

Article

Risk Assessment of Land Subsidence Hazard Due to Groundwater Depletion for Water Conservation

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Abstract

Hazard risk monitoring of groundwater depletion and land subsidence due to excessive groundwater extraction is crucial for groundwater resource development, especially in densely populated, small-island developing sites. The island of Bali, Indonesia, represents such an urban environment at risk of land subsidence arising from groundwater depletion. The total percentage of groundwater depletion was calculated and interpolated spatially using measurements of groundwater level from 2008 to 2017 at 18 monitoring well sites available in the area. Furthermore, time-series synthetic-aperture radar (SAR) interferometry processing was applied to estimate the temporal change in land displacement using the Phased Array type L-band SAR (PALSAR) data from 2007 to 2010. The result of downward displacement, signifying subsidence, corresponded with the Global Navigation Satellite System (GNSS) data measurements at stations distributed in the observed subsided areas, i.e., CDPN and CPBI. The displacement varied consistently with changes in groundwater level. In regard to maintaining groundwater utilization, the hazard–risk relation of the groundwater depletion, i.e., low (<10%), moderate (10–25%), and high (>25%), and the presence/absence of subsidence were utilized to classify groundwater conservation into safe, vulnerable, critical, and damaged zones. This application can be considered effective in providing spatial information for sustainable groundwater management.

Keywords: geoinformation; groundwater depletion; land displacement; SAR remote sensing; spatial data analysis; water conservation



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1. Introduction

In recent decades, groundwater has become one of the most important sources of water among the available resources throughout the world [1–3]. The importance of groundwater as a water resource is increasing as a result of the continuous growth of the global population, which is predicted to exceed 11 billion in 2100 [2]. Nevertheless, many cities are currently facing severe water resource instability [4], with developing and poor urban areas being the most vulnerable to such instability. A total of 21 of the world’s 33 megacities are located on the coast, and in Asia, for example, more than one billion people live within 100 km of the sea [5]. The impact of climate change on water resources and their management has already been seen in various regions around the globe [6]. In 2010, one-fifth of the world’s population, roughly 1.2 billion people, were living in areas with water scarcity. Following projected urban and industrial water use, this

number will double to 2.4 billion by 2050 [5]. From these figures, it is clear that sustainable water resource management, particularly of groundwater, is critical to maintaining water demand. In many areas, a lack of management measures for groundwater utilization has led to the extensive over-exploitation of this resource, inducing groundwater depletion and thereby becoming a threat to the sustainable development of socioeconomic and ecological health [1,4].

Concerning groundwater resource management, the development and integration of pilot case studies on hazard–damage relationships at local or regional scales are essential to provide information for relevant agency managers and policy makers [7–9]. Despite its criticality, the relationship between hazards and damage is poorly studied [7]. Regarding the inter-correlation of water-related hazards with damage to land, such as land subsidence, it is considered advantageous as a parameter in assessing the phenomenon of groundwater depletion. Land subsidence can be defined as a geological phenomenon that causes a slow lowering of ground surface elevation [10]. One of the factors responsible for land subsidence is groundwater extraction [11,12]. Land subsidence also impacts groundwater in that it reduces the capacity of aquifers to store water [13].

Land deformation measurements derived from InSAR data processing [14,15] allow a method to be employed to estimate the groundwater level; this is particularly true of confined aquifers that are below the land surface [16,17]. Land deformation results from soil compression caused by groundwater extraction and natural consolidation processes [18]. The extraction of groundwater decreases the pressure in the pore water; this increases the effective stress and causes the compaction of both aquifers and aquitards. The resulting increase in the groundwater's elevation is similar to the total volume of compacted soil throughout the confined aquifer system [18,19]. In unconfined or partially confined aquifers, the response of the surface to groundwater extraction may be delayed or less significant because of the more complex hydro-mechanical interplay [9]. As a result, while the deformation derived from InSAR is effective at estimating changes in confined aquifers, it is important to consider the limitations of this approach when interpreting subsidence in unconfined systems, and the relationship between extraction and land subsidence may differ across aquifer types [19]. Due to the lack of conventional groundwater level measurement owing to inherent shortcomings, InSAR-derived land deformation data present a novel technique that is efficient for producing information necessary for groundwater-related estimation.

The utilization of the InSAR technique, which facilitates measurements with centimeter-scale accuracy, makes it possible to assess deformation due to groundwater pumping activities. For instance, elastic storage coefficients have been effectively estimated using collocated InSAR and well measurements [20,21]. Furthermore, it was possible to perform a long-term analysis of aquifer system responses to pumping based on InSAR time-series analysis using the Persistent Scatterer (PS) method [22,23] and Small Baseline Subset (SBAS) method [19,24–26]. These methods highlight the advantages of the advanced InSAR technique for obtaining groundwater levels based on time-series land deformation measurements. Moreover, regarding the evaluation of InSAR results, centimeter-scale elevation accuracy can be achieved through measurement of continuous satellite navigation technology such as a Global Navigation Satellite System (GNSS) [27–29].

Groundwater is primarily supplied for domestic usage in urban areas and for irrigation in agricultural areas [2]. The application of InSAR can be challenging in different areas, such as urban and agricultural regions. Conventional InSAR processing encompasses decorrelation of the interferometric signal. Moreover, the characteristic electrical changes in scatterers lead to the appearance of temporal and geometric decorrelations. Time-series SAR interferometry represents an advanced technique of differential InSAR. It

involves processing multiple SAR images acquired at different times over the same area through an effective data processing and analysis procedure to extract information on phase displacement from the other phase components [30]. The analysis enables a decrease in atmospheric and topographic errors to reduce signal decorrelation and residuals. The PS [31–33] and SBAS [34,35] methods of time-series InSAR have been mainly applied to the study of the temporal evolution of land deformation. These methods offer a temporal solution based on the principle of dominant reflectivity of centers of permanent scatterers to dilute the uncorrelated phenomena [32]. The PS method mainly records Persistent Scatterer (PS) reflectors, such as those found in urban areas, whereas the SBAS method responds to Distributed Scatterers (DSs), which are typically found in agricultural regions [30] where the groundwater level information is available in areas with wide area coverage. Although InSAR is commonly employed for detecting land subsidence and analyzing groundwater, the majority of research treats these processes in isolation and never incorporates them into a cohesive geospatial hazard-risk framework for groundwater conservation. This gap is especially clear in small, quickly urbanizing island settings like Bali, where actual conservation zoning based on both groundwater depletion and subsidence indicators is still limited.

In this study, the utilization of time-series InSAR to retrieve land displacement is proposed to assess the change in groundwater level in urban and agricultural regions on the island of Bali, Indonesia. Despite its importance, groundwater has become an issue on the island due to risks related to large-scale groundwater extraction [36–40]. Appropriate water management is crucial for sustainable groundwater development. Information regarding the groundwater condition, such as the water level, is fundamental for resource development strategies in the area [40]. In this regard, in this study, the distribution of land displacement generated from time-series InSAR processing using the PS and SBAS methods is integrated with the distribution of groundwater level interpolated from monitoring well site data in order to evaluate the correlation of land subsidence with groundwater depletion in the area. Geospatial information on groundwater depletion throughout Bali Province, Indonesia, is presented based on the analysis, with this information being essential for the development of groundwater utilization strategies for sustainable water management.

2. Materials and Methods

2.1. Study Area

The research region of Bali (Figure 1) is between 8°03'14" and 8°50'48" S and 114°25'53" and 115°20'02" E. Bali Province is about 5632 km² in size and includes a number of smaller islands nearby, such as Nusa Penida, Nusa Lembongan, Nusa Ceningan, Serangan, and Menjangan. Denpasar City is the capital of the province, which also has eight regencies. Bali's physiography contains large alluvial plains and volcanic highlands that have a big effect on its hydrogeological setting. Most of the time, groundwater is found in unconfined alluvial aquifers and semi-confined volcanic and limestone aquifers. The hydrogeological regime is made up of shallow alluvial deposits that are usually less than 50 m deep and deeper volcanic aquifers that are between 50 and 150 m deep. These are the principal sources of water for homes and farms. About 61.3% of the land in the research region is used for dryland agriculture, 23.4% is forest, and 14.3% is wetland rice fields. The most common types of soil are alluvial, Regosol, Andosol, Latosol, and Mediterranean. Most of the alluvial soils are on the western side of the island, especially in Jembrana Regency. Most of the Latosols are in the south, in places like Badung Regency and Denpasar City. Regosols are mostly found in the northern section of Karangasem Regency and in Singaraja Regency [41]. Groundwater level interpolation was carried out from 18 observation wells over a study area of 5632 km². It is a relatively low density that

might pose limitations on the accuracy of values in some places, especially where complex geology might be involved between transition zones, and should be kept in mind while interpreting spatial patterns of groundwater depletion.

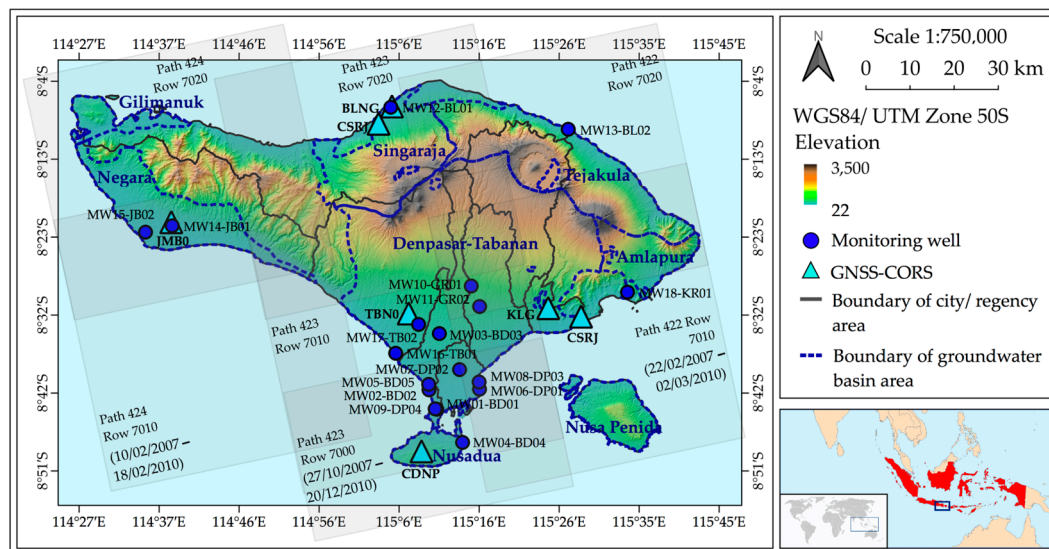


Figure 1. Map of the study area in Bali, Indonesia. The groundwater basin is delineated into eight basins based on the Presidential Law of Indonesia Number 26 Year 2011. There are seven Continuously Operating Reference Stations (CORSs) of the Global Navigation Satellite System (GNSS) and 18 monitoring wells distributed in the area.

2.2. Data Sources and Instruments

Well data and satellite data were used as data sources for analysis. The well data consists of groundwater level measurements at monitoring wells. A report on groundwater level measurement from 2008 to 2013 at 18 monitoring wells in the study area was provided by the Ministry of Mining and Natural Resources (ESDM) of Indonesia in Bali Province (see Table 1). These 18 wells were chosen because they represent the typical coverage of urban, agricultural, and coastal regions, and they capture the typical variation in groundwater levels across the area. Despite the limited number of wells, their distribution is strategic, which ensures that they have sufficient data to perform spatial interpolation and to integrate with InSAR-derived water table fluctuations. This enables the assessment of groundwater depletion and its association with land subsidence. The monitoring wells (see Figure 1) are distributed within the groundwater basin boundaries. A groundwater level measurement was conducted in 2017 at the monitoring wells through field observation by utilizing a water-level measurement tool. Additionally, a handheld GPS was used to record and check the position information of the wells.

The primary data used for generating land subsidence information were satellite data, i.e., SAR data of the PALSAR from the Advanced Land Observing Satellite (ALOS), Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM), and GNSS-CORS data. Open-source computer software was employed for the processing of satellite data. InSAR processing was conducted using GMT5SAR software <https://topex.ucsd.edu/gmtsar/>, accessed on 20 December 2025 (Scripps Institution of Oceanography, University of California, San Diego, CA, USA); this software runs on the UNIX operating system using C codes [42,43]. RTKLIB software <https://www.rtklib.com/rtklib.htm>, accessed on 20 December 2025 (Tokyo University of Marine Science and Technology, Tokyo, Japan) was specifically utilized for GNSS positioning based on the CORS data [44,45]. Moreover, the QGIS image processing software (Spatial Planning and Information, Department

of Land Affairs, East London, South Africa) was used to view, edit, and analyze geospatial information from the processed satellite data [46,47].

Table 1. Monitoring well data of groundwater level in Bali, Indonesia.

Well Number	Monitoring Well ID	Construction Year	Depth (m)	Groundwater Level (m Below Ground Surface)						
				2008 ¹	2009 ¹	2010 ¹	2011 ¹	2012 ¹	2013 ¹	2017 ²
1	MW01-BD01	1996	50	6.25	6.40	6.00	6.35	6.50	6.00	6.10
2	MW02-BD02	1997	50	6.30	6.86	6.70	6.80	7.82	6.35	7.74
3	MW03-BD03	2002	40	2.15	2.20	1.75	1.84	3.01	3.50	3.20
4	MW04-BD04	2003	40	3.60	3.80	4.05	4.38	3.78	3.70	4.58
5	MW05-BD05	2004	65	15.75	16.57	16.20	16.75	15.05	18.20	17.66
6	MW06-DP01	1997	50	2.85	2.67	3.25	3.37	3.87	3.20	3.18
7	MW07-DP02	2001	40	8.45	8.45	6.25	6.38	8.45	7.00	6.30
8	MW08-DP03	2004	60	2.55	2.66	3.16	3.25	2.85	3.20	3.63
9	MW09-DP04	2008	60	-	6.25	9.01	9.21	7.69	8.70	10.39
10	MW10-GR01	1998	90	39.15	39.40	39.15	39.40	40.08	39.30	39.20
11	MW11-GR02	2009	60	7-	-	7.85	7.85	7.16	12.10	12.00
12	MW12-BL01	1998	40	0.55	0.55	0.50	0.58	0.75	0.50	0.48
13	MW13-BL02	2007	60	7.35	7.10	6.75	7.00	7.66	7.12	7.08
14	MW14-JB01	2006	60	10.35	10.27	9.82	9.95	10.74	9.50	10.61
15	MW15-JB02	2006	60	17.26	17.50	17.20	16.00	16.83	16.00	17.53
16	MW16-TB01	2005	60	8.47	8.55	7.85	7.90	8.26	8.00	8.20
17	MW17-TB02	2008	65	-	7.82	8.25	8.34	7.87	8.50	8.55
18	MW18-KR01	2007	70	4.68	6.87	4.25	7.60	4.82	7.25	7.32

¹ Data collected from the ESDM of Indonesia in Bali Province; ² field observations of groundwater level.

Seven ALOS PALSAR track acquisitions cover the entire study area (see Figure 1), with a total of 63 scenes from 2007 to 2010. The tracks consist of three paths, i.e., path numbers 422, 423, and 424, with two, three, and two rows, respectively (see Table 2). The data characteristics used for the analysis were fine mode, single polarization (HH), processing level of 1.0, 236 mm wavelength, 46-day orbital revisit period, ascending, 34.3° incidence angle, and 13.1 km critical baseline [48,49]. Based on the look-direction characteristic of PALSAR, the azimuth (compass) direction of the radar illumination is perpendicular to and oriented toward the right of the satellite track [50,51]. Put simply, based on Figure 1, the illumination azimuth direction is East North East (ENE). Moreover, one scene of the SRTM DEM data was utilized for topographic phase removal of InSAR processing. The data was SRTM 1 Arc-Second Global elevation data that extends to latitudes of $\pm 60^\circ$ and has a resolution of 1 arc-second, or approximately 30 m [52]. In order to evaluate the InSAR-derived land displacement, data recorded at three CORSs, i.e., CSRJ, CDPN, and CPBI (see Table 3), that provide GNSS data consisting of carrier phase and code range measurements were used to generate ground surface elevation in subsided areas. GNSS enables autonomous global geospatial positioning [28,53]. CORS networks have been rapidly installed in Indonesia to provide practical measurement capabilities, in addition to high-accuracy positioning [54].

Table 2. List of multi-temporal Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic-Aperture Radar (PALSAR) data covering the entire area of Bali from 2007 to 2010 for Interferometric Synthetic-Aperture Radar (InSAR) time-series processing.

Path	Scene ID	Acquisition Date (yyyy/mm/dd)	Number of Days	Baselines for InSAR Processing with a Super Master			
				Temporal Baseline (Days)	Perpendicular Baseline (m)		
					Row 7000	Row 7010	Row 7020
422	05740	2007/02/22	417	(Super Master)	-	0	0
	09766	2007/11/25	693	276	-	−280	−262
	11108	2008/02/25	785	368	-	−566	−535
	11779	2008/04/10	831	414	-	−579	−543
	15134	2008/11/27	1061	644	-	623	597
	16476	2009/02/27	1152	735	-	121	107
	20502	2009/11/30	1428	1011	-	26	30
	21173	2010/01/15	1474	1057	-	−209	−199
	21844	2010/03/02	1520	1103	-	−247	−231
423	09343	2007/10/27	664	(Super Master)	0	0	0
	10014	2007/12/12	710	46	−274	−271	−269
	10685	2008/01/27	756	92	−482	−472	−464
	14711	2008/10/29	1032	368	770	725	681
	15382	2008/12/14	1078	414	732	691	651
	16053	2009/01/29	1123	459	427	393	358
	20079	2009/11/01	1399	735	103	88	72
	21421	2010/02/01	1491	827	−62	−66	−71
	26118	2010/12/20	1813	1149	−962	−943	−926
424	05565	2007/02/10	405	(Super Master)	-	0	0
	09591	2007/11/13	681	276	-	−154	−134
	11604	2008/03/30	819	414	-	−992	−956
	14959	2008/11/15	1049	644	-	838	814
	15630	2008/12/31	1095	690	-	279	260
	16301	2009/02/15	1140	735	-	279	443
	20327	2009/11/18	1416	1011	-	−76	−71
	20998	2010/01/03	1462	1057	-	−181	−171
	21669	2010/02/18	1508	1103	-	−301	−283

Table 3. List of Continuously Operating Reference Stations (CORSs) in Bali from 2008 to 2010 for Global Navigation Satellite System (GNSS) data measurement ¹.

Station	Station ID	Location	Latitude	Longitude	Height (m)	Data Period	Distance (km)
Base station	CSRJ	Singaraja	−8.1497	115.0580	60.33	2008–2010	-
Rover station	CDNP	Denpasar	−8.8181	115.1456	234.52	2008–2010	74.97
Rover station	CPBI	Bukit Tengah	−8.5433	115.4708	278.75	2008–2010	63.07

¹ Data obtained from the Indonesian Geospatial Information Agency (BIG).

2.3. Research Scheme

A research scheme (see Figure 2) was developed for the hazard risk assessment of groundwater depletion due to land subsidence. The method was applied to the study

area of Bali, Indonesia, which represents a small-island developing site with limited water resources. Information on InSAR-derived subsidence distribution was integrated with groundwater depletion information calculated from monitoring well data. Specifically, the InSAR result was compared with GNSS-CORS data measurement. Lastly, a map was produced to present the conservation zones that were found to be vulnerable to land subsidence as a result of groundwater utilization, based on spatial information of groundwater depletion. Such measures are essential for sustainable groundwater management.

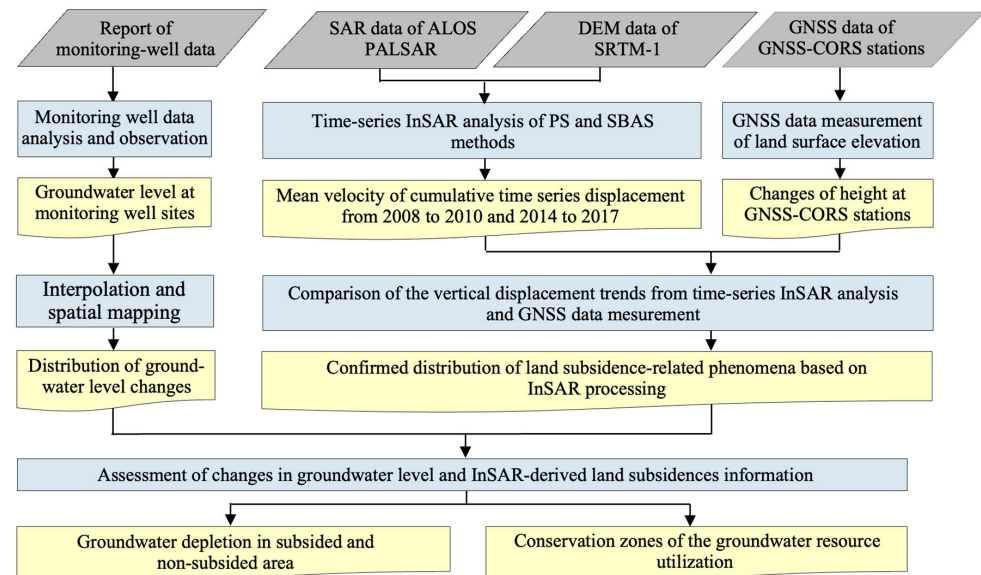


Figure 2. The scheme of hazard risk assessment for land subsidence caused by groundwater depletion. SAR: synthetic-aperture radar; ALOS: Advanced Land Observing Satellite; PALSAR: Phased Array type L-band SAR; DEM: Digital Elevation Model; SRTM: Shuttle Radar Topography Mission; GNSS: Global Navigation Satellite System; CORS: Continuously Operating Reference Station; InSAR: Interferometric SAR; PS: Persistent Scatterer; SBAS: Small Baseline Subset.

2.4. Groundwater Depletion Monitoring

Groundwater depletion was calculated using the collected secondary data of groundwater level from 2008 to 2013 and field observation data from 2017. The percentage of groundwater depletion (Δh) was determined using groundwater level in the initial year (h_1) and groundwater level in the final year (h_2) of the data in 2008 and 2017, as follows:

$$\Delta h = \left(\frac{h_1 - h_2}{h_1} \right) \times 100\% \quad (1)$$

The total groundwater depletion was determined by subtracting the final groundwater level from the initial level in the period 2008–2017 for each monitoring well. The values of total groundwater depletion (in percent) were input into the monitoring well points as vector data. The information was then interpolated to create a map of the distribution of groundwater depletion throughout the study area. Despite the fact that the InSAR analysis covers 2007–2010, it primarily captures the main subsidence response to groundwater extraction; the temporal discrepancy may introduce a minor error, which can be addressed in future studies using continuous data from the InSAR system.

Spatial interpolation involves the use of vector points with known values to estimate values at locations where the value is unknown to create a raster surface covering an entire area. The interpolation result is typically a raster layer. It is important to find a suitable interpolation method to optimally estimate values for unknown locations [55]. For the distribution of groundwater depletion, the interpolation was performed in the

QGIS application using the Inverse Distance Weighting (IDW) method. In this method, the sample points are weighted during interpolation such that the influence of one point relative to others declines with distance from the unknown point that will be created. Weighting is assigned to sample points through the use of a weighting coefficient that controls how the weighting influence will decline as the distance from the new point increases. The greater the weighting coefficient, the less influence distant points from the unknown point will have during the interpolation process. As the coefficient increases, the value of the unknown point approaches the value of the nearest observational point [55]. In general, values greater than or equal to 1 are used for the coefficient. The weighting coefficient was set to 2, which represents the default value known as the inverse distance squared weighted interpolation. The coefficient was adjusted to a number suitable for analysis. The set value resulted in a few different surfaces at a larger distance from nearby points. A weight coefficient of 2 was selected based on sensitivity analysis, which showed minimal variation (<5%) in spatial distribution patterns for coefficients between 1.5 and 2.5.

2.5. Land Displacement Measurement

Measurements of land subsidence were mainly derived from InSAR analysis. Fundamentally, the InSAR technique combines two SAR scenes acquired at different times in the same area, which are then used to generate an interferometric pair [56]. For the measurement of the phase difference caused by ground movement, the differential interferometric (DInSAR) phase for a pixel is composed of phase components as follows [57,58]:

$$\phi_{\text{DInSAR}} = \phi_{\text{defo}} + \phi_{\text{res\_topo}} + \phi_{\text{atmo}} + \phi_{\text{noise}} \quad (2)$$

More recently, advanced time-series InSAR has been developed to overcome some of the limitations of conventional InSAR. The technique involves the use of multi-temporal SAR scenes to reduce atmospheric effects by stacking multiple interferograms. The most common time-series InSAR techniques are PS and SBAS, which are able to provide millimeter-scale precision in deformation mapping [30]. PS is appropriate for retrieving PSs with a single master for baseline configuration and pixel selection criteria based on amplitude dispersion [30,32,33,58]. Conversely, SBAS is suitable for deriving DSs by executing a small baseline configuration and a coherence-based pixel selection criterion [34,35]. In this study, the PS and SBAS methods were combined (see Figure 3) in order to enable displacement to be observed both in urban and agricultural regions. The data processing step conducted using GMT5SAR consists of preprocessing, focus and alignment, pair selection, topographic phase removal, phase filtering and unwrapping, and layer stacking. The time-series technique in GMT5SAR is generated by performing a layer-stacking process whereby the input interferograms are processed using batch processing. The characteristics of the data type affect the parameter values for processing [43].

The first step of the InSAR process was the preprocessing of raw SAR data and orbital information to extract orbit and baseline estimation, i.e., orbital position, velocity, near range, and Doppler centroid. Secondly, the images were focused to create two single-look complex (SLC) images, and the repeat images were aligned with the reference image. The third step was the pair selection of the interferograms based on the PS and SBAS methods. One scene was selected as a super master (reference scene) that was common to the other scenes employed as slaves (repeat scenes), following the PS method. Each surrogate master needs to be aligned with the super master before it can provide a surrogate. Conversely, certain maximum baselines are required for pair selection in the SBAS method. The baselines for SBAS pair selection were determined at 2500 days for the temporal baseline and 1000 m for the perpendicular baseline. Considering the long wavelength of ALOS PALSAR data [48–51], the large baselines are acceptable for the process. Despite

the fact that these starting points are longer than the recommended duration of SBAS (60 cm), the long wavelength of ALOS PALSAR (23.6 cm) will reduce the temporal and spatial correlation, which will allow for the reliable estimation of phase over long baselines. Previous investigations have demonstrated that L-Band SBAS processing can maintain consistency with temporal baselines that are longer than 2000 days and perpendicular baselines that are up to 1000 m. This is particularly true of regions that are both urban and agricultural [49,50]. The experimental validation of this research demonstrated that interferograms with these thresholds produced consistent results that were minimally dependent on the decorrelation; these results supported the selected criteria for choosing an SBAS pair.

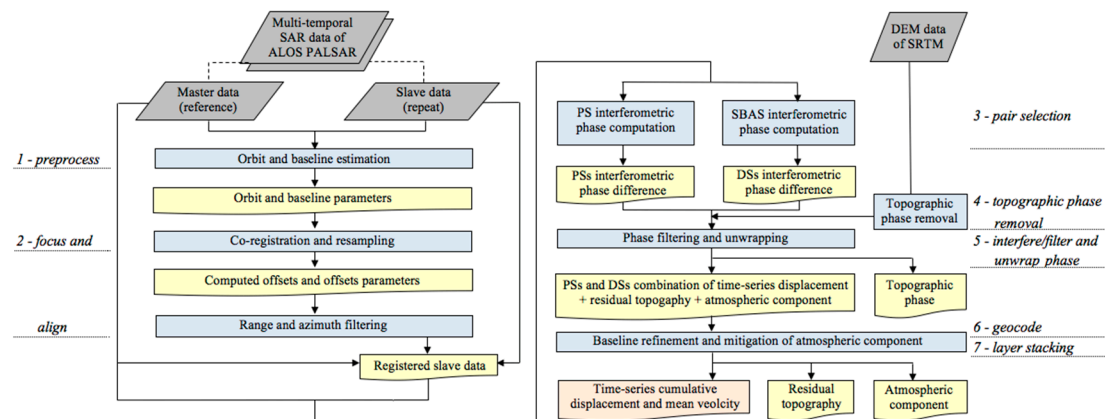


Figure 3. Extraction of time-series displacement based on the PS and SBAS InSAR methods. SAR: synthetic-aperture radar; ALOS: Advanced Land Observing Satellite; PALSAR: Phased Array type L-band SAR; DEM: Digital Elevation Model; SRTM: Shuttle Radar Topography Mission; PS: Persistent Scatterer; SBAS: Small Baseline Subset; PSs: Persistent Scatterer; DSs: Distributed Scatterers.

The subsequent step after pair selection was DEM generation for topography removal and to transform the DEM from longitude, latitude, and topography into range, azimuth, and topography. The next step involved handling the reference and repeating SLCs using the DEM generated from the topographic phase removal, followed by filtering, unwrapping, and geocoding. The processes of interfering, filtering, and unwrapping computed amplitude, phase, and coherence images of the interferograms without the effect of topographic phase. Specifically, the geocoding process transformed all of the products from the range/azimuth coordinate system to longitude and latitude. The parameters of the Gaussian filter wavelength, perform land mask, and unwrap and geocode threshold that needed to be set in the configuration file were Gauss 300, 1 (perform), and 0.45, respectively, for both the PS and SBAS interferograms. Subsequently, layer stacking was conducted to stack the generated interferograms. For SBAS layer stacking, the other parameters for the smoothing factors, namely, wavelength, incidence angle, range, and atmospheric correction, were 0.2362 m, 34.3°, 850,014–848,965, and 1 (perform), respectively.

A comparison of the InSAR result with RTK-GNSS measurements as a reference was carried out for evaluation. Fundamentally, RTK is able to perform measurements with up to centimeter-level accuracy by employing phase measurements of the signals' carrier wave and relying on a single reference station or interpolated virtual station to perform real-time corrections [59,60]. The time required for a signal to travel from the satellite to the receiver is used to calculate the distance between the receiver and the satellite [26]. The data format of GNSS-CORS data downloaded from a receiver was converted into the ASCII format of the Receiver Independent Exchange Format (RINEX).

In regard to the data in the study area (see Table 3), the observation types of L1, L2, C1, P2, S1, and S2 recorded every 30 min can be processed using RTKLIB software. The input for the data consisted of rover, base station, navigation, precise clock, and Earth Orientation Parameters (EOPs). Parameters for running the calculation through the RTK-post tool of RTKLIB, i.e., positioning mode, frequencies/filter type, elevation mask/SNR mask, ionosphere correction, troposphere correction, and satellite ephemeris/clock, were set to static, L1+2 (combined), 15, estimate Slant Total Electron Content (STEC), estimate Standard Deviation (STD), and precise, respectively [45].

3. Results

Hazard risk spatial information of groundwater change and land displacement was extracted from the data analysis. The distribution of land displacement was constructed based on a mean velocity map of InSAR time-series displacement for approximately three years (February/October 2007 to February/December 2010). The result was evaluated with the trend of GNSS-CORS land surface elevation measurements at stations located in subsided areas. Furthermore, a map of groundwater change percentage was established to represent the changes in groundwater level based on the observed land subsidence. In order to present essential information for water conservation measures, vulnerability levels of high, moderate, and low were determined, corresponding to the hazard risk assessment.

3.1. Spatial Information of Groundwater Change

The percentage of total groundwater change from 2008 to 2017 at 18 monitoring wells was interpolated and mapped (see Figure 4) to present spatial information of the distribution of groundwater change throughout the study area. The total percentage of groundwater change ranged from -66.24 to 25.24% (positive values indicate an increase in groundwater level, and negative values indicate a decrease). Spatially, the majority of the large decreases in groundwater levels were located in coastal and urban areas that were low-lying. This is caused by the large number of people who take part in groundwater extraction, including homes, tourists, and businesses. Conversely, the groundwater levels in interior and upland areas were either consistent or increasing. This implies that the pressure to draw water was lower and the natural capacity to recharge was more powerful.

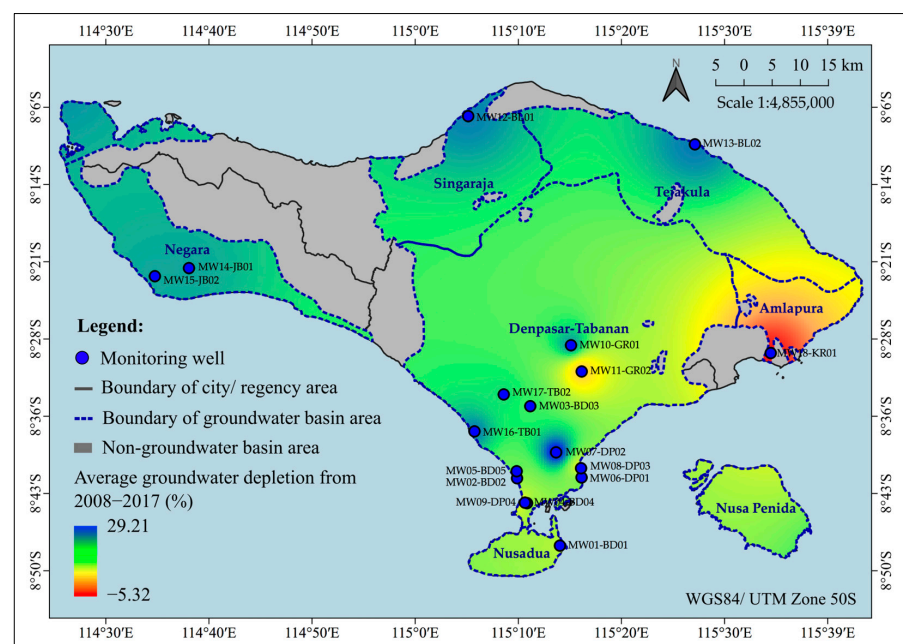


Figure 4. Spatial distribution of groundwater level changes in Bali, Indonesia, from 2008 to 2017.

The volume of the groundwater decreased significantly twice. During the first phase (2008–2012), the groundwater level decreased significantly, especially in Bali's southern region. This implies that the increase in cities' growth rates is causing them to consume groundwater more rapidly. The second phase (2013–2017) saw some areas have a stable and partial recovery of groundwater levels. This is presumably caused by alterations to the way water is utilized, the most significant of which is the increased utilization of surface water, or changes in the climate that affect the recharge process. These differences over time demonstrate the variability of groundwater conditions; this is why it is important to assess them at the appropriate times in order to have the greatest effect.

3.2. Distribution of Land Subsidence

Subsidence was defined based on the InSAR time-series displacement. The InSAR products were estimated using multi-temporal interferograms generated through time-series analysis using the PS and SBAS methods. The PS method was primarily utilized in urban and built-up areas, where there are stable reflectors of radar that are abundant, which enables the reliable identification of persisting scatterers. Conversely, the SBAS method was utilized in agricultural and non-urban areas; the landscape comprised scattered trees and shrubs, the land use was variable, and the vegetation was dense. The outcomes of both methods were spatially combined by combining PS-derived land subsidence values in urban areas with SBAS-derived values in agricultural regions to create a continuous map of land subsidence across the study area. In regard to the PS pairs, eight interferograms for each track (providing a total of 58 interferograms for the seven tracks) were created, with scenes 05750, 09343, and 05565 (see Table 1) as the supermasters for paths 422, 423, and 424, respectively, based on their capacity to cover the territory fully and minimize the perpendicular baselines between the pairs of interferometry. As illustrated in the base distribution plot (Figure 5), the selected super master scenes are situated near the center of the base configuration, with the perpendicular component of the base value close to zero. This will ensure improved coherence and accurate displacement estimates.

In the case of SBAS pairs, a total of 84 interferograms were extracted within 1000 m of the perpendicular baseline and within 950 days of the temporal baseline. A different number of interferogram pairs was generated for each track, i.e., 31, 31, 25, 27, 28, 28, and 29 interferogram pairs for path 422 row 7010, path 422 row 7020, path 423 row 7000, path 423 row 7010, path 423 row 7020, path 424 row 7010, and path 424 row 7020, respectively. The time series of cumulative displacement and mean velocity of the InSAR results indicated upward (+) and downward (−) displacement from 2007 to 2010 in the entire study area. While average trends provide a good overview, significant local variations are observed, particularly between urban and rural areas, or between coastal and inland regions. These differences highlight the importance of spatial distribution monitoring for accurately assessing land subsidence risk. Figure 6 shows the standard deviation of InSAR measurements at each time point and illustrates the spatial variability of land subsidence within the study area.

The calculated mean displacement velocity (see Figure 7), which ranged from −8.4 to 8.4 mm/yr, was used to estimate subsided and non-subsided sites. Areas with upward (+) displacements (i.e., with no subsidence) were observed in the northern and eastern regions of Bali. Downward (−) displacements (i.e., subsidence) were distributed in the southern coastal areas, including an area of Denpasar City and the Badung Regency. These areas have been the center of development activity on the island, i.e., settlements and tourism accommodation. Groundwater is mainly utilized to meet domestic water needs [61]. Likewise, subsidence was also measured on the western side of the island. This

area contains irrigated paddy fields that use groundwater as their main irrigation source due to limited water resources [40,62,63].

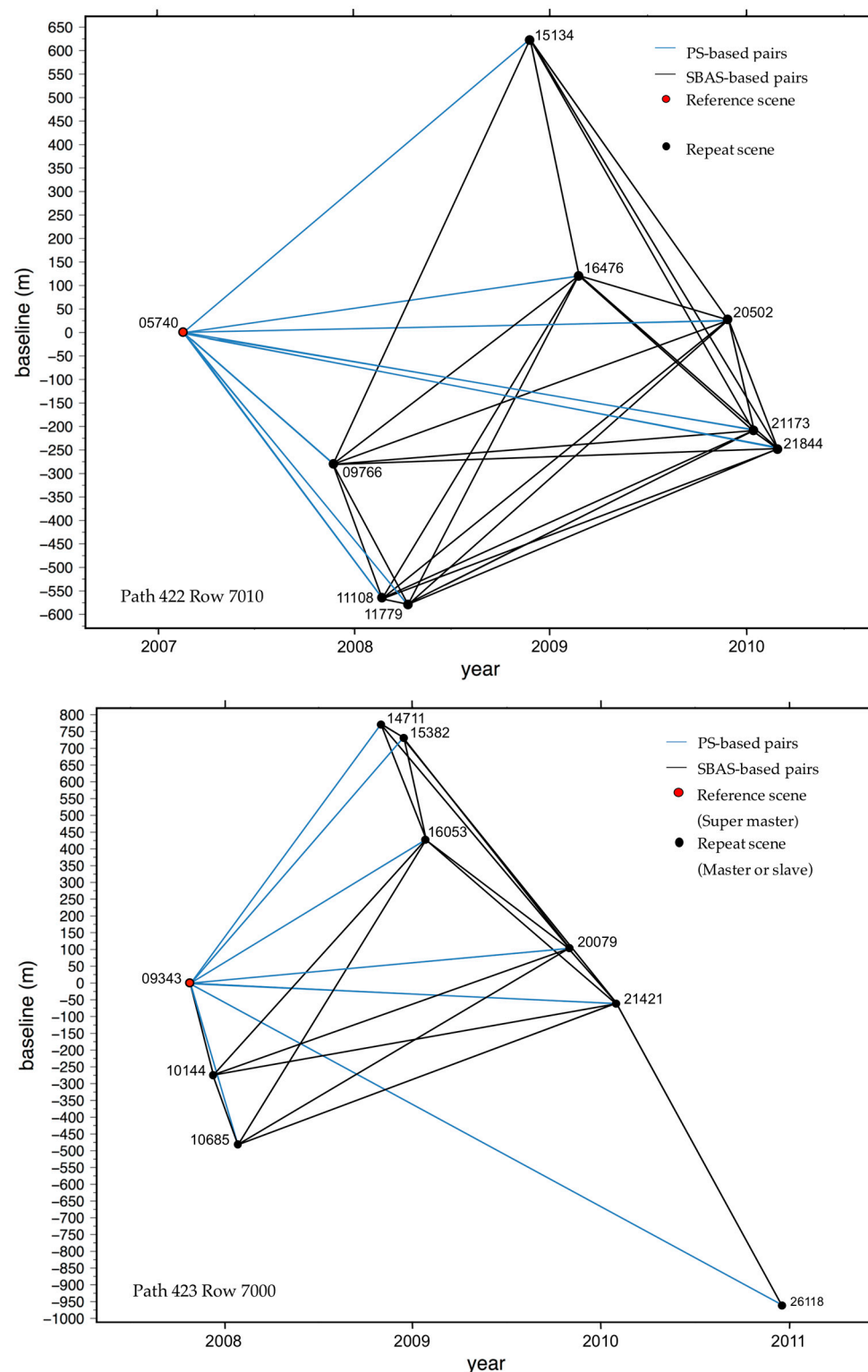


Figure 5. Baseline scatter charts for interferogram pair selection of the PS and SBAS methods of InSAR using the ALOS PALSAR data in Bali from 2007 to 2010. The scatter charts present the baseline distribution for path 422 row 7010, the track with the joint-largest number of interferogram pairs, and path 423 row 7000, the track with the smallest number of interferogram pairs.

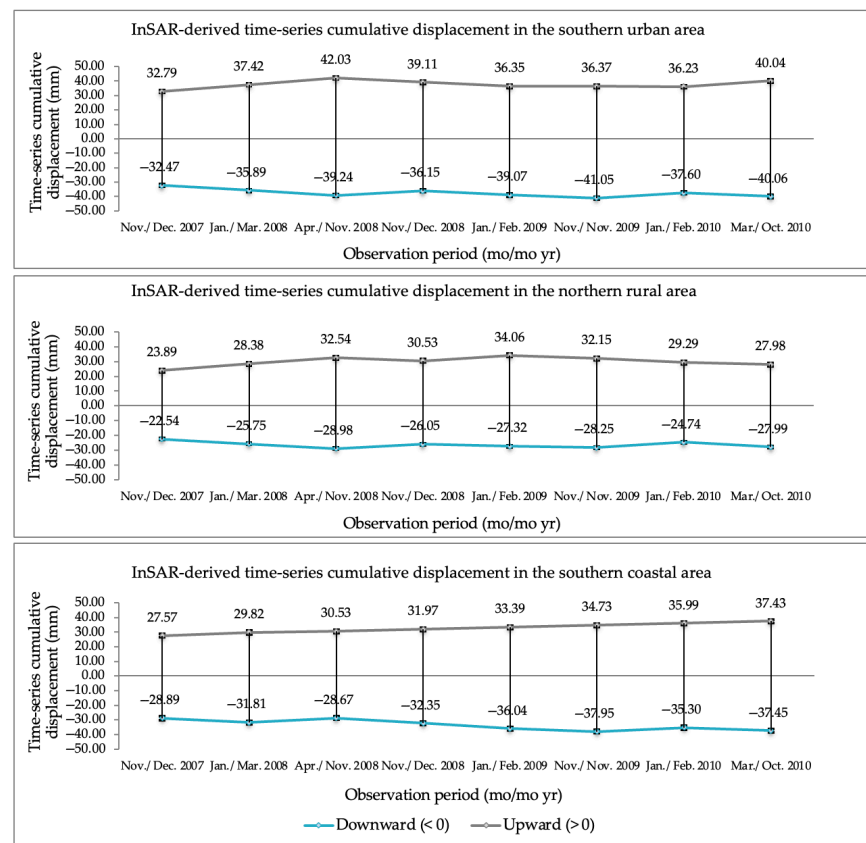


Figure 6. Time-series cumulative displacement generated from InSAR processing throughout the area of Bali, Indonesia, from 2007 to 2010. The displacement values are reported with $\pm 95\%$ confidence intervals.

Additionally, the InSAR measurements were compared to GNSS-CORS data that served as a reference. The vertical displacement was deduced from the displacement in the LOS direction using the angle of incidence, which is the ratio of the two numbers, multiplied by the cosine of the angle of incidence. This approach disregards the potential for horizontal movement, but the area's tectonic stability is relatively high, and horizontal movement is expected to be minimal in comparison to subsidence caused by groundwater depletion. As a result, the simplified calculation provides a concise representation of vertical displacement that is intended to be compared with GNSS data and subsequent groundwater loss assessment. Previous geodetic studies indicate that horizontal movements in Bali are small compared with vertical displacements and thereby justify this simplified vertical-only approach [64,65].

Regarding the GNSS-CORS measurement, the height that represents the land surface elevation in the subsided area was estimated through the RTK-post tool of the RTKLIB processing program using available and processable data. The position of a rover station in the subsided area was measured based on the position of a base station located in the non-subsided area. The distribution of the GNSS-CORSs is shown in the mean displacement velocity map (see Figure 7), which signifies stations in areas with downward (subsided) and upward (non-subsided) displacements. As shown on the map, there are two stations in the subsided area, i.e., CDNP and CPBI, and one station in the non-subsided area, i.e., CSRJ. Based on the distribution of the GNSS-CORSs, stations CDNP and CPBI were designated as rover stations, with station CSRJ as the base station for both rover stations. The reference or base position of the selected base station was set by referring to the latest recorded information of latitude, longitude, and height of the station (see Table 3). The

base station also meets the distance criteria of a base station to rover station distance of less than 80 km [51].

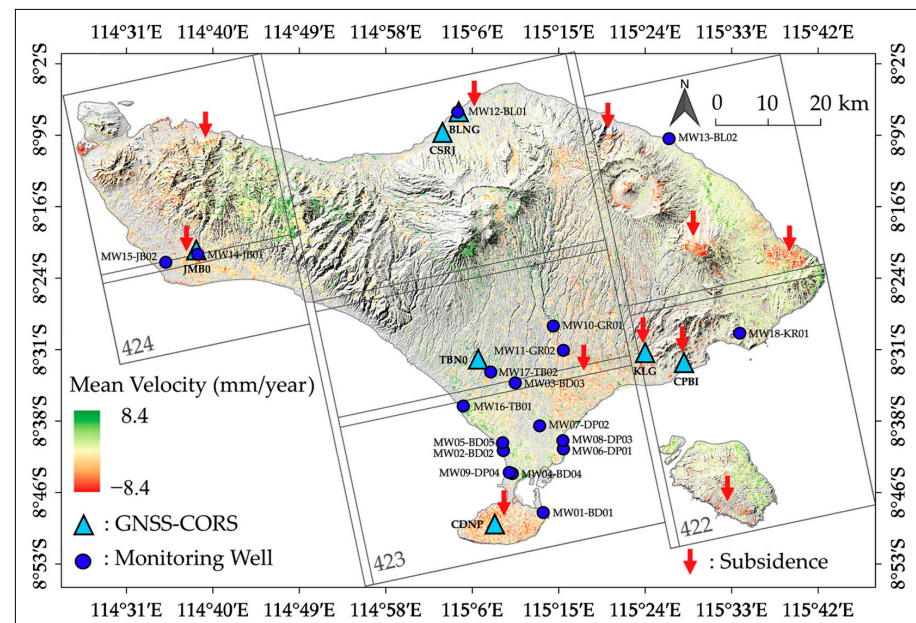


Figure 7. Mean displacement velocity map from InSAR showing subsidence (subsiding areas are indicated by red arrows and red–yellow colors, with groundwater monitoring wells overlaid).

The significant decrease in elevation observed at the CORSs located in the subsiding region, notably CBNP and CPBI (Figure 8), aligns with the subsidence pattern indicated by the InSAR cumulative displacement time series. InSAR measures deformation along the satellite line-of-sight (LOS). To get vertical displacement from LOS displacement, we used the satellite incidence angle and assumed that there was little horizontal motion. This geometric change adds an estimated 10–15% uncertainty to the vertical displacement. Even though there is some ambiguity, the fact that the InSAR-derived subsidence and CORS height reductions happen at the same time confirms the data’s credibility. Furthermore, subsidence zones geographically correlate with drops in groundwater levels at monitoring wells, suggesting that groundwater extraction is a significant factor contributing to deformation in southern Bali.

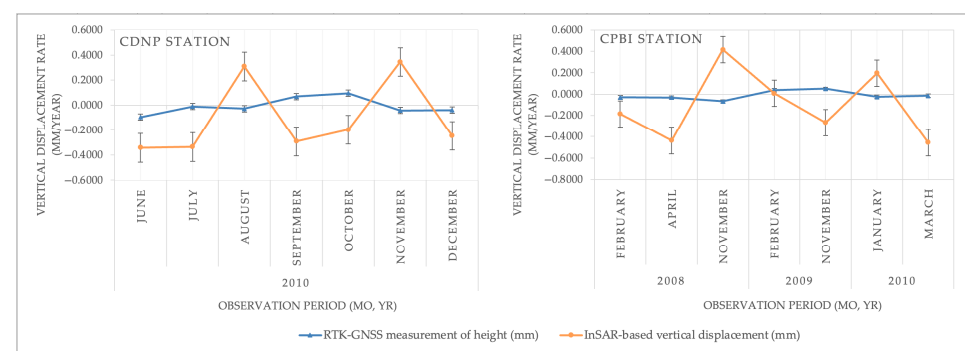


Figure 8. Land displacement measurements generated from InSAR and RTK-GNSS. The InSAR-based measurement represents vertical displacement, and the RTK-GNSS demonstrates the station elevation measurement. The displacement was obtained during a similar observation period. The measurement results at station CBNP cover the period from July to December 2010. The measurement results at station CPBI cover the period from February 2008 to March 2010. The average Root Mean Square Error (RMSE) of the measurements at stations CBNP and CPBI is 0.003.

3.3. Hazard Risk Geospatial-Based Assessment of Groundwater Depletion and Land Subsidence

The values of the average percentage of groundwater level change integrated with the values of downward displacement at each monitoring well were plotted on a graph (see Figure 9) to present a quantitative estimation of the hazard risk correlation between groundwater depletion and land subsidence. Monitoring wells with a decreasing trend of groundwater level changes exhibited downward displacement, denoting subsidence. Based on monitoring well MW04-BD04, which is located in a subsided area, the average groundwater depletion between 2008 and 2017 was 8.03%; in comparison, the average subsidence rate between 2007 and 2010 was 5.58 mm/yr. Conversely, in non-subsided (uplifted) areas, monitoring wells were found to exhibit no trend of decreasing groundwater level. For instance, monitoring well MW12-BL01, which had a negative average groundwater depletion of -0.60% , exhibited a subsidence rate (i.e., uplift) of 3.3 mm/yr.

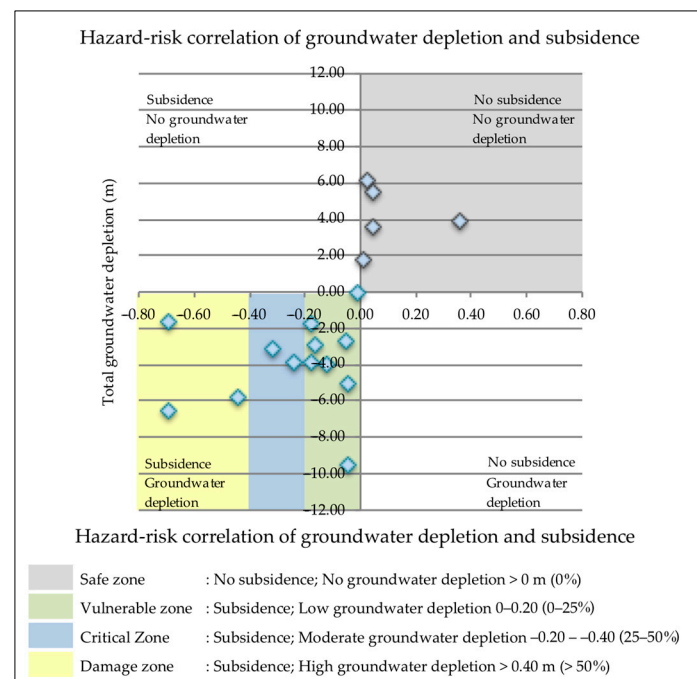


Figure 9. Correlation of groundwater depletion hazard to the risk of land subsidence. The charts plot the total groundwater depletion in 2008–2017 and the subsidence rate in 2007–2010 at 18 monitoring wells. The zonation of groundwater conservation was divided into four zones, i.e., safe, vulnerable, critical, and damaged. The criteria utilized for the classification are the level of groundwater depletion and the absence/presence of subsidence phenomenon.

Furthermore, hazard risk assessment for the zonation of groundwater conservation was performed based on the values of groundwater depletion and land subsidence. The changes in groundwater level related to groundwater depletion and downward displacement, which were considered as subsidence, were classified into four conditions, i.e., safe, vulnerable, critical, and damage zones. Concerning a publication by the local agency of Public Works (DPU) related to the zonation of groundwater conservation [62], the criteria for the zonation (see Figure 9) were determined by considering the significance levels of the decreasing trends of groundwater level or the values of the average percentage of groundwater depletion and the presence/absence of land subsidence. The 10% and 25% thresholds were chosen based on the historical patterns of groundwater depletion and the guidelines of the DPU, which represent low and moderate risk categories, respectively. This method guarantees that the zoning follows both observed hydrological trends and local management methods.

Based on the groundwater conservation zones derived from the hazard risk for land subsidence caused by groundwater depletion (see Figure 10), areas with no groundwater depletion or subsidence, including non-groundwater basin areas, were classified into safe zones. Non-groundwater basin areas are regions where groundwater does not naturally occur or is poorly stored due to insufficient hydrogeological conditions. For instance, structures that obstruct water flow or the absence of productive aquifers. These locations do not utilize significant amounts of groundwater; hence, there are no indications of groundwater depletion or land subsidence. Thus, in accordance with the prevailing regulations governing groundwater usage, these regions may be designated as safe zones. A settlement area with low population density dominated by vegetation such as forests in the northern region of Bali was assigned to this category; for instance, the areas of Tejakula Sub-District, Tejakula District, and Buleleng Regency. Regarding vulnerable zones, areas with subsidence and low (<10%) groundwater depletion in the western region of Bali were classified as vulnerable areas; for instance, a paddy field area in Manis Tutu Sub-District, Melaya District, Jembrana Regency. In 2017, the total area of paddy fields reached 6757 ha in the Jembrana Regency. Groundwater is mainly utilized in the area for irrigation systems, with a total requirement of 10,135.50 L [40].

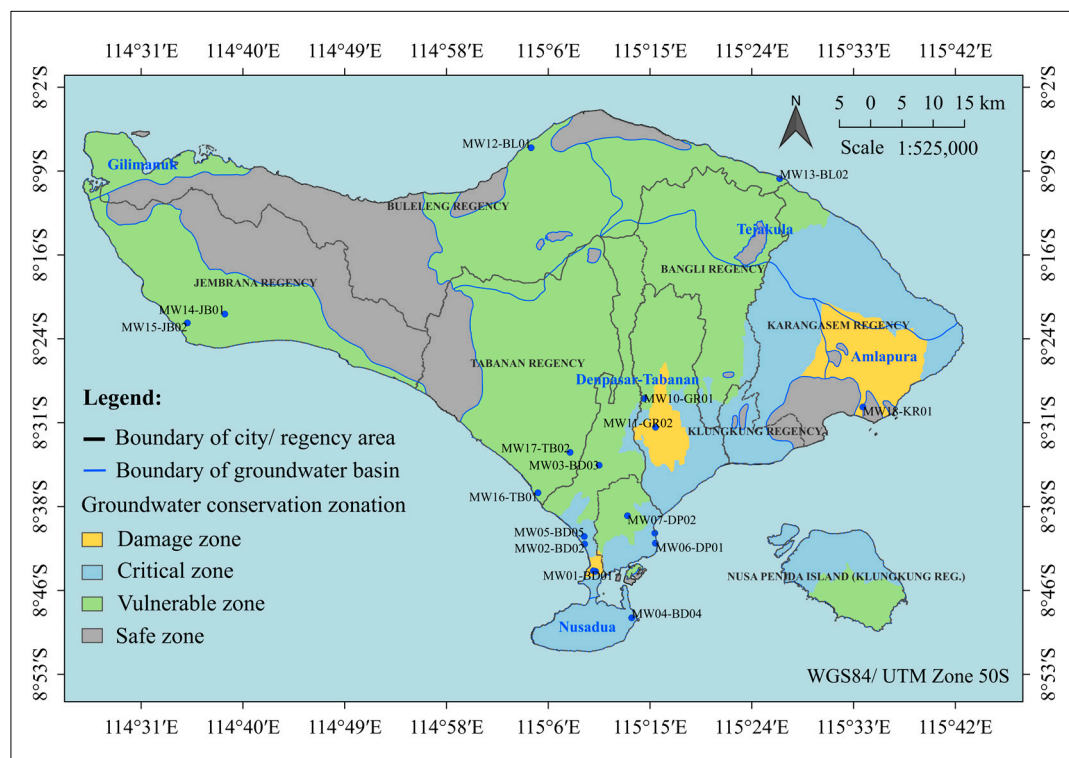


Figure 10. Map of the zonation of groundwater conservation in Bali, Indonesia.

Subsided areas with moderate (10–25%) and high (>25%) groundwater depletion were categorized as critical and damage zones, respectively. Such areas were observed in the southern and eastern regions of Bali, such as Kesiman Sub-District, East Denpasar District, for the critical zone, and Sanur Sub-District, South Denpasar District, for the damage zone that was located in Denpasar City. Besides being developed as a settlement center, the area has also been extended for tourism accommodation, e.g., hotels and villas. The average water requirement for a hotel is 1500 L/room/day, and that for a villa is 2500 L/room/day [38,39].

4. Discussion

Water resources in the province of Bali, Indonesia, are plentiful, including groundwater, river water, lakes, reservoirs, and springs. The water resource of the groundwater basins is the second largest in Bali, and it provides around 1598 million m³ of water every year [61]. This element denotes the significance of groundwater as a viable alternative to water in the region. The utilization of groundwater for water reservoirs has increased following the increase in population and economic activity in Bali. The population of Bali increased by an average of 1.23 percent every year between 2010 and 2015. Agriculture, industries, and services, including tourism, are the primary economic endeavors in the region [41]. Groundwater has primarily been utilized to satisfy domestic needs; it is additionally used to irrigate agricultural areas that have limited water resources [40,62,63].

The InSAR data used here are of the period 2007–2010, and groundwater level measurements continued until 2017. This temporal disparity may lead to an underestimation of risk in areas that were relatively quiescent pre-2010 but became highly urbanized later, with increased groundwater abstraction post-2010. Apparent InSAR downward displacement matched well with GNSS measurements at selected key stations. Hence, early subsidence trends can be taken as indicators for further deformation to be expected in the future. Groundwater depletion interpolated for the years 2008–2017 is another piece of information in areas where subsidence hazard has most likely remained or even increased. Newer SAR data there would fully map ongoing subsidence in those fast-urbanizing regions.

Several problems have arisen due to the over-extraction of groundwater in the region of Bali, i.e., the risk of land subsidence and saline water intrusion [36–39,61–64]. Groundwater depletion was observed in the southern region of Bali from groundwater level monitoring from 2001 to 2015 at wells located in four different area classifications, i.e., tourism, river basin, settlement area, and wetland [38]. Seawater intrusion is a recognized problem in the geohydrological system of the aquifers near Bali's coast. Studies have demonstrated that it causes the groundwater in the Candidasa region of eastern Bali to be saltier. This intrusion alters the way that groundwater levels change, causing water to flow in a densely populated area. This lowers the pressure of freshwater and causes a lot of water to be taken from the ground, especially in coastal areas that have a low population [39]. In addition to climate change, groundwater depletion and land subsidence are considered causes of seawater intrusion. The time frame of 2007 to 2010 was chosen because PALSAR L-band SAR data were available during that time, and it had the right spatial and temporal resolution for InSAR processing. Sentinel-1 SAR data has only been available since 2016; while Sentinel-1 SAR data is useful for continuous monitoring, the PALSAR dataset can be directly compared with GNSS CORS measurements and groundwater monitoring well data from 2008 to 2010. Our study concentrates on the historical period (2007–2017) to validate the methodology and comprehend past trends; however, more recent monitoring (2016–present) utilizing Sentinel-1 data may yield updated insights into current land subsidence trends in Bali. Integrating such data in subsequent studies would facilitate the evaluation of ongoing subsidence dynamics and guide adaptive groundwater management strategies [66–70].

Based on the results of the InSAR analysis, the shortcomings of the technique are evident from inconsistencies in displacement on the InSAR images. InSAR essentially measures object directions and vertical movements relative to the satellite's line of sight. To quantify the impact of these uncertainties on groundwater conservation zoning, we compared InSAR-derived vertical displacement with GNSS-CORS measurements at reference stations. The differences were generally within ± 5 cm, which is small relative to the zoning thresholds (10% and 25% groundwater depletion), indicating that the uncertainties have minimal influence on the classification of safe, vulnerable, critical, and damage zones [62,67,70]. The inconsistencies indicate that the technique may be inadequate for

indicating exact amounts of subsidence, as it also estimates the object movements [31]. The accuracy of the result can be improved by employing more datasets in both ascending and descending orbits. Research has shown the effectiveness of the utilization of multi-track data for extracting a substantial value of vertical displacement [71,72]. Moreover, the trend of height changes at GNSS-CORSs, i.e., CDNP and CPBI, demonstrated good agreement with the subsidence areas identified by means of InSAR. In another study, continuous GPS measurement at stations CDNP and CPBI showed negative deformation in the northern and southern regions of Bali; in comparison, a positive trend was shown in the central region. Station CSRJ was also used as a reference, considering that the area is free from earthquake effects and bias [64,65].

Furthermore, spatial information on the distribution of groundwater depletion can be derived through data interpolation and mapping that cover the entire study area. The groundwater level measurement from institutional data was provided for a five-year period from 2008 to 2013; however, there was a lack of data covering the subsequent period. Regarding this matter, continuous measurement is necessary to monitor the changes in the groundwater level. Concerning the lack of conventional groundwater level measurement due to its shortcomings, InSAR-derived land displacement could be employed to estimate groundwater level with higher temporal resolution. The correlation between groundwater level and InSAR-derived deformation is strongest in compressible, semi-confined aquifers. In fractured or karst aquifers, the response of surface deformation may not fully reflect groundwater fluctuations due to complex subsurface connectivity [14–19].

The study's limitations include the potential for errors in the InSAR-derived displacement caused by the atmospheric delay, which is particularly prevalent during periods of heavy rainfall or rapid humidity changes, as well as the time-lag effect between the groundwater level and the observed land subsidence. These factors may lead to uncertainties in the precise quantification of vertical displacement. Future investigations should incorporate atmospheric correction that takes into account multiple temporal scales and consider hydro-mechanical models that consider the effects of both land and water on the subsidence and predict the accuracy of subsidence.

The application of geospatial analysis for hazard risk assessment offers rapid and low-cost processing [73–75]. Moreover, the information can also be integrated with other parameters as input for groundwater utilization plans. As detailed in the groundwater utilization plan provided by the Ministry of Public Works in Bali Province in 2013, designated protection and utilization zones for groundwater have been developed. The protected zone covers groundwater recharge areas, whereas the utilization zone consists of safe, vulnerable, critical, and damage zones. The amount of groundwater discharge is limited to 150 m³/day in the safety zone and 72 m³/day in the vulnerable zone, and groundwater use is restricted in the critical and damage zones [62,63]. Based on the results of this study, groundwater conservation zoning can be used to guide the planning of utilization zones.

5. Conclusions

In this study, a hazard risk assessment was performed using spatial information of land subsidence distribution and groundwater depletion. The risk of subsidence due to groundwater depletion can be assessed and confirmed according to the conformity of the groundwater level changes based on monitoring well data and subsidence sites identified through InSAR analysis. This type of information is important in supporting the planning of sustainable groundwater development in the area, as it considers the condition of the groundwater and the risk related to it. Concerning its advantages of quick and low-cost processing, InSAR is considered appropriate for establishing continuous spatial information of groundwater conservation zoning based on the risk of land subsidence

caused by groundwater depletion. In supporting sustainable groundwater development, the information can be considered appropriate as input for related water management planning, such as groundwater conservation zonation. Management suggestions include preserving recharge areas, regulating the extraction of water in vulnerable and critical areas, and establishing programs that are continuous in nature; these programs will monitor the temporal variations in water in both confined and unconfined aquifers. These strategies can assist in water distribution, reduce subsidence, and facilitate long-term water sustainability in the ground. Future research should expand the monitoring done by Sentinel-1 or other datasets that have atmospheric correction capabilities, and it should also assess the effects of the time-lag between the groundwater extraction and subsidence. Hydro-mechanical modeling will further enhance the accuracy of predictions. This is especially true of unconfined or fractured aquifers that are surface-deforming, the deformation of which may not directly correspond to changes in groundwater. Overall, the combined approach provides a practical method of dealing with hazards in groundwater management, this method allows policy makers to develop practical strategies that balance the need for water with the conservation of land and the mitigation of small-island developing regions including the tourism industry, where managing water in a way that does not make groundwater depletion worse is important for supporting visitor infrastructure, resorts, and local communities.

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