Dynamics of Ground Subsidence in Beijing Plain Over Last Two Decades and Its Linkage With Government's Mitigation Policy

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Key words: Ground subsidence, InSAR, Beijing plain, subsidence mitigation

Abstract

As a typical water-scarce megacity, Beijing has long been plagued by ground subsidence—a slow-onset geological hazard primarily driven by excessive groundwater extraction. To address the research gap of insufficient systematic analysis on long-term subsidence dynamics (2003–2024) and its synergy with mitigation policies, this study employs multi-sensor SAR data (Envisat ASAR, Radarsat-2, and Sentinel-1) and the Multiple-master Coherent Target Small-Baseline InSAR (MCTSB-InSAR) technique to derive subsidence velocities across 11 time periods. The results show that Beijing Plain's subsidence evolution can be divided into two distinct phases: an expansion phase (2003–2017) with the most severe condition in 2017 (426.68 km² of severe subsidence area) and a steady, substantial mitigation phase (2017–2024), where severe subsidence area shrank to merely 0.66 km² by 2024. Synergistic policies—including the stable water supply from the South-to-North Water Diversion Project (SNWDP) since 2014, strict groundwater extraction control, increased reclaimed water utilization, and the 2017 revision of Beijing's Urban Master Plan—have collectively reduced groundwater reliance and constrained high-intensity development in high-risk areas, playing a decisive role in subsidence mitigation. This study provides a valuable reference for integrating geological hazard data into spatial planning and formulating subsidence control strategies in water-scarce cities globally.

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Introduction

As China's capital, Beijing faces persistent challenges from ground subsidence—a slow-onset geological hazard primarily induced by human activities. Since the late 20th century, insufficient precipitation in the Beijing Plain has forced long-term reliance on groundwater for urban, industrial, and agricultural use, and excessive extraction has triggered widespread subsidence (He et al., 2006). This hazard damages critical infrastructure (e.g., buildings, pipelines, and transportation networks), exacerbates flood risks, and threatens ecological security, thereby hindering the city's sustainable development.

Numerous studies have focused on mapping ground subsidence in the Beijing Plain using interferometric SAR (InSAR) technology, such as Zhu et al. (2015), Zhang et al. (2016), Bai et al. (2022), and Dong et al. (2023). Additional research has investigated the relationship between subsidence and groundwater aquifers (Chen et al., 2020; Zhou et al., 2024), driving factors of subsidence (Li & Ge, 2021; Zhou et al., 2019), subsidence patterns (Lai et al., 2024), and the impact of the South-to-North Water Diversion Project (SNWDP) (Du et al., 2021). However, systematic analysis of two-decade subsidence dynamics (2003–2024) and its direct linkage to policy synergy remains underexplored. Most existing studies have generated subsidence velocity results for multi-year periods, which obscure the temporal dynamic variations of subsidence.

This study aims to: (1) Characterize the 2003–2024 subsidence dynamics in the Beijing Plain using InSAR data from Envisat ASAR (2003–2010), Radarsat-2 (2012–2016), and Sentinel-1 (2017–2024); (2) Identify key drivers of subsidence change, focusing on groundwater extraction, rainfall, and the SNWDP; (3) Analyze the 2004–2017 urban plan revision and its role in subsidence mitigation; (4) Provide a policy-relevant case for integrating hazard data into spatial planning, offering insights for similar water-scarce cities.

Study Area and Data Sources

2.1 Study Area

Beijing is a typical water-scarce megacity located in the transition zone between the mountainous areas of North China and the North China Plain (Fig. 1). Its surface water resources are limited and unevenly distributed across seasons, forcing the city to rely heavily on groundwater for domestic, industrial, and agricultural needs. The Beijing Plain is covered by thick Quaternary unconsolidated sediments (200–800 m thick), mainly consisting of alternating layers of sand, silt, and clay. These loose deposits exhibit high porosity and compressibility; in particular, the middle and deep confined aquifers are overlain by thick clay layers with low permeability. When groundwater is excessively pumped, the hydraulic pressure in the aquifers decreases, leading to the compression of pore spaces in the aquifers and the consolidation of overlying clay layers—this constitutes the core geological mechanism of ground subsidence in the region (He et al., 2006).

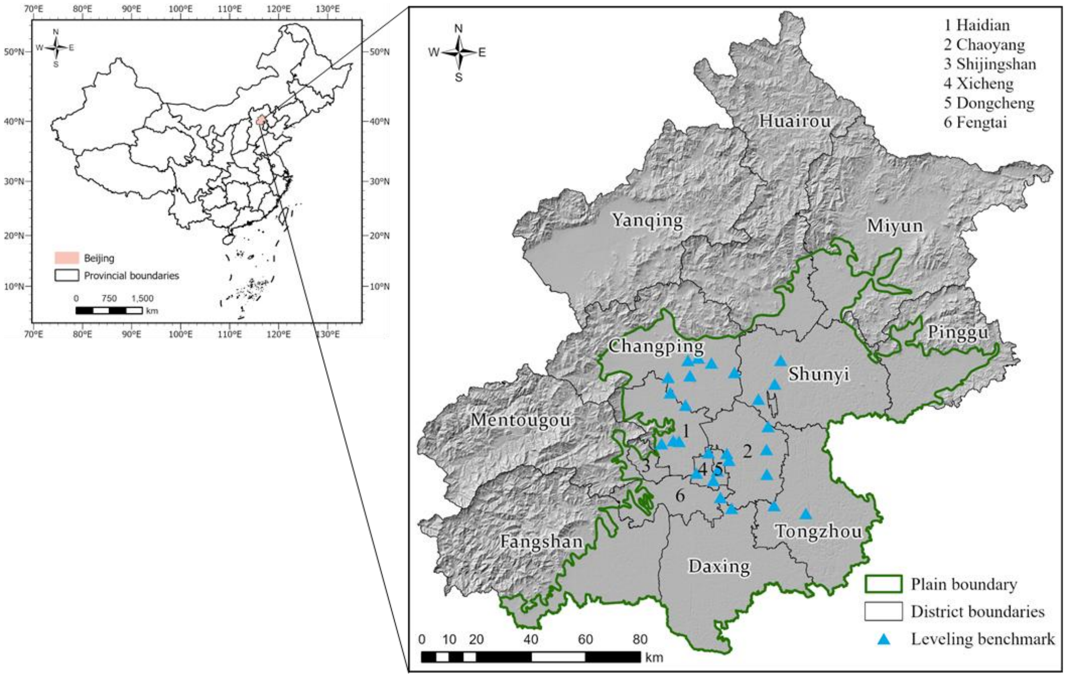

Fig.1. The study area.

2.2 Data Sources

Multi-sensor SAR images, including Envisat ASAR (2003–2010), Radarsat-2 (2012–2016), and Sentinel-1 (2017–2024), were employed to derive long-term subsidence information. The Multiple-master Coherent Target Small-Baseline InSAR (MCTSB-InSAR) technique (Zhang et al., 2016) was used to conduct time-series InSAR analysis. Subsidence velocities were generated for three multi-year epochs (2003–2010, 2012–2014, and 2014–2016) and for each single year from 2017 to 2024 using Sentinel-1 images. Annual or biennial monitoring more clearly reflects the temporal dynamic characteristics of ground subsidence, which is a key distinction between the present study and previous research on Beijing's subsidence.

In addition to SAR data, information on the annual volume of groundwater extraction, water supplied by the SNWDP, surface water supply, and reclaimed water utilization was obtained from the Beijing Water Resources Bulletin. The *Beijing Urban Master Plan (2004–2020)* and *Beijing Urban Master Plan (2016–2035)* were acquired from the Beijing Municipal Commission of Planning and Natural Resources. A total of 27 leveling measurements provided by Beijing's surveying authority were used to validate the InSAR-derived subsidence velocities, with an accuracy ranging from 4.2 mm/year to 5.6 mm/year.

Spatiotemporal Dynamics of landGround Subsidence (2003–2024)

Eleven subsidence velocity results were generated for the 2003–2024 period (Fig. 2). The accuracy of InSAR derived subsidence velocity validated by the 27 leveling measurements is in the range of 4.2 mm/year to 5.6 mm/year.

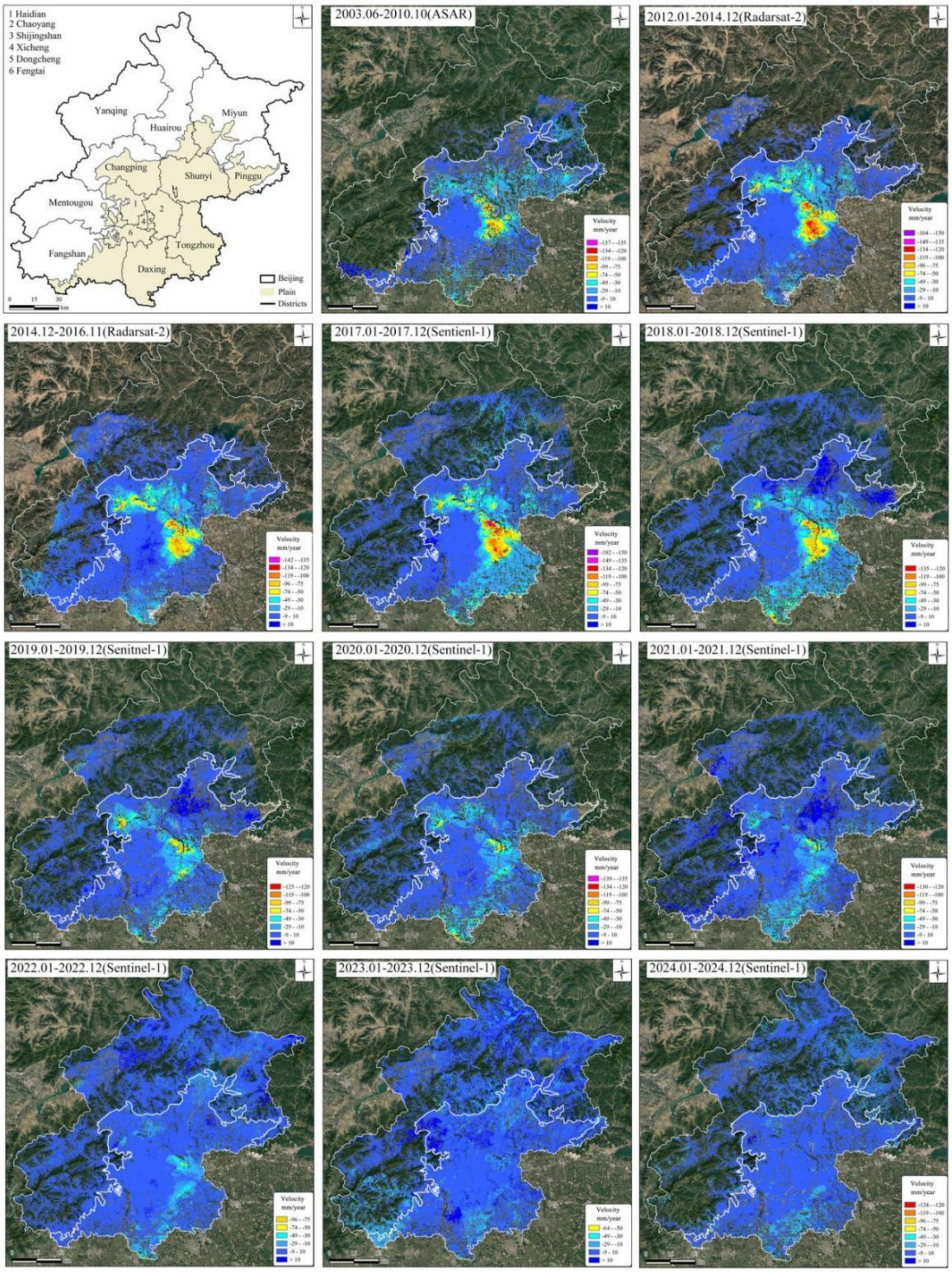

Fig. 2. Subsidence velocities of the Beijing Plain across 11 time intervals (2003–2024). Negative values indicate ground subsidence, and positive values indicate ground uplift.

Ground subsidence was classified into four categories based on velocity to describe risk levels: severe (>50 mm/year), moderately severe (30–50 mm/year), moderate (10–30 mm/year), and slight/stable (<10 mm/year). To quantitatively assess the evolution of subsidence in the Beijing Plain, the area of each category across the 11 time periods was calculated and is presented in Table 1.

Table 1 Area of 4 subsidence categories across 11 time intervals (unit: Km^2).

	2003-2010	2012-2014	2015-2016	2017	2018	2019	2020	2021	2022	2023	2024
Severe	199.16	361.01	351.46	426.68	315.51	113.66	64.64	25.11	9.92	1.09	0.66
Moderately severe	404.21	410.41	417.64	529.28	491.5	276.3	287.78	152.43	116.52	4.77	5.66
Moderate	2360.12	1030.42	1140.7	1754.6	1779.7	989.7	1494.9	1146.5	1359.8	647.24	549.17
Slight and stable	3384.35	4546	4438.0	3637.3	3761.2	4968.2	4500.7	5023.9	4861.6	5694.7	5792.35

As indicated in Table 1 and Fig.2 , subsidence in the Beijing Plain continued to expand from the 2003–2010 period to 2012–2014, slowed slightly during 2014–2016, and intensified again, reaching a peak in 2017 in terms of severe subsidence area. Since 2018, subsidence has been dramatically mitigated annually. Notably, the severe subsidence area in 2024 was 0.66 km^2, accounting for only 0.15% of that in 2017.

In terms of spatial distribution, subsidence in the Beijing Plain was mainly concentrated in the eastern region, particularly eastern Chaoyang District and northwestern Tongzhou District. During 2012–2017, the contiguous subsidence funnel in this area maintained a velocity exceeding 100 mm/year over a large extent. Sporadic subsidence hotspots also appeared in northern Haidian District and southern Changping District, with maximum velocities reaching 100 mm/year during 2012–2014 and 2017.

Linkage With Government Mitigation Policies

4.1 South-to-North Water Diversion Project (SNWDP)

Since December 2014, the SNWDP has supplied over 8.8×10^8 m^3 (880 million cubic meters) of water to Beijing annually, with the minimum volume of 8.81×10^8 m^3 in 2015 and the maximum of 12.78×10^8 m^3 in 2024. This stable water supply reduced Beijing's reliance on groundwater from 78% in 2004 to 29% in 2024, directly reversing aquifer compaction—the primary driver of subsidence—and playing a pivotal role in turning around the worsening subsidence situation observed in 2017.

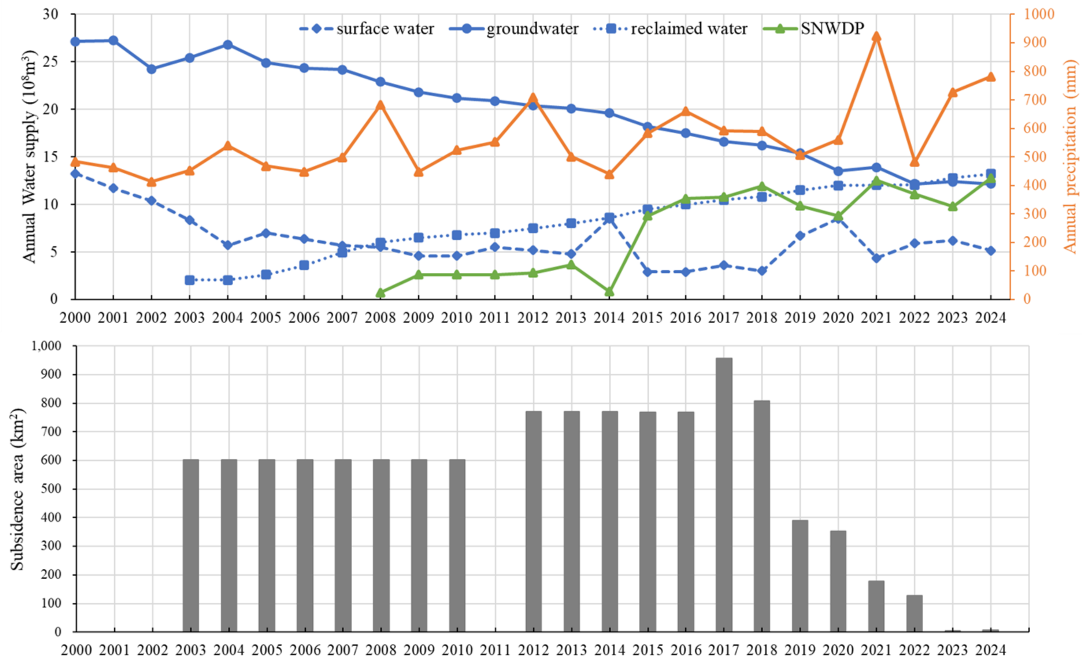

Fig. 3. Annual precipitation and water supply composition in Beijing (2000–2024) (upper panel); annual total area of severe and moderately severe subsidence (2003–2024) (lower panel).

4.2 Groundwater Extraction Control

Beijing has implemented strict groundwater extraction control measures since 2004 (Zhang & Chen, 2023), including: (1) Phasing out agricultural groundwater extraction in subsidence hotspots; (2) Banning new wells in severe subsidence zones (<-50 mm/year); (3) Reducing industrial groundwater extraction by 40%. These measures have led to a steady decline in total groundwater use, from 26.8×10^8 m³ in 2004 to 12.16×10^8 m³ in 2024 (Fig. 3), facilitating the gradual recovery of aquifers.

4.3 Increased utilization of reclaimed water

Since 2004, the utilization of reclaimed water in Beijing has steadily increased from 2.04×10^8 m³ to 13.23×10^8 m³ in 2024, with a total increment of 11.19×10^8 m³—almost equivalent to the 2024 SNWDP water supply (12.78×10^8 m³). The proportion of reclaimed water in Beijing's total water supply rose from 6% in 2004 to 31% in 2024. Similar to groundwater extraction control, increased reclaimed water utilization has effectively reduced groundwater extraction demand.

4.4 Urban Planning Revision

The Beijing Urban Master Plan (2004–2020), promulgated in 2005, had a notable flaw: the Eastern Development Zone overlapped highly in spatial distribution with the subsidence funnel in eastern Beijing (Fig. 4a). To prevent further expansion of subsidence in the east, measures such as groundwater extraction control and restrictions on intensive high-rise building construction were imperative, which conflicted with the zone's positioning as a "key area for future development."

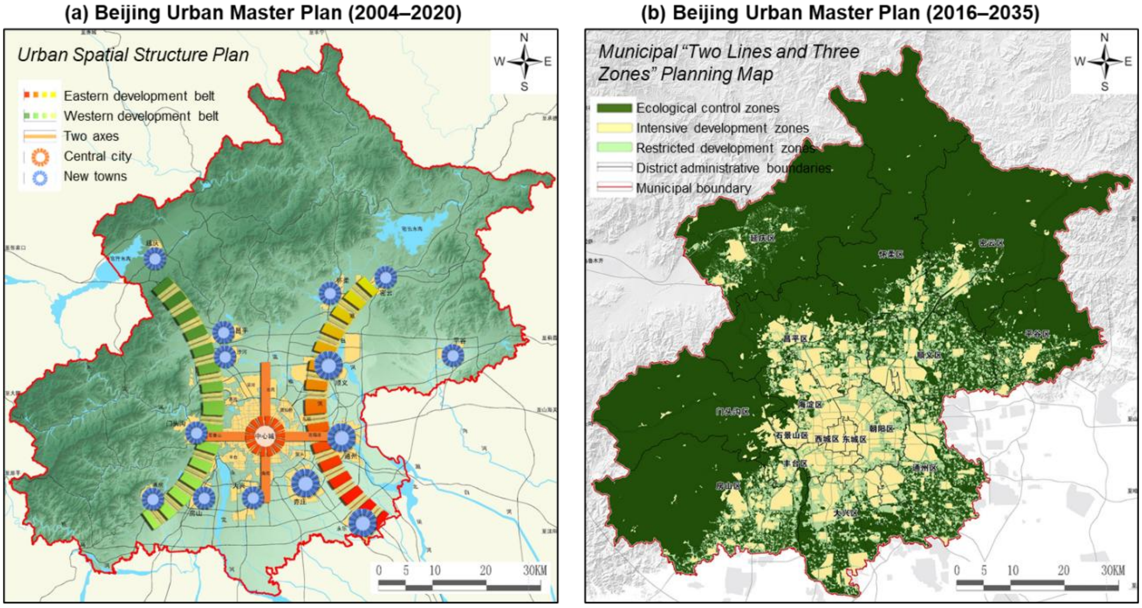

Fig. 4. Beijing Municipal Master Plans

In 2014, the Beijing Municipal Government launched the compilation of a new urban master plan, explicitly stating that "it is necessary to comprehensively assess hazardous factors such as land subsidence, active faults, underground goafs, and groundwater level fluctuations, eliminate disaster risks, and ensure the safety of both above-ground and underground spaces". The Beijing Municipal Master Plan (2016–2035) (Fig. 4b), officially approved in September 2017, carried out a detailed spatial zoning of the administrative area of Beijing in accordance with three categories: ecological control zones, concentrated construction zones, and restricted construction zones.

A comparison between the Beijing Municipal Master Plan (2016–2035) and the ground subsidence velocity map of the Beijing Plain in 2017 reveals that, among the areas with a subsidence rate exceeding 30 mm/year, 20.2% are designated as ecological control zones, 38.3% as restricted construction zones, and only 41.2% as concentrated construction zones in the new plan. This indicates that the revision of Beijing's master plan has fully taken into account the restrictive impact of ground subsidence as a disaster risk. Most areas with moderately severe and severe subsidence have been zoned as ecological control zones or restricted construction zones, which has effectively reduced the development intensity in the plain area and exerted a direct effect on mitigating land subsidence and controlling its associated risks.

Conclusions and Implications

Using Envisat ASAR, Radarsat-2, and Sentinel-1 SAR images, this study extracted ground subsidence velocities of the Beijing Plain across 11 time periods (2003–2024) and analyzed the two-decade dynamic variations of subsidence as well as its linkage with government-implemented mitigation policies. The main conclusions are as follows:

1) The evolutionary process of ground subsidence in the Beijing Plain can be divided into two distinct phases: the expansion phase (2003–2017) and the steady and substantial mitigation phase (2017–2024). In terms of the area of severe subsidence (with subsidence velocity over 50 mm/year), 2017 marked the most severe year with 426.68 Km^2 severe subsidence area in the Beijing Plain. By 2024, such severe subsidence regions had almost vanished, with area of merely 0.66 km^2.
2) Since the end of 2014, the SNWDP has maintained a stable water supply to Beijing with an annual water supply of over 8.8×10^8 m^3. Groundwater consumption has been steadily declining since 2004 (registering a total reduction of 14.64×10^8 m^3 billion tons by 2024), while the utilization of reclaimed water has kept rising steadily over the same period (increasing by 11.19×10^8 m^3 by 2024). These three synergistic measures have resulted in a drastic reduction in groundwater extraction, thereby playing a crucial role in the substantial mitigation of ground subsidence in the region.
3) The revision of Beijing municipal master plan has fully incorporated the restrictive impact of land subsidence as a critical disaster risk. Specifically, over 58% of the regions affected by severe and moderately severe subsidence have been designated as ecological control zones or restricted construction zones in the new plan, which has also exerted an important effect on facilitating the mitigation of ground subsidence.

This study offers valuable implications for other water-scarce cities facing ground subsidence globally. Firstly, InSAR-derived subsidence information—characterized by higher spatial resolution than traditional ground-based techniques such as spirit leveling—can serve as a scientific guide for spatial planning, helping to avoid high-intensity construction or excessive groundwater extraction in high-risk subsidence areas. Secondly, synergistic measures integrating engineering projects (e.g., inter-basin water transfer), resource management (e.g., groundwater control and reclaimed water utilization), and urban planning revisions can mutually reinforce subsidence mitigation effectiveness.

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BIOGRAPHICAL NOTES

Prof. Yonghong Zhang received the bachelor degree in mathematics and Ph.D. degree in photogrammetry and remote sensing from Wuhan University, China, in 1994 and 2001 respectively.

From 2002 May to 2003 December he was a postdoctoral research associate in King's College London, U.K. He has been a research professor in Chinese Academy of Surveying and Mapping (CASM), Beijing, China, since 2004, where he founded the research group on SAR monitoring of environment and disaster in 2008. Currently he serves as the director of the institute of photogrammetry and remote sensing within CASM. His interests include SAR/InSAR/PolSAR technique developments and applications. He received several prestigious national and provincial awards, and authored more than 180 peer-reviewed papers.

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