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Spatio-temporal analysis of land subsidence in Rajshahi District, Bangladesh, using Sentinel-1 SBAS-InSAR

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Abstract

Land subsidence, a gradual downward movement of the land surface with respect to a fixed surface, is one of the most significant slow-onset geohazards in deltaic and fast urbanizing areas, and it poses a risk to the drainage, built infrastructure, and long-term sustainability of groundwater resources. This study describes the characteristics of land subsidence in northwestern Bangladesh, an area that lies between the recent floodplain terraces of the Padma and the older Barind Tract. A total of 45 Sentinel-1A Single Look Complex (SLC) scenes acquired from 2021 to 2025 have been processed using Small Baseline Subset interferometric synthetic aperture radar (SBAS-InSAR) technique, which includes interferometric preprocessing, phase unwrapping, line of sight (LOS) displacement estimation, range-Doppler terrain correction, and time-series inversion. The resulting deformation field was analyzed in conjunction with surface geology and land use and land cover (LULC) data and groundwater records to determine spatial patterns and their possible controlling factors. The mean-velocity field shows a significant north-south gradient, with the mean line-of-sight (LOS) deformation rate in Boalia (south) being approximately -11.89 mm/year, and in the northern Barind upazilas, it is approximately -6.81 mm/year. The data used were only ascending-track Sentinel-1, and the deformation reported is along the radar line of sight, which is interpreted as the majority of subsidence being mostly vertical.

The most rapid subsidence falls along the southern floodplain and the urbanizing corridor, while the Barind Tract is comparatively stable. The water table at the Paba monitoring well dropped from approximately 11.55 m during January 2024 to 15.70 m during May 2024, and the cumulative InSAR displacement values became increasingly negative; but this seasonal trend, from a single monitoring well, does not necessarily reflect it district-wide and does not imply a groundwater contribution. Together, the results indicate the comprehensive effect of groundwater stress, sediment compressibility, and land surface alteration. The study presents a district-scale deformation inventory and a transferable approach for prioritizing future deformation monitoring in the district of Rajshahi.

Keywords: Land subsidence; SBAS-InSAR; Sentinel-1; Groundwater; Land use and land cover; Rajshahi; Bangladesh

1 Introduction

Land subsidence, the downward movement of the ground surface relative to a stable reference frame, is now recognized as one of the most widespread and costly geohazards in urban, agricultural, and deltaic environments. Global assessments show that it is remarkably common and, in most documented cases, closely tied to human activity, principally groundwater extraction, sediment consolidation, urban loading, and land reclamation. In a synthesis of 290 case studies worldwide, Nicholls et al. [19] found that a large share of reported subsidence is anthropogenically induced and that coastal plains and river deltas are disproportionately affected. The consequences are far-reaching and include impaired drainage and heightened flood risk, differential settlement that damages buildings and lifelines, and the permanent loss of aquifer storage capacity [1, 9].

Among these anthropogenic controls, groundwater withdrawal is the dominant driver in compressible aquifer systems. Pumping lowers pore-water pressure and increases the effective stress carried by the sediment skeleton, which compacts fine-grained and unconsolidated deposits. Part of the resulting deformation is elastic and recoverable, but in compaction-prone strata a substantial fraction becomes inelastic and permanent [9, 10]. Long-term, multi-sensor observations in Tehran, for instance, revealed sustained compaction of the aquifer system driven by continued groundwater depletion [11]. Evidence from Mexico City and coastal Indonesia further shows that the coupling between groundwater and deformation is strongly conditioned by geological setting and sediment thickness, so that water-level change alone rarely explains the full spatial pattern of subsidence [5, 6].

Satellite radar interferometry (InSAR) offers an efficient way to observe these processes over large areas. By comparing the phase of repeated synthetic aperture radar acquisitions, InSAR can resolve surface motion at fine spatial resolution. Multi-temporal approaches, in particular Persistent Scatterer Interferometry (PSI) and the Small Baseline Subset (SBAS) method, exploit large stacks of acquisitions to improve temporal sampling and to separate genuine deformation from decorrelation and atmospheric artifacts [4, 7, 8, 13, 17, 20]. These techniques have been applied successfully to

urban subsidence in settings as varied as Surabaya, Nanning, and Semarang [2, 3, 16]. The systematic, C-band, repeat-pass acquisitions of the Sentinel-1 mission have been especially influential, enabling consistent regional time-series analyses at little cost to the user.

Bangladesh is inherently prone to subsidence because much of the country rests on thick alluvial and deltaic sediments and because groundwater underpins both its water supply and its agriculture. InSAR studies in the southwestern delta have measured subsidence of roughly 3–10 mm/year, with local rates exceeding 14 mm/year [21]. Multi-temporal analyses of Dhaka and other large cities have likewise highlighted the combined roles of groundwater abstraction, land-use change, and sediment properties [12]. At the regional scale, a recent Sentinel-1 assessment of northern and central Bangladesh reported deformation of about 8 mm/year in the Rajshahi area [18], indicating that measurable subsidence extends well beyond the classic coastal hotspots.

Rajshahi District occupies a distinctive position in northwestern Bangladesh, on the boundary between the recent Padma (Ganges) floodplain deposits to the south and the older, stiffer Barind Tract to the north. It is a heavily groundwater-dependent district that has undergone steady urban growth around Rajshahi City. Recent geospatial work has documented pronounced land-cover change and coupled surface-water and groundwater dynamics in the city [15], while trend and modeling studies of the surrounding region have reported systematic declines in groundwater level [14]. Compressible floodplain sediments, sustained groundwater stress, and an expanding built environment are precisely the conditions under which subsidence tends to develop.

Despite this, most InSAR-based subsidence research in Bangladesh has focused on Dhaka, the southwestern coastal belt, or broad regional composites. A dedicated, district-scale deformation inventory for Rajshahi, one that resolves subsidence at the upazila level and interprets it jointly against land cover, surface geology, and in-situ groundwater observations, has been lacking. Whereas Middleton et al. [18] mapped deformation across northern and central Bangladesh as a broad regional composite, the present study resolves the deformation field at the level of individual administrative units within a single district and interprets it jointly against surface geology, land-cover change, and an in-situ groundwater record; this district-scale, multi-layer integration is the principal novelty claimed here. In particular, the spatial partitioning of deformation between the floodplain and the Barind Tract, and the temporal relationship between seasonal groundwater drawdown and surface motion, remain poorly quantified at the local scale.

This study addresses that gap. Drawing on a district-focused SBAS-InSAR analysis of Sentinel-1 data, it provides an integrated, district-scale assessment rather than a catalogue of annual maps, with emphasis on the mean-velocity pattern, its relationship to LULC and surface geology, and its coupling with groundwater. The specific objectives are threefold: (i) to estimate the spatial distribution of mean land-subsidence velocity across Rajshahi District from 2021 to 2025 using Sentinel-1 SBAS-InSAR; (ii) to identify the principal deformation zones and interpret them in terms of LULC and surface geology; and (iii) to compare the available groundwater record with the InSAR displacement series and thereby assess how water-table variation relates to

surface motion. The analysis yields a spatially explicit, upazila-ranked subsidence inventory, isolates Boalia and the southern floodplain and urban corridor as the principal deformation-priority zone, and reveals a seasonal coupling between groundwater and deformation that shows signs of a delayed, potentially inelastic component. The resulting framework offers a practical basis for targeted monitoring and points toward future work that integrates denser groundwater networks, independent GNSS or leveling validation, and predictive modeling of subsidence risk.

2 Materials and Methods

2.1 Study area and geological setting

The Rajshahi District is located in the northwestern part of Bangladesh, on the northern shore of the Padma River, with the center of the area at 24°22' N, 88°36' E (Fig. 1). It includes the city of Rajshahi and a mosaic of floodplain and Barind landscapes. The district consists of nine upazilas namely Paba, Charghat, Bagha, Puthia, Durgapur, Mohanpur, Bagmara, Tanore and Godagari and the metropolitan thana of Rajshahi City. The nine upazilas are analysed here as urban administrative units, with the metropolitan thana, forming the southern urban core of the city along the Padma corridor, analysed herein. The relief is generally low, but not uniform; the floodplain in the south is underlain by recent alluvium, while the north and northwest are underlain by the older Barind clay.

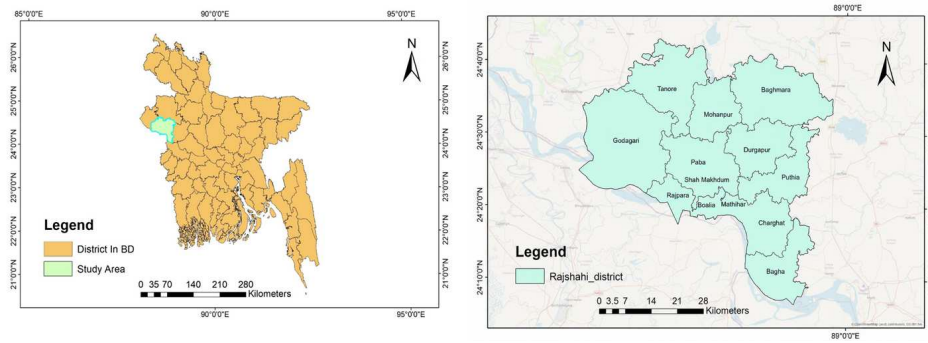


Fig. 1: Location of Rajshahi District within Bangladesh and the administrative-unit boundaries (nine upazilas and the Boalia metropolitan thana) used in the study.

The surface geology mirrors this division (Fig. 2). Recent alluvial sand fringes the Padma corridor through Boalia and southward, grading into extensive alluvial silt across the central district. Patches of alluvial silt and clay occur around Durgapur, Puthia, and Bagha, peat and peaty clay appear near Mohanpur, and the stiff, over-consolidated Barind clay residuum blankets Godagari and Tanore in the northwest. The contrast between young, compressible floodplain sediments and older, more competent Barind material is central to interpreting the deformation field presented below.

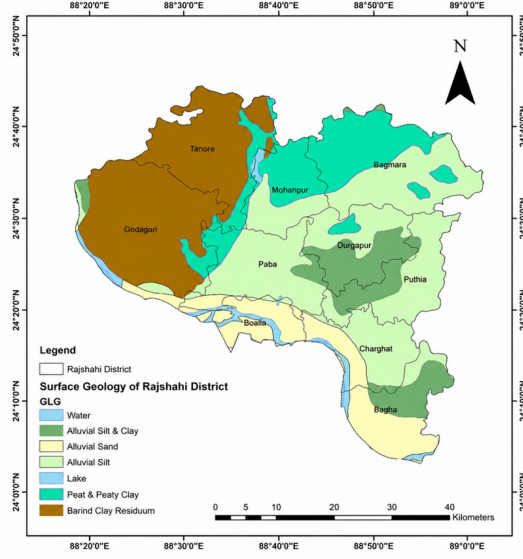


Fig. 2: Surface geology of Rajshahi District derived from the USGS geological dataset.

2.2 Land use and land cover change, 2021–2025

Land use and land cover for 2021 and 2025 were derived from Google Earth Engine products and compared at the district scale (Fig. 3). Cropland remained the dominant class throughout, although its share declined from about 56.2% in 2021 to 52.2% in 2025. Over the same interval the built-up class expanded from 21.1% to 22.7%, and smaller increases occurred in water bodies (9.8% to 10.8%), tree cover (9.7% to 10.3%), bare ground (2.0% to 2.5%), rangeland (1.2% to 1.3%), and flooded vegetation (0.004% to 0.16%) (Fig. 4).

The overall signal is a modest but consistent shift from cropland toward built-up and other modified surfaces. This trend is relevant to subsidence because expanding built-up areas can raise both groundwater demand and surface loading, while the conversion of permeable land alters infiltration and recharge pathways. LULC is therefore best treated as a contextual rather than a causal control on the deformation field.

2.3 Sentinel-1 and ancillary datasets

The InSAR analysis used 45 Sentinel-1A Level-1 Single Look Complex (SLC) images acquired between 2021 and 2025 and obtained through the Alaska Satellite Facility (ASF). All scenes were drawn from the same ascending track and relative orbit to preserve a consistent viewing geometry. The ancillary datasets comprised a USGS-derived surface-geology layer, Google Earth Engine LULC products, and groundwater records from Bangladesh Water Development Board (BWDB) monitoring well GT8172038 in Paba upazila (Table 1). These ancillary layers were not used to produce an independent subsidence estimate; instead, they were combined with the interferometric results to interpret the spatial pattern of deformation and its likely controls.

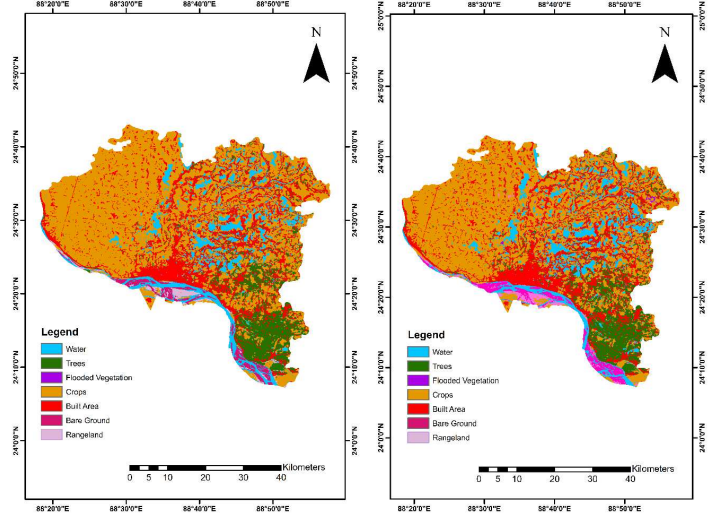


Fig. 3: Land use and land cover distribution of Rajshahi District in 2021 (left) and 2025 (right).

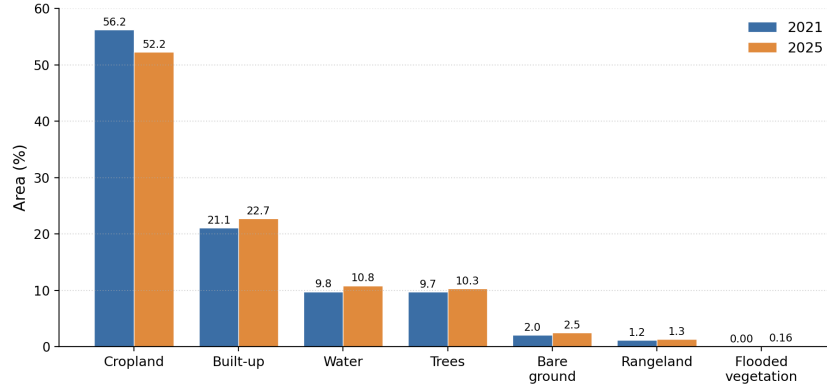


Fig. 4: District-level comparison of land use and land cover between 2021 and 2025.

2.4 Sentinel-1 TOPS interferometric preprocessing

Because the study area spans the Sentinel-1 IW2 and IW3 sub-swaths, both were carried through preprocessing (Fig. 5). The relevant bursts were isolated with TOPSAR-Split, precise orbit files were applied, and each sub-swath was co-registered independently. Enhanced Spectral Diversity (ESD) refined the burst alignment before interferogram formation and TOPSAR-Deburst. The debursted products from the two sub-swaths were then merged to give continuous coverage of the district. Goldstein

Table 1: Datasets used in the study and their roles.

Dataset	Source	Period / coverage	Use
Sentinel-1A SLC	ASF / NASA	2021–2025; 45 scenes	SBAS-InSAR processing
Surface geology	USGS	Rajshahi District	Geological interpretation
Land use and land cover	Google Earth Engine	2021 and 2025	Land-cover comparison
Groundwater level	BWDB well GT8172038	2024 (weekly)	Groundwater and subsidence relation

177 filtering suppressed phase noise and sharpened the fringes, after which the Rajshahi
 178 area of interest was subset ahead of phase unwrapping.

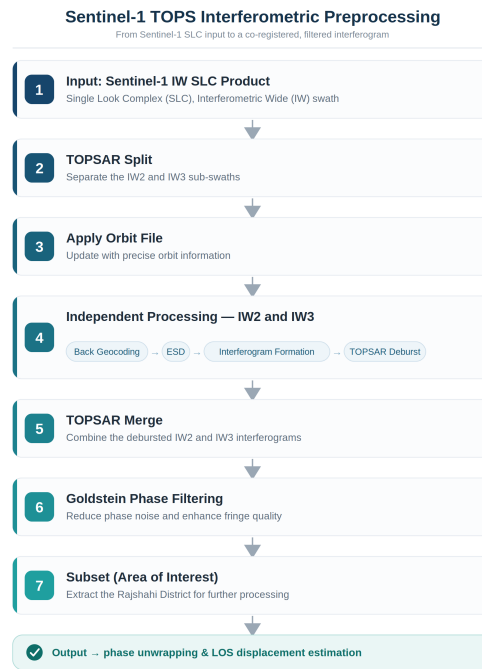


Fig. 5: Sentinel-1 TOPS interferometric preprocessing workflow used in the study.

179 2.5 Phase unwrapping, LOS displacement, and SBAS 180 time-series inversion

181 The wrapped interferograms were unwrapped with SNAPHU to remove the 2π phase
 182 ambiguity and recover a continuous phase field (Fig. 6). The unwrapped products

183 were returned to SNAP and converted to line-of-sight (LOS) displacement, and range–
 184 Doppler terrain correction produced georeferenced displacement stacks. An SBAS
 185 inversion was then applied to the network of small-baseline interferograms, with
 186 January 2021 taken as the reference epoch for the multi-year cumulative series.
 187 All displacements are measured along the radar line of sight and are relative to a
 188 stable reference area within the scene; because only ascending-track data were pro-
 189 cessed, the LOS rates are interpreted as predominantly vertical subsidence rather than
 190 being decomposed into separate vertical and horizontal components. The displace-
 191 ment observations were organized and the time-series products generated in Python,
 192 whereas spatial mapping and integration with the ancillary datasets were carried out
 193 in ArcGIS. The principal outputs, summarized in the next section, are the multi-year
 194 mean-velocity map and the associated time-series products.

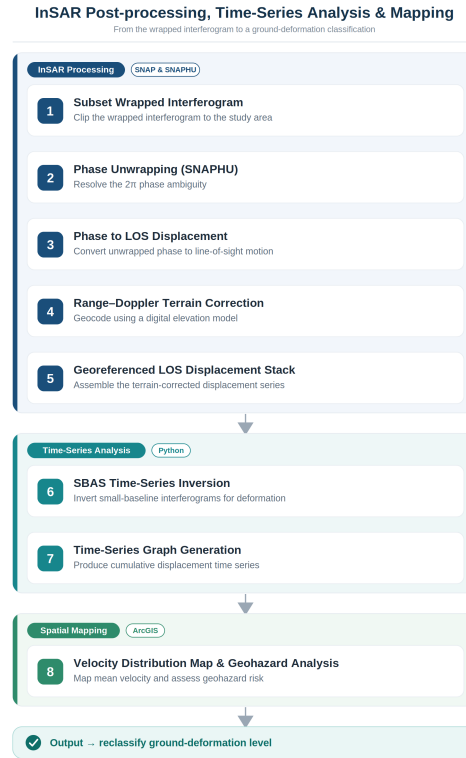


Fig. 6: Post-preprocessing workflow: phase unwrapping, displacement estimation, SBAS time-series inversion, and spatial analysis.

3 Results and Discussion

3.1 Mean land-subsidence velocity

The mean-velocity map shows that subsidence is spatially pervasive across Rajshahi District but varies markedly in magnitude (Fig. 7). The strongest negative velocities occur in the south and south-central district, notably at Boalia, Paba, Charghat, and Bagha, and the largest mean rate, about -11.89 mm/year, is reached at Boalia. The northern upazilas of Godagari, Tanore, Mohanpur, and Bagmara deform more slowly, approaching the regional minimum of about -6.81 mm/year. The result is a strong spatial gradient in which intense deformation along the Padma floodplain and urban corridor gives way to subdued motion across the northwestern Barind Tract. Notably, this gradient does not follow administrative boundaries; it tracks geological and land-use contrasts, and deformation is greatest where recent alluvium, groundwater dependence, and surface modification coincide.

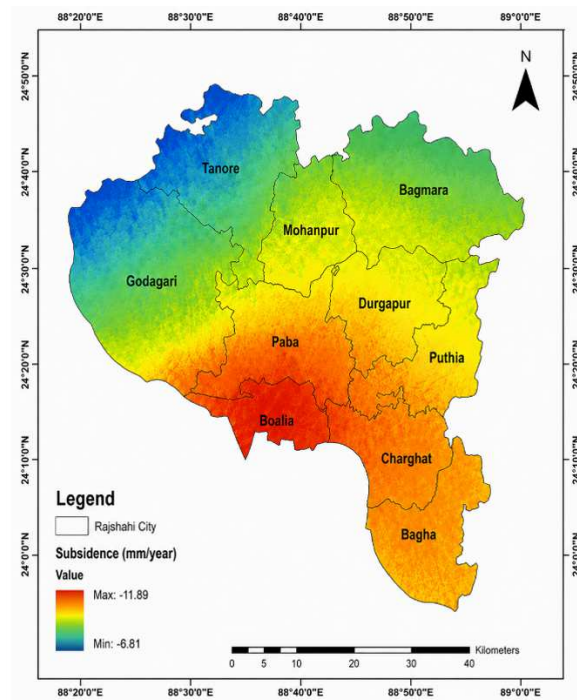


Fig. 7: Mean land-subsidence velocity in Rajshahi District during 2021–2025, derived from Sentinel-1 SBAS-InSAR.

3.2 Subsidence velocity in relation to land use and land cover

Placing the velocity map beside the LULC map clarifies why land cover is a useful interpretive layer (Fig. 8). The most rapid deformation in the south broadly overlies areas of greater built-up extent and modified surfaces, whereas much of the northern Barind Tract remains under cropland. The correspondence is not one-to-one, however: measurable deformation also occurs in agricultural areas where groundwater abstraction can be intense, so LULC by itself does not account for the velocity field.

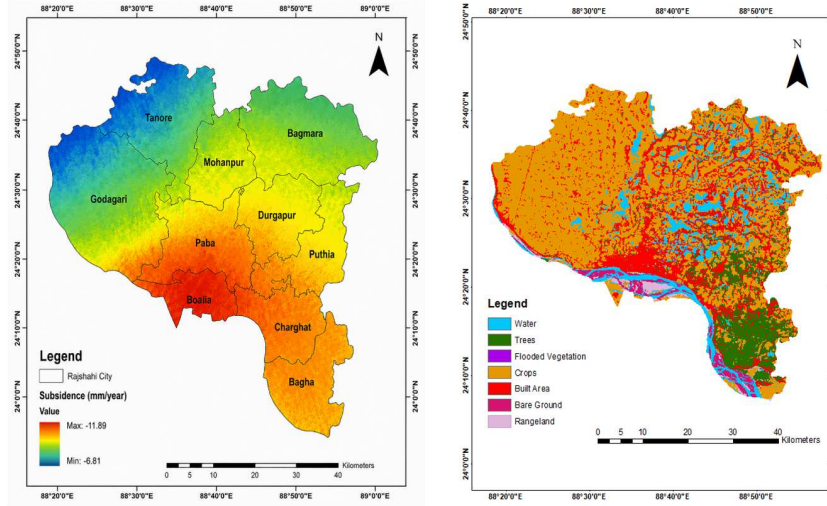


Fig. 8: Mean land-subsidence velocity (left) and land use and land cover (right), shown side by side to reveal spatial overlap.

The most informative reading is the coincidence of three conditions, namely relatively compressible sediments, strong groundwater dependence, and surface alteration. Where these conditions overlap, deformation tends to be more pronounced, and where the stiff Barind clay dominates and land-cover change is limited, the measured velocities are lower; this spatial coincidence is descriptive and has not yet been tested with formal zonal statistics. This multi-factor interpretation is consistent with the wider subsidence literature, which cautions against attributing a regional deformation field to any single driver [9, 10, 20].

3.3 District-scale cumulative time series

The district-averaged time series traces the cumulative subsidence trend from 2021 to 2025 (Fig. 9). Mean cumulative displacement grew steadily from about -3.2 mm in 2021 to -6.2 mm in 2025, a gain of roughly 3.0 mm over the monitoring period, with the largest single-year increase between 2024 and 2025. The consistently negative,

228 downward trajectory indicates that ground deformation in Rajshahi did not level off
 229 during the study period but instead accumulated over time.

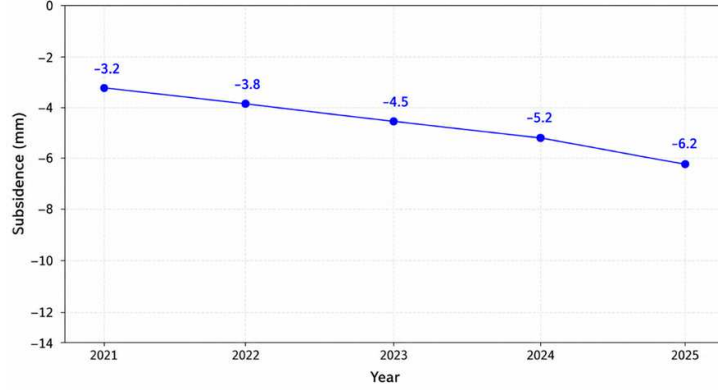


Fig. 9: Annual mean land-subsidence time series for Rajshahi District during 2021–2025.

230 3.4 Administrative-unit velocity ranking

231 Ranking the administrative units by their maximum 2025 rate reproduces the spatial
 232 hierarchy seen in the mean-velocity map (Fig. 10; Table 2). The Boalia metropoli-
 233 tan thana records the highest rate (-11.80 mm/year), followed by Paba (-10.50
 234 mm/year), Charghat (-9.50 mm/year), and Bagha (-9.00 mm/year). Puthia and
 235 Durgapur occupy intermediate positions, the rates are lower at Mohanpur and
 236 Bagmara, and the smallest values are found at Godagari and Tanore. It is worth dis-
 237 tinguishing the two metrics: Fig. 7 summarizes the multi-year mean velocity, whereas
 238 Table 2 reports the maximum rate reached in each administrative unit during 2025.
 239 The two agree closely on the spatial ordering, which confirms that the southern
 240 floodplain and urban corridor form the principal subsidence belt of the district.

241 3.5 Upazila-scale deformation and land-cover dynamics

242 The upazila-scale records add spatial detail to this ranking and link the deformation
 243 rates to local geology and land-cover change. They are examined below, moving from
 244 the strongly deforming southern floodplain to the more stable Barind Tract in the
 245 north.

246 3.5.1 Boalia.

247 Boalia, the metropolitan thana forming the southern urban core of Rajshahi City, is
 248 the most strongly deforming administrative unit, at roughly -11.8 to -11.89 mm/year.
 249 Its position on the loose, recent alluvial sand of the Padma corridor makes it inher-
 250 ently prone to compaction. The land-cover record shows the built-up share rising

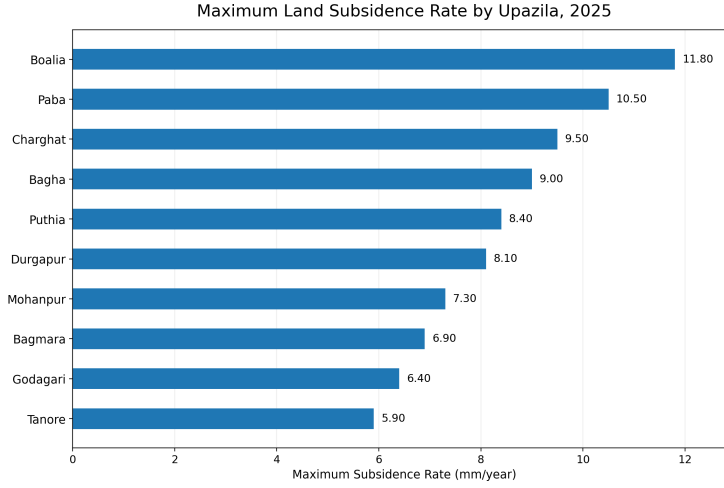


Fig. 10: Maximum reported land-surface deformation rate by administrative unit (nine upazilas and the Boalia metropolitan thana) in 2025.

Table 2: Maximum land-surface deformation rate and relative (descriptive) velocity class by administrative unit for Rajshahi District, including the Boalia metropolitan thana (2025). The velocity classes are descriptive categories ranked by rate and do not represent a hazard or risk standard.

Administrative unit	Maximum rate (mm/year)	Relative velocity class
Boalia	−11.80	Very high
Paba	−10.50	High
Charghat	−9.50	Moderate–high
Bagha	−9.00	Moderate–high
Puthia	−8.40	Moderate
Durgapur	−8.10	Moderate
Mohanpur	−7.30	Low–moderate
Bagmara	−6.90	Low
Godagari	−6.40	Very low
Tanore	−5.90	Very low

from 24.78% in 2021 to 25.24% in 2025, while open water contracts from 23.12% to 18.55% (Fig. 11a); over the same interval the subsidence rate steepens from about −6.8 mm/year to −11.8 mm/year (Fig. 11b). Together these observations identify Boalia as a place where geological vulnerability and surface modification reinforce one another, in line with reports that subsidence intensifies where soft alluvium, groundwater extraction, and urban development overlap [1, 5].

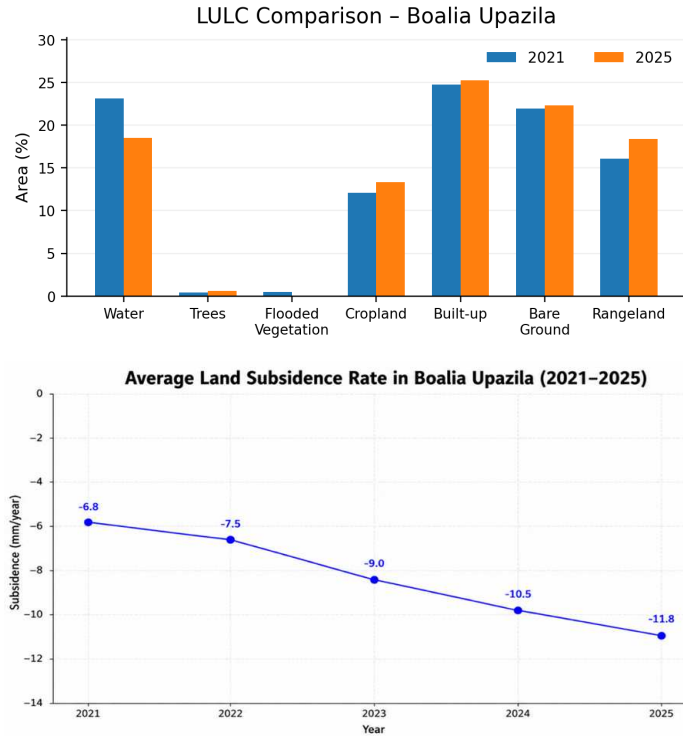


Fig. 11: Boalia Upazila: (a) land use and land cover comparison between 2021 and 2025; (b) mean land-subsidence trend, 2021–2025.

3.5.2 Paba.

Paba combines alluvial silt with thin alluvial-sand belts and pronounced built-up growth. Built-up land increased from 37.42% to 40.27% while cropland fell from 46.75% to 39.74% (Fig. 12a), and the mean subsidence rate rose from about -6.2 mm/year in 2021 to -10.5 mm/year in 2025 (Fig. 12b). The overlap of land-use change and accelerating deformation points to a strong anthropogenic influence; as discussed in Sect. 3.7, the co-located groundwater record offers a localized line of hydrogeological evidence for this unit.

3.5.3 Bagha and Charchat.

Bagha and Charchat lie along the southern Padma drainage and are dominated by alluvial sand, silt, and clay. Bagha shows minor losses of tree cover and cropland together with gains in built-up area and bare ground, while in Charchat cropland declined from 29.73% to 19.43% and built-up land rose slightly from 25.33% to 26.20% (Fig. 13a, b). Subsidence rates accelerated over the study period, from about -5.4 to -9.0 mm/year in Bagha and from -5.6 to -9.5 mm/year in Charchat (Fig. 13c). That both upazilas deform rapidly despite only moderate urbanization underlines the

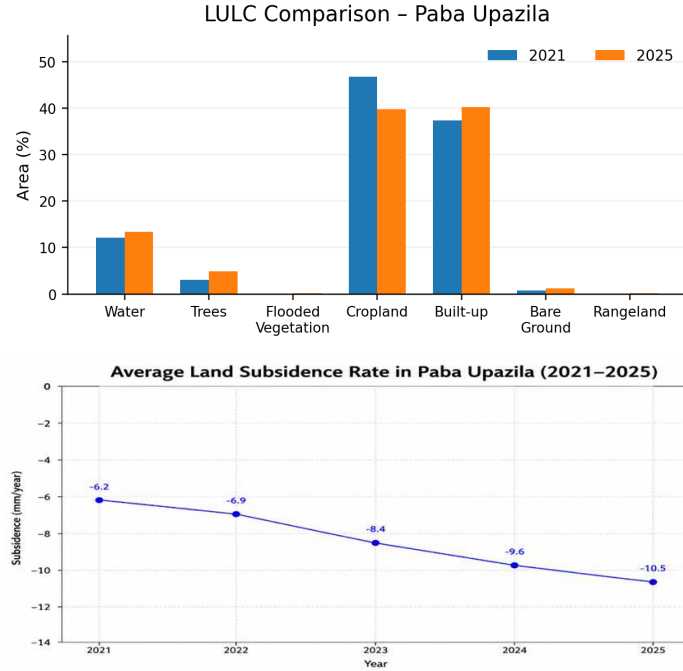


Fig. 12: Paba Upazila: (a) land use and land cover comparison between 2021 and 2025; (b) mean land-subsidence trend, 2021–2025.

importance of floodplain geology and groundwater reliance rather than urban growth alone.

3.5.4 Puthia and Durgapur.

Puthia and Durgapur sit in the transition between the Barind Tract and the Ganges floodplain, on alluvial silt, alluvial clay, and Barind clay residuum. Cropland in Puthia declined from 47.01% to 41.56% as built-up land grew from 23.37% to 27.53%, and Durgapur shows a particularly sharp reallocation between built-up land and tree cover (about +9.26% and −9.26%, respectively) (Fig. 14a, b). Subsidence rates rose to between −5.0 and −8.1 mm/year in Durgapur and between −5.2 and −8.4 mm/year in Puthia (Fig. 14c). Their intermediate magnitudes are consistent with a geological transition from the more deformable floodplain to the more stable Barind Tract.

3.5.5 Bagmara and Mohanpur.

Agriculture remains dominant in both Bagmara and Mohanpur. Cropland in Bagmara increased from 52.16% to 55.24% with a slight fall in built-up land, and in Mohanpur cropland rose from 50.87% to 59.16% while built-up land edged down from 27.24% to 26.13% (Fig. 15a, b). Even so, deformation intensified over time, from about −4.0 to −6.9 mm/year in Bagmara and −4.2 to −7.3 mm/year in Mohanpur (Fig. 15c).

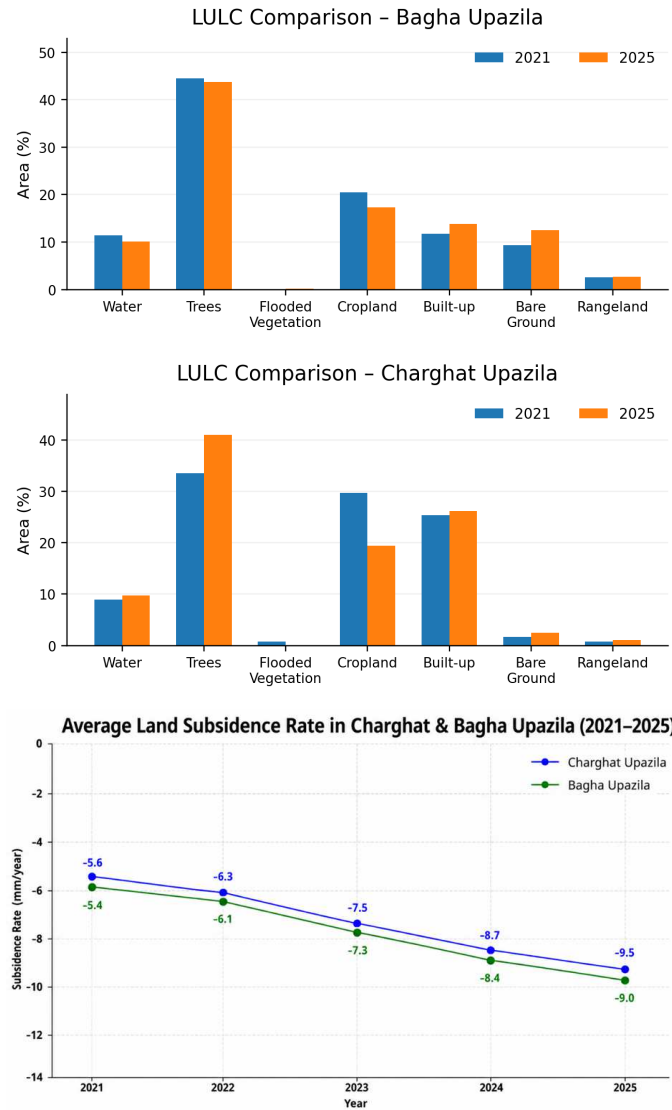


Fig. 13: Southern floodplain upazilas: (a) LULC comparison for Bagha; (b) LULC comparison for Charghat; (c) mean land-subsidence trends for Bagha and Charghat, 2021–2025.

290 This is an important result, because it shows that appreciable subsidence can persist
 291 without rapid urban growth, implicating sustained groundwater abstraction and the
 292 response of the Barind aquifer system as the more likely controls here.

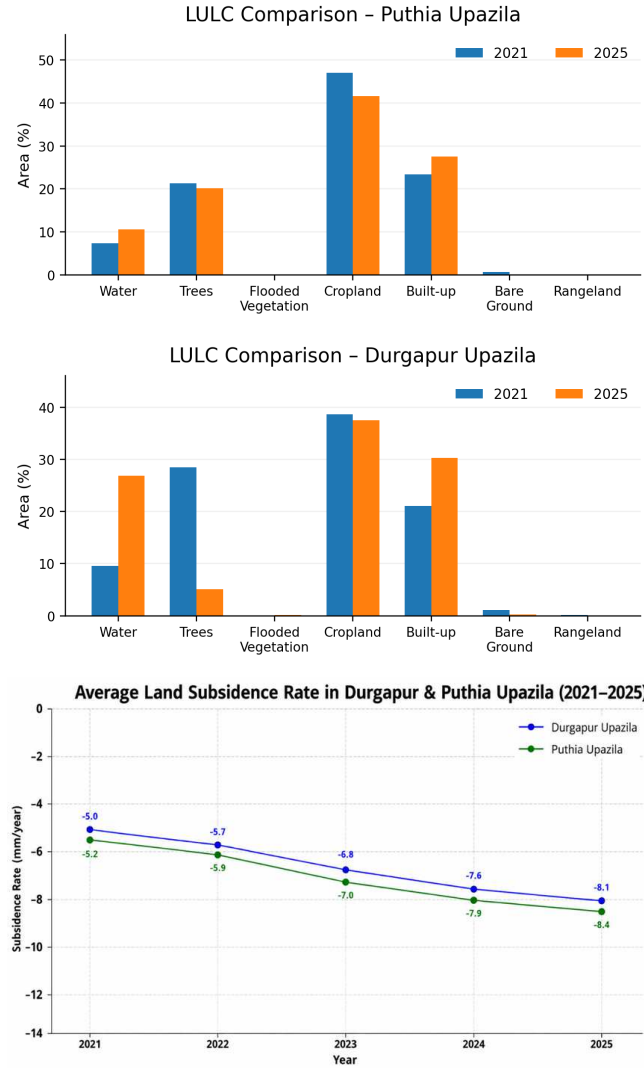


Fig. 14: Transition-zone upazilas: (a) LULC comparison for Puthia; (b) LULC comparison for Durgapur; (c) mean land-subsidence trends for Puthia and Durgapur, 2021–2025.

3.5.6 Godagari and Tanore.

Godagari and Tanore, in the High Barind Tract, are largely agricultural and underlain by relatively stiff, over-consolidated Pleistocene Barind clay residuum. Cropland exceeds 80% in both upazilas, with little change in built-up land (Fig. 16a, b). Their deformation rates are the lowest in the district, from about -4.0 to -6.4 mm/year in Godagari and -3.7 to -5.9 mm/year in Tanore (Fig. 16c). That subsidence stays

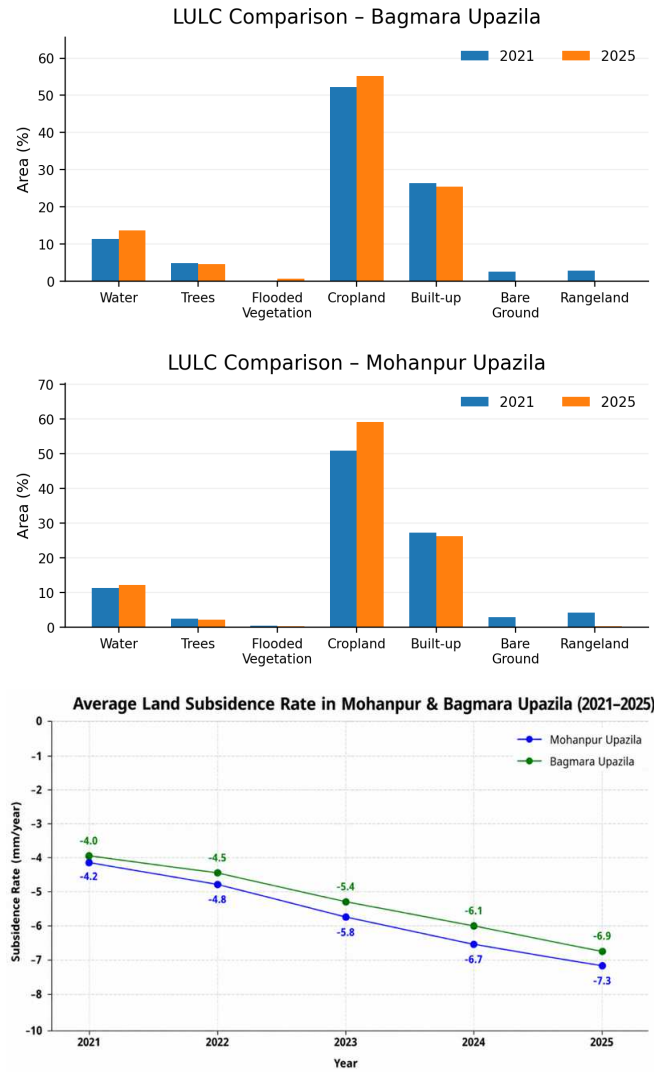


Fig. 15: Agricultural upazilas: (a) LULC comparison for Bagmara; (b) LULC comparison for Mohanpur; (c) mean land-subsidence trends for Bagmara and Mohanpur, 2021–2025.

low to moderate despite evident groundwater pressure highlights the role of sediment compressibility and geological history in governing the surface response.

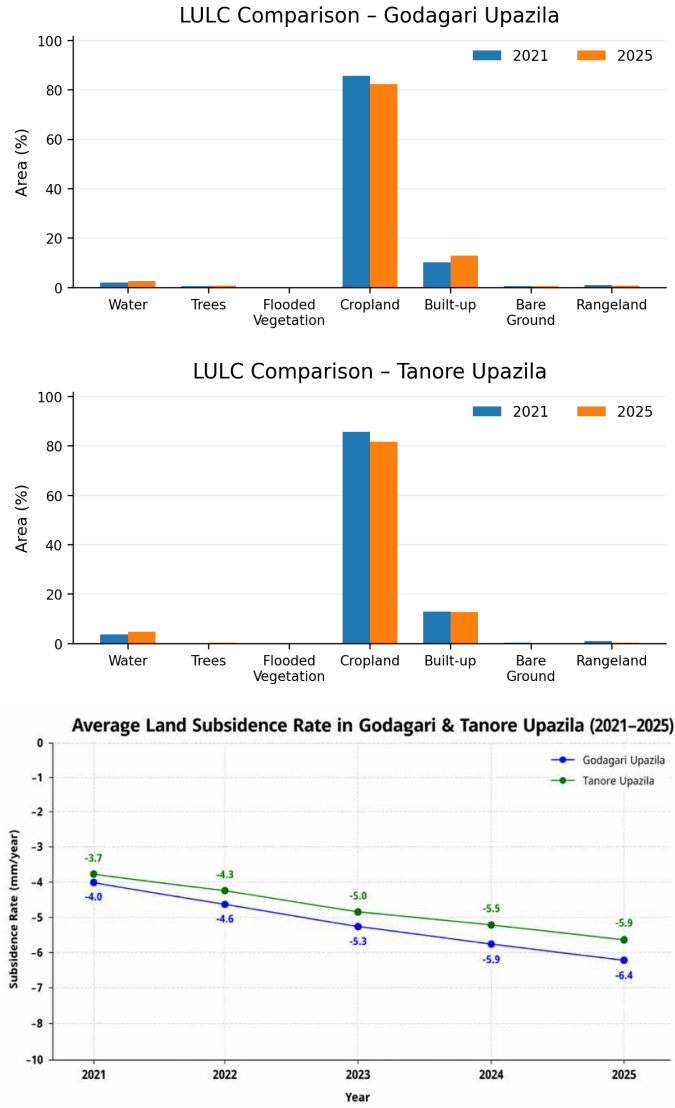


Fig. 16: Barind Tract upazilas: (a) LULC comparison for Godagari; (b) LULC comparison for Tanore; (c) mean land-subsidence trends for Godagari and Tanore, 2021–2025.

3.6 District-wide synthesis of controls

Taken together, the upazila-scale evidence resolves the district into three broad deformation regimes. The southern floodplain and urban corridor form the highest-deformation zone, with the strongest rates at Boalia, Paba, Charghat, and Bagha. The transition zone around Puthia and Durgapur shows intermediate deformation.

The northern Barind upazilas subside more slowly but persistently. This structure is more instructive than any single annual map because it links the velocity field to the geological and land-use framework of the district. The district-scale LULC statistics reinforce the point: although built-up land is expanding, cropland still dominates the surface, so the most plausible explanation is not urbanization on its own but the interaction of urban growth and groundwater demand with a geologically sensitive subsurface. The agricultural north, which subsides despite limited built-up expansion, shows that groundwater abstraction can be significant even without conspicuous land-cover change. As the wider literature emphasizes, a robust attribution of subsidence requires the joint use of geodetic, geological, hydrological, and land-use information [6, 20].

3.7 Relationship between groundwater and subsidence

The relationship between water-table change and InSAR-measured subsidence at Paba during 2024 provides a localized line of hydrogeological evidence (Fig. 17). Groundwater level is expressed here as depth in metres below ground level, so larger values denote a deeper water table, that is, a decline. Through the pre-monsoon period the water table deepened substantially, from about 11.55 m in January to 15.70 m in May, while cumulative InSAR displacement became progressively more negative, reaching about -5.73 mm in April and -7.04 mm by June. During the monsoon recovery the water table rose again, shallowing to about 8.55 m in September, yet subsidence continued, albeit at a slower pace. The persistence of deformation after groundwater recovery is consistent with a temporal lag between drawdown and surface response and with delayed, potentially inelastic compaction, although a single well cannot establish this mechanism on its own. Comparable groundwater and deformation behavior has been reported at Semarang, although other studies caution that water level alone is not always a reliable predictor of deformation where sediment properties and aquitard thickness vary [2, 6]. The regional decline in groundwater levels documented for the Rajshahi area [14, 15] is consistent with the drawdown-driven component inferred here.

3.8 Validation and limitations

No continuous GNSS or leveling data were available within the study area for direct validation. Validation was therefore indirect, based on the magnitude, spatial pattern, and controlling factors of the deformation and on comparison with earlier work. Middleton et al. [18] reported about 8 mm/year across the broader Rajshahi area, whereas the present district-focused analysis yields somewhat larger local values, up to about 11.9 mm/year, with a district average of roughly -9.12 mm/year. This difference is reasonable given the contrasts in observation period, processing strategy, and spatial averaging, and the agreement on the location of maximum deformation in southern Rajshahi is corroborating, even though it does not replace direct geodetic validation. It should also be emphasised that agreement between two InSAR-derived products does not by itself constitute independent validation, because such products may share processing assumptions and systematic errors. In addition, the reported rates are relative to the selected reference area rather than an absolute geodetic datum and, being

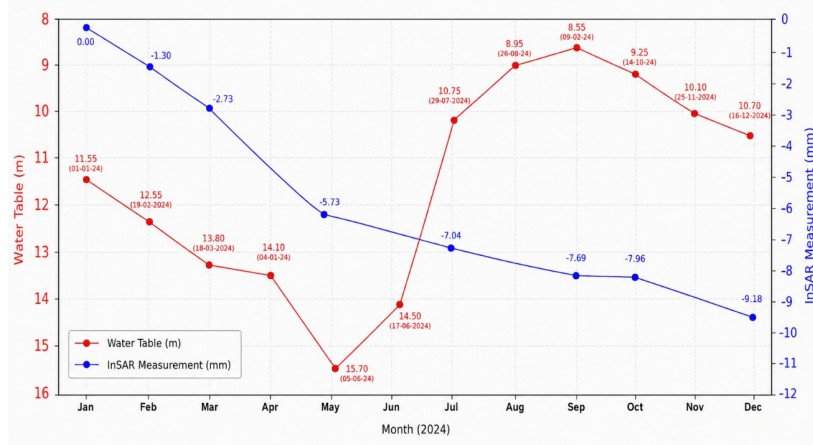


Fig. 17: Groundwater level at BWDB well GT8172038 and the corresponding InSAR displacement series for Paba upazila, 2024.

derived from a single ascending track, cannot be decomposed into separate vertical and horizontal components; they are therefore best regarded as line-of-sight estimates of predominantly vertical motion. Formal per-pixel uncertainties, such as velocity standard errors or temporal-coherence maps, are not yet reported and should accompany the deformation field.

A second limitation is the sparse groundwater sampling. The Paba well offers an informative seasonal case study, but a single observation point cannot establish a district-wide causal relationship. Future work should combine the InSAR series with several BWDB wells, records of groundwater abstraction, rainfall and recharge data, and independent GNSS or leveling measurements. Such additions would make it possible to separate the elastic seasonal response more rigorously from the longer-term, irreversible component of compaction.

4 Conclusions

This study used 45 Sentinel-1A SLC scenes and SBAS-InSAR processing to characterize land subsidence across Rajshahi District between 2021 and 2025. The resulting mean-velocity field shows a clear decrease in deformation from south to north, from a maximum mean rate of about -11.89 mm/year at Boalia to roughly -6.81 mm/year across the northern Barind upazilas.

Comparison with LULC shows that the most intense deformation generally coincides with areas of stronger built-up growth and surface modification, especially in the southern and south-central district. Measurable subsidence nonetheless occurs under agricultural cover as well, which confirms that land cover alone cannot explain the deformation field. The surface-geology map adds a further clue: the recent alluvial deposits of the Padma floodplain appear more susceptible to compaction than the

372 stiffer Barind material to the north, although this contrast is inferred from surface
373 geology rather than from subsurface stratigraphy or geotechnical measurements.

374 The groundwater analysis at Paba reveals a distinct seasonal relationship. As
375 the water table deepened to 11.55 m in January and 15.70 m in May 2024, InSAR
376 displacement became increasingly negative, with only partial recovery during the
377 monsoon. The near-absence of surface rebound after groundwater recovery is con-
378 sistent with delayed, potentially inelastic compaction contributing to the observed
379 response, though this cannot be confirmed from a single well. Overall, the results
380 identify Boalia and the wider southern floodplain and urban corridor as the prin-
381 cipal deformation-priority area, followed by Paba, Charghat, and Bagha. Continued
382 Sentinel-1 monitoring, together with denser groundwater observations and indepen-
383 dent geodetic validation, would strengthen early detection, attribution, and planning
384 for land subsidence in Rajshahi. In sum, the spatial and temporal patterns of line-
385 of-sight deformation are the observed result of this study; their association with
386 geological setting, land cover, and groundwater variation is a supported interpreta-
387 tion; and district-wide causal attribution to groundwater extraction or to irreversible
388 compaction remains to be demonstrated with denser in-situ and geodetic data.

389 **Declarations**

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395 **Competing interests**

396 The authors declare that they have no competing interests.

397 **Data availability**

398 Sentinel-1 SLC data are freely available from the Alaska Satellite Facility ([https://](https://asf.alaska.edu)
399 asf.alaska.edu). Land use and land cover products were generated in Google Earth
400 Engine, surface-geology data were obtained from the USGS, and groundwater records
401 are available from the Bangladesh Water Development Board (BWDB). Processed
402 datasets generated during the study are available from the corresponding author on
403 reasonable request.

404 **Author contributions**

405 Md. Samiul Islam Sany carried out methodology data collection and data analysis
406 and prepared the figures. Ragib Nur Srijan contributed to the conceptualization of the
407 study and supervision. Golam Kibria was responsible for writing the original draft of

the manuscript, reviewing and editing the paper, and performing formal analysis. All authors contributed to the study as a collaborative team and read and approved the final manuscript.

Ethics Approval

This study does not involve human participants or animals, and ethical approval is not applicable.

Consent to Participate

Not applicable

Consent for Publication

All authors consent to the publication of this manuscript.

Clinical Trial

Not applicable.

References

- [1] H. Z. Abidin, H. Andreas, I. Gumilar, and J. J. Brinkman. Study on the risk and impacts of land subsidence in Jakarta. *Proceedings of IAHS*, 372:115–120, 2015. doi: 10.5194/piahs-372-115-2015.
- [2] A. Aditiya and T. Ito. Present-day land subsidence over Semarang revealed by time series InSAR: new small baseline subset technique. *International Journal of Applied Earth Observation and Geoinformation*, 125:103579, 2023. doi: 10.1016/j.jag.2023.103579.
- [3] I. M. Anjasmara, S. A. Yulyta, and M. Taufik. Application of time series InSAR (SBAS) using Sentinel-1A data for land subsidence detection in Surabaya City. *International Journal on Advanced Science, Engineering and Information Technology*, 10:191–197, 2020. doi: 10.18517/ijaseit.10.1.6749.
- [4] P. Berardino, G. Fornaro, R. Lanari, and E. Sansosti. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing*, 40:2375–2383, 2002. doi: 10.1109/TGRS.2002.803792.
- [5] E. Chaussard, F. Amelung, H. Abidin, and S.-H. Hong. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sensing of Environment*, 128:150–161, 2013. doi: 10.1016/j.rse.2012.10.015.

- 440 [6] E. Chaussard, E. Havazli, H. Fattahi, E. Cabral-Cano, and D. Solano-Rojas.
441 Over a century of sinking in Mexico City: no hope for significant elevation and
442 storage capacity recovery. *Journal of Geophysical Research: Solid Earth*, 126:
443 e2020JB020648, 2021. doi: 10.1029/2020JB020648.
- 444 [7] M. Crosetto, O. Monserrat, M. Cuevas-González, N. Devanthéry, and B. Crippa.
445 Persistent scatterer interferometry: a review. *ISPRS Journal of Photogrammetry*
446 *and Remote Sensing*, 115:78–89, 2016. doi: 10.1016/j.isprsjprs.2015.10.011.
- 447 [8] A. Ferretti, C. Prati, and F. Rocca. Permanent scatterers in SAR interferometry.
448 *IEEE Transactions on Geoscience and Remote Sensing*, 39:8–20, 2001. doi: 10.
449 1109/36.898661.
- 450 [9] D. L. Galloway and T. J. Burbey. Regional land subsidence accompany-
451 ing groundwater extraction. *Hydrogeology Journal*, 19:1459–1486, 2011. doi:
452 10.1007/s10040-011-0775-5.
- 453 [10] A. Guzy and A. A. Malinowska. State of the art and recent advancements in the
454 modelling of land subsidence induced by groundwater withdrawal. *Water*, 12:
455 2051, 2020. doi: 10.3390/w12072051.
- 456 [11] M. H. Haghighi and M. Motagh. Ground surface response to continuous com-
457 paction of aquifer system in Tehran, Iran: results from a long-term multi-sensor
458 InSAR analysis. *Remote Sensing of Environment*, 221:534–550, 2019. doi:
459 10.1016/j.rse.2018.11.003.
- 460 [12] D. M. E. Haque, T. Hayat, and S. Tasnim. Time series analysis of subsidence
461 in Dhaka City, Bangladesh using InSAR. *Malaysian Journal of Geosciences*, 3:
462 32–44, 2019. doi: 10.26480/mjg.01.2019.32.44.
- 463 [13] A. Hooper, H. Zebker, P. Segall, and B. Kampes. A new method for measur-
464 ing deformation on volcanoes and other natural terrains using InSAR persistent
465 scatterers. *Geophysical Research Letters*, 31:L23611, 2004. doi: 10.1029/
466 2004GL021737.
- 467 [14] M. A. Hoque, R. Islam, K. Farhana, N. Abdullah Ali, A. M. A. Kalam, and M. I.
468 Islam. Assessment of groundwater level variation by ANN and ARIMA modeling
469 coupled with Mann–Kendall trend analysis and GIS spatial interpolation. *H2Open*
470 *Journal*, 9:100034, 2026. doi: 10.1016/j.htopen.2026.100034.
- 471 [15] F. M. Ismail, I. M. Shajedul, and S. M. Latifur Rahman. Long-term geospatial
472 assessment of land cover dynamics and surface–groundwater resources in Rajshahi
473 City for sustainable urban management. *Applied Water Science*, 16:51, 2026. doi:
474 10.1007/s13201-025-02722-9.
- 475 [16] B. Li, Z. Wang, J. An, C. Zhou, and Y. Ma. Time-series analysis of subsidence in
476 Nanning, China, based on Sentinel-1A data by the SBAS InSAR method. *PF*

- 477 *Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 2020.
478 doi: 10.1007/s41064-020-00118-9.
- 479 [17] S. Li, W. Xu, and Z. Li. Review of the SBAS InSAR time-series algorithms,
480 applications, and challenges. *Geodesy and Geodynamics*, 13:114–126, 2022. doi:
481 10.1016/j.geog.2021.09.007.
- 482 [18] G. D. Middleton, N. D. Gani, and M. R. Gani. Advancing geohazard monitor-
483 ing: Sentinel-1 InSAR observations of land subsidence in northern and central
484 Bangladesh. *Geological Journal*, 60:1106–1128, 2025. doi: 10.1002/gj.5206.
- 485 [19] R. J. Nicholls et al. Land subsidence: a global challenge. *Science of the Total*
486 *Environment*, 778:146193, 2021. doi: 10.1016/j.scitotenv.2021.146193.
- 487 [20] F. Raspini, F. Caleca, M. Del Soldato, D. Festa, P. Confuorto, and S. Bianchini.
488 Review of satellite radar interferometry for subsidence analysis. *Earth-Science*
489 *Reviews*, 235:104239, 2022. doi: 10.1016/j.earscirev.2022.104239.
- 490 [21] M. S. Sarker, A. S. M. M. Kamal, M. Z. Rahman, and A. K. F. Fahim. Land
491 subsidence monitoring using InSAR technique in the southwestern region of
492 Bangladesh. *Geomatics, Natural Hazards and Risk*, 15:2333795, 2024. doi:
493 10.1080/19475705.2024.2333795.