as an active component of broader hydrological and environmental systems. Advances in computational hydrology have expanded our ability to simulate, monitor, and manage groundwater systems with greater spatial and temporal resolution. These tools support more comprehensive and predictive understanding of groundwater behaviour and its implications for long-term water security and environmental resilience.

2.1 Groundwater as a dynamic component of the hydrological cycle

Groundwater is a vital component of the Earth's hydrological cycle, representing the largest unfrozen freshwater resource and the principal liquid freshwater storage on the planet. It plays a foundational role in sustaining ecosystems, agriculture, and human water supply (Condon et al., 2021; Singh, 2014). Functioning at the bottom of the hydrologic cycle, groundwater redistributes water across vast spatial and temporal scales, from headwater catchments to continental aquifers, over periods ranging from days to centuries (Condon et al., 2021). These dynamic interactions link shallow and deep systems and connect land surface processes, surface water bodies, and the atmosphere, helping maintain streamflows, wetlands, and aquifer recharge under variable climatic conditions (Wörman, 2007).

Because of its slow movement, groundwater buffers fluctuations in the water and energy cycles, enhancing predictability across hydrological systems (Sutanto et al., 2020). Groundwater and surface water exchanges provide resilience during droughts and allow vegetation to access deeper water stores, stabilizing ecosystems during low-flow periods (Marchionni, 2020). Shifts in groundwater depth can also influence biogeochemical processes, triggering transitions in groundwater-dependent ecosystems between carbon sinks and sources (Genereux, 2013). However, growing pressures from population expansion, land use change, climate variability, and unsustainable extraction pose serious risks to groundwater sustainability (Wu & Zeng, 2013; Döll et al., 2012; Gleeson, 2016). With groundwater extraction accounting for 35 percent of global freshwater withdrawals, managing these systems requires a deep understanding of both natural processes and human influences (Canales et al., 2024).

To address these challenges, groundwater modelling has become an essential tool for simulating aquifer dynamics, recharge processes, and interactions with surface water systems (Sanford, 2002). Modelling supports improved resource management by enabling forecasts of withdrawal impacts, assessing contamination risks, and quantifying groundwater availability (Singh, 2014). Recent developments in modelling approaches, such as surrogate modelling techniques, offer computational efficiency while retaining predictive accuracy in simulating complex subsurface behaviour (Asher et al., 2015). Uncertainty analysis has become integral to these models, improving confidence in predictions and guiding risk-aware decisions (Wu & Zeng, 2013).

Emerging computational techniques, especially machine learning and metaheuristic optimization, further enhance groundwater modelling by enabling better parameter estimation and capturing nonlinear system behaviour (Osman et al., 2022; Chen & Dai, 2024). Additionally, agent-based modelling is increasingly employed to incorporate socio-economic feedback and stakeholder behaviours, allowing for more holistic assessments of groundwater and society interactions (Canales et al., 2024). These modelling innovations, when integrated with observational data and system-level understanding, are critical for addressing the multifaceted challenges of groundwater sustainability and effective water resource management.

2.2 Groundwater-surface water interactions

Groundwater interactions with surface water systems form a continuous, hydraulically connected network that significantly influences water availability and distribution across landscapes (Banerjee & Ganguly, 2023). These interactions occur through processes such as surface water recharging aquifers (losing streams), groundwater discharging into rivers (gaining streams), and variable exchanges that shift seasonally or spatially along a single watercourse. In some cases, streams may become hydraulically disconnected from aquifers when a substantial unsaturated zone develops. Groundwater pumping near rivers can also induce riverbank filtration, drawing surface water into aquifers (Rossetto et al., 2020; Alley et al., 2002).

A key zone of exchange is the hyporheic zone, located beneath and alongside streambeds, where surface water and groundwater mix. Its physical characteristics, such as streambed topography and sediment permeability, control the magnitude and direction of exchange flows. These flow dynamics influence residence times and contribute to the spatial distribution of recharge and discharge areas (Banerjee et al., 2023).

The intensity and pattern of groundwater-surface water (GW-SW) interactions are controlled by multiple physical factors, including topography, subsurface hydraulic properties, precipitation variability, and seasonal shifts in water levels (Winter et al., 1998; Sophocleous, 2002). Continuous extraction also alters natural exchange dynamics (Alley et al., 2002). At a broader scale, spatial variability in aquifer heterogeneity, surface geomorphology, and transient surface flow events such as floods govern the complexity of groundwater-surface water connectivity (Harvey & Gooseff, 2015; Fleckenstein et al., 2010). Human interventions, such as irrigation, dam construction, and land use change, further modify these interactions (Gleeson et al., 2012; Kondoh et al., 2004).

These exchanges operate across multiple spatial scales, typically categorized as sediment scale (less than 1 meter, related to hyporheic exchange), reach scale (up to 1,000 meters, local flow systems), and catchment scale (more than 1,000 meters, regional systems) (Keery et al., 2007; Ma et al., 2024). The nature and magnitude of interaction depend on factors such as the vertical position of the water table relative to the streambed, aquifer anisotropy, and boundary conditions that influence groundwater gradients and seepage directions (Banerjee et al., 2023).

Understanding GW-SW connectivity is essential for accurate water balance assessments, flow forecasting, and aquifer recharge estimation. These interactions are key in determining streamflow contributions during dry periods and quantifying groundwater availability at multiple scales (Winter et al., 1998; Sophocleous, 2002). Excessive groundwater extraction can lower piezometric surfaces, reducing baseflow to rivers and diminishing surface water availability, especially in dry climates (Gleeson et al., 2012). In coastal regions, overpumping can also lead to seawater intrusion, altering the hydraulic gradient and further reducing freshwater yield (Bear et al., 1999).

Quantitative assessment of these interactions is central to integrated hydrological modelling frameworks. Advances in remote sensing, groundwater flow modelling, and data-driven approaches now provide improved tools to simulate and monitor the spatial and temporal dynamics of GW-SW exchange, supporting more effective water resource management under changing environmental conditions (Winter et al., 1998; Kalbus et al., 2006).

2.3 Advances in global and multiscale groundwater modelling

Given its critical role and dynamic interactions, accurately representing groundwater within modelling frameworks is essential to fully understand global hydrology dynamics. Transient global groundwater modelling is needed to obtain spatially and temporally continuous and consistent information about this resource, especially in the context of changing global conditions. A global groundwater framework is necessary to address critical gaps in our understanding and predictive capacity of the hydrologic cycle (Condon et al 2021).

There has been an international effort to develop global-scale groundwater modelling and analysis, including a push to incorporate groundwater representations into existing global land surface and earth system models (de Graaf et al, 2017; Maxwell et al, 2015; Gleeson et al, 2016 & 2021). Significant progress has been made in continental to global scale groundwater modelling (Gleeson et al, 2021), but much additional work is required to achieve a consistent global framework that seamlessly interacts with observational datasets and other Earth system models. This requires community engagement and interdisciplinary collaboration on best practices.

In this context, satellite-based remote sensing technologies have become indispensable for supporting large- and small-scale groundwater modelling efforts. Observational datasets derived from satellite missions such as GRACE (Gravity Recovery and Climate Experiment) provide estimates of terrestrial water storage anomalies, enabling coarse-scale evaluation of groundwater trends in areas lacking sufficient in-situ data (Rodell et al., 2009; Long et al., 2015). Similarly, surface deformation data from InSAR offer valuable spatial information on aquifer compaction and subsidence, which can be used to infer changes in groundwater storage and support calibration of numerical models at finer scales (Chen et al., 2016; Jaramillo et al., 2024).

By integrating satellite observations with hydrological simulations, researchers can reduce uncertainty in parameter estimation, improve spatial coverage in data-scarce regions, and better assess the impacts of climate variability and human activities on groundwater systems. While the detailed role of these remote sensing techniques is discussed in later sections, it is important to recognize their contribution to evolving multiscale modelling frameworks.

Simulation models are often the only feasible means to provide input for groundwater management decisions due to their predictive capabilities (Singh, 2014). They can help forecast the likely impacts of different water management strategies, and the results of simulation studies can form the basis for identifying suitable future management plans. Groundwater inverse modelling is a vital technique for enhancing numerical simulation accuracy by estimating unmeasurable model parameters (Chen & Dai 2024).

Accurate simulation and prediction require capturing the dynamic interactions between groundwater and other parts of the system. Specifically, accurate representation of anomalies in shallow groundwater and their connections to soil moisture and evapotranspiration dynamics could further improve forecast performance at sub-seasonal to decadal timescales and for assessing long-term impacts of global change (Condon et al, 2021). Groundwater flow models must be capable of capturing three-dimensional flow at multiple spatial scales and resolutions and must be connected to land surface and overland flow processes. They need to include both shallow and deep groundwater systems to encompass the connections between them and the impact of human pumping. The integration of human activities that influence the groundwater system, such as pumping and irrigation, is also essential in modelling platforms.

While steady-state models provide estimates of static conditions, transient simulations are needed to cover the dynamic changes within the groundwater system. The vision for a Global Groundwater Platform (GGP) includes combining observations and models to provide spatially and temporally continuous groundwater information (Condon et al, 2021). Such a platform should be designed to be compatible with observation networks to facilitate direct data assimilation and model evaluation. It also requires spatially continuous and consistent datasets of hydrogeologic properties, which are challenging to generate globally. Models can be improved by progressively incorporating better data and hydro-stratigraphic characterizations.

2.4 Groundwater flow and deformation processes

Groundwater is stored in different types of aquifers, each exhibiting distinct hydraulic behaviours that influence how water flows and responds to stress. Unconfined aquifers are directly recharged by precipitation and interact openly with the atmosphere, while confined aquifers are bounded by low-permeability layers (aquitards) that restrict vertical flow, leading to pressurized conditions. Semi-confined or leaky aquifers allow limited vertical leakage through confining layers. These classifications are fundamental for understanding aquifer response to recharge, pumping, and deformation (Freeze & Cherry, 1979; Fetter, 2001). Aquifer characteristics such as storativity and compressibility vary significantly among these aquifer types and directly affect both hydrodynamic behaviour and soil compaction under stress.

Accurate characterization of aquifer types, confined, semi-confined, or unconfined, and their extents traditionally necessitates extensive field investigations, including borehole stratigraphy, pumping tests, and geophysical investigations (Morakaladi & Atangana, 2023). However, such conventional methods become increasingly challenging in regions characterized by complex or insufficiently understood hydrostratigraphy, particularly under conditions of intense groundwater pumping.

Terzaghi's theory of consolidation provides a foundational framework for interpreting aquifer deformation in response to changes in hydraulic heads (Terzaghi, 1943). The skeletal storage coefficient s_k quantitatively links vertical land surface deformation Δb with changes in hydraulic head Δh through the relationship:

$$s_k = \frac{\Delta b}{\Delta h} \tag{1}$$

Given a known aquifer thickness b_0, this skeletal storage can further be related to the specific storage coefficient s_{s_k} as:

$$s_k = s_{s_k} b_0 \tag{2}$$

For unconfined aquifers, the relationship must be adjusted to account for specific yield s_y, leading to a modified skeletal storage coefficient s_k^*:

$$s_k^* = (1 - s_y) s_k \tag{3}$$

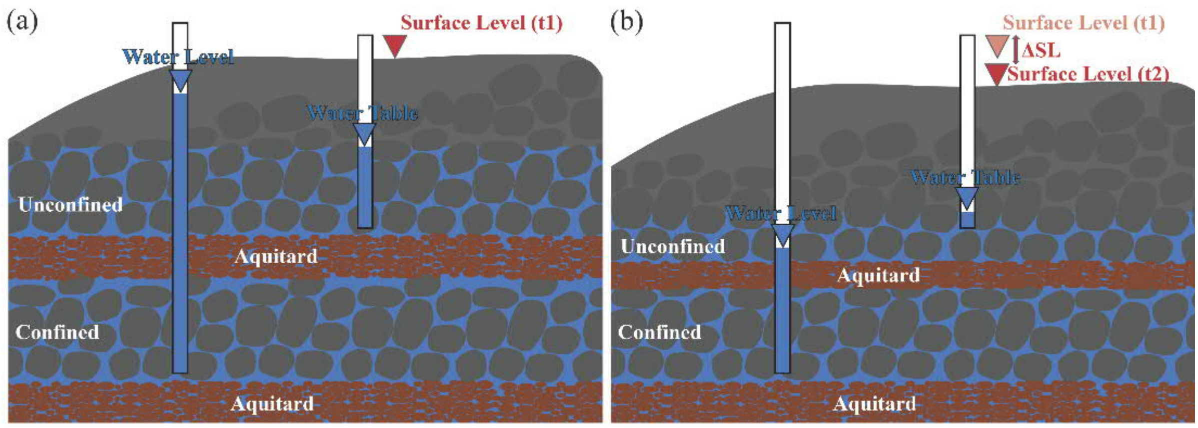


Figure 2.1: (a) Shows the aquifer in a balanced state with stable groundwater levels in both unconfined and confined zones. (b) Excessive groundwater withdrawal lowers water levels, most notably in the confined aquifer, causing compaction of subsurface layers and ground surface subsidence.

Groundwater extraction reduces pore-water pressures in the (semi-)confined unit, triggering subsurface compaction primarily through rearrangement of soil particles within the aquifer matrix. In unconfined aquifers, compaction arises predominantly from gravity-driven drying and resulting structural adjustments of upper soil layers. Confined aquifers experience additional stress from overlying layers (e.g., aquitards), resulting in significant deformation to maintain equilibrium under the altered hydraulic conditions. Semi-confined aquifers demonstrate deformation characteristics intermediate between these extremes, integrating the responses of both confined and unconfined conditions. Figure 2.1 illustrates this concept clearly.

Surface deformation reflects the integrated mechanical response of multiple aquifer types within a given region. While traditionally these responses are classified into elastic and inelastic components based on pre-consolidation thresholds, such delineations often lack clear field-derived boundaries. Land surface deformation due to groundwater extraction primarily results from the compaction of fine-grained, compressible layers such as clay and silt, where declining pore-water pressures increase effective stress and drive vertical settlement of the aquifer system (Terzaghi, 1943; Galloway & Burbey, 2011).

Numerous studies have integrated deformation data with in-situ groundwater observations to estimate aquifer storativity parameters using diverse approaches, including grid-search inversion, spatial regression, Markov Chain Monte Carlo (MCMC)-based reconstruction, and component decomposition methods like PCA and wavelet analysis (e.g., Chen et al., 2016; Ali et al., 2022; Smith & Li, 2021; Chaussard et al., 2014; Miller & Shirzaei, 2015; Jiang et al., 2018), highlighting the value of deformation monitoring for aquifer characterization (Motagh, 2017; Ghorbani et al., 2022; Shanker et al., 2011).

A critical complexity in interpreting deformation data is estimating the time lag between hydraulic head changes and observed surface deformation due to delayed interbed drainage in low-permeability strata. Hoffman et al. (2003) offer an analytical model to quantify this lag:

$$\Delta b_{inelastic}(t) = s_{skv}.\, b_0.\, \Delta h.\, (1 - \frac{8}{\pi^2}\ e^{-\frac{\pi^2}{4}\frac{t}{\tau_0}}) \qquad (4)$$

where s_{skv} is the inelastic skeletal storage coefficient, τ_0 is the system's time constant and denotes elapsed time since head alteration. In regions with limited observational data, cross-correlation techniques effectively estimate this time lag from seasonal deformation and groundwater head variations (Bai et al., 2022).

Despite considerable advances, previous research has largely concentrated on elastic deformation parameters within well-characterized aquifer systems. This study proposes an innovative yet streamlined methodological framework leveraging InSAR-derived deformation combined with groundwater head data from piezometric wells to robustly infer aquifer storativity, even in settings with sparse or incomplete hydrogeological information.

2.5 Peatlands as climate-sensitive hydrological systems

Peatland ecosystems are distinct hydrological systems intricately connected to groundwater and surface water processes. Their high water retention capacity and sensitive water table dynamics reflect subsurface interactions and surface inputs, making them particularly responsive to hydroclimatic variations, including shifts in precipitation, temperature, and evaporation regimes (Holden, 2005; Waddington et al., 2015). As such, peatlands act as critical indicators of landscape-scale hydrological conditions, offering insight into GW-SW dynamics and ecosystem responses to climate variability and change (Baird et al., 2009; Limpens et al., 2008).

Although they occupy only a small fraction of Earth's land surface, peatlands store a disproportionately large share of global soil carbon, estimated at 21-30% despite covering just 3-4% of terrestrial areas (Minasny et al., 2024; Ghazaryan et al., 2024). Northern peatlands, in particular, represent vast carbon reserves (Antala et al., 2022). These ecosystems also provide critical hydrological and ecological functions, regulating water balances, mitigating floods, and contributing to climate regulation through their coupled water and carbon cycling (Mozafari et al., 2023). Their effectiveness depends on the interplay between hydrology, vegetation, and carbon dynamics (Leifeld & Menichetti, 2018; Nordbeck & Högl, 2024).

Water table fluctuations drive the most direct and measurable physical responses in peatlands. Drawdown exposes peat to aeration, accelerating organic matter decomposition and causing subsidence, while stable or rising water tables promote organic accumulation and vegetation growth, driving surface uplift (Price, 2003; Fritz et al., 2008; Potvin et al., 2015). These vertical motions are key indicators of peatland hydrological and carbon states, as subsidence is often associated with greenhouse gas release, whereas uplift typically corresponds to carbon sequestration (Hooijer et al., 2012; Hoyt et al., 2020).

Monitoring these subtle yet widespread surface changes is challenging using conventional ground-based methods, which are limited in spatial coverage and are time- and cost-intensive. InSAR on the other hand offers an effective alternative, providing sub-centimeter precision in tracking seasonal and long-term vertical deformation across extensive peatland landscapes (Alshammari et al., 2018; Zhou et al., 2019). By capturing trends in uplift and subsidence, InSAR enables direct assessment of peatland responses to hydrological and climatic drivers, while also supporting evaluations of their role in regional and global carbon cycles. Continuous deformation monitoring with InSAR can inform early detection of degradation, guide restoration, and improve carbon budget assessments under changing climate conditions.

2.6 ML in groundwater studies

Machine learning has emerged as a powerful complement to traditional physics-based groundwater modelling, particularly in addressing data scarcity, high-dimensional parameter spaces, and nonlinear system behaviours. These data-driven approaches are well suited for estimating groundwater levels, predicting land subsidence, and inferring aquifer properties using limited or remote observations (Osman et al., 2022; Chen & Dai, 2024).

Supervised ML algorithms, such as decision trees, support vector machines, and artificial neural networks, have been increasingly employed to forecast groundwater head fluctuations using climatic, topographic, and satellite-based datasets. Ensemble models such as boosted regression trees and extreme gradient boosting have shown strong performance in spatiotemporal prediction tasks by capturing complex interactions across variables (Naghibi et al., 2022).

Hybrid frameworks combining machine learning with physically based models are also gaining attraction. These include surrogate modelling techniques that approximate numerical simulations to reduce computational cost (Asher et al., 2015), physics-informed neural networks for improved generalization, and ML-assisted inverse modelling to support parameter estimation and uncertainty reduction (Chen & Dai, 2024).

The growing availability of remote sensing products such as InSAR-derived deformation, vegetation indices, and land use maps further enhances the utility of machine learning for regional groundwater assessments, particularly in data scarce environments (Jaramillo et al., 2024). In these contexts, ML approaches provide a scalable and flexible alternative to traditional methods, facilitating near real time monitoring and supporting more adaptive management decisions.

By integrating observational data and physical understanding, ML models now serve as valuable tools for advancing quantitative water assessment in response to increasing climatic and anthropogenic pressures on groundwater systems (Osman et al., 2022; Canales et al., 2024).

2.7 Remote sensing of ground deformation for hydrological assessment

Given the increasing complexity of groundwater modelling and hydrological assessments discussed above, accurate and extensive observational datasets are essential. Remote sensing, particularly InSAR, provides critical observational support to validate and enhance these modelling efforts. InSAR technology has revolutionized the field of hydrological research by enabling detailed, precise, and extensive spatial monitoring of Earth's surface changes associated with water dynamics. It has also demonstrated its utility in surface water assessment, including wetland monitoring, flood extent mapping, and evaluating changes in surface water storage in wetlands, lakes, and reservoirs (Aminjafari et al., 2024; Das & Hossain, 2025), while its most transformative impact has been in groundwater assessment. Its ability to capture millimetre-level surface deformation over vast geographic scales makes it particularly powerful for groundwater-related applications, especially in addressing contemporary challenges such as water availability assessment, aquifer management, and sustainable water resource use (Smith, 2002; Liu et al., 2020; Jaramillo et al., 2024).

The strength of InSAR lies in its unparalleled capacity to detect subtle changes in land elevation caused by diverse geophysical processes such as tectonic movements, volcanic activity, and, most relevant here, hydrological phenomena including variations in groundwater storage, aquifer compaction, and hydrological cycle dynamics. Groundwater depletion, a significant issue worldwide, particularly in arid and semi-arid regions, has been effectively monitored through InSAR, enabling the identification of land subsidence hotspots and quantification of aquifer overdraft rates with high temporal and spatial resolution. Studies globally have demonstrated its effectiveness, notably in regions suffering severe groundwater extraction pressures, such as in Iran, where extensive land subsidence has been clearly mapped and analysed through InSAR data (Haghshenas Haghighi & Motagh, 2024).

InSAR's utility extends beyond groundwater monitoring to include broader aspects of hydrological connectivity and surface water storage changes. It is particularly effective in identifying flow obstacles and tracking connections within complex and patchy wetland systems. This capability significantly improves water management strategies by providing crucial information about water movement, recharge zones, and areas where aquifers may be at risk (Liu et al., 2020). This wide-area coverage is especially valuable for decision-makers in regions with limited ground-based monitoring infrastructure.

Furthermore, InSAR has facilitated advancements in understanding surface water storage dynamics, critical for regions prone to droughts and floods. By integrating InSAR-derived data with hydrological modelling, researchers can better assess water availability and predict water scarcity risks, enabling proactive resource management and mitigation strategies (Papa & Frappart, 2021). The integration of InSAR data into hydrogeodesy frameworks further allows for robust quantification of water resources, essential for addressing sustainability and water security concerns globally (Jaramillo et al., 2024).

The extensive spatial coverage, accuracy, and cost-effectiveness of InSAR position it as an indispensable tool in water availability assessments, particularly beneficial for regions experiencing limitations in conventional hydrological data availability (Springer et al., 2023; Ibrahim et al., 2024). Its role in supporting sustainable management practices, informed policymaking, and strategic planning cannot be overstated, particularly in regions characterized by complex hydrological interactions and escalating pressures from human and climatic factors (Jaramillo et al., 2024; Bru et al., 2024).

This technique offers a spatially extensive and temporally consistent dataset, bridging gaps between surface and subsurface hydrological monitoring. InSAR complements traditional in-situ measurements by enabling large-scale assessments of aquifer compaction, land subsidence, and their relationship to groundwater fluctuations. It also contributes to better understanding the connectivity between groundwater, surface water, and ecosystems such as wetlands and peatlands by providing insights into hydrologic responses at various scales. As such, InSAR represents a critical advancement in the integrated monitoring of hydrological systems, enhancing modelling capabilities and supporting more informed water resource management strategies in the context of global change.

2.8 Introduction to SAR and InSAR

Building upon the importance of remote sensing in hydrological studies established in the previous sections, this section presents detailed information on SAR and InSAR, outlining their operational principles, data handling, and applicability within groundwater and hydrological studies. Synthetic Aperture Radar (SAR) is an active microwave imaging system that emits electromagnetic waves and records the energy backscattered from a target in the antenna's look direction (Ferretti et al., 2007; Griffiths, 1995). It offers unique advantages for Earth observation due to its all-weather, all-time capability, being able to penetrate clouds, fog, and depending on wavelength and conditions, some vegetation, snow, and sand (Zhou et al., 2009; Smith, 2002; Hong & Wdowinski, 2017; Lee et al., 2020). These characteristics of SAR data make it valuable for a wide range of applications. Mapping, land cover and land use classification are popular methodologies utilizing SAR data. SAR, particularly through InSAR techniques, contributes to topographic products and deformation detection maps (Ferretti et al., 2007; Osmanoglu et al., 2016). In oceanography, SAR is used for wind and wave speed retrieval. It also plays a significant role in glaciology, geography, and geology (Smith, 2002; Zhou et al., 2009). Parameter retrieval, such as soil moisture, is another key application important for agriculture and climate monitoring (Smith, 2002; Hong & Wdowinski, 2017; Lee et al, 2020).

The strength and characteristics of this backscatter are used to calculate the Radar Cross Section (RCS), which provides information about the physical and geometric properties of surface features (Ferretti et al., 2007; Griffiths, 1995). SAR images are maps of backscatter intensity in range-azimuth dimensions. SAR systems use coherent, microwave-frequency signals (often chirped pulses) that allow preservation of both amplitude and phase information. The amplitude (strength of the backscattered wave) is influenced by the target's shape, orientation, and electrical properties, while the phase (the state of the wave as it propagates) is highly sensitive to the distance between the sensor and the target. While SAR systems can measure the phase of the return signal with great precision, directly measuring the total range (number of wavelengths) is challenging, leading to phase measurements that are "wrapped" between $-\pi$ and $+\pi$. The wavelength (distance between two consecutive maxima or minima) defines the unit distance for SAR phase measurements, with each wavelength corresponding to 360° or 2π radians (Hu et al 2014; Osmanoglu et al 2016).

2.8.1 Satellite SAR data

Space-borne SAR technology has evolved significantly since the launch of the first satellite SAR mission, Seasat, in 1978. Seasat, operating at L-band, demonstrated the potential of SAR for Earth observation. Following this pioneering mission, a series of satellite SAR systems with increasingly sophisticated capabilities were developed. The Shuttle Imaging Radar missions, SIR-A and SIR-B, in the 1980s, further explored SAR applications, with SIR-C/X-SAR in the 1990s marking a significant advancement by operating at multiple frequencies (X-, C-, and L-bands), with C- and L-band supporting full polarimetry (Freeman et al., 2019).

The European Remote Sensing satellites, ERS-1 and ERS-2, launched in the 1990s, provided long-term C-band SAR data (Zebker et al., 1994). Japan's JERS-1 SAR also contributed L-band imagery during this period. Canada's RADARSAT-1, launched in 1995, offered versatile C-band data with varying resolutions and swath widths (Kroupnik et al., 2021). The Shuttle Radar Topography Mission (SRTM) in 2000 was a landmark event, utilizing C-band SAR globally (with limited X-band coverage) to generate a near-global digital elevation model (Farr et al., 2007).

The subsequent decades witnessed the deployment of advanced SAR missions with enhanced spatial resolution, shorter revisit times, and multi-polarization capabilities. These include the European ENVISAT with its Advanced SAR (ASAR) instrument, the Japanese ALOS with its PALSAR sensor, and its successor

ALOS-2. The German constellation SAR-Lupe and the Italian COSMO-SkyMed constellation provided high-resolution X-band imagery with frequent revisits. Germany's TerraSAR-X and its twin TanDEM-X offered very high-resolution X-band data and enabled innovative interferometric applications like single-pass interferometry for precise height measurements. In terms of temporal resolution moderate-resolution satellites historically had revisit times of around a month (e.g., 24 days for RADARSAT-1, 35 days for ERS-1/2 and ENVISAT, and 46 days for JERS-1 and ALOS). However, high-resolution satellites now offer revisit times of several days (e.g., 11 days for TerraSAR-X, and 1–16 days for COSMO-SkyMed). This improved temporal resolution allows for more dynamic monitoring of the Earth's surface, which is crucial for many applications (Hu et al., 2025).

The frequency (wavelength) of the microwave signal used in SAR provides band-dependent information about surface interactions (Manavalan, 2018). While not a continuous spectrum like optical sensors, different microwave bands interact uniquely with the Earth's surface, offering some degree of spectral discrimination (Tsang et al., 2022). L-, C-, and X-bands are the most widely employed. These different frequencies interact uniquely with the Earth's surface, providing some degree of discriminatory information in terms of how different materials and surface conditions scatter microwaves at these specific bands (Arii et al., 2019). While not directly analogous to the continuous spectral range of optical sensors, the use of multiple frequencies (as in multi-frequency SAR) allows for discrimination based on these interactions. Lower frequencies (longer wavelengths) generally allow for increased penetration, depending on the medium’s properties such as moisture and density. Early SAR instruments typically operated in a single polarization mode, either VV (vertical transmit, vertical receive) or HH (horizontal transmit, horizontal receive). Modern SARs offer dual- and quad-polarized images (Polarimetric SAR or PolSAR), capturing diverse structural and texture information and enabling the recognition of different scattering mechanisms (Verma et al., 2022). This polarimetric capability adds another dimension of information beyond simple backscatter intensity, aiding in various applications.

The spatial resolution of SAR imagery has significantly improved since the early systems. Early SAR systems had coarser resolution, while advanced sensors now provide fine resolution measurements. The spatial resolution is influenced by factors like the processing of the synthesized antenna aperture and the chosen radar mode (European Space Agency, 2012).

Among these, the Sentinel-1 mission, comprising Sentinel-1A (launched in 2014) and Sentinel-1B (launched in 2016, though currently not operational), has become a cornerstone for a wide array of applications (Piter et al., 2024; Cheng et al., 2025). Its key characteristics include a wide Interferometric Wide swath (IW) mode with a spatial resolution of 5 m by 20 m in Single Look Complex (SLC) products, providing a balance between coverage and detail. SLC products preserve both the amplitude and phase information of the radar signal in complex format, making them suitable for interferometric and advanced SAR analyses (European Space Agency, 2012). The C-band SAR instrument operates with selectable dual polarization modes (HH+HV and VV+VH), offering valuable information about the scattering characteristics of the Earth's surface. A significant advantage of Sentinel-1 is its high temporal resolution, with a repeat cycle of approximately 6 days when both satellites were operational, facilitating the monitoring of dynamic phenomena. Furthermore, the data from the Sentinel-1 mission are available free of charge, making it highly accessible to researchers, practitioners, and policymakers globally.

2.8.2 InSAR as a technique

InSAR is a technique that combines two or more SAR images acquired over the same area but at different times to extract information based on the phase difference between these images. This phase difference, or interferometric phase ($\Delta\varphi$), contains contributions from the topography, atmospheric effects, noise, and changes in the path length between the satellite and the ground. By exploiting these phase differences, InSAR can be used to construct Digital Elevation Models (DEM) and/or measure ground movement that occurred between the acquisition times. For mapping surface displacement, the technique is commonly referred to as differential InSAR (D-InSAR). The ground movements detectable by D-InSAR can be caused by various geophysical and anthropogenic phenomena, including inter-, co-, and post-earthquake deformations, glacier motion, tectonic activity, volcanic eruptions, landslides, underground mining, groundwater extraction, and land reclamation (Massonnet & Feigl, 1998). Theoretically, D-InSAR allows the detection of surface changes with centimeter and even millimetre precision.

2.8.3 Workflow of preparing InSAR data

i. Individual interferogram generation:

The InSAR process begins with the acquisition of at least two SAR images of the same area from slightly different look angles or at different times. These are often referred to as the primary (master) and secondary images (Zhou et al., 2009). A key criterion for successful interferometry is coherence between the two SAR images. This means the radar reflectivity of the ground targets must remain relatively stable between the two acquisitions. Short temporal and perpendicular baselines between acquisitions help to maintain coherence (Raucoules et al., 2007; Yu et al., 2020).

The two SAR images (master and secondary) are then co-registered with sub-pixel accuracy, ensuring that corresponding pixels in the two images represent the same ground location (Keydel et al., 2007; Zhou et al., 2009). Accurate co-registration is crucial for precise phase difference measurements (Zou et al., 2009). An interferogram is formed by multiplying each pixel of a master image with the complex conjugate of the corresponding pixel in a secondary image, which effectively computes the phase difference between the two acquisitions (Besoya, 2021). This results in a complex-valued interferogram where the phase component contains information about the range difference to the ground targets between the two acquisitions (Griffiths et al., 1995; Sneed et al., 2003). Flat earth removal is typically performed to remove the phase contribution due to the Earth's curvature and the sensor geometry. Orbital information is vital for this step (Besoya et al., 2021). The topographic phase component is often removed using an available DEM (Xu et al., 2020). The remaining phase is then primarily related to surface deformation and atmospheric delays. Phase filtering can be applied to reduce noise and improve the visibility of the interferometric fringes (Loffeld et al., 2007). The phase component of the interferogram, which is initially wrapped between $-\pi$ and $+\pi$ radians, may undergo phase unwrapping to obtain continuous phase values proportional to the displacement (Chen & Zebker, 2000; Ma et al., 2022). However, notes that for some applications like averaging and differencing interferograms using the phase gradient approach, phase unwrapping might be delayed until later in the processing. Unwrapping errors can bias time-series analysis (Sandwell et al., 1998; Yunjun et al., 2019).

ii. Interferogram stacking:

For time series analysis, multiple interferograms spanning a period of time are generated, forming an interferogram stack (Yunjun et al., 2019). These interferograms are created from multiple SAR acquisitions over the same area. The interferograms in the stack may have different temporal baselines (the time difference between the two acquisitions) and spatial baselines (the perpendicular separation between the satellite passes) (Sneed et al., 2003).

iii. InSAR time series production:

Once a stack of interferograms is available, time series analysis techniques are applied to extract the temporal evolution of surface deformation (Yunjun et al., 2019; Li et al., 2019). Different InSAR time series analysis techniques construct networks of interferograms based on distinct criteria:

- Conventional InSAR uses two SAR images acquired at different times to create an interferogram, which contains a combination of topography, potential surface displacement, atmospheric effects, and noise (Sneed et al., 2003). The phase component of the interferogram is analysed to map deformation. However, conventional InSAR can be limited by temporal decorrelation, atmospheric artifacts, and the need for phase unwrapping (Besoya et al., 2021).
- Differential InSAR (D-InSAR) focuses specifically on deformation monitoring by removing the topographic phase, typically using a DEM (Zhang et al., 2021), though residual DEM errors can propagate into the deformation signal. It shares

limitations with conventional InSAR, including susceptibility to decorrelation and atmospheric disturbances.

- Persistent Scatterer Interferometry (PSInSAR) utilizes stacks of SAR images over time, focusing on stable point scatterers (PS), such as buildings, bridges, or rock outcrops, characterized by consistent radar backscatter (Ferretti et al., 1999; Ferretti et al., 2002; Hooper et al., 2004; Devanthéry et al., 2016). By analysing amplitude and phase stability of these scatterers, PSInSAR accurately estimates surface deformation, atmospheric delays, and topographic errors (Ferretti et al., 2000). It is particularly effective for detecting subtle, long-term surface deformations in urbanized or infrastructure-rich areas but requires a sufficient density of stable scatterers and adequate SAR acquisitions. However, PS techniques might suffer from large errors in Near-Real-Time (NRT) processing due to phase unwrapping errors more likely caused by steep phase gradients, large noise, and atmospheric disturbance over long time spans, especially in non-urban areas with poor spatial distribution of PS (Ma et al., 2022). PSInSAR requires a sufficient number of images and PS points in the area of interest.
- Small Baseline Subset (SBAS) InSAR leverages interferograms with small temporal and spatial baselines to minimize decorrelation, particularly suitable for distributed deformation areas with fewer coherent scatterers (Berardino et al., 2002; Schmidt & Bürgmann, 2003). It involves solving a system of linear equations through least squares or L1-norm minimization, enabling detailed displacement histories even in vegetated or rapidly changing environments (Lauknes et al., 2010). Modern SAR satellites, with shorter revisit times, allow for fully connected interferogram networks, simplifying inversion through unbiased weighted least squares (WLS) estimation (Yunjun et al., 2019).
- Phase Gradient Approach allows averaging and differencing interferograms without prior phase unwrapping, using the phase gradient to enhance fringe clarity and reduce errors. However, it is less commonly applied in modern large-scale time series analyses. (Sandwell & Price, 1998).
- A hybrid approach combining PSInSAR and SBAS methods merges the strengths of stable point-based and distributed scatterer analyses, enabling deformation monitoring in mixed urban-natural landscapes (Hooper, 2008). This combined technique increases spatial coverage, accuracy, and reliability of deformation measurements, particularly beneficial in regions with variable scatterer distribution (Ma et al., 2022).

The choice among these techniques depends on factors such as deformation nature, site characteristics (vegetation vs. urbanization), SAR data availability, and required accuracy and resolution. Advanced methods like PSInSAR generally provide higher precision in coherent urban environments, while SBAS and combined PS-SBAS approaches excel in mixed and less coherent regions.

A key step in time series analysis is network inversion, in which the system of linear observation equations from the interferogram stack is solved to obtain the raw phase time series (Berardino et al., 2002). For a fully connected interferogram network, this inversion can provide unbiased estimates, often improved by applying weighting schemes based on coherence or baseline length. To mitigate errors introduced during phase unwrapping (particularly for 2D algorithms) various correction strategies can be applied, including bridging, phase closure checks, and coherence-based network modification (Chen & Zebker, 2002).

Correction for deterministic phase components is crucial for obtaining accurate displacement time series (Hanssen, 2001; Li et al., 2009; Ferretti et al., 2011; Yunjun et al., 2019). These corrections include:

- Tropospheric delay correction using global atmospheric models, delay-elevation ratios, or spatio-temporal filtering. Atmospheric delays can introduce significant errors in InSAR measurements.
- Topographic residual correction.
- Phase ramp removal to account for orbital errors or other long-wavelength errors. Residual interferograms (single interferogram minus stack) can show tilts reflecting orbit error and atmospheric delay.

Outlier detection methods can be used to identify and exclude noisy SAR acquisitions.

The resulting output of the time series analysis is typically a displacement time series for each coherent pixel or selected point, representing the cumulative surface deformation over the analysed period with respect to a reference acquisition. Average velocity maps can also be estimated.

2.8.4 InSAR software and applications

Open-source InSAR software packages are highly flexible, customizable, and supported by active communities, although they generally require a higher level of technical expertise from users. Among these, GMTSAR and StaMPS/MTI are particularly proficient and widely used in research due to their robust capabilities and interoperability with other prominent software packages.

GMTSAR (Generic Mapping Tools Synthetic Aperture Radar), developed by Scripps Institution of Oceanography and San Diego State University, is a widely used open-source software known for its effective integration with Generic Mapping Tools (GMT), offering users powerful command-line tools for processing and visualizing InSAR data (Sandwell et al., 2011). It provides users with significant flexibility and precise control over interferometric workflows. GMTSAR is also recognized for its computational efficiency, robust handling of interferogram networks, and accurate co-registration using a geometric approach based on DEMs. These features make it especially suitable for studies requiring comprehensive spatial coverage and temporal continuity, such as groundwater monitoring aimed at capturing long-term aquifer deformation dynamics (Sandwell et al., 2011; Xu et al., 2020).

StaMPS/MTI (Stanford Method for Persistent Scatterers and Multi-Temporal InSAR) is another highly regarded software, widely recognized for its effectiveness in Persistent Scatterer Interferometry (PSI) and Multi-Temporal InSAR applications (Hooper et al., 2012). StaMPS initially developed at Stanford University, addresses decorrelation issues effectively by exploiting spatial correlations, making it particularly valuable in regions with sparse or natural scatterers. It is especially well-suited for vegetated and agricultural regions, where conventional persistent scatterers are limited. By identifying and utilizing Slowly Decorrelating Filtered Phase (SDFP) pixels, StaMPS provides robust deformation estimates in areas with complex, time-variable land cover conditions (Hooper et al., 2012; Fattahi & Amelung, 2015). The software is often integrated with foundational processing packages such as DORIS (Kampes et al., 2004) and ISCE (Agram et al., 2013), enabling comprehensive workflows from raw SAR data to advanced deformation analysis. Additionally, it can seamlessly incorporate GMTSAR output, offering users a flexible and powerful toolkit that combines the strengths of both platforms.

Other notable open-source tools complementing GMTSAR and StaMPS include ISCE (Caltech/JPL and Stanford), highly customizable and technically robust, especially useful in initial interferogram generation and baseline management. ROI_PAC (Caltech/JPL) shares similar features with ISCE but is more focused on core interferometric processing tasks (Rosen et al., 2012). LiCSBAS (Morishita et al., 2020) specializes in Sentinel-1 time series analysis and integrates efficiently with automated LiCSAR products, optimizing resource usage. MintPy (Miami InSAR Time-series software in PYthon) provides powerful small-baseline time series analysis capabilities, particularly strong in unwrapping error correction (Yunjun et al., 2019). Its Python-based environment offers considerable flexibility, making it highly complementary to GMTSAR for sophisticated post-processing and temporal analyses.

Commercial alternatives such as ENVI SARScape (Sahraoui, 2006), DIAPASON (Massonnet et al., 1997), Gamma SAR (Werner et al., 2000), and Sarproz (Perissin et al., 2011) offer comprehensive, user-friendly interfaces, robust technical support, and extensive processing capabilities but involve licensing costs.

Selecting the appropriate InSAR software or a combination of them depends on budget, technical skill, specific project goals, the type of SAR data available, and desired levels of automation and support. Researchers frequently combine packages like GMTSAR and StaMPS to leverage their complementary strengths, creating powerful and flexible workflows to suit their specific research objectives.

InSAR and its various techniques have a wide range of applications in Earth science and other fields (Zhou et al, 2009), including seismic deformation monitoring (Weston et al., 2012), volcano monitoring (Spaans & Hooper, 2016; Hooper et al., 2020), landslide monitoring (Natijne et al., 2022), and studying glacier, permafrost, and ice sheet dynamics (Sánchez-Gámez & Navarro, 2017; Zhang et al., 2021; Zhang et al., 2022; Feng et al., 2023). InSAR is also crucial for land subsidence monitoring related to groundwater withdrawal (Smith et al., 2019; Smith et al., 2021; Ghorbani et al., 2022), mining (Yang et al., 2020), oil and gas extraction (Filatov & Yevtyushkin, 2010), and natural compaction (Teatini et al., 2024), with MT-InSAR offering high effectiveness for long-term trends (Luo et al., 2021). Infrastructure deformation can be monitored using PSI techniques (Ibrahim et al., 2024; Banic et al., 2025; Tao et al., 2025), while DEM generation relies on interferometric phase data (Gao et al., 2017; Wang et al., 2018). InSAR contributes to atmospheric studies (Miranda et al., 2019; Mateus et al., 2021), coastal subsidence and shoreline change monitoring (Udugbezi et al., 2018; Zhao et al., 2021), wetland water level changes (Hong & Wdowinski, 2017; Mohammadimanesh et al., 2018; Lee et al., 2020), and tracking peatland surface dynamics, an indicator of health and greenhouse gas emissions (Hrysiewicz et al., 2024).

3 Materials and methods

This dissertation applies an integrated methodological approach for advancing water resource assessment with remote sensing. The work is organized around six interrelated research papers, each contributing to the progressive combination of remote sensing, physics-based modelling, and machine learning. Together, these studies aim to improve the investigation of hydrological systems, with emphasis on groundwater dynamics, land surface deformation, and interactions between groundwater, surface water, and ecosystems.

A logical and coherent narrative guides the methodological progression across the papers. Initially, comprehensive land surface deformation maps are generated, which serve as foundational datasets for subsequent analyses. These deformation maps facilitate inferences regarding aquifer behaviour, enable monitoring of groundwater levels, and support the exploration of coupled GW-SW interactions, thereby elucidating implications for ecohydrological stability.

The fundamental aspect across all subprojects in this dissertation is the interpretation of groundwater-induced land deformation measured through InSAR, particularly in relation to assessing water availability within complex hydrological systems. Paper I investigates the interconnection between groundwater-induced land subsidence and hydro-environmental factors, aiming to generate a full-coverage map of deformation across the study area. Papers II to IV specifically address groundwater quantity assessment, while Paper V examines interactions between groundwater and surface water systems, and Paper VI focuses on peatland ecosystems, using InSAR to assess peatland health and quantify their potential role in carbon sequestration.

In arid and semi-arid regions, increasing domestic water demands intensify reliance on groundwater resources. Combined with challenging hydrogeological conditions, this reliance results in significant deformation due to extensive groundwater extraction. Such measurable deformation provides a valuable proxy for monitoring groundwater changes, especially in regions lacking sufficient ground-based observational data, such as piezometric measurements, accurate geological maps, and comprehensive well-log data.

Recognizing the limitations of traditional monitoring methods, this dissertation incorporates auxiliary data sources into quantitative modelling efforts. Papers I & III address the identification and categorization of relevant auxiliary datasets, ensuring their meaningful interpretability and effective integration into data driven ML-based models.

The estimation of groundwater level time series employs an inverse deformation-hydrology approach, emphasizing the role of storativity parameters as reliable indicators for quantifying groundwater changes. Papers III and IV share this objective but apply different methodologies. Paper III builds upon the physical foundation established in Paper II to extend groundwater head estimation across space and time using a physics-assisted machine learning framework. Paper IV, in turn, employs a numerical groundwater flow model (MODFLOW), calibrated with InSAR-derived deformation and groundwater observations, and extends inverse Terzaghi's theory to validate historical groundwater conditions and assess model performance.

Building upon these foundations, Paper V expands the investigation by analysing the critical interactions between groundwater and surface water in a river basin characterized by substantial anthropogenic activity, including dense agricultural practices and domestic water use. Finally, Paper VI broadens the scope further, examining InSAR-deformation signals as health indicators for water-dependent ecosystems. This paper specifically investigates peatlands in temperate regions, emphasizing their crucial roles as climate indicators.

3.1 Study areas

The study areas considered within this research were consciously selected to encompass a broad spectrum of hydrological and climatic conditions, ranging from arid and semi-arid zones in Iran to temperate zones in southern Sweden. The geographic distribution of the Iranian and Swedish case studies is presented in Figures 3.1, while Figure 3.2 shows the monthly time series and long-term monthly average precipitation based on IMERG data, revealing clear contrasts in rainfall regimes across the study sites. This selection reflects a deliberate effort to evaluate and validate the developed hydrological modelling frameworks and remote sensing techniques across diverse environmental contexts, thereby demonstrating their generality and adaptability.

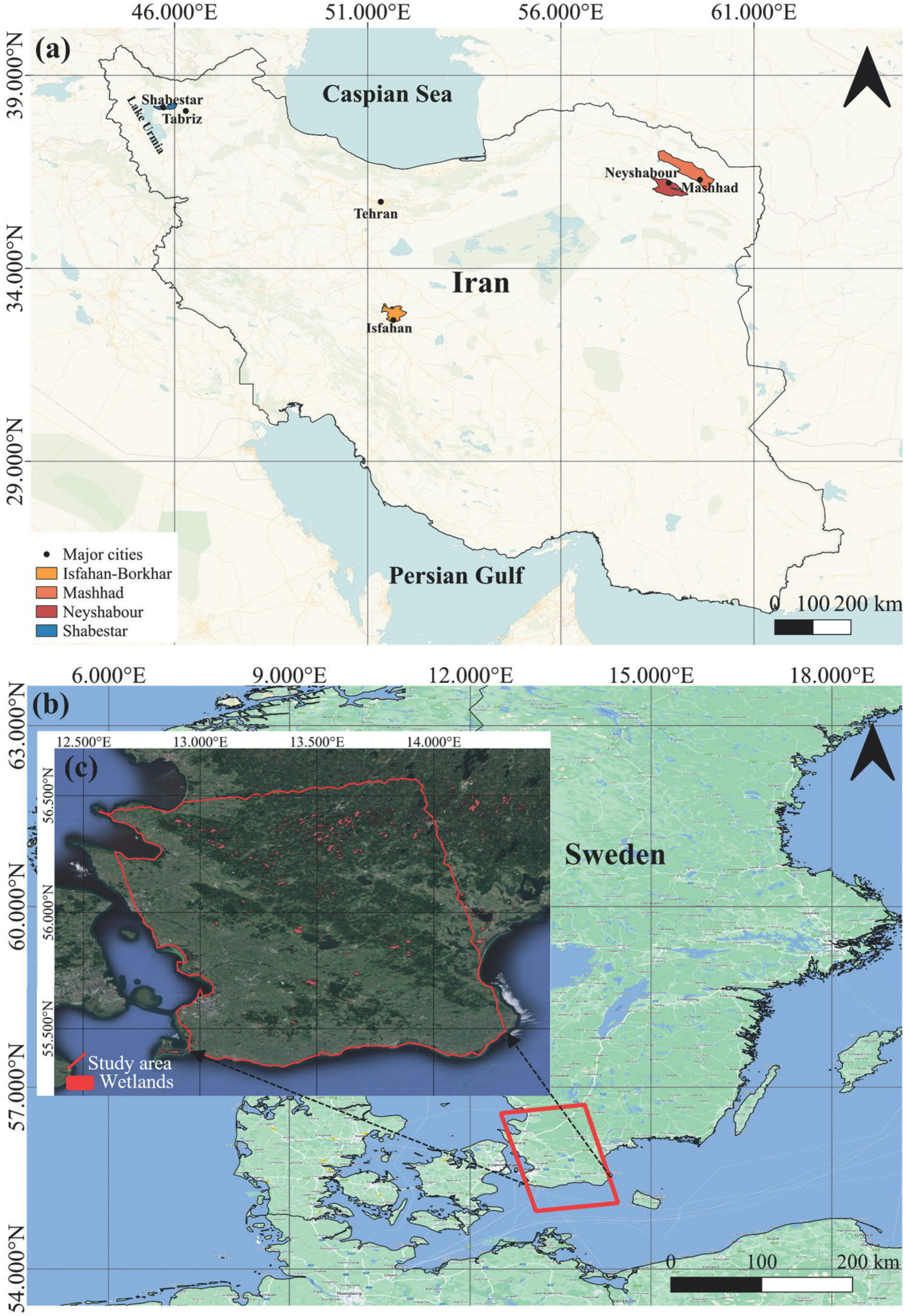


Figure 3.1: Map of study areas in Iran (a) (Papers I-V) and Sweden (b-c) (Paper VI).

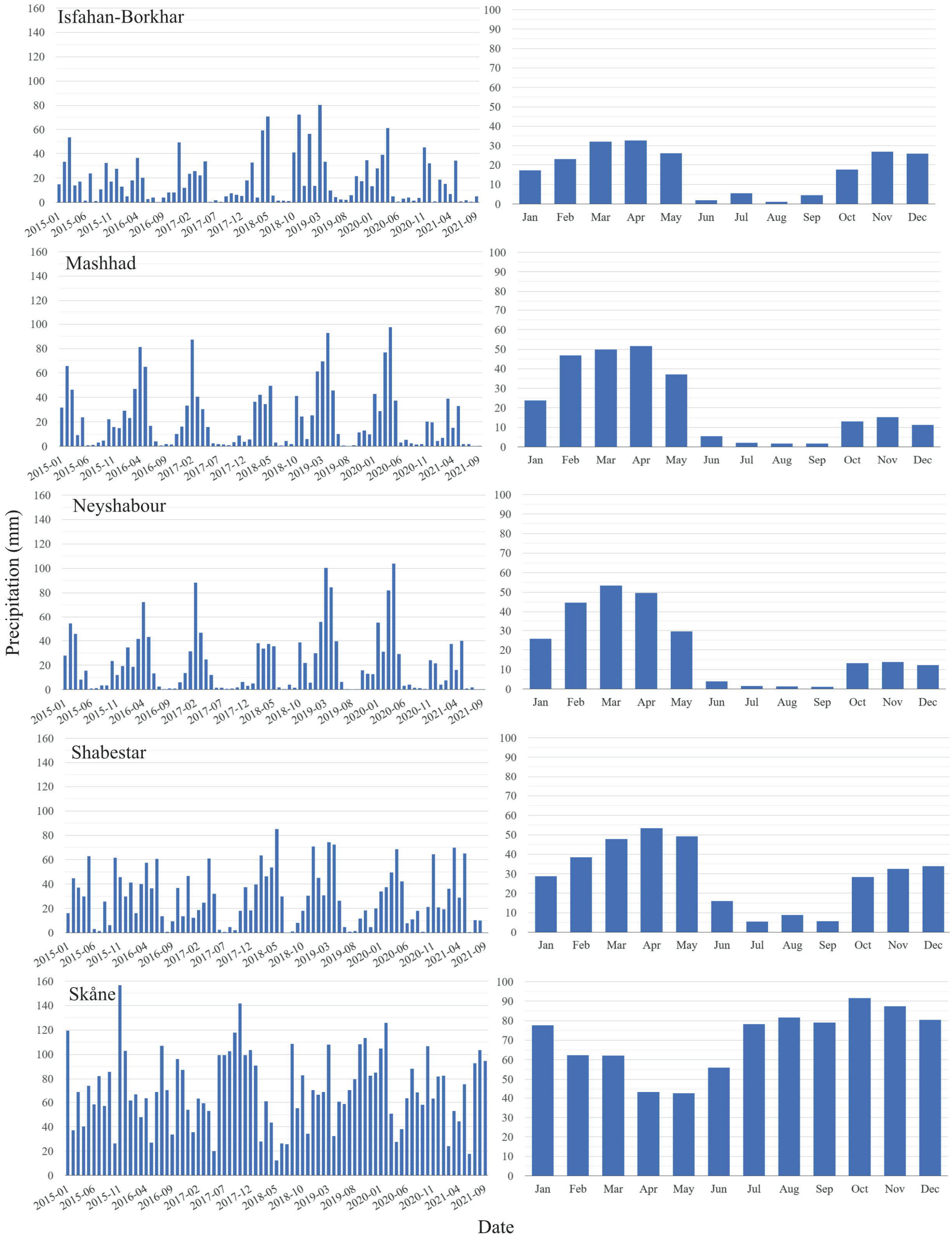


Figure 3.2.: Monthly precipitation time series and long-term monthly averages across the study areas, derived from NASA's IMERG dataset for the period from January 2015 to December 2022.

In the arid and semi-arid regions of Iran, extensive groundwater extraction has led to significant aquifer depletion and land subsidence. Groundwater supplies more than half of the country’s freshwater consumption, making its sustainable use critical. Prolonged droughts and groundwater overexploitation, especially for agricultural activities, accelerated groundwater depletion. Some selected aquifer systems, such as those in Shabestar and Neyshabour, are geologically complex and multi-layered, often containing clay-rich strata with varying compressibility, which makes their precise classification challenging. The Mashhad aquifer (Paper I) is an unconfined Quaternary system with heterogeneous thickness and finer sediments in the central and southern portions, receiving groundwater inflow from northwest to southeast. In Neyshabour, an arid to semi-arid sub-basin within the central desert catchment (Paper II & IV), the aquifer is primarily classified as unconfined, but documented evidence indicates the presence of confined units. The coarse piedmont deposits offer high storage potential, while finer sediments dominate the central areas. Here, flow is predominantly from the east and northeast to the southwest. Shabestar (Paper II & III), located near Urmia Lake, comprises confined and unconfined units with sediment textures transitioning from coarse near the mountains to fine in the central plain, where salinity increases towards the lake due to ancient saline entrapment and evaporation effects. The Isfahan-Borkhar aquifer studied in Paper V, located in the Zayandeh-Rud River Basin, is largely mountainous with a considerable average bedrock depth, and precipitation decreases toward Isfahan City. Groundwater generally flows from the basin's edges toward its Centre, and numerous wells, Qanats, and springs withdraw substantial volumes annually to meet agricultural, domestic, and industrial demands. Although the river supplies part of the basin's water needs, groundwater remains the primary source. This case also illustrates the critical link between surface water management and groundwater sustainability, as regulation of the Zayandeh-Rud River has directly influenced aquifer recharge. In recent years, severe declines in water table levels and drying of the river have contributed to land subsidence and structural damage in the urban fabric of Isfahan, including heritage sites and critical infrastructure.

Across all Iranian study aquifers, groundwater serves as the dominant water source for agricultural, domestic, and industrial activities, making these systems highly vulnerable to overexploitation and climatic variability. This reliance has already caused widespread water table decline and land subsidence. The predominance of agricultural and urban land use across these basins, illustrated in the Land Use Land Cover (LULC) map of Figure 3.3, underscores the intensity of groundwater demand. The same figure also presents the DEM and elevation contour lines of the study areas, providing insight into how topography may influence groundwater distribution and vulnerability.

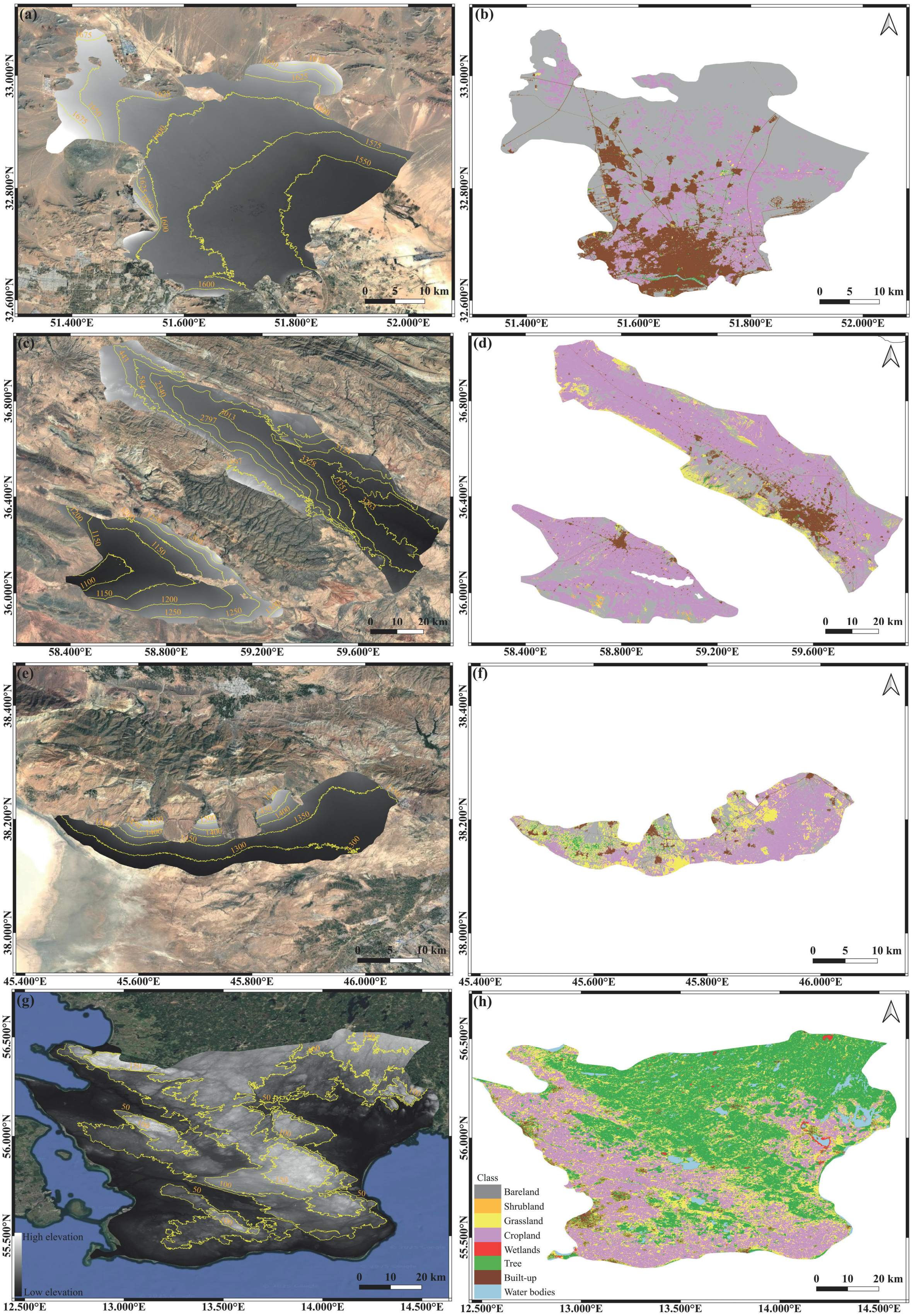


Figure 3.3: Elevation and LULC maps of Isfahan (a-b), Mashhad and Neyshabour (c-d), Shabestar (e-f) in Iran, and Skåne (g-h) in Sweden. Elevation data were obtained from the Copernicus Global DEM at 30-meter resolution, and land cover classification is based on the 2020 ESA WorldCover product with a spatial resolution of 10 meters.

Conversely, southern Sweden presented a contrasting temperate hydrological system. Here, the focus shifted towards peatland ecosystems, which serve as significant carbon sinks and water storage systems. The study area encompasses a large portion of Skåne County which is the southernmost region of Sweden, characterized by a temperate climate, relatively flat topography, and extensive organic soils. The peatlands are surrounded by agricultural land, forests, and wetlands, creating a heterogeneous landscape influenced by both natural processes and human activities. The region's peat deposits vary in thickness and hydrological connectivity, with some areas subject to drainage for agriculture, while others remain in near-natural conditions. The Swedish peatland study area is shown in Figure 3.1(c), indicating the spatial distribution of monitored sites used for deformation and carbon flux analysis, with the average precipitation illustrated in Figure 3.2 and the LULC and topography shown in Figure 3.3.

Overall, the comprehensive coverage of arid, semi-arid, and temperate hydrological systems within this research not only justified the application of diverse modelling approaches but also strengthened the overall storyline of this dissertation, emphasizing the broad applicability and reliability of the developed techniques across different environmental and hydrological conditions.

3.2 InSAR data processing

Satellite-based remote sensing, particularly InSAR, underpins the deformation-driven groundwater modelling in this dissertation. Sentinel-1 SAR data form the core of land surface monitoring across study areas, enabling both regional-scale assessment and point-based validation. InSAR's capability to measure millimetre-scale surface displacements over time allows quantification of aquifer compaction and hydrological responses in the absence of dense in-situ networks (Hooper et al., 2004; Ferretti et al., 2007). To extract reliable deformation signals, the choice of the InSAR processing package was carefully matched to the environmental characteristics and objectives of each study. The two main processing packages employed in this research are GMTSAR and StaMPS/MTI.

StaMPS/MTI is well-suited for vegetated and agricultural areas where conventional persistent scatterers are limited. Therefore, StaMPS/MTI was strategically chosen for deformation mapping in agriculturally intensive areas of the Mashhad Plain (Paper I) and vegetation-rich regions and peatland ecosystems of southern Sweden (Paper VI). In both studies, the identification of SDFP pixels was central to the analysis, as these pixels were considered the most reliable deformation measurement points, serving as the basis for characterizing land subsidence in Paper I and for evaluating surface dynamics and peatland health in Paper VI. StaMPS/MTI's ability to handle highly decorrelated signals made it ideal for assessing deformation signals in croplands, vegetated landscapes, and peatlands typically characterized by low radar coherence due to rapid vegetation growth and seasonal variability (Hooper et al., 2012).

GMTSAR is well known for its computational efficiency and its ability to generate consistent, large-scale interferogram networks with precise co-registration using DEMs. In Papers II to V, GMTSAR was selected primarily for its robust performance in generating spatially continuous and temporally coherent deformation time series which are essential for the reliable assessment of aquifer systems. These studies focused on characterizing hydrodynamics over broad regions, where seamless deformation data were fundamental to capturing the spatial variability of aquifer response. The resulting deformation products provided the critical input for quantitative modelling efforts, including the DHE model in Papers II and III and the MODFLOW calibration in Paper IV, enabling rigorous simulation and interpretation of groundwater storage changes and aquifer compaction. In Paper V, seamless deformation data were essential for assessing river regulation impacts on land subsidence and GW-SW interactions.

Importantly, although StaMPS and GMTSAR packages differ significantly in the approach and methods used in the interferometric phase unwrapping, both methodologies relied on the GMT-based co-registration tools available within the GMTSAR software. This co-registration method ensures precise alignment of SAR image pairs by rigorously accounting for geometric distortions using orbital data and a DEM-based procedure, crucially enhancing the reliability of subsequent interferometric phase analyses (Sandwell et al., 2016).

The phase unwrapping processes of these two packages differ distinctly. StaMPS employs a three-dimensional phase-unwrapping algorithm optimized for identifying persistent and slowly decorrelating pixels, effectively handling spatially scattered stable phase points typical in vegetated and dynamic landscapes (Hooper et al., 2012). In contrast, GMTSAR integrates the SNAPHU (Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping) approach, adept at processing extensive and spatially continuous interferogram networks commonly encountered in regional groundwater studies (Chen & Zebker, 2002).

All projects in this dissertation employed the SBAS approach, chosen explicitly due to the extensive non-urban coverage, including croplands and vegetated areas in all studied aquifers and basins. Careful selection of appropriate spatial and temporal baselines was essential to maintaining coherence and signal reliability. Additionally, interferogram networks underwent rigorous evaluation, repair, and filtering processes to remove unreliable interferograms, significantly enhancing the robustness of final InSAR products, as detailed specifically in each paper.

Recognizing the computational demands of large-scale InSAR analyses, processing speed was significantly enhanced by leveraging the parallel computation capabilities provided by the GMTSAR package (Sandwell et al., 2016), executed on the supercomputing infrastructure at Lund University (LUNARC). This approach enabled efficient handling of extensive data volumes inherent in regional-scale deformation analyses, substantially reducing processing times and enabling comprehensive methodological evaluations.

Furthermore, addressing the critical challenge of selecting reliable reference points in regions lacking stable GNSS stations or permanent scatterers, an innovative methodological advancement was introduced. This involved a custom-developed analysis applied directly to the filtered interferometric phase grids. The algorithm computed the mean and standard deviation of phase values across all interferograms and derived the coefficient of variation and entropy over sliding spatial windows. Areas exhibiting minimal variability across interferograms and low spatial entropy were systematically identified as stable reference zones assumed to be deformation-free. Once identified, these regions served not only for phase referencing in visualization but also for numerically normalizing each interferogram prior to time series analysis. Specifically, a GMT-based batch-processing script was employed to subtract the mean phase value of the identified stable region from each unwrapped interferogram. This step, often termed phase pinning, ensured that all interferograms shared a common reference frame before interferogram stacking, significantly enhancing the consistency and accuracy of the deformation time series. This integrated and automated approach proved essential in improving the robustness of InSAR analysis across all study areas, particularly in groundwater deformation monitoring contexts characterized by low radar coherence and a lack of established geodetic benchmarks.

Validation of InSAR results was performed rigorously. In study areas equipped with GNSS satellite positioning stations, InSAR-derived time series were directly compared against observed displacement data. Additionally, parallel InSAR analyses provided complementary validation. These parallel analyses employed either the same SAR datasets processed through alternative software packages or utilized SAR data acquired from opposite orbit directions or complementary satellite constellations. Detailed validation methodologies are comprehensively presented within each respective paper. Figure 3.4 illustrates the InSAR analysis workflow implemented across the different studies in this dissertation.

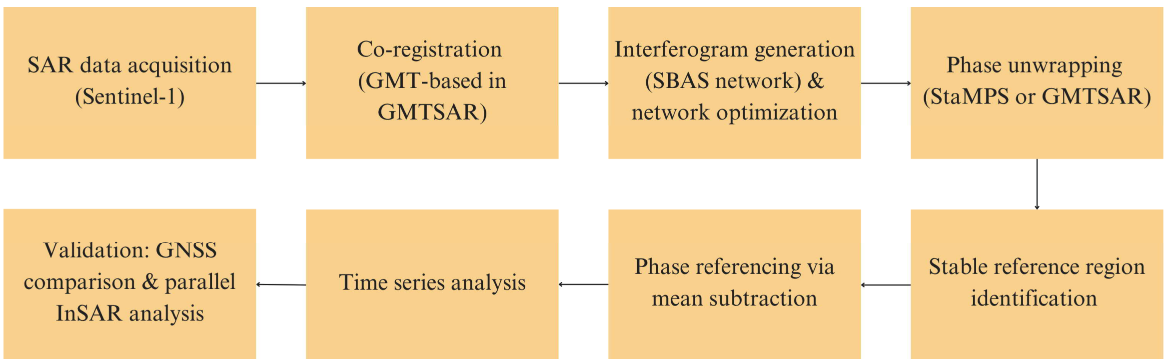


Figure 3.4: Flowchart for InSAR analysis.

3.3 Other remote sensing and in-situ data

Throughout this dissertation, an extensive range of remote sensing and in-situ datasets were systematically prepared and utilized to advance groundwater modelling and hydrological assessments across varied environmental contexts. Besides InSAR, which has been elaborated in detail, several complementary remote sensing datasets were integral to various analyses, particularly in Papers I and III, where machine learning models were employed extensively.

DEM data, predominantly the void-filled Shuttle Radar Topography Mission (SRTM) dataset with a resolution of 90 meters, provided essential topographical information and were also utilized for InSAR processing, particularly for topographic phase removal. These DEM data facilitated topographical and hydrogeological analyses, including extracting slope, aspect, curvature, and various other topo-hydrological variables. The preprocessing and extraction of these variables were performed using the System for Automated Geoscientific Analyses (SAGA) within QGIS.

Several hydrometeorological and environmental data were acquired from satellite platforms, providing critical inputs for modelling and analysis. MODIS-derived Enhanced Vegetation Index (EVI), Land Surface Temperature (LST), Landsat-based Evapotranspiration (ET), Copernicus Soil Water Index (SWI), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) were among these datasets. These data were sourced from their respective online repositories (e.g., NASA's Earthdata, USGS EarthExplorer, and Copernicus Global Land Service) and systematically processed, filtered, and resampled to match the spatial and temporal resolutions required for ML analyses and hydrological modelling.

In-situ data played a crucial role across multiple studies, providing ground-truth for validation and model calibration. Geological and hydrogeological information, including aquifer thickness, transmissivity, fault locations, bedrock geology, and horizontal hydraulic conductivity, were collected from regional water authorities and geological surveys. Groundwater level and pumping data from piezometric wells (regional water authorities and local contributors) were extensively used, with quality control and temporal resampling applied to ensure consistency with remote sensing datasets. In Papers II, III, and IV, these observations formed a critical modelling foundation, supplemented in Paper IV by deep percolation estimates derived from a previously calibrated SWAT (Soil and Water Assessment Tool) model. Paper V extensively utilized groundwater level records from the regional water company, alongside hydrological records from the Zayandeh-Rud River flow rate to study GW-SW interactions.

Additionally, cropland distribution and land use dynamics in Paper V were analysed using MODIS Global land cover products, employing classification and masking techniques to isolate cropland areas effectively.

In Paper VI, detailed peatland information was acquired from the Swedish National Wetland Inventory (VMI), which has systematically mapped wetland ecosystems since the 1980s. This dataset provided both spatial delineation and ecological classification of peatlands based on vegetation composition and conservation value.

GNSS data used for validating InSAR-derived deformation were obtained from the National Cartographic Centre (NCC) of Iran and Lantmäteriet in Sweden. In Sweden, high-frequency positioning data were accessed from SWEPOS permanent stations (Class A and B), while selected GNSS data from NCC were similarly used in Iran to support validation in papers addressing groundwater-induced subsidence.

Together, the integration and careful preprocessing of a wide array of remote sensing and in-situ datasets formed the backbone of this dissertation. From regional topography to dynamic surface processes, the reliability and richness of these inputs have critically enhanced the modelling, interpretation, and scientific impact of the groundwater and ecohydrological analyses across multiple environmental settings.

3.4 Foundations: InSAR-ML synergy for deformation mapping

The methodological foundation of this work was laid in Paper I, which addresses a critical challenge in InSAR-based deformation analysis, specifically the spatial incompleteness of InSAR observations due to vegetation decorrelation and land cover variability, particularly in agricultural regions. In this study, deformation data derived from Sentinel-1A using the SBAS technique and processed with StaMPS/MTI were integrated with a suite of topographical, hydrogeological, hydrological/climatic, and anthropogenic drivers to produce a full-coverage ground deformation map for the Mashhad Plain in Iran. Figure 3.5 summarizes the workflow in this study.

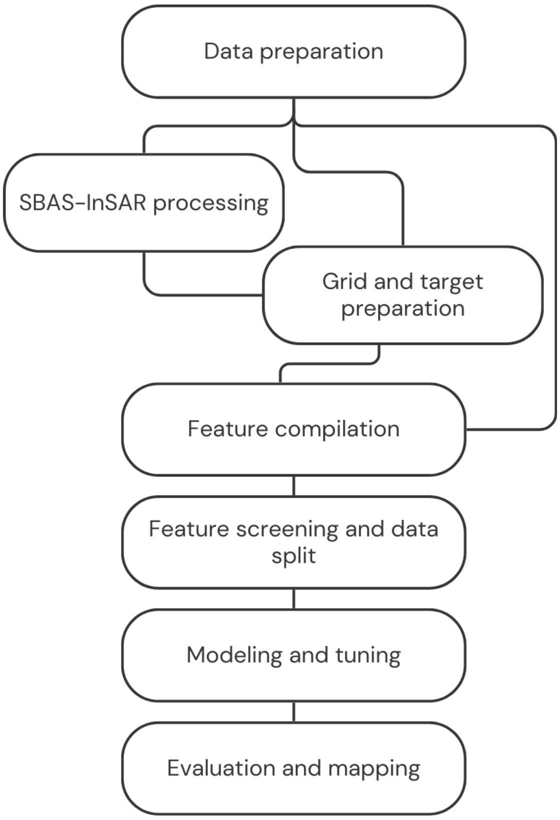


Figure 3.5: Workflow for Paper I.

The long-term InSAR deformation rate (target) was resampled to a regular grid to align with the input features and then used to train and validate machine learning models. We employed Boosted Regression Tree (BRT) and eXtreme Gradient Boosting (XGBoost) algorithms both known for their strong performance in regression problems and ability to handle complex, nonlinear relationships. XGBoost was applied using different boosters (tree, linear, and Dropouts meet Multiple Additive Regression Trees (DART)) to evaluate predictive performance from multiple perspectives. The input features comprised geo-environmental variables categorized into topographical, hydrogeological, hydrological/climatic, and anthropogenic groups, such as aquifer thickness, transmissivity, distance to faults, land use, normalized difference vegetation index (NDVI), proximity to pumping wells and qanats, and long-term groundwater level change. All features were harmonized to the same grid as InSAR products. Prior to modelling, multicollinearity was assessed using variance inflation factor (VIF) and tolerance diagnostics, and variables were screened accordingly. The InSAR-derived deformation measurements were partitioned into training and validation sets and models were evaluated using standard regression evaluation metrics (i.e. Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and (Coefficient of Determination) R^2 metrics, supported by visual analysis with a Taylor Diagram. Additionally, Frequency Ratio (FR) analysis was used to interpret the spatial relationship between the most influential predictors and the observed deformation trends.

This work serves as a precursor to subsequent methodologies. By generating a spatially continuous deformation dataset and analysing the contributions of various geo-environmental factors, Paper I established a basis for assessing how land subsidence correlates with groundwater exploitation patterns and aquifer heterogeneity. Moreover, it introduced a reliable modelling structure for handling large spatial datasets, integrating RS-derived inputs with ML techniques, and validating outputs against ground truth data. This full-coverage deformation dataset would later serve as a critical input for characterizing groundwater storage dynamics. In particular, it provided the foundation for the physics-assisted machine learning framework developed in Paper III, which further advanced groundwater head estimation using InSAR-derived deformation.

3.5 Inference of groundwater head from InSAR deformation: DHE model

Building upon the established connection between groundwater head changes and surface deformation outlined in Paper I, we introduce an innovative deformation-driven head estimation (DHE) model in Paper II. This model bridges remotely sensed surface deformation with subsurface hydraulic head variations, particularly beneficial in arid and semi-arid regions characterized by sparse borehole data and limited stratigraphic information. The DHE model leverages the physical relationship between land surface deformation and aquifer pressure changes prevalent in confined and semi-confined systems, providing a streamlined, data-efficient approach for groundwater monitoring.

As an initial step for aquifer characterization, the DHE model begins with the extraction of deformation data and temporal resampling of deformation and groundwater head time series at well locations. This resampling utilized a Finite Impulse Response (FIR) anti-aliasing low-pass filter, effectively preserving signal integrity and satisfying the Nyquist-Shannon sampling theorem (Harris, 2022). Since deformation and groundwater measurements were initially acquired on differing dates, temporal resampling standardized these signals to a common temporal resolution which here is daily interval.

The periodic fluctuations observed in both groundwater head and deformation signals are driven predominantly by seasonal recharge and discharge cycles linked to precipitation and agricultural practices. Therefore, each signal was decomposed into two distinct components: a seasonal component associated with annual variations, and a long-term component reflecting the cumulative effects of sustained groundwater pumping. Cross-correlation analysis was employed to estimate the lag-time between groundwater head changes and associated deformation signals around each well location, considering a maximum lag-time of up to two years (Chaussard et al., 2017). The optimal lag-time was identified by locating the peak in the cross-correlation function, constrained by positivity and local extremum conditions of the skeletal storage coefficients. This analysis proved especially insightful in differentiating aquifer responses in clay-rich zones, where delayed compaction effects were evident due to slow drainage from compressible layers.

Assuming a linear relationship between groundwater head variations and consequent deformation, the skeletal storage coefficients for seasonal and long-term components at each well location were calculated as:

$$s_{k_S} = \frac{\Delta D_S}{\Delta H_S}, s_{k_{LT}} = \frac{\Delta D_{LT}}{\Delta H_{LT}} \tag{5}$$

where s_{k_S} and $s_{k_{LT}}$ are seasonal (S) and long-term (LT) skeletal storage coefficients, ΔD_S and ΔD_{LT} represent seasonal and long-term deformation components, and ΔH_S and ΔH_{LT} correspond to the respective groundwater head changes components. These coefficients were refined using a least-squares estimation method after accounting for the calculated lag-times:

$$s_{k_{S/LT}} = \frac{1}{\left[\Delta D_{S/LT}^T \, \Delta D_{S/LT}\right]^{-1} \Delta D_{S/LT}^T \Delta H_{S/LT}} \tag{6}$$

The skeletal storage coefficients allowed the reconstruction (simulation and prediction) of groundwater head changes using deformation data:

$$\Delta H_{simulated/predicted} = \frac{\Delta D_S}{s_{k_S}} + \frac{\Delta D_{LT}}{s_{k_{LT}}} \tag{7}$$

"Simulated" refers to groundwater head values reconstructed from deformation data and estimated skeletal storage coefficients for the model calibration period while "Predicted" refers to a one-year forecast based on deformation data from the excluded final year, independent of calibration. Additionally, an independent verification of the derived coefficients was performed using a semi-logarithmic analytical approach based on soil mechanics principles (USACE, 1990; Hughes et al., 2022; Rocscience Inc., 2025). In one-dimensional consolidation, the primary settlement D over a compressible thickness H is:

$$D = \frac{C}{1 + e_0} H \log_{10}\left(\frac{\sigma_2'}{\sigma_1'}\right) \tag{8}$$

where C is the compression index on the virgin branch (C_c) or the recompression index on the reloading branch (C_r), e_0 is the initial void ratio, and σ' is effective stress. If vertical deformation is plotted against $\log_{10}\sigma'$, the semi-log slope m_D satisfies:

$$m_D = \frac{dD}{d\log_{10}\sigma'} = \frac{H}{1+e_0}C \tag{9}$$

so C is proportional to the semi-log slope once scaled by $\frac{H}{1+e_0}$. Under confined or semi-confined conditions, head change (Δh) maps to effective stress change ($\Delta\sigma'$) via $\Delta\sigma' \approx \gamma_\omega \Delta h$, which supports regression of deformation versus $\log_{10}(\Delta h)$ to estimate m_s, the semi-logarithmic slope of deformation with respect to head change. This slope is mathematically equivalent to m_D, defined with respect to effective stress σ', but expressed in terms of groundwater head as a proxy for σ'. Operationally we regress deformation D against $\log_{10}(\Delta h + 1.65h_0)$, where the constant $1.65h_0$ represents the effective overburden stress (Khodaei et al., 2025). The offset h_0 is systematically scanned and the first stabilized fit is selected based on R^2. The stabilized semi-log slope is therefore a direct proxy for C up to the multiplicative factor $\frac{H}{1+e_0}$. Because reliable values of the compressible thickness H and initial void ratio e_0 are not available in the study areas, we do not convert these slopes to absolute C_c or C_r. Instead, we use the stabilized slopes solely as a verification tool for the DHE-estimated storativity components. This provided physical consistency checks for the DHE outputs and reinforced the model's reliability in estimating aquifer behaviour, even in the absence of detailed subsurface information.

The DHE model was successfully implemented in two distinct hydrogeological contexts in Iran: Shabestar and Neyshabour Plains. Demonstrating robust predictive accuracy and flexibility, the model's methodological rigor and minimal data dependency enhance its applicability across various settings, particularly in data-scarce environments. In addition to its forecasting ability, the DHE model also provides insight into aquifer system properties, such as storativity and compaction behaviour, making it a valuable diagnostic tool in regions lacking detailed stratigraphic or geomechanical data. This model, therefore, serves as a foundational methodological pillar within the comprehensive groundwater characterization framework elaborated across Paper III of this dissertation.

3.6 Extending groundwater monitoring in space and time: physics-assisted ML framework

Paper III builds upon the foundation established in Paper II by integrating the DHE model into a physics-assisted ML framework. While the previous study focused on point-based InSAR-derived groundwater head estimation at piezometric well locations, this work extends the approach to enable spatiotemporal prediction of groundwater head dynamics across the entire aquifer system. The key methodological advance is to use supervised ML to predict DHE parameters at unsampled locations and then propagate those parameters through an inverse DHE step to obtain groundwater-head levels. Specifically, we fuse DHE-derived parameters (seasonal and long-term skeletal storage coefficients (s_{k_S}, $s_{k_{LT}}$) and estimated lag time (τ)) with a supervised ML regression model to generate spatially continuous parameter maps that drive head simulations in areas without direct observations. The methodology was implemented in the Shabestar aquifer, a stressed groundwater basin containing both confined and unconfined zones, where the confined portion was the primary focus.

The workflow consisted of two main stages. First, DHE model was applied at the well locations to estimate the three target variables, i.e. s_{k_S}, $s_{k_{LT}}$, and τ, through joint analysis of deformation and groundwater head time series. These were obtained by decomposing the time series into seasonal and long-term components, followed by cross-correlation analysis and least squares estimation.

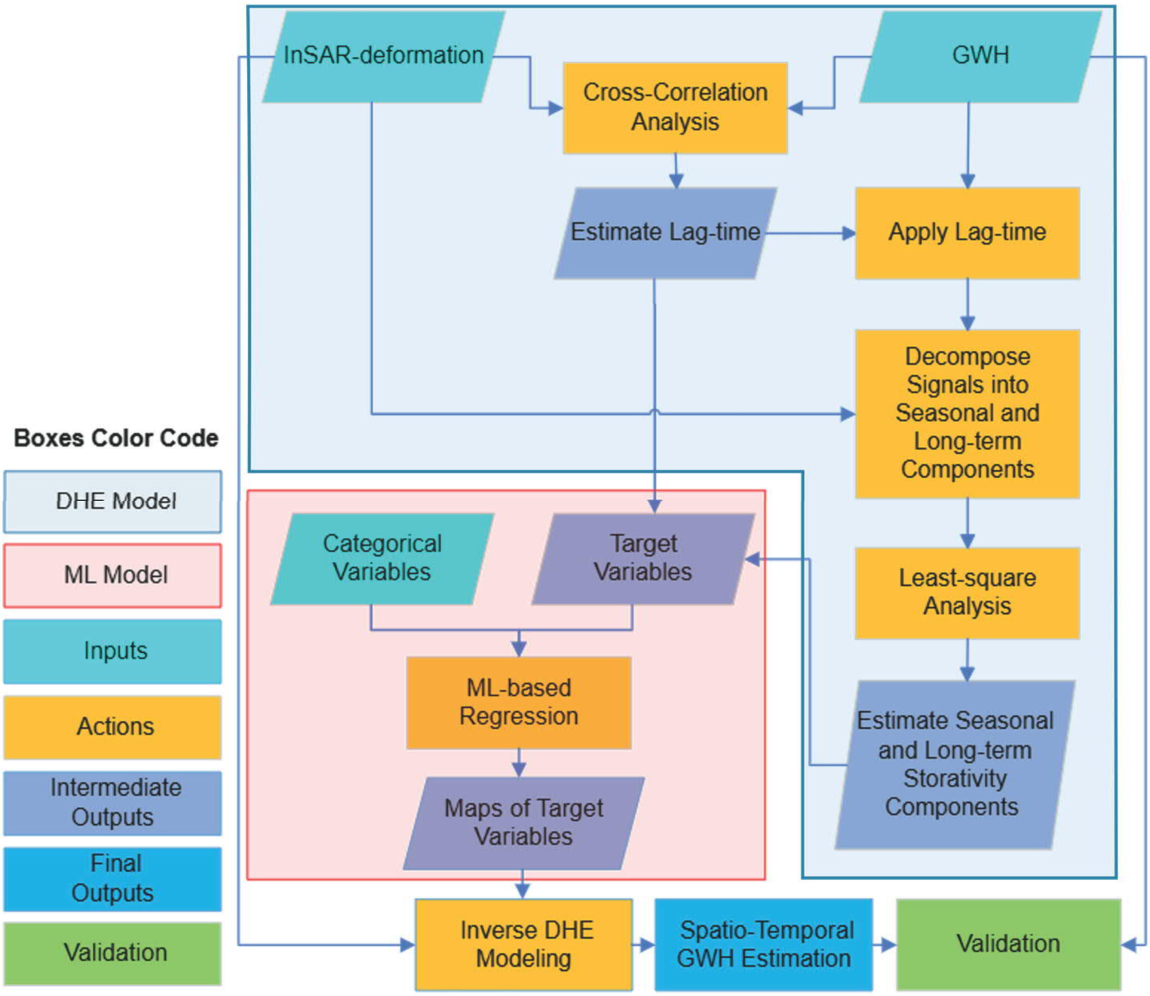


Figure 3.6: Flowchart of physics-assisted model implemented in Paper III.

Before defining the feature categories, we performed feature engineering to make temporally rich datasets usable in a static supervised-learning setup. Spatio-temporal datasets (InSAR-deformation, land surface temperature, precipitation, evapotranspiration, vegetation indices and soil moisture) were transformed into static features by estimating lag at maximum cross-correlation between each pair of time series, effectively encoding spatiotemporal dependencies into spatial predictors. To counter the limited number of piezometric wells (small n) and preserve informative structure, we expanded the auxiliary feature space by systematically integrating environmental predictors that capture topographical, hydrogeological, hydrometeorological, and anthropogenic controls. In addition, we incorporated DHE-derived parameters (s_{k_S}, $s_{k_{LT}}$, and τ) as physics-based constraints, ensuring that the regression was guided not only by statistical correlations but also by process understanding of aquifer deformation and storage. All datasets were harmonized to the spatial resolution compatible with the InSAR data and resampled to daily temporal resolution for consistency. This combination of environmental feature augmentation and physics-based constraints provides a coherent input representation for the subsequent ML stage. The full modelling workflow is illustrated in Figure 3.6, which outlines the sequential integration of DHE-based parameter estimation, feature preparation, and XGBoost-driven groundwater head simulation. To organize heterogeneous inputs, enhance interpretability, and support diagnostics (correlation screening), we categorized all input variables (features) into four physically motivated groups: (i) hydrogeological, (ii) anthropogenic, (iii) topographical, and (iv) hydrometeorological. The complete feature inventory, including their spatial and temporal resolutions, is provided in Tables 3.1 and 3.2.

Table 3.1: List of input variables (with abbreviations) for the ML-based regression in Paper III.

Category	Features
hydrogeological	transmissivity (Tr), total thickness (ThTot), aquifer layer thickness (ThAq1 and ThAq2), fault distance (Fdst)
anthropogenic	village distance (Vdst), city distance (Cdst), road distance (Rdst), long-term InSAR-deformation (InSAR-LT), enhanced vegetation index (EVI)
topographical	closed depression (CD), profile curvature (PrfC), plan curvature (PlnC), length slope factor (LSfactor), stream power index (SPI), slope gradient (SlpG), valley depth (Vdpth), convergence index (CI), slope (Slp), relative slope position (RslpP), aspect (Aspct), analytical hill-shading (AH), bedrock thickness (BR)
hydrometeorological	channel network distance (CND), channel network base level (CNBL), total catchment area (TCA), river distance (Rvrdst), drainage density (DD), topographic wetness index (TWI), lag-time values extracted from the joint analysis of precipitation (P), evapotranspiration (ET), land surface temperature (LST), soil water index (SWI), and InSAR-deformation time series: InSAR-ET, InSAR-LST, InSAR-PREC, InSAR-EVI, InSAR-SWI, ET-LST, ET-PREC, ET-EVI, ET-SWI, LST-PREC, LST-EVI, LST-SWI, PREC-EVI, PREC-SWI, EVI-SWI, InSAR-LT

Table 3.2: List of the spatial and temporal variables used in Paper III.

Type	Features	Resolution	Source of data
Spatial	Tr, ThTot, ThAq1, ThAq2, Fdst, Vdst, Cdst, Rdst	-	Extracted from the analysis of the available in-situ vector maps provided by the Regional Water Authority of East Azerbaijan Province and resampled to be consistent with the InSAR-deformation data
	CD, PrfC, PlnC, LSfactor, SPI, SlpG, Vdpth, CI, Slp, RslpP, Aspct, AH, BR, CND, CNBL, TCA, Rvrdst, DD, TWI	90 m	Extracted from the analysis of the void-filled version of the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a resolution of 3 arc-second with the System for Automated Geoscientific Analyses (SAGA) tools in QGIS
Spatio-temporal	InSAR	5×20 m/ 12-24 days	Sentinel-1A SAR dataset acquired from descending orbit pass with relative orbit number 79
	P	4 km/ daily	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN) system developed by the Centre for Hydrometeorology and Remote Sensing (CHRS)
	ET	30 m/ 16 days	Landsat Collection 2 (C2)
	EVI	250 m/16 days	MODIS
	LST	1 km/ daily	Daily level 3 MODIS LST and Emissivity (MOD11A1)
	SWI	1 km/ 10 days	Copernicus Soil Water Index

Prior to model training we performed a correlation screening to characterize redundancy and guide interpretation of the feature set. Specifically, we computed feature-feature Pearson correlations for the full set and flagged high-correlation pairs using a pre-specified threshold ($|r| > 0.90$) and feature-target correlations for each response (Dormann et al., 2013; Li et al., 2020). Because the study operates in a large-p (43 predictors features), small-n (19 well location), and multi-target, (3 target variables) setting, classical multicollinearity diagnostics such as the VIF are unstable or undefined when the predictor matrix is rank-deficient or nearly so (when $p \geq n$ or predictors are highly collinear), and VIF-based elimination risks discarding informative signal (O'brien, 2007). We therefore retain the full feature set and adopt XGBoost, which does not require matrix inversion, is comparatively robust to multicollinearity (splits consider one feature at a time), captures nonlinearities and interactions, and includes strong regularization to mitigate overfitting under small-sample, correlated-feature conditions (Breiman et al., 2017; Hastie et al., 2009; Ni et al., 2020; Osman et al., 2021; Niazkar et al., 2024). Hyperparameters were tuned via grid search with k-fold cross-validation (He et al., 2025; Kumar et al., 2025). The spatially predicted storativity and lag-time maps over the entire aquifer were then used in inverse DHE modelling to simulate groundwater head dynamics at every pixel across the study area. Model interpretation was supported by post-hoc gain-based feature-importance analyses to relate predictions to hydro-environmental drivers.

This integrated physics-assisted ML approach not only addresses critical data scarcity challenges but also establishes a scalable and generalizable framework applicable to other aquifers facing similar hydrogeological complexities.

3.7 Numerical coupling of InSAR and MODFLOW: SIGH-Map framework

Paper IV presents a novel integration of remote sensing and numerical groundwater modelling through the development of the SIGH-Map (Satellite-Informed Groundwater-Head Mapping) framework. This approach effectively couples InSAR-derived land subsidence data with the MODFLOW-SUB groundwater simulation package, enabling improved estimation and forecasting of aquifer behaviour in data-scarce, groundwater-stressed environments. The study was implemented in the Neyshabour Plain, a highly exploited semi-arid aquifer system in northeastern Iran, where fine-grained interbeds and intensive abstraction make hydro-mechanical coupling both relevant and observable. Although parts of the Neyshabour aquifer are unconfined, borehole and historical evidence indicate confined/semi-confined interbeds in the central plain where subsidence is concentrated. The modelling therefore emphasizes these compactable units, while results in marginal unconfined zones should be interpreted cautiously. The modelling framework adopted a single-layer MODFLOW setup with the SUB package configured to simulate both no-delay (elastic) and delay (inelastic) interbed compaction processes.

The InSAR-deformation data, derived from Sentinel-1A SAR imagery using the SBAS technique in GMTSAR, provided spatially continuous surface displacement rates with high temporal resolution. Geospatial layers included a medium-resolution (90-m) SRTM DEM, plain boundaries, regional geology, bedrock elevation, and geoelectrical maps. These inputs supported delineation of hydrodynamic zones (e.g., horizontal hydraulic conductivity and specific yield) consistent with the mapped lithostratigraphy. Time-series data comprised monthly pumping rates derived from a comprehensive well inventory using a simple trend assumption following prior studies (Izady et al., 2014), long-term groundwater head records from a network of monitoring wells distributed across the plain, and deep percolation (recharge) from a previously calibrated SWAT model (Izady et al., 2015). Together, these datasets provided the observations required for coupled calibration.

We built on the established MODFLOW model from 2000-2012 (Nazarieh et al., 2018) and extended the simulation to a multi-decadal period (2000-2020) with monthly stress steps and fine internal time stepping. Boundary conditions were represented with General-Head Boundaries (GHB) for lateral inflows from alluvial fans, along with standard Well (WEL) and Recharge (RCH) packages for distributed stresses. Subsidence was simulated with the Subsidence (SUB) package, which links head variations to effective-stress changes following Terzaghi's principle. Skeletal specific storage was partitioned into elastic and inelastic components, with behaviour conditioned on preconsolidation stress. Both instantaneous (no-delay) and diffusive (delay) interbed responses were included while the latter follows a one-dimensional diffusion formulation with a characteristic delay time governing the temporal lag between head decline and compaction.

SIGH-Map uses deformation and head data as dual calibration targets in a multi-objective inverse modelling scheme. Estimated parameters included elastic and inelastic skeletal storage for no-delay interbeds, elastic and inelastic skeletal specific storage for delay interbeds, and the vertical hydraulic conductivity of delay interbeds. Spatial parameterization followed deformation-informed zoning where the aquifer was partitioned into polygons derived from InSAR deformation classes to allow distributed estimation of storage terms while preserving geological coherence. Clay interbed thickness was assigned from published subsurface constraints (Nameghi et al., 2013). Initial storage terms were estimated from colocated deformation-head changes, with elastic values set smaller than inelastic ones. The initial vertical hydraulic conductivity of delay interbeds was tied to the horizontal conductivity by a fixed fraction. Given widespread inelastic behaviour in the main subsidence area, the preconsolidation head was taken as the initial head at the start of simulation. Parameter estimation and sensitivity analysis were conducted with PEST, with limited manual refinement to ensure physical realism and stable convergence. We set aside the last part of the dataset to independently check the head calculations.

Following calibration, the model was applied in forecasting mode, where InSAR-derived subsidence time series were used inversely with the calibrated storage parameters to reconstruct groundwater head dynamics. Calibrated storage parameters particularly the inelastic component for delay interbeds together with mapped clay thickness and the InSAR time series were inserted into the hydro-mechanical relation at the pixel scale to recover heads through time and space. Where the inferred delay time is non-negligible, the deformation series is temporally shifted prior to conversion to ensure phase consistency between deformation and head. This inverse application shows that deformation signals can stand in for spatio-temporal head dynamics and, if aquifer properties remain roughly stable over the update window, head maps can be generated directly from new InSAR using the calibrated storage fields. The approach is most suitable for confined to semi-confined systems with compactable clay interbeds where pumping-induced compaction is the dominant mechanism.

3.8 Coupling groundwater and surface water dynamics in urban basins

In Paper V, we examined GW-SW linkages in a heavily managed system by integrating river flow, groundwater levels, deformation, and land-use data over the Isfahan-Borkhar aquifer. We assembled monthly groundwater level records from 31 piezometric wells (2000-2022), annual Zayandeh-Rud River flow series (1983-2023), and a Sentinel-1A time-series InSAR dataset (November 2016-September 2021). MODIS global land-cover products at 500 m resolution (LC-Type1) were used to extract cropland extent for 2001, 2010, and 2020 as a proxy for pumping pressure.

All datasets were harmonized to monthly resolution for joint analysis. Aquifer-average groundwater levels were computed from Thiessen-weighted well data, with wells containing excessive gaps removed and short gaps conservatively interpolated to preserve low-frequency variability. Spatiotemporal trends in groundwater, river flow, and deformation were quantified using the non-parametric Innovative Trend Analysis (ITA), applied at both well and aquifer scales. To relate deformation to hydrologic forcing, InSAR time-series values were extracted within buffers around well locations and along river-adjacent urban zones, and synchronized trend slopes were compared over rolling windows. Cross-correlation and lag scans were used as a sensitivity check to explore possible lead-lag structure between river flow anomalies, groundwater-level changes, and deformation rates. Cropland fraction was derived by masking non-cropland classes in MODIS and summarized within hydrologic reporting units (well buffers and river-adjacent belts) to contextualize pumping intensity through time.

3.9 Extending InSAR application to peatlands and carbon flux estimation

Paper VI marks a thematic shift from subsidence-driven aquifer studies to ecohydrological monitoring in peatland environments. Here, InSAR was used not only to monitor land surface dynamics but also to infer ecological processes such as carbon sequestration. This study targets peatland ecohydrology across Skåne County in southern Sweden, a temperate region with a substantial share of organic soils. We analysed peatland surface dynamics over June 2017-November 2020 using Sentinel-1B data processed with SBAS-InSAR in StaMPS/MTI.

Peatland boundaries, conservation status, and vegetation types were obtained from VMI. VMI classes (I–IV) and site descriptors (including intactness and vegetation category such as bog, fen, or mixed) were used to stratify analysis and to contextualize potential anthropogenic influence (e.g., drainage, land use, historical modification). From the InSAR products, we retained peat sites with sufficient coherent sampling to derive site-level mean vertical deformation rates and associated time series.

To connect surface dynamics with carbon cycling, we converted site-level mean vertical deformation to carbon flux using a semi-empirical mass-balance relation:

$$C_{flux} = \wr \times D_v \times BD \times C_{org} \quad (10)$$

where $\wr$ is the site area, D_v is the mean vertical deformation rate, BD is the representative dry bulk density and C_{org} is the organic carbon fraction. Literature-based values appropriate for temperate peat were adopted for BD and C_{org} in the absence of site-specific measurements (Couwenberg & Hooijer, 2013; Liu & Lennartz 2019; Hoyt et al 2020; Morris et al., 2022). Negative D_v (subsidence) was interpreted as net carbon emission and positive D_v (uplift) as net carbon absorption.

Recognizing the combined climatic and anthropogenic pressures on Skåne's peatlands, risk was defined as the overlap between persistent subsidence and indicators of reduced intactness or intensive management from VMI. The pronounced drought during the study period was explicitly considered as a key climatic stressor when interpreting temporal patterns. This integration of satellite deformation, national wetland inventory data, and a carbon-flux proxy enables systematic screening of peatlands that are potentially most vulnerable to degradation and carbon loss under ongoing climatic variability and human modification.

3.10 Synthesis

Collectively, these six studies contribute a cohesive and scalable methodology to assessing groundwater systems, their interactions with the land surface, and their role within the broader hydrological cycle. The approach integrates satellite-based deformation monitoring, machine learning, signal processing, data-driven modelling, and numerical modelling to provide tools for real-time, large-scale, and data-efficient hydrological assessment. Papers II, III, and IV highlights the methodological innovation in inferring and predicting groundwater head dynamics without relying on dense monitoring networks. Papers I and V frame the problem and extend the scope to InSAR- and ML- assisted surface deformation modelling and coupled surface-groundwater systems, while Paper VI demonstrates the extensibility of the approach to ecological domains.

The methodological framework developed herein is adaptable to various environmental settings and scalable across geographic extents, offering a robust solution for managing water resources under increasing climatic and anthropogenic pressures.

4 Results and discussions

The integration of InSAR with a range of modelling approaches has led to substantial advancements in the understanding of complex hydrological processes and associated environmental changes across various hydrological systems. As a foundational step in each of the conducted studies, InSAR-based deformation analyses were performed. The specific techniques and processing platforms employed varied depending on the objectives and contextual characteristics of each case study, with detailed methodologies outlined in the respective papers. The accompanying figures (Figure 4.1 and Figure 4.2) presents long-term deformation maps derived from InSAR analysis for each study area, corresponding to the respective observational periods. The key findings from the collective body of research are summarized in the subsections that follow.

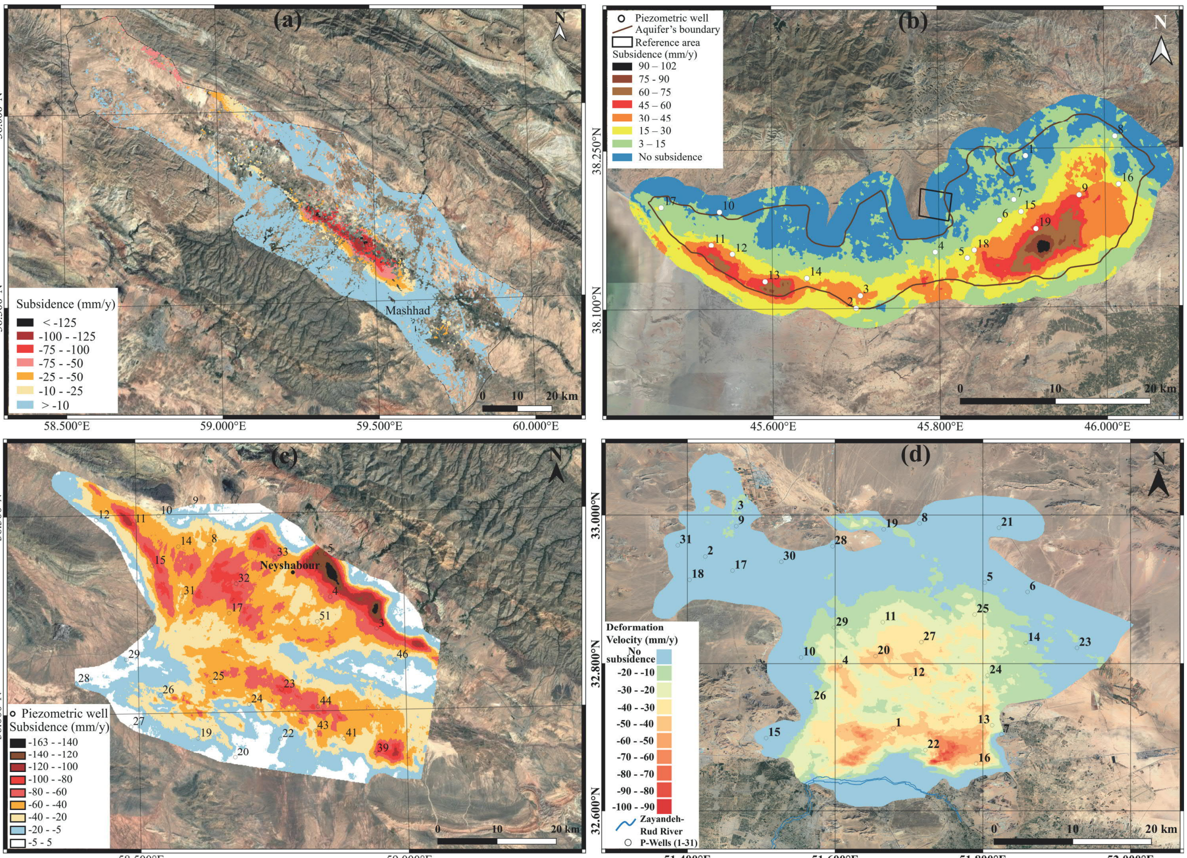


Figure 4.1: InSAR-derived deformation in Iranian study areas with piezometric wells used directly in the groundwater analyses overlaid. (a) Mashhad, StaMPS/MTI, Oct 2014-Mar 2019 (Paper I), (b) Shabestar, GMTSAR, Jan 2016-Apr 2022 (Paper II & III), (c) Neyshabour, GMTSAR, Oct 2014-Mar 2022 (Paper II & IV), and (d) Isfahan, GMTSAR, Nov 2016-Sep 2021 (Paper V).

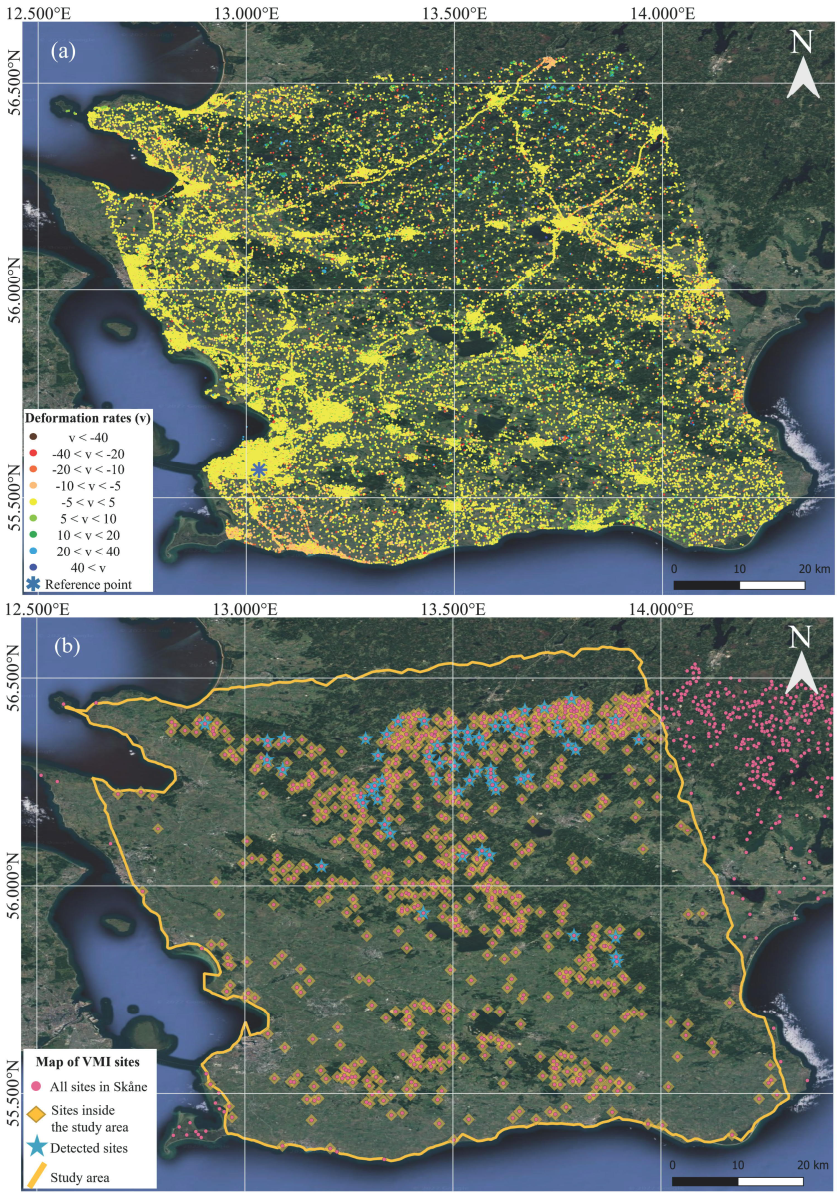


Figure 4.2: (a) InSAR-derived deformation for the study area in Skåne County, southern Sweden, StaMPS/MTI, Jun 2017-Nov 2020 (Paper VI). (b) Location of VMI sites: all regional sites (n=1,239; circles), those within the study region (n=834; diamonds), and sites with detected deformation (n=64; stars).

4.1 Ground deformation and groundwater dynamics

The analysis revealed a strong correspondence between land surface deformation and groundwater fluctuations. This relationship, however, exhibits spatial variability contingent upon the underlying geophysical and hydrogeological characteristics of the study area. Specifically, in confined and semi-confined aquifers located in arid and semi-arid regions, the deformation signal often reflects a composite of long-term trends and seasonal variations. These seasonal oscillations are particularly evident when the aquifer system remains within its elastic response regime, wherein changes in pore pressure are primarily accommodated through reversible compaction and expansion of the aquifer matrix. This behaviour is exemplified in the Shabestar aquifer, as discussed in Papers II and III, where the InSAR-derived deformation patterns display a distinct periodicity synchronized with recharge and withdrawal cycles. In contrast, prolonged over-extraction in the Neyshabour aquifer has muted the seasonal component, with subsidence dominated by long-term monotonic trends (Figure 4.3). This contrast between elastic (Shabestar) and inelastic (Neyshabour) behaviour is clearly visible in the deformation–head time series.

In aquifers where inelastic deformation dominates, the seasonal pattern is largely absent because the mechanical properties of the aquifer have been altered, often due to collapse of pore structures within fine-grained sediments. This inelastic deformation not only reduces storage capacity (irreversible loss of porosity and specific storage) but also obscures cyclic signals that normally reflect elastic behaviour. As a result, land subsidence records show mainly long-term downward trends, indicating a degraded hydro-mechanical response.

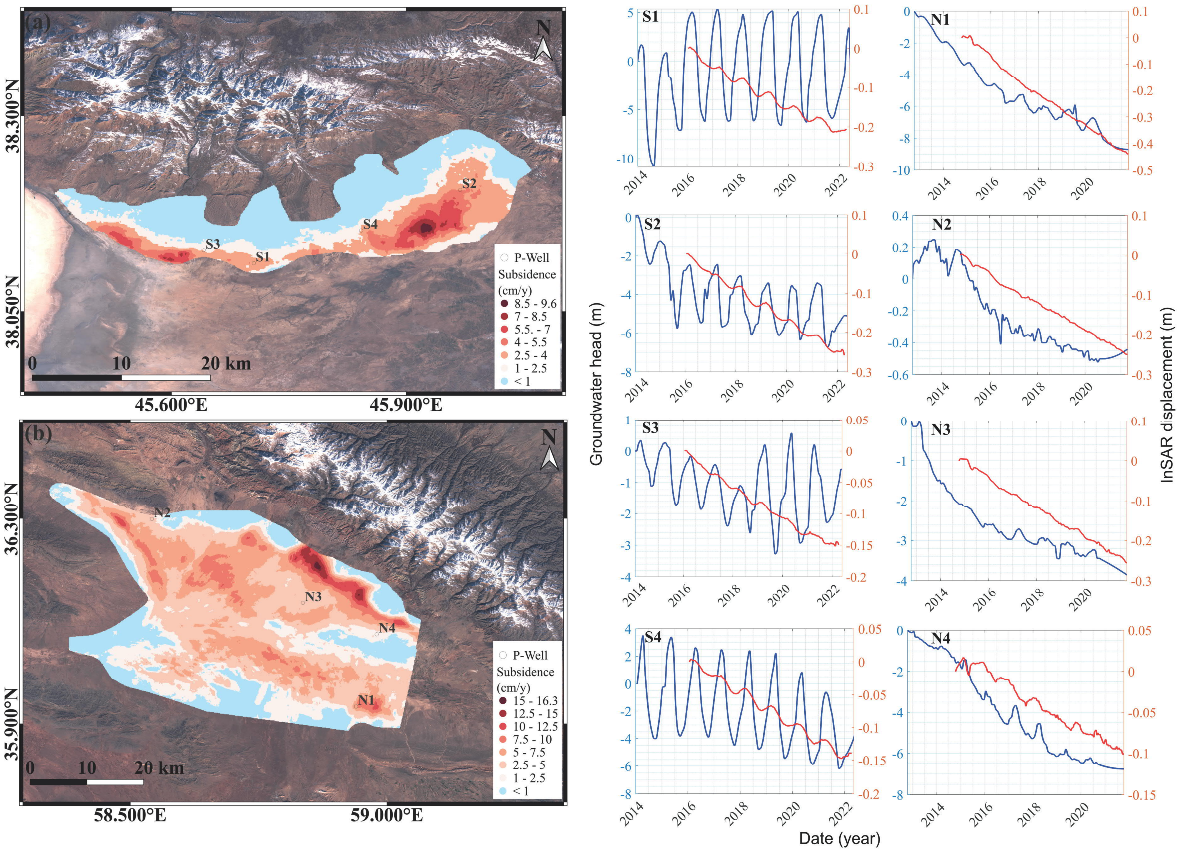


Figure 4.3: Groundwater head versus InSAR displacement over four representative wells across (a) Shabestar (left column, S1-S4) and (b) Neyshabour (right column, N1-N4) plains. The graphs illustrate the differing seasonal behaviours between the two plains: while seasonal fluctuations are pronounced in both groundwater head and InSAR displacement in the Shabestar Plain, they are significantly attenuated in both variables in the Neyshabour Plain (Paper II).

When inelastic compaction continues over extended periods, the rate of subsidence itself evolves. The slope of the displacement time series (here referring to the instantaneous deformation rate) may decrease as the soil structure approaches residual consolidation, where further compaction potential is limited. However, this evolution is not necessarily monotonic. Rates can slow during intervals of hydraulic recovery, when effective stresses are reduced, and accelerate again when heads decline below preconsolidation thresholds or when deeper layers enter the inelastic range. Shorter-term oscillations are also superimposed due to aquitard drainage and hydrodynamic lag, which delay pressure equilibration. These alternating phases of acceleration and deceleration are signatures of non-stationary compaction governed by stress-path history, evolving compressibility, and progressive loss of specific storage. They indicate ongoing shifts in aquifer regime rather than a single, steady trajectory toward consolidation (Galloway et al., 1999; Galloway & Burbey, 2011). Figure 4.4 illustrates how these temporal rate changes manifest: Shabestar shows bounded, relatively stable fluctuations consistent with elastic cycling, while Neyshabour exhibits irregular accelerations and decelerations, including both positive and negative excursions, reflecting evolving compressibility under sustained over-extraction.

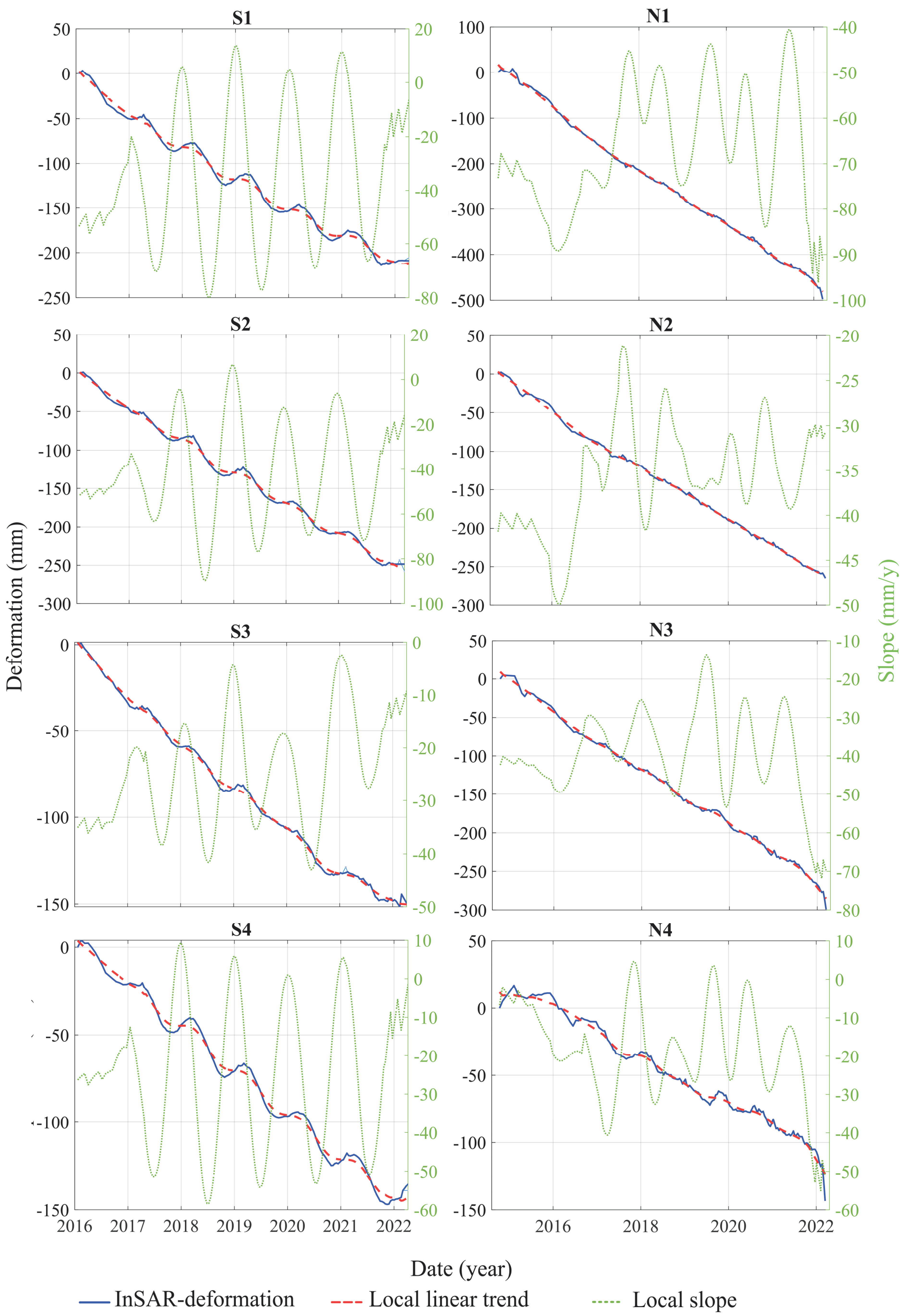


Figure 4.4: InSAR-derived vertical displacement for four representative wells in Shabestar (S1-S4) and Neyshabour (N1-N4) (blue) with a local linear trend (red dashed; 1-year span, Centred) and the corresponding local slope (green dotted; mm/yr, right axis). Shabestar's rate fluctuations cluster within a constant band, consistent with largely elastic behaviour, whereas Neyshabour shows broader, inconsistent excursions (both positive and negative), indicative of time-varying inelastic compaction and changing aquifer compressibility under over-abstraction.

From a hydro-mechanical perspective, analysing slope variations provides valuable insight into aquifer state and trajectory. The time-varying slope serves as a proxy for the instantaneous deformation rate, where more negative values indicate accelerating subsidence and values closer to zero reflect slowing rates and possible elastic recovery. Tracking these shifts helps identify transitions from seasonal elastic deformation to long-term inelastic compaction and eventually to residual consolidation once pore collapse is largely complete. These patterns are consistent with aquitard drainage and the role of preconsolidation stress in controlling delayed or renewed compaction (Wisely & Schmidt, 2010; Galloway et al., 1999; Galloway & Burbey, 2011). Evidence from InSAR and extensometer studies confirms that subsidence can continue despite short-term head rises and then diminish once pressures equilibrate and compressibility decreases (Miller et al., 2017). Such diagnostics are essential for predictive modelling and for groundwater management, since they highlight zones where irreversible compaction has reached critical thresholds and where mitigation strategies such as artificial recharge or controlled pumping may still preserve elastic behaviour.

Another factor influencing deformation patterns is the presence of nearby surface water bodies. Lakes, rivers, and wetlands can act as hydraulic buffers, attenuating drawdowns and subsidence through recharge or head stabilization. This buffering is evident in both the Shabestar aquifer (Paper III) and the Isfahan-Borkhar aquifer (Paper V), where areas close to perennial water features experienced less deformation than more distant, heavily exploited zones (Neely et al., 2021). These observations suggest that hydrological support from surface water can delay or limit the transition to inelastic deformation.

Peatland systems add a different complexity. Unlike sedimentary aquifers, peat is highly heterogeneous, elastic, and porous, leading to volumetric expansion and contraction, the so-called "peat breath", in response to water table fluctuations. These reversible surface changes do not translate directly into groundwater head dynamics, and deformation cannot be interpreted with the same hydro-mechanical framework. Instead, understanding peat deformation requires integrating InSAR with hydrological and ecological observations to distinguish natural variability from anthropogenic effects. This distinction is critical for managing peatlands as ecological buffers and carbon sinks (Price & Schlotzhauer, 1999; Lambert & Lissey, 2022).

4.2 Aquifer storativity: estimation and verification (Papers II-IV)

Ground deformation and groundwater head are linked through aquifer storativity, which plays a pivotal role in quantifying this interrelationship. Here we compile all storativity estimation across the dissertation. Seasonal and long-term skeletal storage were first estimated from the DHE model (Paper II), then mapped using a physics-assisted ML framework (Paper III), and finally calibrated as elastic and inelastic storage parameters in MODFLOW (Paper IV). This section also gathers the verification against a semi-log compression-index analytical approach.

Using the DHE model introduced in Paper II, the skeletal storage coefficient was partitioned into seasonal and long-term components, thereby capturing both transient and sustained deformation behaviours. Although these components do not correspond directly to purely elastic and inelastic states, their physical consistency was evaluated using the semi-log compression-index relation. Even without explicit values for compressible thickness (H) and initial void ratio (e_0) (whose importance was described in Section 3.5), the semi-log slope varies monotonically with the compression index (C). As long as H and e_0 vary modestly within an aquifer, comparisons across wells preserve the relative ordering implied by C. Consequently, strong cross-method correlations between DHE storativity and the semi-log slopes indicate that both methods respond to the same stress-strain physics associated with compression indices (C_c and C_r). In Neyshabour, the very high correlation for the long-term component reflects sustained drawdown in clay-rich sequences that produce persistent compaction behaviour. Under these conditions, the DHE long-term storativity $s_{k_{LT}}$ and the semi-log slope track the same consolidation mechanism, the one that would be quantified by C_c if H and e_0 were known. In contrast, seasonal responses are more sensitive to lag, partial drainage, and non-stationary forcing, so agreement is naturally more site dependent. Figure 4.5 shows this verification, with DHE-derived seasonal and long-term skeletal storage plotted against the stabilized semi-log slopes, and the strongest agreement evident in Neyshabour for the long-term component.

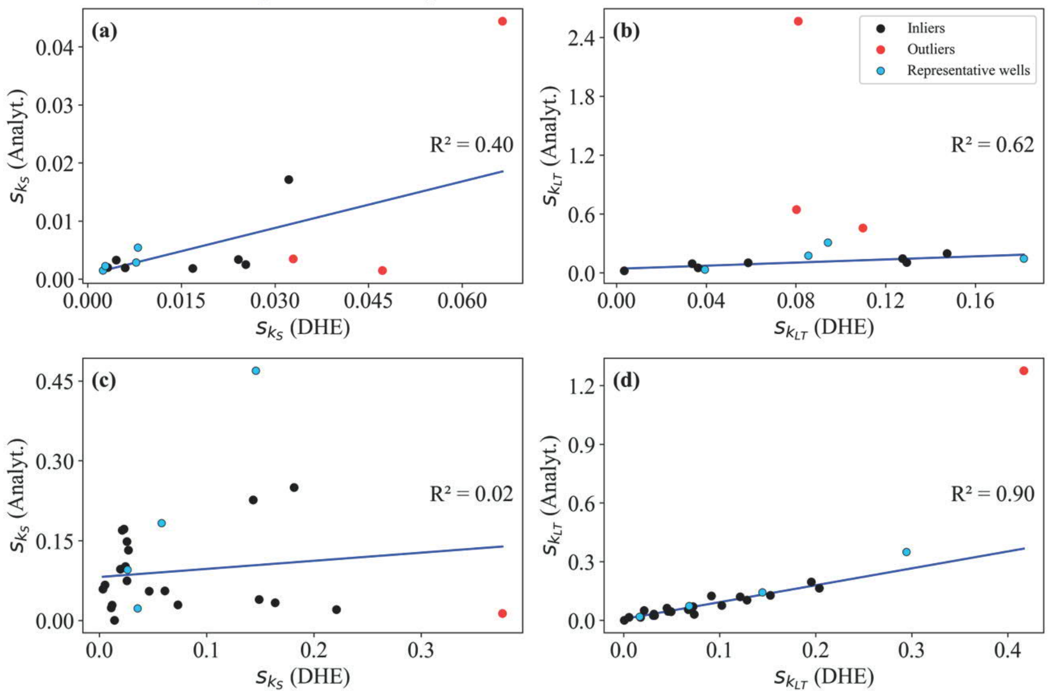


Figure 4.5: Scatter plots comparing skeletal storage coefficients estimated by the DHE method and the semi-logarithmic analytical approach for seasonal and long-term components in the Shabestar (a-b) and Neyshabour (c-d) aquifers. In Neyshabour, the long-term DHE-verification correlation is consistently high across representative wells ($R^2 \approx 0.90$), reflecting inelastic compaction dominance. In contrast, Shabestar shows moderate correlation for both components, suggesting predominantly elastic behaviour in parts of the aquifer (Khodaei et al., 2025).

Building upon this foundation, Paper III expands the analysis by mapping storativity and lag (τ) across Shabestar aquifer through a ML-based regression framework. Specifically, an XGBoost regression model is trained to extrapolate the storativity parameters (seasonal, long-term, and τ) from a limited number of observation wells to the entire aquifer system. The model uses a broad array of remote-sensing and in-situ datasets, including static spatial layers and dynamic indicators. Figure 4.6 provides an integrated view of the correlation structure, pairing the full feature-feature matrix with feature-target correlations for the seasonal and long-term skeletal storage and τ, with features grouped by category for direct comparison. The correlation screening shows a small cluster of highly correlated features, mainly temporally related remote-sensing composites (e.g., soil water index cross-products with evapotranspiration, land surface temperature, vegetation, and precipitation) and a few distance/terrain metrics, which exceed the high-correlation threshold (0.9). Outside this cluster, most pairwise correlations are low to moderate, indicating that many predictors contribute non-overlapping information. Feature-target analyses further show that the three target variables, i.e. s_{k_S}, $s_{k_{LT}}$, and τ, align with partially distinct subsets of predictors drawn from different families (topographic, hydrogeological, hydrometeorological, anthropogenic), with only limited overlap among the strongest correlates. This points to different physical controls for each target. The correlation structure at the well locations closely matches the structure computed over all pixels, indicating that the training sites represent the broader feature space and that spatial extrapolation is unlikely to be biased by site selection. Taken together, these findings support keeping the full feature set and using a model that tolerates some collinearity while capturing nonlinear relationships, such as gradient boosted decision trees.

It is worth noting that the systematic categorization and evaluation of auxiliary data carried out in Paper I laid essential groundwork for this stage. By organizing static and dynamic predictors ranging from topographical attributes and land use to clay thickness and meteorological variables, according to their relevance for aquifer deformation and groundwater storage, the earlier study improved feature selection and interpretability in the present ML framework. This structured approach ensured that auxiliary datasets contributed meaningfully to predictive performance rather than functioning as black-box inputs, ultimately strengthening the ability of the XGBoost model to capture spatial heterogeneities in aquifer behaviour.

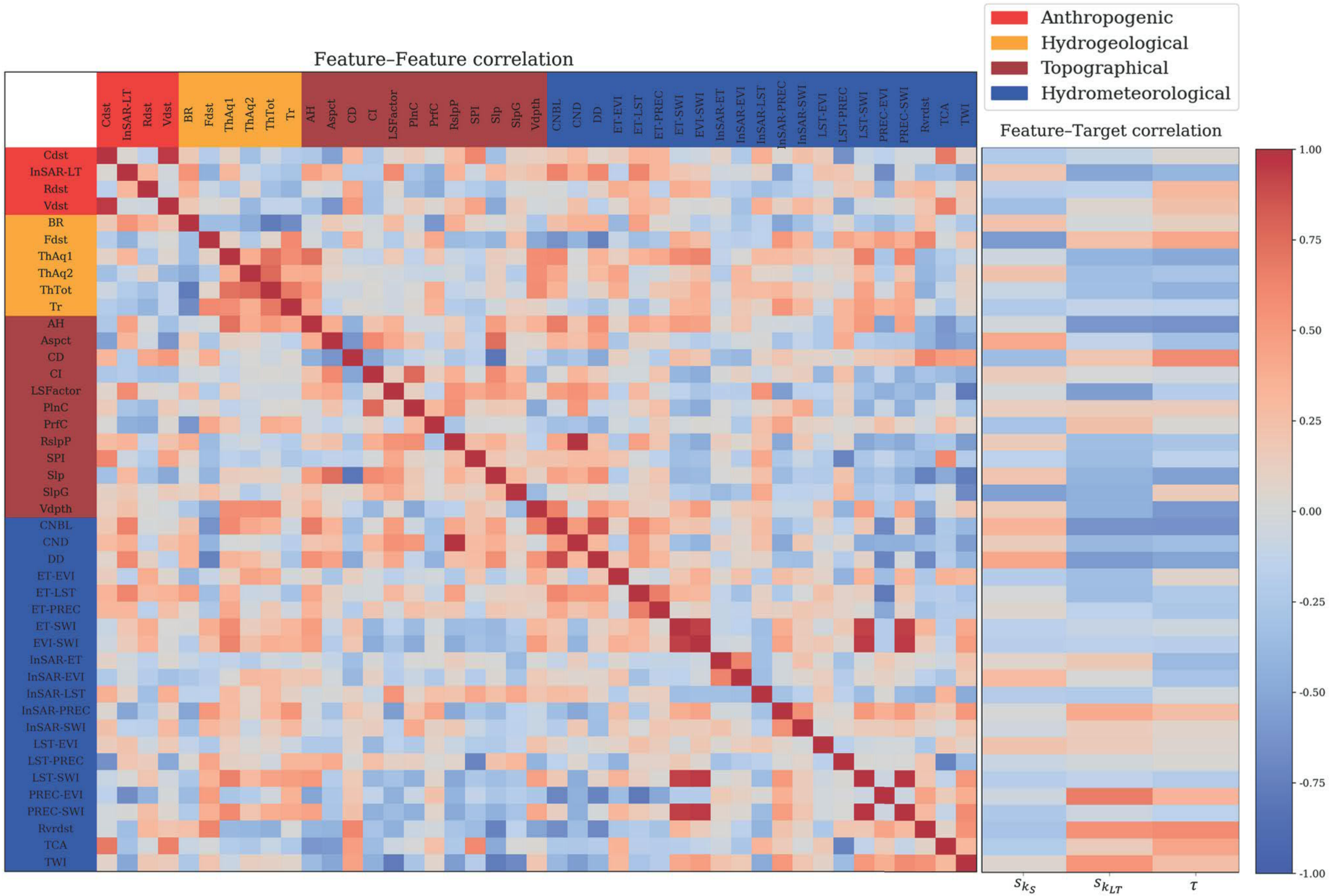


Figure 4.6: Integrated correlation view for the full feature set. The left panel shows feature-feature Pearson correlations while the right panel shows feature-target correlations for the three target variables ($s_{k_S}, s_{k_{LT}}, \tau$). Features are grouped by category and labelled inside a coloured strip.

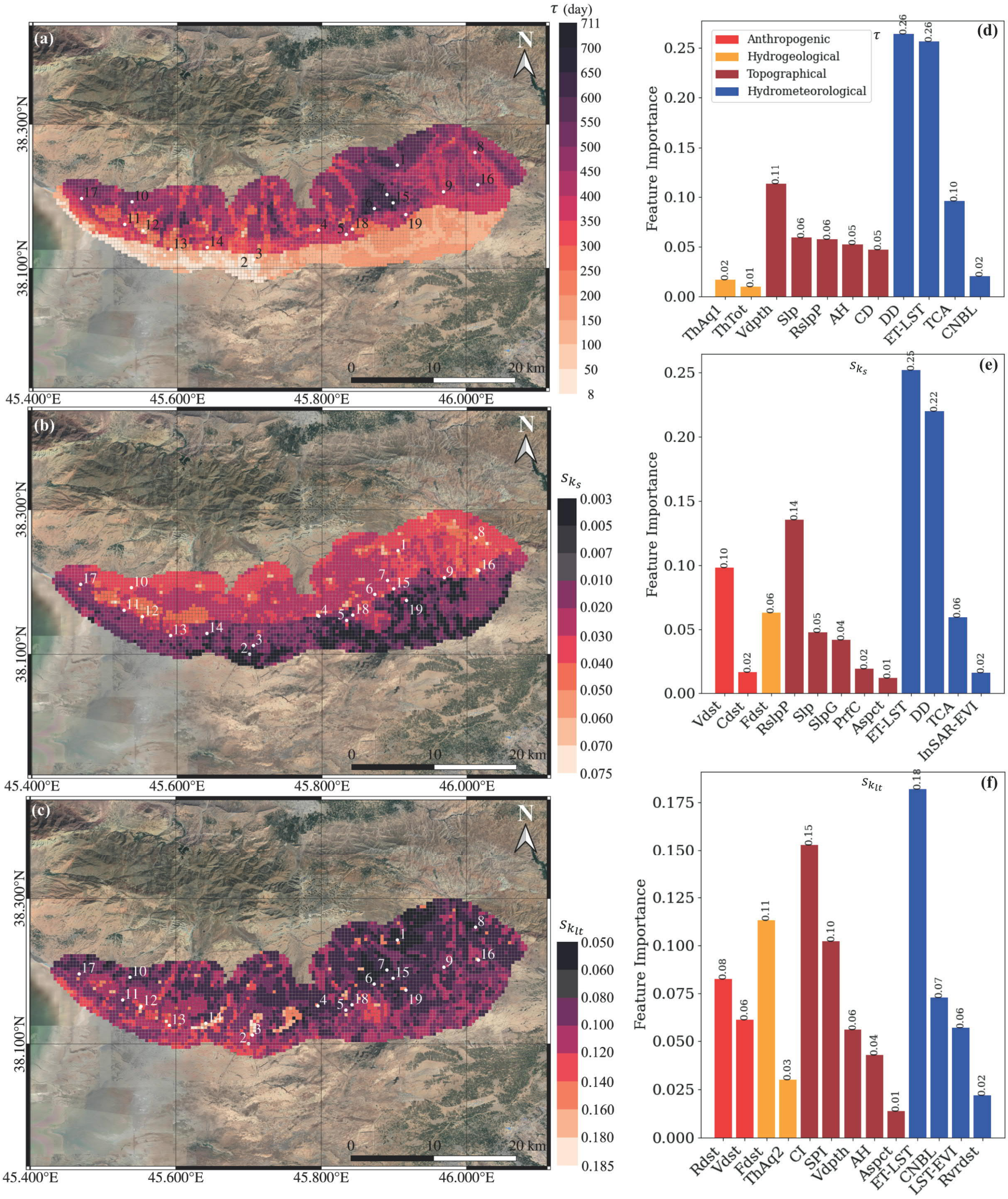
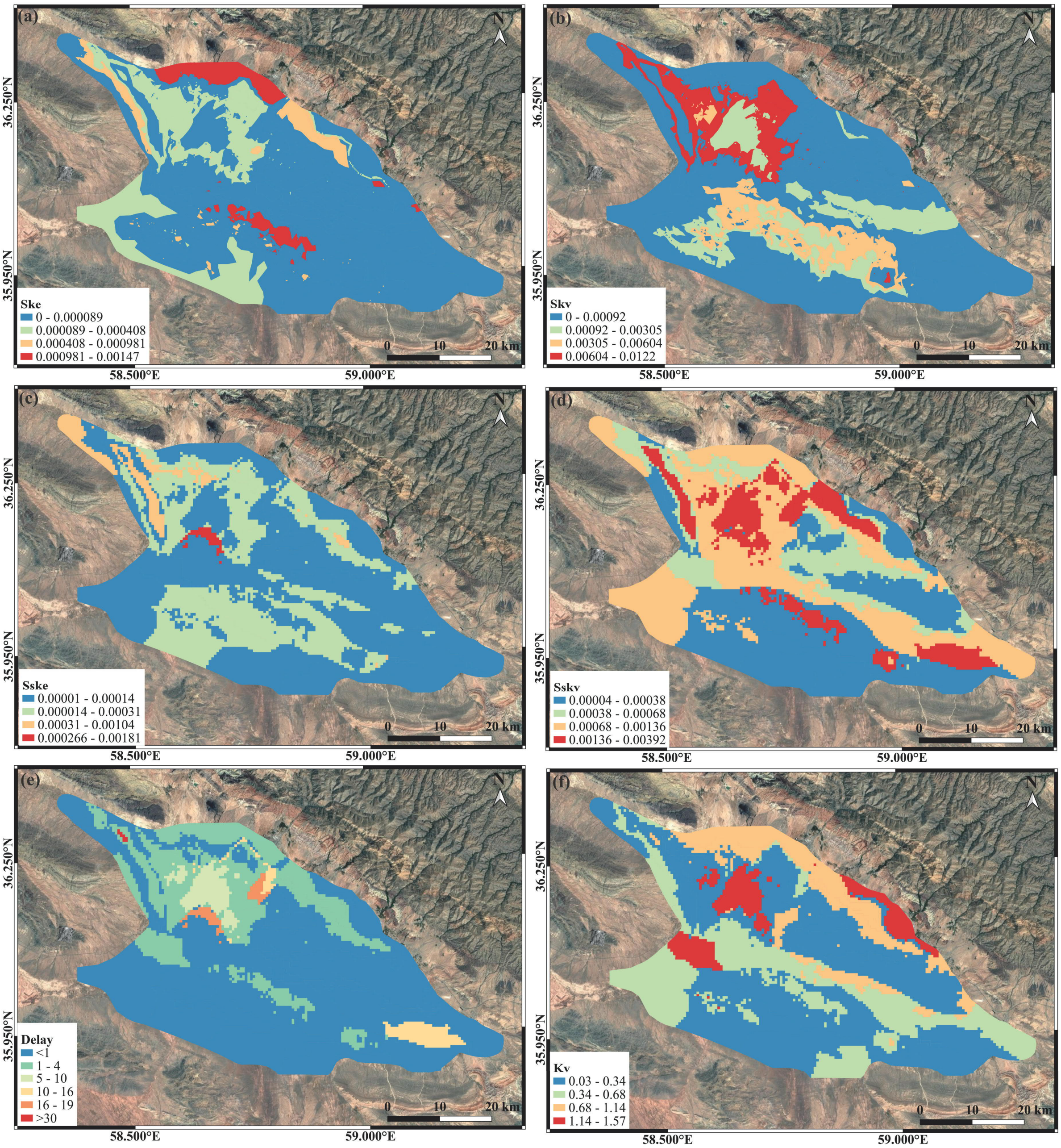


Figure 4.7: XGBoost-based regression modelling for estimating and mapping key aquifer storativity parameters (τ, sk_S, and sk_{LT}). Panels a-c shows spatial distribution of the estimated variables (τ, sk_S, and sk_{LT}, respectively), highlighting zones of significant subsidence associated with moderate τ (100-200 days), low s_{k_S}, and high sk_{LT}, indicative of irreversible deformation driven by prolonged groundwater extraction. Panels d-f display feature importance rankings, emphasizing the dominant role of hydrometeorological variables in predicting aquifer storativity, alongside contributions from topographical, hydrogeological, and anthropogenic factors (Paper III).

The resulting spatial storativity and τ maps (Figure 4.7) reveal coherent patterns that are physically interpretable and consistent with observed deformation bowls and hydrostratigraphic contrasts. At the point scale, the DHE model quantifies seasonal and long-term storativity coefficients at monitoring sites, enabling a classification of mechanical state. Sites on aquifer margins and at higher elevations tend to exhibit larger seasonal storativity (elastic, recharge-driven, and recoverable responses), whereas sites located within or adjacent to subsidence bowls show larger long-term storativity (greater likelihood of irreversible compaction under sustained pumping).

Extending beyond the point scale, the XGBoost-based hybrid model generalizes these storativity characteristics across the entire aquifer. Areas exhibiting short to moderate lag (τ) values and dominant long-term skeletal storage coefficients coincide with zones of intense deformation and limited recharge potential, underscoring the compounded impact of anthropogenic stress and unfavourable hydrogeological conditions. In contrast, elevated τ values in the upland or stratigraphically complex areas reflects delayed deformation relative to head change. Feature-importance analysis indicates that hydro-meteorological drivers together with topographic, hydrogeologic, and anthropogenic factors are key controls, underscoring the value of integrating multi-source data to explain heterogeneous groundwater behaviour.

Complementing the numerical and ML based methods, Paper IV calibrates elastic and inelastic skeletal storage using a MODFLOW-SUB model constrained by InSAR-derived vertical deformation, groundwater observations, and geological inputs. Two subsidence scenarios, i.e. delay and no-delay interbeds were evaluated to distinguish short-term elastic from long-term inelastic responses. Calibration under the delay-interbed assumption provided a more accurate representation of inelastic processes in regions experiencing prolonged subsidence. Figure 4.8 shows the spatial distribution of the calibrated storage parameters and associated vertical hydraulic conductivity and delay time fields that help explain spatial variations in aquifer response.



Figures 4.8: Spatial distribution of calibrated storage coefficients (S_{ke}, S_{kv}) and their thickness-normalized forms (S_{ske}, S_{skv}) for no-delay (a-b) and delay (c-d) interbed cases, derived using the SUB package (Paper IV). The delay interbed model (S_{ske}, S_{skv}) shows stronger spatial correlation with InSAR-derived subsidence patterns, especially in capturing localized elastic and inelastic deformation. Panels e-f presents the estimated time delay (τ), in days and vertical hydraulic conductivity (K_v) in m/day, highlighting zones of slower vertical water flux from aquitards.

4.3 Estimating groundwater head

This dissertation employs a comprehensive suite of modelling approaches aimed at quantifying groundwater head dynamics across spatial and temporal scales. At the core lies DHE, a physically informed data-driven model (Paper II), that relates groundwater head variations to land surface deformation induced by groundwater depletion at monitoring well locations. This connection is articulated through storativity, expressed in seasonal and long-term components. By analysing these temporal behaviours, DHE provides insight into the varying mechanical responses of the aquifer under different hydrological stress regimes. Unlike studies that rely on intricate parameterizations or purely empirical frameworks, this dissertation adopts a simplified yet robust semi-analytical methodology. The DHE storativity coefficients act as diagnostic indicators of aquifer behaviour, anchored in the physics of subsurface compaction and validated using both groundwater head and InSAR deformation time series. While the seasonal and long-term coefficients are not strict proxies for elastic and inelastic deformation, they serve as useful surrogates for the aquifer's hydro-mechanical state.

Using the estimated storativity and lag, heads are reconstructed from deformation at piezometric wells. The model effectively reproduces both seasonal fluctuations and long-term trends, with stronger skill in areas where elastic storage changes dominate and weaker performance where complex, non-linear seasonal effects prevail. Error metrics (Figure 4.9) confirm robust predictive ability, particularly in Shabestar where both seasonal cycles and long-term decline are well represented. In contrast, performance in Neyshabour is primarily governed by inelastic compaction, leading to more monotonic trends that the model captures with moderate accuracy. These outcomes are consistent with the mechanistic understanding elaborated in Paper II, where it was shown that integrating deformation signals with groundwater head data through the DHE framework improves predictive skill, while accuracy depends on the interplay between elastic and inelastic aquifer responses.

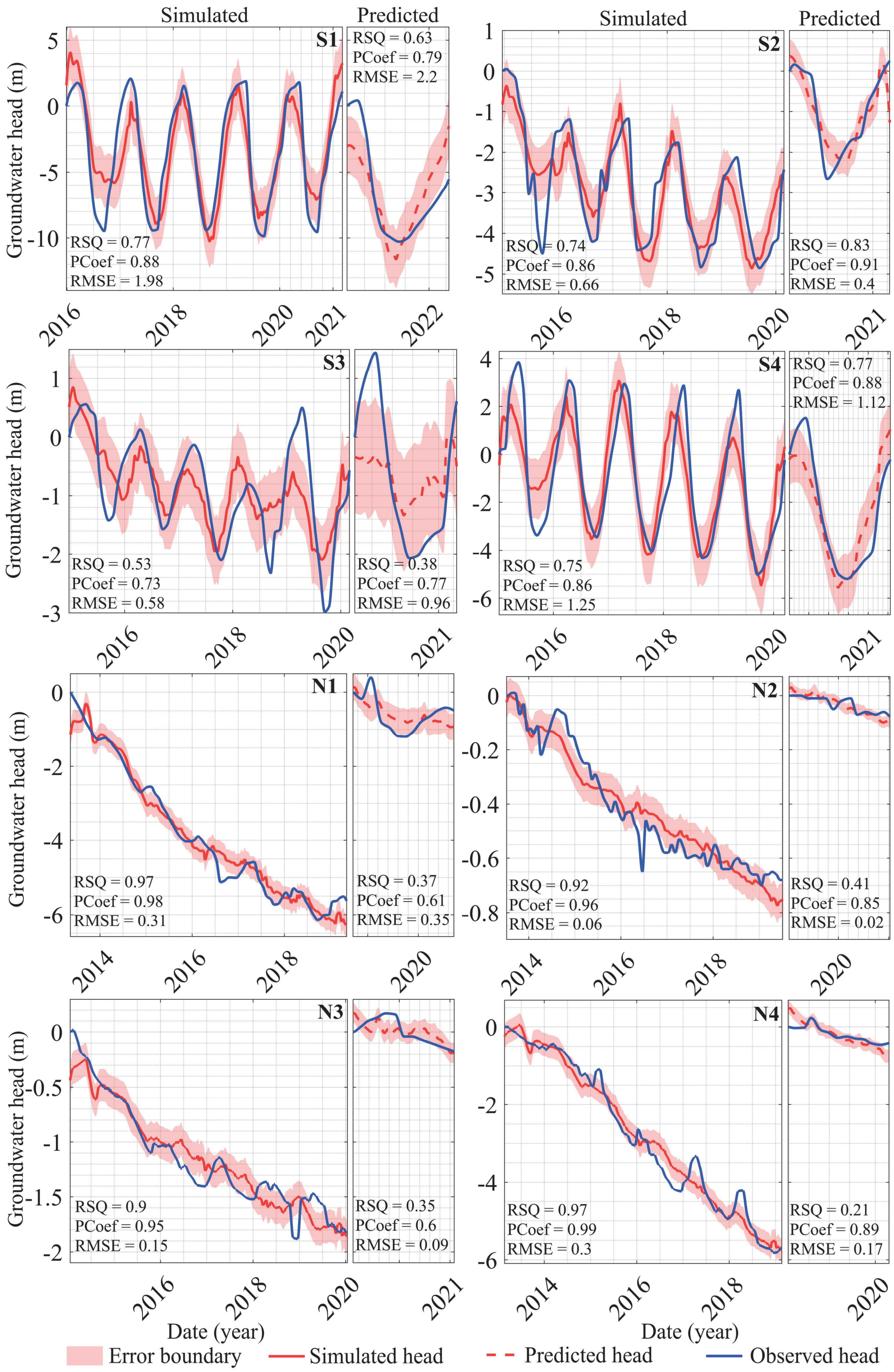


Figure 4.9: Simulated and predicted groundwater head (red) versus observed head (blue) for wells in the Shabestar (S1-S4) and Neyshabour (N1-N4) aquifers, with error bounds based on RMSE values. In Shabestar, the model effectively captures seasonal and long-term head dynamics, including slope shifts, though performance declines near Urmia Lake probably due to non-linear seasonal effects. In Neyshabour, dominated by long-term, inelastic deformation, the model successfully captures broad trends, but struggles with non-linear, semi-seasonal variations (particularly in N3) due to diminished aquifer elasticity.

In Paper III, we couple the DHE model's physics-based constraints with an XGBoost framework that infers seasonal and long-term storativity and lag from sparse wells using multi-source remote-sensing and in-situ predictors. This combination enables the simulation of groundwater head as a spatiotemporal variable, thereby bridging the gap between point-based measurements and aquifer-wide assessments. The result is a scalable and transferable framework capable of producing high-resolution groundwater head time series across complex aquifer systems, with clear benefits for resource management in arid and semi-arid regions.

Validation against independent test wells (Figure 4.10) showed strong agreement between simulated and observed groundwater heads, with a mean correlation coefficient of 0.84 and low RMSE values. The model achieved particularly high accuracy at wells 7 and 11, while reduced agreement at well 18 was linked to underestimated seasonal storage coefficient in a subsidence-prone zone (well locations are shown in Figure 4.7). Importantly, the framework maintained good performance even in hydrologically complex areas, such as near Urmia Lake and fault-controlled zones, highlighting the value of integrating categorical and environmental predictors.

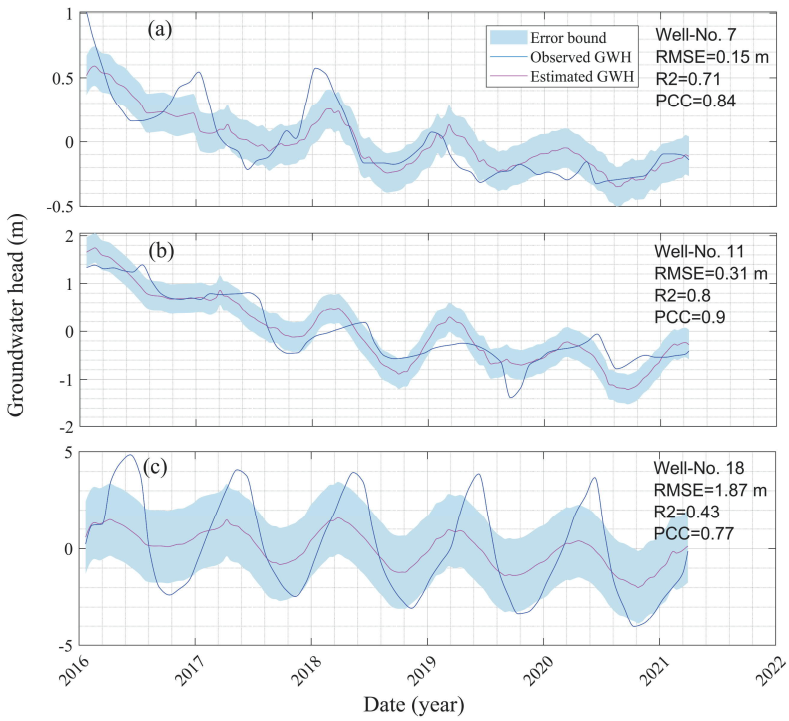
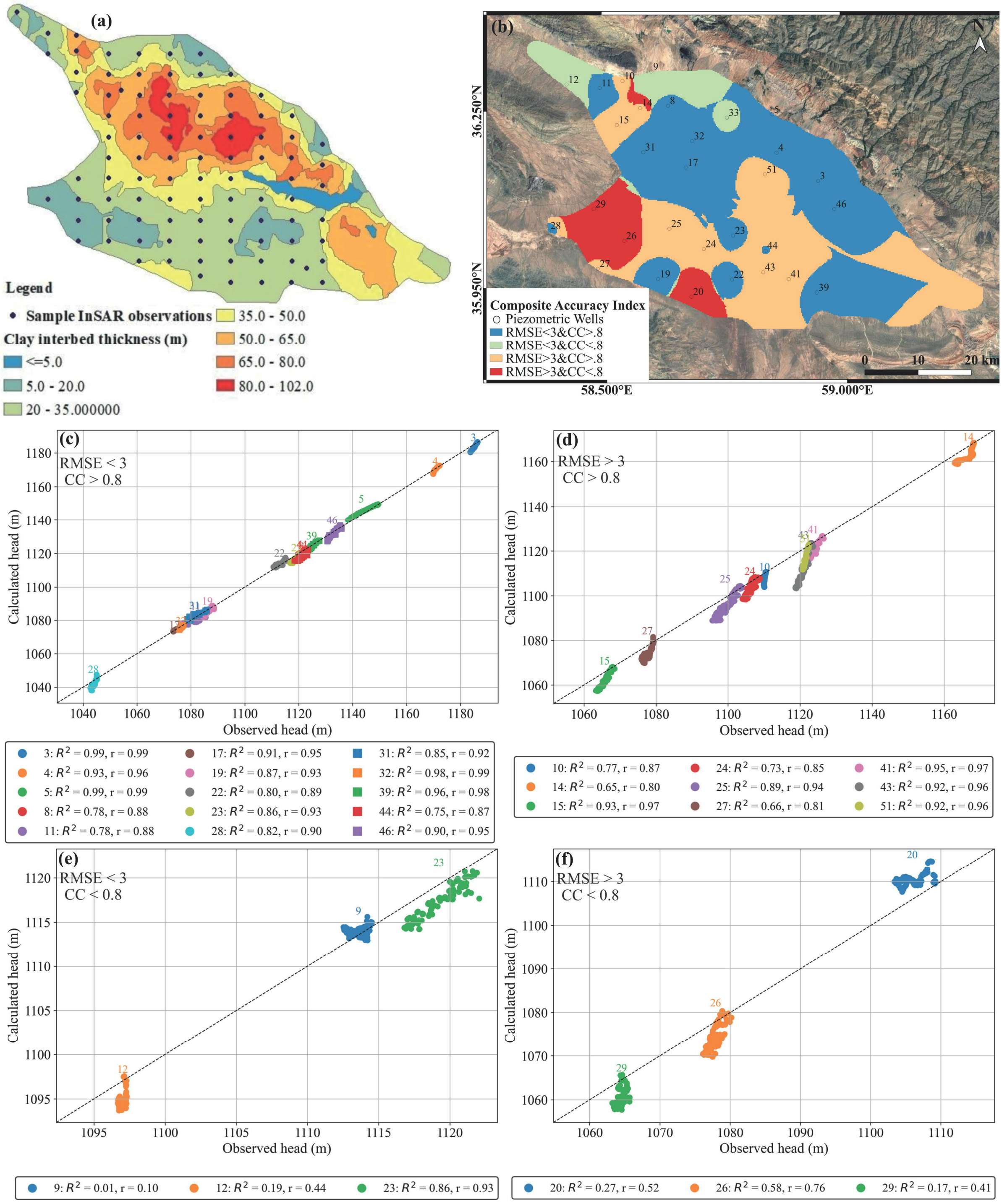


Figure 4.10: Comparison of computed groundwater head (from the ML-based model presented in Paper III) and observed head for three test wells (a-c), with accuracy metrics (R^2, PCC, RMSE) shown in each panel.

Together, these results confirm that the physics-assisted ML framework effectively extends point-based DHE estimations to aquifer-wide groundwater head monitoring. Beyond producing high-resolution time series, it also enhances interpretability of groundwater-deformation linkages, laying the groundwork for real-time monitoring tools to support groundwater management under conditions of data scarcity and climatic stress.

In addition to the approaches developed in Papers II and III, Paper IV further advanced groundwater head estimation by integrating InSAR deformation data with a physics-based numerical model. In this framework, a MODFLOW model equipped with the SUB package was calibrated using InSAR-derived deformation and in-situ head observations from the Neyshabour aquifer. Through the calibration process, we established that the storage coefficients derived under the delay interbed assumption provided a more accurate representation of inelastic deformation processes in regions experiencing prolonged subsidence. These calibrated coefficients, in conjunction with the InSAR deformation time series, were then used to compute groundwater head variations across space and time. The resulting head estimates showed strong agreement with observed well data, achieving correlation coefficients exceeding 0.8-0.9 and RMSE values typically below 2-3 m over a 7.5-year period (2014-2022). Accuracy was highest in the primary subsidence zone, where the framework successfully reproduced both seasonal fluctuations and long-term declines, while reduced performance was noted in marginal unconfined areas. Spatial accuracy maps (Figure 4.11) demonstrate the model's capacity to distinguish zones of reliable prediction and highlight areas where head estimates remain uncertain.

Overall, this InSAR-MODFLOW integration (SIGH-Map) provides a cost-effective and transferable tool for producing high-resolution groundwater head time series, complementing the DHE and ML-based approaches by offering a fully deterministic extension to aquifer scale. The framework shows particular promise for near real-time groundwater monitoring in confined and semi-confined aquifers prone to subsidence.



Figures 4.11: Model performance evaluation for groundwater head calculation in the Neyshabour aquifer using InSAR-derived deformation and MODFLOW (delay interbed case, $D - S_{S_{kv}}$). (a) Clay thickness map, (b) spatial accuracy of calculated heads with four performance zones defined by RMSE and correlation, (c-f) scatter plots of calculated versus observed groundwater heads at representative wells. Highest accuracy is achieved in areas with thick clay interbeds, while reduced performance occurs in shallow or unconfined zones.

4.4 GW-SW interactions and ecosystem responses

Moving beyond groundwater quantity estimation, Paper V extended the scope of the dissertation by investigating the hydrological connectivity between groundwater extraction and surface water systems. While this study did not explicitly aim to quantify groundwater content, it provided essential insights into the integrated behaviour of groundwater and streamflow in a highly manipulated river basin. By combining long-term InSAR deformation trends with spatial distribution of irrigation wells and hydrograph data, the study identified significant spatial overlaps between intensive groundwater withdrawal zones and streamflow reductions. The findings indicated that maintaining river flow into the Zayandeh-Rud River significantly mitigates land subsidence, particularly in urban-adjacent agricultural settings. This paper underscores the critical interdependence between groundwater management and surface water sustainability, especially in basins subjected to concurrent domestic and agricultural demand. It complements the earlier models by emphasizing the hydroecological feedback that are often overlooked in deformation-centric analyses. This relationship is illustrated in Figure 4.12, which compares land subsidence at selected wells near the Zayandeh-Rud River with corresponding river flow data. The figure clearly shows that subsidence rates increased after river flow ceased, highlighting the direct impact of surface water availability on aquifer stability.

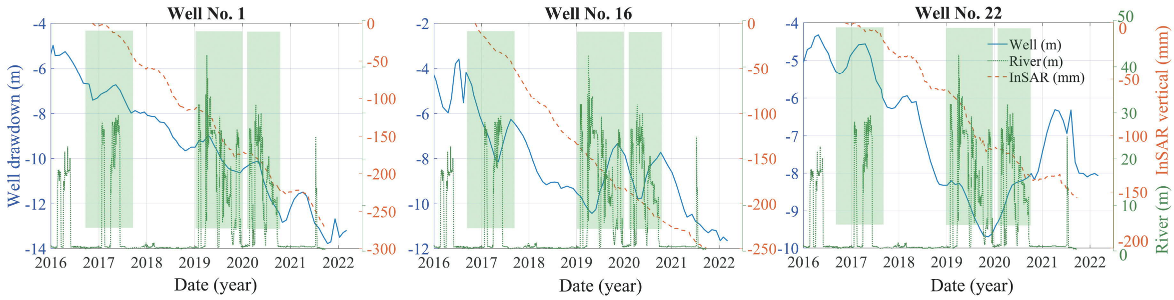


Figure 4.12: Time series of InSAR deformation (red) for three piezometric wells (number 1, 16, and 22) near the Zayandeh-Rud River, compared with the river's average flow (green) and groundwater head (blue). Green rectangles highlight periods (2016–2022) where subsidence rates decreased following temporary water releases into the river, demonstrating the clear link between surface water availability, groundwater dynamics, and subsidence pattern (Sharifi et al., 2024).

Finally, Paper VI broadened the dissertation's geographical and ecological scope by focusing on peatland ecosystems in temperate climates, examining their deformation behaviour and carbon sequestration capacity under drought stress using InSAR. While not directly aligned with groundwater quantity estimation, this study reinforced the dissertation’s central theme by emphasizing deformation as an indicator of subsurface water dynamics. Here, the concept of “peat breathing” i.e., volumetric changes in peat due to fluctuating water tables, was applied to interpret seasonal surface motion across classified peatland sites.

The methodological framework combined InSAR-derived deformation with site descriptors from the VMI, allowing classification of peatlands by type (bogs (eccentric, concentric, and raised bogs), fens, and mixed types), environmental value (Classes I-IV, from highest to lowest conservation and ecological importance), and deformation behaviour (uplift, subsidence, or stability). A total of 64 sites with sufficient coherent scatterers were analysed. Raised bogs dominated the sample (84%) and showed the most consistent uplift patterns, even under drought stress, while mixed fens and wetlands accounted for smaller shares (13% and 3%, respectively). Quantitative summaries indicated that 17%, 50%, 22%, and 11% of the sites fell into VMI Classes I–IV. Despite the extreme 2018 drought, 86% of the monitored peatlands exhibited uplift, corresponding to an estimated annual carbon uptake of ~47 kilotons, particularly in bog-type peatlands resilient to climatic extremes (Khodaei et al., 2023).

Figures 4.13 and 4.14 illustrate this classification and highlight that deformation signals, when combined with peatland type, conservation value, and drought records, provide critical insights into ecosystem health, resilience, and carbon cycle contributions. This expands the application of InSAR-based deformation analysis beyond hydrogeology to ecological monitoring and climate change mitigation.

Together, Papers V and VI complement the quantitative modelling core of this dissertation by offering qualitative depth, cross-system insights, and ecological context. The GW-SW linkage (Paper V) illuminated broader resource management implications, and the peatland deformation study (Paper VI) highlighted the versatility of InSAR in assessing subsurface hydrological behaviour across diverse environmental systems. Collectively, these contributions underscore the value of a multidisciplinary approach in addressing the complex, interconnected challenges of water resource monitoring and sustainability.

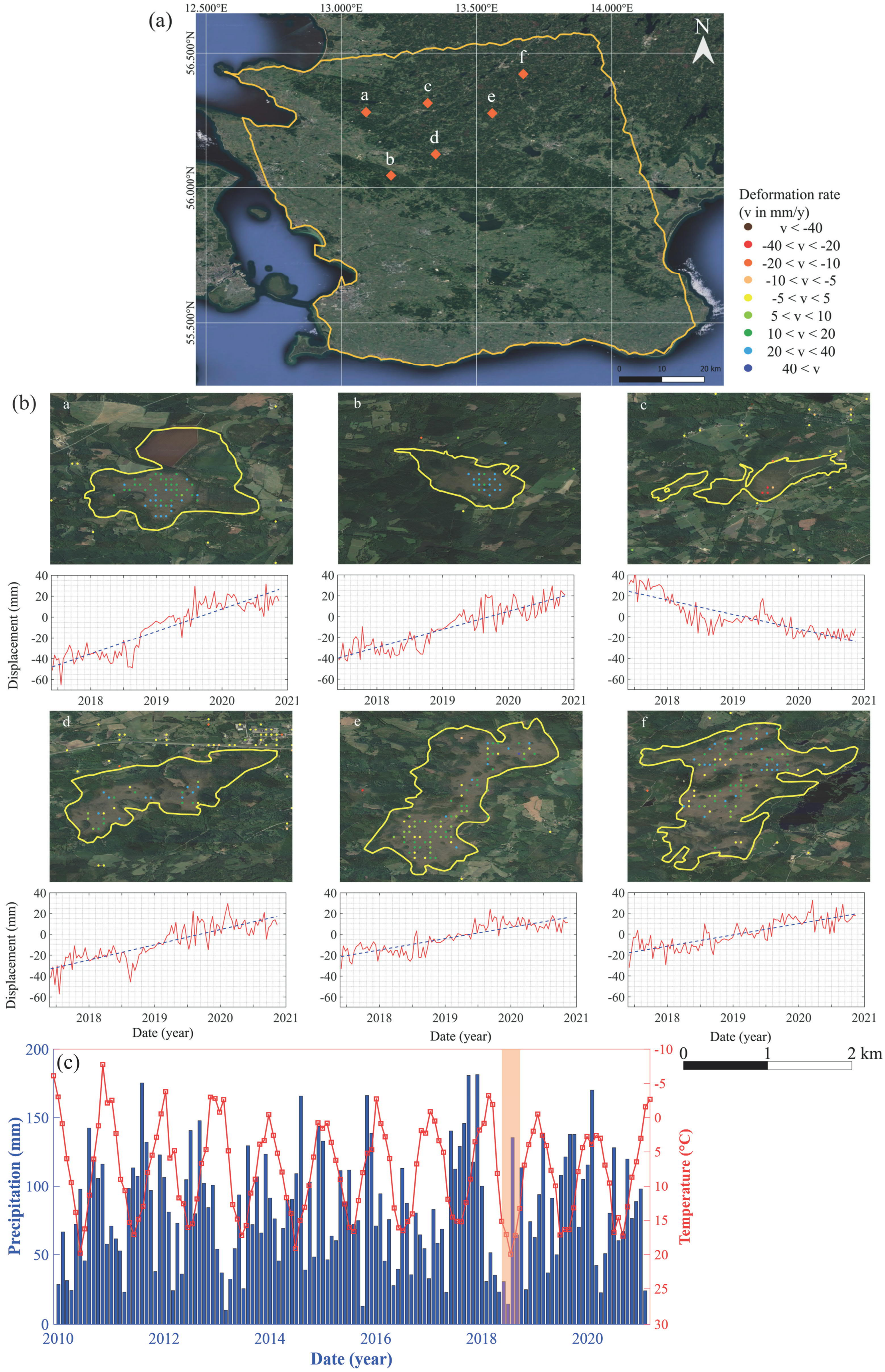


Figure 4.13: Overview of the study area, deformation results, and climatic context from Paper VI. (a) Geographical location of representative peatland sites; (b) InSAR-derived deformation at sites (a–f); (c) Climate panel showing precipitation, temperature, and drought period (highlighted in bright red).

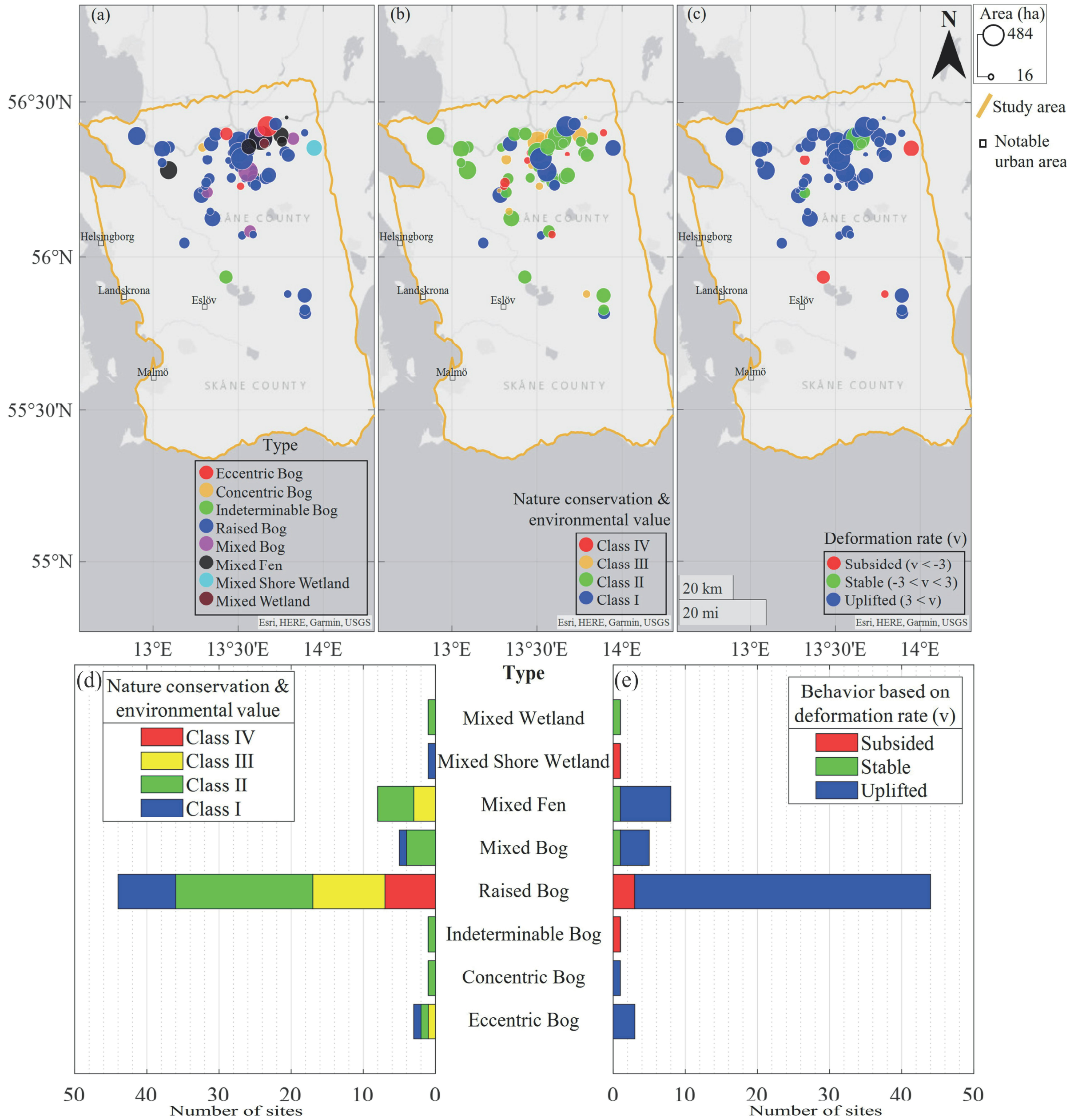


Figure 4.14: Overview of results from Paper VI: (a–c) classification of 64 peatlands by type (a), conservation value (b), and deformation behaviour (c); (d–e) quantitative summary of site classifications.

4.5 Validation

Across the six studies presented in this dissertation, validation methodologies were consistently employed to assess both the reliability of InSAR-derived deformation data and the performance of hydrological models developed for spatiotemporal assessment of groundwater systems and land deformation. These methodologies were structured around several well-defined categories, ensuring consistency, robustness, and interpretability across varying modelling frameworks and case studies.

i. Comparison with in-situ monitoring data

A primary validation approach involved comparing modelled or estimated outputs, such as InSAR-derived deformation and groundwater head time series, with observations from ground-based monitoring networks. These included piezometric well measurements and permanent satellite-based positioning stations (such as GNSS stations). Accuracy analysis was conducted using standard statistical metrics, including Root Mean Square Error (RMSE), Pearson Correlation Coefficient (PCC or PCoef), and Coefficient of Determination (R^2), providing a comprehensive assessment of model performance and predictive reliability.

ii. Cross-validation and temporal splitting

For models that required training, such as the machine learning approaches, the available datasets were divided into subsets for training and testing or validation. The model's performance was then evaluated on the independent validation set that was not used during training (Papers I and III). For deformation-driven and numerical modelling, temporal partitioning was applied by reserving data from a specific period for validation after calibrating the model on an earlier period (Papers II and IV).

iii. Comparison with alternative remote sensing/processing methods

To validate the InSAR data, results obtained from one InSAR processing package or method (e.g., SBAS-InSAR processed with GMTSAR) were compared with results from an alternative, independent package or method (e.g., StaMPS/MTI) over the same area and period. This confirmed the consistency and reliability of the remote sensing observations.

iv. Verification with analytical and numerical approaches

Some studies extended validation by also verifying intermediate parameters derived from InSAR and well data using independent physically based methods. For example, skeletal storage coefficients estimated with the DHE model were compared with values obtained using a semi-logarithmic analytical method (Paper II). This type of verification reinforced the physical basis of the proposed methodologies.

The validation efforts collectively support the reliability of the methods developed and applied throughout this dissertation. Models used to predict or reconstruct groundwater head, whether data-driven, numerical, or hybrid, showed consistent agreement with observed well data, effectively capturing both seasonal fluctuations and long-term depletion trends. Despite known limitations in observation density, these models showed high potential for extending spatiotemporal groundwater information beyond sparse monitoring networks. The convergence of statistical, observational, and physical validation across the studies further confirms that integrating InSAR with advanced modelling tools provides scientifically robust, transferable, and operationally useful approaches for groundwater monitoring, offering a scalable path toward sustainable resource management under conditions of data scarcity, environmental stress, and ecological vulnerability.

4.6 Uncertainties

Despite the promising capabilities of InSAR-derived deformation when integrated with data-driven, numerical, and machine learning approaches for hydrological monitoring, it is essential to critically acknowledge the inherent uncertainties and limitations that may affect the robustness, accuracy, and generalizability of the findings. These limitations arise from three principal domains: (i) remote sensing and InSAR processing, (ii) input dataset quality and availability, and (iii) modelling assumptions and geological complexity.

i. Remote sensing data and InSAR processing uncertainties

A primary source of uncertainty originates from the InSAR analysis itself. Atmospheric artifacts can obscure ground deformation signals, although these are partially mitigated through filtering techniques and temporal coherence analysis. Phase unwrapping errors, while typically negligible for gradual processes such as groundwater-induced subsidence, can still pose challenges in regions lacking a continuous temporal series of SAR acquisitions. Vegetation-induced decorrelation and complex topography further limit data continuity and signal stability, particularly in agricultural or mountainous areas.

Another critical consideration is the selection of a stable reference area for deformation calculation. In regions without permanent ground-truth stations (e.g., satellite positioning stations or leveling benchmarks), reference point selection often relies on interferometric phase stability, which can introduce systematic bias. Moreover, differences in deformation estimates obtained from distinct processing software (e.g., GMTSAR vs. StaMPS/MTI) highlight the influence of processing choices, with comparative metrics such as RMSE and R^2 used to quantify variability.

Additional uncertainties arise from other satellite-based datasets employed in the modelling, including soil moisture, precipitation, evapotranspiration, land surface temperature, and land cover products. These datasets are subject to errors from sensor limitations, processing methods, and atmospheric conditions. Their temporal and spatial resolutions are often inconsistent with each other and with InSAR data, requiring resampling and harmonization that may smooth out extremes, distort variability, or introduce artifacts. Such inconsistencies can affect correlation structures, feature importance analyses, and ultimately the reliability of groundwater head and storativity estimations.

ii. Data availability and quality constraints

The limited availability and heterogeneous quality of auxiliary and in-situ datasets constitute significant constraints. Groundwater head data are typically sparse, especially in confined aquifers where well distribution is inherently limited. In several case studies, the number of observation wells with reliable and complete records was insufficient, compelling the exclusion of incomplete datasets or reliance on minimal calibration data. This sparse sampling increases the risk of overfitting in ML-based modelling and reduces model generalizability, although robust cross-validation techniques are employed to mitigate such risks.

Additional uncertainties arise from auxiliary datasets such as clay thickness maps and lithological profiles. Inaccuracies in well location or depth and mismatches between logs and piezometric measurements can further limit their utility for parameter estimation.

iii. Modelling assumptions and geological heterogeneity

The parameter estimation processes, in both numerical and data-driven models, are susceptible to uncertainty due to simplified assumptions and incomplete geological characterization. Skeletal storage coefficients, lag times, and transmissivity values are often estimated from limited data using inverse modelling or analytical approximations. These assumptions include attributing deformation solely to groundwater withdrawal or assuming aquifer confinement in parameter derivation. While verification against independent analytical approaches supports the plausibility of derived parameters, this does not guarantee accuracy in simulated groundwater heads or deformation magnitudes. In machine learning frameworks, additional uncertainty arises from the sensitivity of model performance to training data quality, feature selection, and the risk of overfitting when extrapolating beyond observed conditions.

Intrinsic geological complexities, such as spatial variability in clay layer thickness, aquitard presence, and aquifer stratification, contribute significantly to prediction uncertainty. In particular, distinguishing between elastic and inelastic compaction phases and accurately modelling their transitions remain challenging. These complexities remain poorly constrained in the absence of high-resolution geological and geophysical data.

4.7 General implications and future recommendations

The cumulative effect of these uncertainties underscores the need for caution when interpreting model outputs and transferring findings across hydrogeological contexts. To enhance methodological robustness and applicability, future research should prioritize:

- Expanding the spatial and temporal density of in-situ observation networks.
- Acquiring higher-resolution and harmonized remote sensing and geological datasets.
- Enhancing subsurface characterization through geophysical surveys, borehole analysis, and laboratory testing.
- Strengthening external validation with independent ground-truth datasets.
- Incorporating diverse hydrogeological case studies to improve model generalizability and predictive reliability.

Despite these limitations, the integrated methodology presented in this dissertation demonstrates strong potential for large-scale hydrological monitoring in data-scarce regions where traditional measurements are limited or unreliable.

5 General conclusions

This dissertation employed a set of complementary modelling approaches, combined with remote sensing, to explore, quantify, and interpret groundwater dynamics and associated land surface deformation. Across six interrelated studies, we developed and validated novel approaches to understand and manage hydrological resources, with a particular focus on groundwater systems in arid, semi-arid, and temperate regions, while also evaluating interactions between groundwater, surface water, and ecosystems.

The initial research phase (Paper I) established a foundation by leveraging InSAR data and advanced ML algorithms to overcome spatial discontinuities in deformation data. A critical contribution of this study was the systematic categorization and evaluation of auxiliary data, including topographical, hydrogeological, anthropogenic, and hydrometeorological factors. This classification process facilitated more precise and interpretable ML models, laying a robust basis for subsequent modelling phases.

Building upon this foundation, the DHE model (Paper II) emerged as a pivotal contribution by linking groundwater head variations directly to land surface deformation measured through InSAR techniques. This physics-assisted data-driven model proved capable of reliably simulating groundwater dynamics even in data-scarce areas, advancing our capability to manage aquifers sustainably. Partitioning storativity into seasonal and long-term components provided nuanced insights into aquifer mechanics, enhancing both interpretability and practical applicability.

Further advancing this methodology, Paper III presented an integrated approach combining the DHE model's physics-informed insights with ML techniques. This hybrid model successfully extrapolated the calculated storativity parameters to the entire aquifer system, improving spatial coverage and predictive reliability. Validation demonstrated strong correlations between observed and predicted groundwater heads, while feature importance analysis highlighted the influence of hydrometeorological and anthropogenic factors in aquifer deformation.

Recognizing the value of integrating multiple methodological perspectives, Paper IV employed a modified MODFLOW-SUB model calibrated with InSAR-derived deformation data. This physics-based numerical approach directly estimated skeletal storage parameters, demonstrating the strengths of deterministic numerical modelling combined with satellite-based constraints. The calibrated model effectively simulated groundwater head changes in time and space, offering a reliable tool for timely groundwater resource management in subsidence-prone regions.

In addition to groundwater quantity assessments, Paper V highlighted the critical hydrological interdependencies between groundwater extraction and surface water systems. By examining a key river system in one of Iran's most densely populated agricultural regions, this study underscored how both climatic variability and socio-political decision-making influence the sustainability of groundwater resources. These interconnected factors directly affect aquifer deformation and land subsidence. The findings provide compelling evidence that sustaining river flows can mitigate subsidence, reinforcing the need to integrate socio-economic priorities and political realities into holistic water management strategies that balance surface and groundwater systems.

Finally, Paper VI expanded the geographical and ecological scope by investigating temperate peatland sites in southern Sweden and their role in carbon sequestration using InSAR deformation data. Despite severe drought conditions during the study period, most monitored peatland sites demonstrated resilience, characterized by surface uplift and substantial carbon sequestration. This emphasized the ecological importance of peatlands as carbon sinks and highlighted the value of InSAR as a monitoring tool for assessing ecosystem health under climatic stress.

In conclusion, this dissertation demonstrated that the combined use of remote sensing with physics-assisted, data-driven, numerical, and machine learning modelling approaches provides powerful and scientifically rigorous means for monitoring and managing complex hydrological systems. Through the development of distinct yet complementary frameworks, the research not only enhanced understanding of groundwater dynamics and land surface deformation but also revealed critical interactions between groundwater, surface water, and ecosystems. These findings provide essential insights for sustainable water resource management under the pressing challenges of climate change and increasing anthropogenic pressures, and they offer a transferable methodological foundation for future applications in diverse hydrogeological settings.

References

Agram, P. S., Jolivet, R., Riel, B., Lin, Y. N., Simons, M., Hetland, E., Doin, M., & Lasserre, C. 2013. "New radar interferometric time series analysis toolbox released." *Eos, Transactions American Geophysical Union, 94(7)* 69-70.

Ali, M. Z., Chu, H. J., Tatas, & Burbey, T. J. 2022. "Estimation of annual groundwater changes from InSAR-derived land subsidence." *Water and Environment Journal, 36(4)* 622-632.

Alley, W. M., Reilly, T. E., & Franke, O. L. 2002. *Sustainability of Ground-Water Resources.* U.S. Geological Survey Circular 1186.

Alshammari, L., Large, D. J., Boyd, D. S., Sowter, A., Anderson, R., Andersen, R., & Marsh, S. 2018. "Long-term peatland condition assessment via surface motion monitoring using the ISBAS DInSAR technique over the Flow Country, Scotland." *Remote Sensing, 10(7)* 1103.

Aminjafari, S., Brown, I., Mayamey, F. V., & Jaramillo, F. 2024. "Tracking centimeter-scale water level changes in Swedish lakes using D-InSAR." *Water Resources Research, 60(2)* e2022WR034290.

Antala, M., Juszczak, R., van der Tol, C., & Rastogi, A. 2022. "Impact of climate change-induced alterations in peatland vegetation phenology and composition on carbon balance." *Science of the Total Environment, 827* 154294.

Arii, M., Yamada, H., Kojima, S., & Ohki, M. 2019. "Review of the Comprehensive SAR Approach to Identify Scattering Mechanisms of Radar Backscatter from Vegetated Terrain." *Electronics, 8(10)* 1098.

Asher, M. J., Croke, B. F. W., Jakeman, A. J., & Peeters, L. J. M. 2015. "A review of surrogate models and their application to groundwater modeling." *Water Resources Research, 51(8)* 5957–5973.

Bai, L., Jiang, L., Zhao, Y., Li, Z., Cao, G., Zhao, C., Liu, R., & Wang, H. 2022. "Quantifying the influence of long-term overexploitation on deep groundwater resources across Cangzhou in the North China Plain using InSAR measurements." *Journal of Hydrology, 605* 127368.

Baird, A. J., Belyea, L. R., & Morris, P. J. 2009. "Upscaling Peatland-Atmosphere Fluxes of Carbon Gases: Small-Scale Heterogeneity in Process Rates and the Pitfalls of 'Bucket-and-Slab' Models." In A. J. Baird, L. R. Belyea, X.

Comas, A. S. Reeve, & L. D. Slater (Eds.), *Carbon Cycling in Northern Peatlands* (pp. 37–53). American Geophysical Union.

Banerjee, D., & Ganguly, S. 2023. "A review on the research advances in groundwater–surface water interaction with an overview of the phenomenon." *Water, 15(8)* 1552.

Banic, M., Ristic-Durrant, D., Madic, M., Klapper, A., Trifunovic, M., Simonovic, M., & Fischer, S. 2025. "The Use of Earth Observation Data for Railway Infrastructure Monitoring—A Review." *Infrastructures, 10(3)* 66.

Bear, J., Cheng, A. H. D., Sorek, S., Ouazar, D., & Herrera, I. (Eds.). 1999. *Seawater intrusion in coastal aquifers: concepts, methods and practices (Vol. 14).* Springer Science & Business Media.

Berardino, P., Fornaro, G., Lanari, R., & Sansosti, E. 2002. "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms." *IEEE Transactions on geoscience and remote sensing, 40(11)* 2375-2383.

Besoya, M., Govil, H., & Bhaumik, P. 2021. "A review on surface deformation evaluation using multitemporal SAR interferometry techniques." *Spatial Information Research* 29, 267-280.

Breiman, L., Friedman, J., Olshen, R. A., & Stone, C. J. 2017. *Classification and regression trees. Chapman and Hall/CRC.* New York: Taylor & Francis Group.

Bru, G., Ezquerro, P., Béjar-Pizarro, M., Guardiola-Albert, C., Fernández-Merodo, J. A., Díaz, J. E. H., & Herrera, G. 2024, April. "InSAR-Based Assessment of Land Subsidence Related to Aquifer Overexploitation in Spain: A Comprehensive Review." *In 2024 IEEE Mediterranean and Middle-East Geoscience and Remote Sensing Symposium (M2GARSS). IEEE.* pp. 386-390.

Canales, M., Castilla-Rho, J., Rojas, R., Vicuña, S., & Ball, J. 2024. "Agent-based models of groundwater systems: A review of an emerging approach to simulate the interactions between groundwater and society." *Environmental Modelling & Software, 175* 105980.

Chaussard, E., Bürgmann, R., Shirzaei, M., Fielding, E. J., & Baker, B. 2014. "Predictability of hydraulic head changes and characterization of aquifer-system and fault properties from InSAR-derived ground deformation." *Journal of Geophysical Research: Solid Earth, 119(8)* 6572-6590.

Chaussard, E., Milillo, P., Bürgmann, R., Perissin, D., Fielding, E. J., & Baker, B. 2017. "Remote sensing of ground deformation for monitoring groundwater management practices: Application to the Santa Clara Valley during the 2012–2015 California drought." *Journal of Geophysical Research: Solid Earth, 122(10)* 8566-8582.

Chen, C. W., & Zebker, H. A. 2000. "Network approaches to two-dimensional phase unwrapping: intractability and two new algorithms." *Journal of the Optical Society of America A, 17(3)* 401-414.

Chen, C. W., & Zebker, H. A. 2002. "Phase unwrapping for large SAR interferograms: Statistical segmentation and generalized network models." *IEEE Transactions on Geoscience and Remote Sensing, 40(8)* 1709-1719.

Chen, J., & Dai, Z. 2024. "Metaheuristic algorithms for groundwater model parameter inversion: Advances and prospects." *Deep Resources Engineering, 1(2)* 100009.

Chen, J., Knight, R., Zebker, H. A., & Schreüder, W. A. 2016. "Confined aquifer head measurements and storage properties in the San Luis Valley, Colorado, from spaceborne InSAR observations." *Water Resources Research, 52(5)* 3623-3636.

Cheng, Y., Pang, H., Li, Y., Fan, L., Wei, S., Yuan, Z., & Fang, Y. 2025. "Applications and advancements of spaceborne InSAR in landslide monitoring and susceptibility mapping: a systematic review." *Remote Sensing, 17(6)* 999.

Condon, L. E., Kollet, S., Bierkens, M. F., Fogg, G. E., Maxwell, R. M., Hill, M. C., ... & Abesser, C. 2021. "Global groundwater modeling and monitoring: Opportunities and challenges." *Water Resources Research, 57(12)* e2020WR029500.

Couwenberg, J. & Hooijer A. 2013. "Towards robust subsidence-based soil carbon emission factors for peat soils in south-east Asia, with special reference to oil palm plantations." *Mires Peat 12, 1.*

Das, P., & Hossain, F. 2025. "Multi-satellite tracking of surface water storage change in the era of Surface Water and Ocean Topography (SWOT) satellite mission." *e2024EA004178* e2024EA004178.

de Graaf, I. E., van Beek, R. L., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, E. H., & Bierkens, M. F. 2017. "A global-scale two-layer transient groundwater model: Development and application to groundwater depletion." *Advances in water Resources, 102* 53-67.

Devanthéry, N., Crosetto, M., Cuevas-González, M., Monserrat, O., Barra, A., & Crippa, B. 2016. "Deformation monitoring using persistent scatterer interferometry and Sentinel-1 SAR data." *Procedia Computer Science, 100* 1121-1126.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., ... & Scanlon, B. R. 2012. "Impact of water withdrawals from groundwater and surface water on continental water storage variations." *Journal of Geodynamics, 59* 143-156.

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, Marquéz, J. R. G. et al. 2013. "Collinearity: a review of methods to deal with it and a simulation study evaluating their performance." *Ecography, 36(1)* 27-46.

European Space Agency (2012) Sentinel-1 user handbook. ESA Standard Document, ESA/ESRIN. Available at: https://sentinel.esa.int/documents/247904/685163/Sentinel-1-User-Handbook (Accessed: September 2025).

Famiglietti, J.S. 2014. "The global groundwater crisis." *Nature Climate Change, 4(11)* 945–948.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D. 2007. "The Shuttle Radar Topography Mission." *Reviews of Geophysics, 45(2)* RG2004.

Fattahi, H., & Amelung, F. 2015. "InSAR bias and uncertainty due to the systematic and stochastic tropospheric delay." *Journal of Geophysical Research: Solid Earth, 120* 8758–8773.

Feng, X., Chen, Z., Li, G., Ju, Q., Yang, Z., & Cheng, X. 2023. "Improving the capability of D-InSAR combined with offset-tracking for monitoring glacier velocity." *Remote Sensing of Environment, 285* 113394.

Ferretti, A., Fumagalli, A., Novali, F., Prati, C., Rocca, F., & Rucci, A. 2011. "A new algorithm for processing interferometric data-stacks: SqueeSAR." *IEEE transactions on geoscience and remote sensing, 49(9)* 3460-3470.

Ferretti, A., Monti-Guarnieri, A., Prati, C., Rocca, F., & Massonnet, D. 2007. *InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation.* ESA Publication TM-19.

Ferretti, A., Prati, C., & Rocca, F. 2000. "Analysis of permanent scatterers in SAR interferometry." *IGARSS 2000. IEEE 2000 International Geoscience and Remote Sensing Symposium.* IEEE. Vol. 2, pp. 761-763.

Ferretti, A., Prati, C., & Rocca, F. 2002. Permanent scatterers in SAR interferometry. IEEE Transactions on geoscience and remote sensing, 39(1). 8-20.

Ferretti, A., Prati, C., & Rocca, F. 1999. Permanent scatterers in SAR interferometry. In. IEEE International Geoscience and Remote Sensing Symposium. IGARSS'99 (Cat. No. 99CH36293), 1999, June . IEEE. Vol. 3, pp. 1528-1530.

Fetter, C. W. 2001. *Applied Hydrogeology. 4th ed.* Upper Saddle River, NJ: Prentice Hall.

Filatov, A., & Yevtyushkin, A. 2010. "Detection of ground surface displacements in area of intensive oil and gas production by InSAR data." *Proceedings of the*

ESA Living Planet Symposium. Bergen. Norway. (2010, December). . ESA SP-686.
Fleckenstein, J. H., Krause, S., Hannah, D. M., & Boano, F. 2010. "Groundwater–surface water interactions: New methods and models to improve understanding of processes and dynamics." *Advances in Water Resources, 33(11)* 1291–1295.
Freeman, A., Zink, M., Caro, E., Moreira, A., Veilleux, L., & Werner, M. 2019. "The legacy of the SIR-C/X-SAR radar system: 25 years on." *Remote Sensing of Environment, 231* 111255.
Freeze, R. A., & Cherry J. A. 1979. *Groundwater.* Englewood Cliffs, NJ: Prentice-Hall.
Fritz, C., Campbell, D. I., & Schipper, L. A. 2008. "Oscillating peat surface levels in a restiad peatland, New Zealand - magnitude and spatiotemporal variability." *Hydrological Processes: An International Journal, 22(17)* 3264-3274.
Galloway, D. L., Jones, D. R., Ingebritsen, S. E. 1999. *Land subsidence in the United States, Circular 1182.* Ohio-Kentucky-Indiana Water Science Center, United States: U.S. Geological Survey.
Galloway, D., & Burbey, T. J. 2011. "Review: Regional land subsidence accompanying groundwater extraction." *Hydrogeology Journal, 19(8)* 1459–1486.
Gao, X., Liu, Y., Li, T., & Wu, D. 2017. "High precision DEM generation algorithm based on InSAR multi-look iteration." *Remote Sensing, 9(7)* 741.
Genereux, D. P., Nagy, L. A., Osburn, C. L., & Oberbauer, S. F. 2013. "A connection to deep groundwater alters ecosystem carbon fluxes and budgets: Example from a Costa Rican rainforest." *Geophysical Research Letters, 40(10)* 2066-2070.
Ghazaryan, G., Krupp, L., Seyfried, S., Landgraf, N., & Nendel, C. 2024. "Enhancing peatland monitoring through multisource remote sensing: optical and radar data applications." *International Journal of Remote Sensing, 45(18)* 6372-6394.
Ghorbani, Z., Khosravi, A., Maghsoudi, Y., Mojtahedi, F. F., Javadnia, E., & Nazari, A. 2022. "Use of InSAR data for measuring land subsidence induced by groundwater withdrawal and climate change in Ardabil Plain, Iran." *Scientific Reports, 12(1)* 13998.
Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. 2016. "The global volume and distribution of modern groundwater." *Nature Geoscience, 9(2)* 161-167.

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. 2012. "Water balance of global aquifers revealed by groundwater footprint." *Nature, 488* 197–200.

Gleeson, T., Wagener, T., Döll, P., Zipper, S. C., West, C., Wada, Y., ... & Bierkens, M. F. 2021. "GMD Perspective: The quest to improve the evaluation of groundwater representation in continental to global scale models." *Geoscientific Model Development, 14(12)* 7545-7571.

Griffiths, H. 1995. "Interferometric synthetic aperture radar." *Electronics and Communication Engineering Journal, 7(6)* 247.

Gupta, R., & Sharma, P. K. 2023. "A review of groundwater-surface water interaction studies in India." *Journal of Hydrology, 621* 129592.

Haghshenas Haghighi, M., & Motagh, M. 2024. "Uncovering the impacts of depleting aquifers: A remote sensing analysis of land subsidence in Iran." *Science Advances, 10(19)* eadk3039.

Harris, F. J. 2022. *Multirate signal processing for communication systems.* Boca Raton, Florida: CRC Press.

Harvey, J. W., & Gooseff, M. N. 2015. "River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins." *Water Resources Research, 51(9)* 6893–6922.

Hastie, T., Tibshirani, R., & Friedman, J. 2009. *The Elements of Statistical Learning (2nd ed.).* Springer.

He, M., Sandhu, P., Namadi, P., Reyes, E., Guivetchi, K., & Chung, F. 2025. "Protocols for water and environmental modeling using machine learning in California." *Hydrology, 12(3)* 59.

Hoffmann, J., Leake, S. A., Galloway, D. L., & Wilson, A. M. 2003. *MODFLOW-2000 Ground-Water Model: User Guide to the Subsidence and Aquifer-System Compaction(SUB) Package.* Open-file Report 03-233, Tucson, Arizona: U. S. Geological Survey.

Holden, J. 2005. "Peatland hydrology and carbon release: why small-scale process matters." *Philosophical Transactions of the Royal Society A, 363(1837)* 2891-2913.

Hong, S. H., & Wdowinski, S. 2017. "A review on monitoring the everglades wetlands in the southern florida using space-based synthetic aperture radar (sar) observations." *Korean Journal of Remote Sensing, 33(4)* 377-390.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A., & Anshari, G. 2012. "Subsidence and carbon loss in drained tropical peatlands." *Biogeosciences, 9(3)* 1053-1071.

Hooper, A. 2008. "A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches." *Geophysical Research Letters,* 35, L16302.

Hooper, A., Bekaert, D., Spaans, K., & Arıkan, M. 2012. "Recent advances in SAR interferometry time series analysis for measuring crustal deformation." *Tectonophysics, 514* 1-13.

Hooper, A., Wright, T. J., Weiss, J. R., Rollins, C., Gaddes, M., Lazecky, M., ... & Hussain, E. 2020. "Exploiting InSAR on a large scale for tectonics and volcano monitoring." *IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium. IEEE. (2020, September).* 6857-6858.

Hooper, A., Zebker, H., Segall, P., & Kampes, B. 2004. "A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers." *Geophysical research letters, 31,* L23611.

Hoyt, A. M., Chaussard, E., Seppalainen, S. S., & Harvey, C. F. 2020. "Widespread subsidence and carbon emissions across Southeast Asian peatlands." *Nature Geoscience, 13(6)* 435-440.

Hrysiewicz, A., Williamson, J., Evans, C. D., Jovani-Sancho, A. J., Callaghan, N., Lyons, J., ... & Holohan, E. P. 2024. "Estimation and validation of InSAR-derived surface displacements at temperate raised peatlands." *Remote Sensing of Environment, 311* 114232.

Hu, C., Li, Y., Chen, Z., Liu, F., Zhang, Q., Monti-Guarnieri, A. V., Hobbs, S., Anghel. A., & Datcu, M. 2025. "Distributed Spaceborne SAR: A review of systems, applications, and the road ahead." *IEEE Geoscience and Remote Sensing Magazine* 329-361.

Hu, J., Li, Z. W., Ding, X. L., Zhu, J. J., Zhang, L., & Sun, Q. 2014. "Resolving three-dimensional surface displacements from InSAR measurements: A review." *Earth-Science Reviews* 133, 1-17.

Hughes, J. D., Leake, S. A., Galloway, D. L., & White, J. T. 2022. "Documentation for the Skeletal Storage, Compaction, and Subsidence (CSUB) Package of MODFLOW 6 (No. 6-A62). US Geological Survey." In *Book 6, Modeling Techniques, Section A, Groundwater* . Reston, Virginia: U.S. Geological Survey.

Ibrahim, A., Wayayok, A., Shafri, H. Z. M., & Toridi, N. M. 2024. "Remote sensing technologies for modelling groundwater storage dynamics: Comprehensive review." *Journal of Hydrology X* 100175.

Ibrahim, H. B., Salah, M., Zarzoura, F., & El-Mewafi, M. 2024. "Persistent scatterer interferometry (PSI) technique for road infrastructure monitoring: a case study of the roadway network of the Nile Delta (Egypt)." *Innovative Infrastructure Solutions, 9(4)* 119.

Inc., Rocscience. 2025. *Settle3: Settlement and consolidation analysis — Theory manual.* Rocscience Inc.

Izady, A. 2014. *Application and assessment of a developed coupled-groundwater-surface water model in the Neishaboor watershed, Iran (Doctoral* *dissertation, PhD Dissertation.* Mashhad, Iran: Water Engineering Department, Agriculture Faculty, Ferdowsi University of Mashhad.

Izady, A., Davary, K., Alizadeh, A., Ziaei, A. N., Akhavan, S., Alipoor, A., Joodavi, A., & Brusseau, M. L. 2015. "Groundwater conceptualization and modeling using distributed SWAT-based recharge for the semi-arid agricultural Neishaboor plain, Iran." *Hydrogeology Journal, 23(1)* 47-68.

Jaramillo, F., Aminjafari, S., Castellazzi, P., Fleischmann, A., Fluet-Chouinard, E., Hashemi, H., Hubinger, C., Martens, H.R., Papa, F., Schöne, T. and Tarpanelli, A. 2024. "The potential of hydrogeodesy to address water-related and sustainability challenges." *Water Resources Research, 60(11)* e2023WR037020.

Jiang, L., Bai, L., Zhao, Y., Cao, G., Wang, H., & Sun, Q. 2018. "Combining InSAR and hydraulic head measurements to estimate aquifer parameters and storage variations of confined aquifer system in Cangzhou, North China Plain." *Water resources research, 54(10)* 8234-8252.

Kalbus, E., Reinstorf, F., & Schirmer, M. 2006. "Measuring methods for groundwater–surface water interactions: A review." *Hydrology and Earth System Sciences, 10(6)* 873–887.

Kampes, B. M., Hanssen, R. F., & Perski, Z. 2004. "Radar interferometry with public domain tools." *FRINGE 2003 workshop (Vol. 550, p. 10) (2004, June).*

Keery, J., Binley, A., Crook, N., & Smith, J. W. 2007. "Temporal and spatial variability of groundwater–surface water fluxes: Development and application of an analytical method using temperature time series." *Journal of Hydrology, 336(1-2)* 1-16.

Keydel, W. 2007. "Normal and differential SAR interferometry." *Radar Polarimetry and Interferometry* 3-1-3–36.

Khodaei, B., Hashemi, H., Kompanizare, M., Naghibi, A., & Berndtsson, R. 2025. "An integrated InSAR-numerical approach for accurate groundwater head prediction." *Journal of Hydrology* 134023.

Khodaei, B., Hashemi, H., Salimi, S., & Berndtsson, R. 2023. "Substantial carbon sequestration by peatlands in temperate areas revealed by InSAR." *Environmental Research Letters, 18(4)* 044012.

Kondoh, A., Nishiyama, J., & Higashi, O. 2004. "Influence of urbanization on water and heat balance in the Tokyo metropolitan area: Analysis of water cycle using an integrated model." *Hydrological Processes, 18(10)* 2067–2083.

Kroupnik, G., Lisle, D. D., Côté, S., Lapointe, M., Casgrain, C., & Fortier, R. 2021. "RADARSAT constellation mission overview and status." *in Proc. IEEE Radar Conf. (RadarConf21).* pp. 1-5.

Kumar, C., Walton, G., Santi, P., & Luza, C. 2025. "Random Cross-Validation Produces Biased Assessment of Machine Learning Performance in Regional Landslide Susceptibility Prediction. ." *Remote Sensing, 17(2)* 213.

Lambert, C., Larocque, M., Gagné, S., & Garneau, M. 2022. " Aquifer-peatland hydrological connectivity and controlling factors in boreal peatlands." *Frontiers in Earth Science, 10* 835817.

Lauknes, T. R., Zebker, H. A., & Larsen, Y. 2010. "InSAR deformation time series using an L1-norm small-baseline approach." *IEEE Transactions on Geoscience and Remote Sensing, 49(1)* 536-546.

Lee, H., Yuan, T., Yu, H., & Jung, H. C. 2020. "Interferometric SAR for Wetland Hydrology: An Overview of Methods, Challenges, and Trends." *IEEE Geoscience and Remote Sensing Magazine, 8(1)* 120-135.

Leifeld, J., & Menichetti, L. 2018. "The underappreciated potential of peatlands in global climate change mitigation strategies." *Nature communications, 9(1)* 1-7.

Li, Y., Li, M., Li, C., & Liu, Z. 2020. "Optimized maxent model predictions of climate change impacts on the suitable distribution of cunninghamia lanceolata in China." *Forests, 11(3)* 302.

Li, Z., Cao, Y., Wei, J., Duan, M., Wu, L., Hou, J., & Zhu, J. 2019. "Time-series InSAR ground deformation monitoring: Atmospheric delay modeling and estimating." *Earth-Science Reviews, 192* 258-284.

Li, Z., Fielding, E. J., & Cross, P. 2009. "Integration of InSAR time-series analysis and water-vapor correction for mapping postseismic motion after the 2003 Bam (Iran) earthquake." *IEEE Transactions on Geoscience and Remote Sensing, 47(9)* 3220–3230.

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., ... & Schaepman-Strub, G. 2008. "Peatlands and the carbon cycle: from local processes to global implications—a synthesis." *Biogeosciences, 5(5)* 1475-1491.

Liu, D., Wang, X., Aminjafari, S., Yang, W., Cui, B., Yan, S., ... & Jaramillo, F. 2020. "Using InSAR to identify hydrological connectivity and barriers in a highly fragmented wetland." *Hydrological Processes, 34(23)* 4417-4430.

Liu, H., & Lennartz, B. 2019. "Hydraulic properties of peat soils along a bulk density gradient—A meta study." *Hydrological Processes, 33(1)* 101-114.

Loffeld, O., Nies, H., Knedlik, S., & Yu, W. 2007. "Phase unwrapping for SAR interferometry—A data fusion approach by Kalman filtering." *IEEE Transactions on Geoscience and Remote Sensing, 46(1)* 47-58.

Long, D., Longuevergne, L., & Scanlon, B. R. 2015. "Global analysis of approaches for deriving total water storage changes from GRACE satellites." *Water Resources Research, 51(4)* 2574-2594.

LUNARC. (n.d.). LUNARC documentation. Lund University. Retrieved June 30, 2025, from https://lunarc-documentation.readthedocs.io.

Luo, S., Feng, G., Xiong, Z., Wang, H., Zhao, Y., Li, K., ... & Wang, Y. 2021. "An improved method for automatic identification and assessment of potential geohazards based on MT-InSAR measurements." *Remote Sensing, 13(17)* 3490.

Ma, Z., Liu, J., Aoki, Y., Wei, S., Liu, X., Cui, Y., Hu, J., Zhou, C., Qin., S., Huang, T., & Li, Z. 2022. "Towards big SAR data era: An efficient Sentinel-1 Near-Real-Time InSAR processing workflow with an emphasis on co-registration and phase unwrapping." *Isprs journal of photogrammetry and remote sensing, 188* 286-300.

Ma, Z., Wang, W., Zhang, Z., Ji, D., Wang, J., Zhao, M., Wang, Y., Wang, F., & Zhang, J. 2024. "River–groundwater interactions in the arid and semiarid areas of northwestern China." *Hydrogeology Journal, 32(1)* 37-57.

Manavalan, R. 2018. "Review of synthetic aperture radar frequency, polarization, and incidence angle in flood area mapping." *Journal of Applied Remote Sensing, 12(2)* 021501.

Marchionni, V., Daly, E., Manoli, G., Tapper, N. J., Walker, J. P., & Fatichi, S. 2020. "Groundwater buffers drought effects and climate variability in urban reserves." *Water Resources Research, 56(5)* e2019WR026192.

Massonnet, D. 1997. "Producing ground deformation maps automatically: The DIAPASON concept." *IGARSS'97. 1997 IEEE International Geoscience and Remote Sensing Symposium Proceedings. Remote Sensing-A Scientific Vision for Sustainable Development (Vol. 3, pp. 1338-1340). IEEE, (1997, August).*

Massonnet, D., & Feigl, K. L. 1998. "Radar interferometry and its application to changes in the Earth's surface." *Reviews of Geophysics, 36(4)* 441–500.

Mateus, P., Miranda, P. M. A., Nico, G., & Catalao, J. 2021. "Continuous multitrack assimilation of Sentinel-1 precipitable water vapor maps for numerical weather prediction: How far can we go with current InSAR data?" *Journal of Geophysical Research: Atmospheres, 126(3)* e2020JD034171.

Maxwell, R. M., Condon, L. E., & Kollet, S. J. 2015. "A high-resolution simulation of groundwater and surface water over most of the continental US with the integrated hydrologic model ParFlow v3." *Geoscientific model development, 8(3)* 923-937.

Miller, M. M., & Shirzaei, M. 2015. "Spatiotemporal characterization of land subsidence and uplift in Phoenix using InSAR time series and wavelet transforms." *Journal of Geophysical Research: Solid Earth, 120(8)* 5822-5842.

Miller, M. M., Shirzaei, M., & Argus, D. 2017. "Aquifer mechanical properties and decelerated compaction in Tucson, Arizona." *Journal of Geophysical Research: Solid Earth, 122(10)* 8402-8416.

Minasny, B., Adetsu, D. V., Aitkenhead, M., Artz, R. R., Baggaley, N., Barthelmes, A., ... & Zak, D. 2024. "Mapping and monitoring peatland conditions from global to field scale." *Biogeochemistry, 167(4)* 383-425.

Miranda, P. M., Mateus, P., Nico, G., Catalão, J., Tomé, R., & Nogueira, M. 2019. "InSAR meteorology: High-resolution geodetic data can increase atmospheric predictability." *Geophysical Research Letters, 46(5)* 2949-2955.

Mohammadimanesh, F., Salehi, B., Mahdianpari, M., Brisco, B., & Motagh, M. 2018. "Wetland water level monitoring using interferometric synthetic aperture radar (InSAR): A review." *Canadian Journal of Remote Sensing, 44(4)* 247-262.

Monteverde, S., Healy, M. G., O'Leary, D., Daly, E., & Callery, O. 2022. "Management and rehabilitation of peatlands: The role of water chemistry, hydrology, policy, and emerging monitoring methods to ensure informed decision making." *Ecological Informatics, 69* 101638.

Morakaladi, M. I. C., & Atangana, A. 2023. "Mathematical model for conversion of groundwater flow from confined to unconfined aquifers with power law processes." *Open Geosciences, 15(1)* 20220446.

Morishita, Y., Lazecky, M., Wright, T. J., Weiss, J. R., Elliott, J. R., & Hooper, A. 2020. "LiCSBAS: An open-source InSAR time series analysis package integrated with the LiCSAR automated Sentinel-1 InSAR processor." *Remote Sensing, 12(3)* 424.

Morris, P. J., Davies, M. L., Baird, A. J., Balliston, N., et al. 2022. "Saturated hydraulic conductivity in northern peats inferred from other measurements." *Water Resources Research, 58(11)* e2022WR033181.

Motagh, M., Shamshiri, R., Haghighi, M. H., Wetzel, H. U., Akbari, B., Nahavandchi, H., ... & Arabi, S. 2017. "Quantifying groundwater exploitation induced subsidence in the Rafsanjan plain, southeastern Iran, using InSAR time-series and in situ measurements." *Engineering geology, 218* 134-151.

Mozafari, B., Bruen, M., Donohue, S., Renou-Wilson, F., & O'Loughlin, F. 2023. "Peatland dynamics: A review of process-based models and approaches." *Science of the Total Environment, 877* 162890.

Naghibi, S. A., Khodaei, B., & Hashemi, H. 2022. "An integrated InSAR-machine learning approach for ground deformation rate modeling in arid areas." *Journal of Hydrology, 608* 127627.

Nameghi, H., Hosseini, S. M., & Sharifi, M. B. 2013. "An analytical procedure for estimating land subsidence parameters using field data and InSAR images in Neyshabur plain." *Scientific Quarterly Journal of Iranian Association of Engineering Geology, 6(1 & 2)* 33-50.

Natijne, A. L. v., Bogaard, T. A., van Leijen, F. J., Hanssen, R. F., & Lindenbergh, R. C. 2022. "World-wide InSAR sensitivity index for landslide deformation tracking." *International Journal of Applied Earth Observation and Geoinformation, 111* 102829.

Nazarieh, F., Ansari, H., Ziaei, A. N., Izady, A., Davari, K., & Brunner, P. 2018. "Spatial and temporal dynamics of deep percolation, lag time and recharge in an irrigated semi-arid region." *Hydrogeology Journal, 26(7)* 2507-2520.

Neely, W. R., Borsa, A. A., Burney, J. A., Levy, M. C., Silverii, F., & Sneed, M. 2021. "Characterization of groundwater recharge and flow in California's San Joaquin Valley from InSAR-observed surface deformation." *Water Resources Research, 57(9)* e2020WR028451.

Ni, L., Wang, D., Wu, J., Wang, Y., Tao, Y., Zhang, J., & Liu, J. 2020. "Streamflow forecasting using extreme gradient boosting model coupled with Gaussian mixture model." *Journal of Hydrology, 586* 124901.

Niazkar, M., Menapace, A., Brentan, B., Piraei, R., Jimenez, D., Dhawan, P., & Righetti, M. 2024. "Applications of XGBoost in water resources engineering: A systematic literature review (Dec 2018–May 2023)." *Environmental Modelling & Software, 174* 105971.

Nordbeck, R., & Hogl, K. 2024. "National peatland strategies in Europe: current status, key themes, and challenges." *Regional Environmental Change, 24(1)* 5.

O'brien, R. M. 2007. "A caution regarding rules of thumb for variance inflation factors." *Quality & quantity, 41(5)* 673-690.

Osman, A. I. A., Ahmed, A. N., Chow, M. F., Huang, Y. F., & El-Shafie, A. 2021. "Extreme gradient boosting (Xgboost) model to predict the groundwater levels in Selangor Malaysia." *Ain Shams Engineering Journal, 12(2)* 1545-1556.

Osman, A. I. A., Ahmed, A. N., Huang, Y. F., Kumar, P., Birima, A. H., Sherif, M., ... & El-Shafie, A. 2022. "Past, present and perspective methodology for groundwater modeling-based machine learning approaches." *Archives of Computational Methods in Engineering, 29(6)* 3843-3859.

Osmanoğlu, B., Sunar, F., Wdowinski, S., & Cabral-Cano, E. 2016. "Time series analysis of InSAR data: Methods and trends." *ISPRS Journal of Photogrammetry and Remote Sensing, 115* 90-102.

Papa, F., & Frappart, F. 2021. "Surface water storage in rivers and wetlands derived from satellite observations: a review of current advances and future opportunities for hydrological sciences." *Remote Sensing, 13(20)* 4162.

Perissin, D., Wang, Z., & Wang, T. 2011. "The SARPROZ InSAR tool for urban subsidence/manmade structure stability monitoring in China." *Proceedings of the ISRSE.* Sidney, Australia, 1015.

Piter, A., Haghshenas Haghighi, M., & Motagh, M. 2024. "Challenges and Opportunities of Sentinel-1 InSAR for Transport Infrastructure Monitoring." *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 92(5)* 609-627.

Potvin, L. R., Kane, E. S., Chimner, R. A., Kolka, R. K., & Lilleskov, E. A. 2015. "Effects of water table position and plant functional group on plant community, aboveground production, and peat properties in a peatland mesocosm experiment (PEATcosm)." *Plant and soil, 387(1)* 277-294.

Price, J. S. 2003. "Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands." *Water Resources Research, 39(9).*

Price, J. S., & Schlotzhauer, S. M. 1999. "Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland." *Hydrological Processes, 13(16)* 2591–2601.

Raucoules, D., Colesanti, C., & Carnec, C. 2007. "Use of SAR interferometry for detecting and assessing ground subsidence." *Comptes Rendus Geoscience, 339(5)* 289–302.

Rodell, M., Velicogna, I., & Famiglietti, J. S. 2009. "Satellite-based estimates of groundwater depletion in India." *Nature, 460(7258)* 999-1002.

Rosen, P. A., Gurrola, E., Sacco, G. F., & Zebker, H. 2012. "The InSAR scientific computing environment." *EUSAR 2012; 9th European conference on synthetic aperture radar (pp. 730-733). VDE, (2012, April).*

Rossetto, R., Barbagli, A., De Filippis, G., Marchina, C., Vienken, T., & Mazzanti, G. 2020. "Importance of the induced recharge term in riverbank filtration: Hydrodynamics, hydrochemical, and numerical modelling investigations." *Hydrology, 7(4)* 96.

Sahraoui, O. H., Hassaine, B., Serief, C., & Hasni, K. October 8–13, 2006. "Radar Interferometry with SARscape Software." *Presented at the XXIII FIG Congress – Photogrammetry and Remote Sensing.* Munich, Germany.

Sánchez-Gámez, P., & Navarro, F. J. 2017. "Glacier surface velocity retrieval using D-InSAR and offset tracking techniques applied to ascending and descending passes of Sentinel-1 data for southern Ellesmere ice caps, Canadian Arctic." *Remote Sensing, 9(5)* 442.

Sandwell, D., Mellors, R., Tong, X., Wei, M., & Wessel, P. 2011. "Open radar interferometry software for mapping surface deformation." *Eos Trans. AGU* 92(28).

Sandwell, D. T., & Price, E. J. 1998. "Phase gradient approach to stacking interferograms." *Journal of Geophysical Research: Solid Earth, 103(B12)* 30183-30204.

Sandwell, D., Mellors, R., Xiaopeng, T., Xiaohua, X., Wei, M., & Wessel, P. 2016. "*GMTSAR: An InSAR processing system based on Generic Mapping Tools* (2nd ed.)." UC San Diego, Scripps Institution of Oceanography.

Sanford, W. 2002. "Recharge and groundwater models: an overview." *Hydrogeology journal, 10* 110-120.

Schmidt, D. A., & Bürgmann, R. 2003. "Time-dependent land uplift and subsidence in the Santa Clara valley, California, from a large interferometric synthetic aperture radar data set." *Journal of Geophysical Research: Solid Earth* 108(B9).

Shahnazi, S., Roushangar, K., Khodaei, B., & Hashemi, H. 2025. "Insights into the Interconnected Dynamics of Groundwater Drought and InSAR-Derived Subsidence in the Marand Plain, Northwestern Iran." *Remote Sensing, 17(7)* 1173.

Shanker, P., Casu, F., Zebker, H. A., & Lanari, R. 2011. "Comparison of persistent scatterers and small baseline time-series InSAR results: A case study of the San Francisco bay area." *IEEE Geoscience and Remote Sensing Letters, 8(4)* 592-596.

Sharifi, A., Khodaei, B., Ahrari, A., Hashemi, H., & Haghighi, A. T. 2024. "Can river flow prevent land subsidence in urban areas?" *Science of the Total Environment, 917* 170557.

Singh, A. 2014. "Groundwater resources management through the applications of simulation modeling: A review." *Science of the Total Environment, 499* 414-423.

Smith, L. C. 2002. "Emerging applications of interferometric synthetic aperture radar (InSAR) in geomorphology and hydrology." *Annals of the Association of American Geographers, 92(3)* 385-398.

Smith, R. G., Hashemi, H., Chen, J., & Knight, R. 2021. "Apportioning deformation among depth intervals in an aquifer system using InSAR and head data." *Hydrogeology Journal, 29(7)* 2475-2486.

Smith, R., & Li, J. 2021. "Modeling elastic and inelastic pumping-induced deformation with incomplete water level records in Parowan Valley, Utah." *Journal of Hydrology, 601* 126654.

Sneed, M., Ikehara, M. E., Stork, S. V., Amelung, F., & Galloway, D. L. 2003. "Detection and measurement of land subsidence using interferometric synthetic aperture radar and global positioning system, San Bernardino County, Mojave Desert, California." *Water-Resources Investigations Report, 3* 4015.

Sophocleous, M. 2002. "Interactions between groundwater and surface water: The state of the science." *Hydrogeology Journal, 10(1)* 52–67.

Spaans, K., & Hooper, A. 2016. "InSAR processing for volcano monitoring and other near-real time applications." *Journal of Geophysical Research: Solid Earth, 121(4)* 2947-2960.

Springer, A., Lopez, T., Owor, M., Frappart, F., & Stieglitz, T. 2023. "The role of space-based observations for groundwater resource monitoring over Africa." *Surveys in Geophysics, 44(1)* 123-172.

Stachowicz, M., Manton, M., Abramchuk, M., Banaszuk, P., Jarašius, L., Kamocki, A., ... & Grygoruk, M. 2022. "To store or to drain—To lose or to gain? Rewetting drained peatlands as a measure for increasing water storage in the transboundary Neman River Basin." *Science of the Total Environment, 829* 154560.

Sutanto, S. J., Wetterhall, F., & Van Lanen, H. A. 2020. "Hydrological drought forecasts outperform meteorological drought forecasts." *Environmental Research Letters, 15(8)* 084010.

Tao, R., Lau, A., Mossefin, M. E., Kong, G., Nordal, S., & Pan, Y. 2025. "Monitoring of ground displacement-induced railway anomalies using PS-InSAR techniques." *Measurement* 116863.

Teatini, P., Da Lio, C., Zoccarato, C., & Tosi, L. 2024. "Natural Compaction of Sediments. In Remote Sensing for Characterization of Geohazards and Natural Resources." *Remote Sensing for Characterization of Geohazards and Natural Resources.* Cham: Springer International Publishing. pp. 389-403.

Terzaghi, K. 1943. *Theoretical Soil Mechanics.* New York: Wiley.

Timár, G., Jakab, G., & Székely, B. 2024. "A Step from Vulnerability to Resilience: Restoring the Landscape Water-Storage Capacity of the Great Hungarian Plain—An Assessment and a Proposal." *Land, 13(2)* 146.

Tsang, L., Liao, T.-H., Gao, R., Xu, H., Gu, W., & Zhu, J. 2022. "Theory of Microwave Remote Sensing of Vegetation Effects, SoOp and Rough Soil Surface Backscattering." *Remote Sensing, 14(15)* 3640.

Udugbezi, E. 2018. "Evaluating interferometric synthetic aperture radar coherence for coastal geomorphological changes." (Doctoral dissertation). University of Dundee. Retrieved from https://discovery.dundee.ac.uk/ws/portalfiles/portal/26963413/Udugbezi_thesis.pdf (Accessed: September 2025)

U.S. Army Corps of Engineers. 1990. *Engineering and design: Settlement analysis* (EM 1110-1-1904). Washington, DC: USACE.

Verma, S., Kumar, S., Mishra, V. N., & Raj, R. 2022. "Multifrequency spaceborne synthetic aperture radar data for backscatter-based characterization of land use and land cover." *Frontiers in Earth Science, 10* 825255.

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. 2015. "Hydrological feedbacks in northern peatlands." *Ecohydrology, 8(1)* 113-127.

Wang, X., Liu, L., Shi, X., Huang, X., & Geng, W. 2018. "A high precision DEM extraction method based on InSAR data." *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 4,* 211-216.

Werner, C., Wegmüller, U., Strozzi, T., & Wiesmann, A. 2000. "Gamma SAR and interferometric processing software." *Proceedings of the ers-envisat symposium, Gothenburg, Sweden (Vol. 1620, p. 1620), (2000, October).*

Weston, J., Ferreira, A. M., & Funning, G. J. 2012. "Systematic comparisons of earthquake source models determined using InSAR and seismic data." *Tectonophysics, 532* 61-81.

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. 1998. *Ground Water and Surface Water: A Single Resource.* U.S. Geological Survey Circular 1139.

Wisely, B. A., & Schmidt, D. 2010. "Deciphering vertical deformation and poroelastic parameters in a tectonically active fault-bound aquifer using InSAR and well level data, San Bernardino basin, California." *Geophysical Journal International, 181(3)* 1185-1200.

Wörman, A., Packman, A. I., Marklund, L., Harvey, J. W., & Stone, S. H. 2007. "Fractal topography and subsurface water flows from fluvial bedforms to the continental shield." *Geophysical Research Letters, 34(7).*

Wu, J., & Zeng, X. 2013. "Review of the uncertainty analysis of groundwater numerical simulation." *Chinese Science Bulletin, 58* 3044-3052.

Xu, G., Gao, Y., Li, J., & Xing, M. 2020. "InSAR phase denoising: A review of current technologies and future directions." *IEEE Geoscience and Remote Sensing Magazine, 8(2)* 64-82.

Xu, X., Wang, G., & Chen, Q. 2020. "Advanced InSAR time-series techniques and applications over urban areas." *ISPRS Journal of Photogrammetry and Remote Sensing, 160* 110–124.

Yang, Z., Li, Z., Zhu, J., Wang, Y., & Wu, L. 2020. "Use of SAR/InSAR in mining deformation monitoring, parameter inversion, and forward predictions: A review." *IEEE Geoscience and Remote Sensing Magazine, 8(1)* 71-90.

Yu, H., Xing, M., & Yuan, Z. 2020. "Baseline design for multibaseline InSAR system: A review." *IEEE Journal on Miniaturization for Air and Space Systems, 2(1)* 17-24.

Yunjun, Z., Fattahi, H., & Amelung, F. 2019. "Small baseline InSAR time series analysis: Unwrapping error correction and noise reduction." *Computers & Geosciences, 133* 104331.

Zebker, H. A., Farr, T. G., Salazar, R. P., & Dixon, T. H. Dec. 1994. "Mapping the world's topography using radar interferometry: The TOPSAT mission." *Proc. IEEE, vol. 82, no. 12.* 1774–1786.

Zhang, G., Xu, W., Huang, P., Tan, W., Qi, Y., & Zhang, Z. 2021. "Land Subsidence Monitoring in Wuhai City Based on D-InSAR." *IEEE Photonics & Electromagnetics Research Symposium (PIERS), 2021, November.* pp. 1961-1966.

Zhang, X., Feng, M., Zhang, H., Wang, C., Tang, Y., Xu, J., ... & Wang, C. 2021. "Detecting rock glacier displacement in the central Himalayas using multi-temporal InSAR." *Remote Sensing, 13(23)* 4738.

Zhang, Z., Lin, H., Wang, M., Liu, X., Chen, Q., Wang, C., & Zhang, H. 2022. "A review of satellite synthetic aperture radar interferometry applications in permafrost regions: Current status, challenges, and trends." *IEEE Geoscience and Remote Sensing Magazine, 10(3)* 93-114.

Zhao, Q., Pepe, A., Devlin, A., Zhang, S., Falabella, F., Zeni, G., ... & Pan, J. 2021. "Impact of sea-level-rise and human activities in coastal regions: an overview." *Journal of Geodesy and Geoinformation Science, 4(1)* 124.

Zhou, X., Chang, N., & Li, S. 2009. "Applications of SAR Interferometry in earth and environmental science research." *Sensors, 9(3)* 1876–1912.

Zhou, Z., Li, Z., Waldron, S., & Tanaka, A. 2019. "InSAR Time Series Analysis of L-Band Data for Understanding Tropical Peatland Degradation and Restoration." *Remote Sensing, 11(21)* 2592.

Zou, W., Li, Y., Li, Z., & Ding, X. 2009. "Improvement of the accuracy of InSAR image co-registration based on tie points–a review." *Sensors, 9(2)* 1259-1281.

This thesis is rooted in the author's childhood and shaped by a family whose lives were closely connected with nature. What began as a simple fascination gradually grew into a deep commitment to understanding and protecting the natural environment, with a particular focus on water as one of its most vital resources, ultimately finding expression in the research presented here.

LUND UNIVERSITY

Lund University
Faculty of Engineering
Report: TVVR-1104
ISBN: 978-91-8104-693-9 (print)
ISBN:978-91-8104-694-6 (electronic)
ISSN: 1101-9824