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ESTIMATION OF LAND SUBSIDENCE IN THE MEKONG DELTA AND ITS SURROUNDING AREAS

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Abstract. Land subsidence becomes a trouble for the different regions of the Mekong delta, where many places will be severely affected by sea-level rise in the context of climate change. Land subsidence could amplify this situation by inducing interactive hazards such as submerged land and saline intrusion, etc. Mapping the spatial distribution of land subsidence become a crucial task, and the Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) approach was applied to 120 Sentinel-1A images within three scenes, captured from October 2016 to October 2020 with the interval of 36 days between two consecutive images. This approach allows mapping ground displacement by continuously extracting deformation signals and estimating the position of targets that persistently scatter radar beams. The average velocity map shows that eight main subsidence areas in the Mekong delta have been affected in recent years with the maximum velocity of -39.61 mm year^{-1} and the cumulative displacement ranging from 60 to 100 mm in the Line Of Sight (LOS) direction over four years. The validation using 40 Sentinel-1B images, captured in identical periods indicates a consistent result in comparison with the one issued from Sentinel-1A. These pieces of knowledge are essential for improving both citizen’s life and reducing the impact of land subsidence on the natural environment.

Keywords: Mekong delta, Interferometry, PSInSAR, Sentinel-1A/1B, land subsidence.

1. Introduction

With the geophysical properties, the Mekong delta has plentiful resources of surface water, as well as groundwater. However, the Mekong delta in general is facing a great challenge when upstream countries have built a series of reservoirs at different altitudes to simultaneously supply hydroelectricity and irrigation. Such structures are attenuating the seasonal river flow variability in recent years [1], together with the pollution

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of surface water, the reduction of water runoff causes difficulties and challenges in water supply for downstream regions [2]. In consequence, the Mekong delta has been directly aggravated by negative impacts such as riverbank erosion, coastal erosion [3-5], severe drought, and saline intrusion in the dry season [6]. Since then, the over-exploitation of groundwater has been indirectly promoted, inducing the phenomenon of land subsidence. Not only that, several studies recognized that the Mekong delta is one of the regions in the World severely affected by sea-level rise in the context of climate change, causing the immersion for thousands of hectares of agricultural land [7-9], and saline intrusion will surge tens of kilometers from estuary [10]. Land subsidence will worsen the impacts induced by these phenomena [11, 12]. Therefore, the precise and continuous monitoring of land subsidence in the Mekong delta and its surrounding areas has constituted an urgent and important task since it is necessary to reduce dangerous effects, undesirable impacts, and stimulate a suitable construction technique in the affected areas. Radar satellite images with Interferometry Synthetic Aperture Radar technique (InSAR) could respond to that requirement, together with in-situ investigation, which will create a reliable basis for implementing the environmental management in this delta region.

Some works on land subsidence have been conducted in the Southern part of Vietnam during the last decade. Specifically, using the interferometric synthetic aperture radar (InSAR) technique, Ho Tong Minh Dinh et al. (2015), Le Van Trung et al. (2008) identified subsidence in Ho Chi Minh city [13, 14], where the groundwater withdrawal is the main cause of land subsidence [15]. Otherwise, Karlsrud et al. (2020) installed piezometric equipment in three observation wells for determining subsidence due to the possible consolidation within the upper capping soft clay layer in Ca Mau province [16]. Land subsidence for the whole Mekong delta was firstly mapped by Erban et al. (2014) using Advanced Land Observation Satellite 1 (ALOS-1) data [17]. Then, Minderhoud et al. (2017) got a quantitative assessment of groundwater extraction-induced land subsidence via modeling the soil behavior for the Mekong delta since 1991 [18]. In addition, there are also other efforts of Vietnamese researchers for studying land subsidence in the Mekong delta using various in situ methods. However, these above-mentioned researches either focused on a limited area or provided outdated information while the subsidence situation is worsening and expanding in the Mekong delta and its surrounding areas.

The availability of Sentinel-1 data has increased with the launches of Sentinel-1A satellite (2014) and Sentinel-1B satellite (2016). Together with advanced InSAR techniques for processing big data, many applications on land deformation have been deployed over the World using this dataset [19-22], even on land subsidence in the Mekong delta [23]. Owing to the effectiveness of multitemporal InSAR techniques and the characteristics of Sentinel-1 sensors with a high spatial resolution, short repeated imaging cycles, which can minimize constraints in the InSAR technique by the means of twin satellite constellation (Sentinel 1A/1B) [24]. Moreover, Sentinel-1 images are free of cost and accessible to all via Copernicus hub. Consequently, they are considered as an effective data source for monitoring the land subsidence at the regional scale with high spatial and temporal resolutions [25]. The present study aims to: a/ identify the spatial distribution of land subsidence phenomenon on the large territory of the Mekong delta and its surrounding areas based on the Sentinel-1 images with multitemporal InSAR technique. b/ determine a suitable procedure to simultaneously process several radar scenes for reliable results. The obtained results will provide an important reference for the Governmental authorities in urban planning, agricultural, aquacultural production activities in this environmentally sensitive region. Since then, it is possible to propose an effective measure to limit future damages and it also contributes to testing the application of Sentinel radar in the specific conditions of Vietnam.

2. Content

2.1. Study area

The study area includes the Mekong delta and its surrounding areas, but it focuses mainly on the delta territory because this one plays a particularly important role in the socio-economic development of Vietnam. Regardless Ho Chi Minh City, this Vietnam’s largest delta has a surface of 40547 km^2, consisting of one city and 12 provinces for 17.28 million people, provides and ensuring food safety for the country with a contribution of 50% food production, 70% of seafood exports, 90% of the country's rice exports, and 20% of global commercial rice production [26].

This delta forms the downstream part of the Mekong River which flows into Vietnamese territory by two branches: Tien River and Hau River at Chau Doc city, and Tan Chau town (An Giang province). This river splits into several tributaries before pouring into the East Sea at nine estuaries (Figure 1). Therefore, the study area has an intertwined system of rivers, lakes, and canals which could influence the distribution pattern of inhabitants in the whole territory. The population installs their houses in a decentralized manner along the streams instead of the clump in villages. The hydrological regime is directly influenced by many factors such as water discharge from upstream, the tidal regime of the East Sea, the Gulf of Thailand, and the internal precipitation regime. The total annual flow of the Mekong delta for many years is about 500 km^3, of which 23 km^3 is formed within the internal territory, while 477 km^3 is transferred from the middle and upstream [27]. The average annual rainfall varies from 1600 to 1800 mm. The rainy season lasts 6 months, from May to October, occupying 90% of the annual rainfall. The dry season lasts from November to April, occupying 10% of the annual rainfall. During the dry period, the flow regime on most rivers is strongly influenced by the tidal regime of the East Sea; but some catchments in Ca Mau, Bac Lieu, and Kien Giang provinces are affected by the tidal regime of the Gulf of Thailand [28].

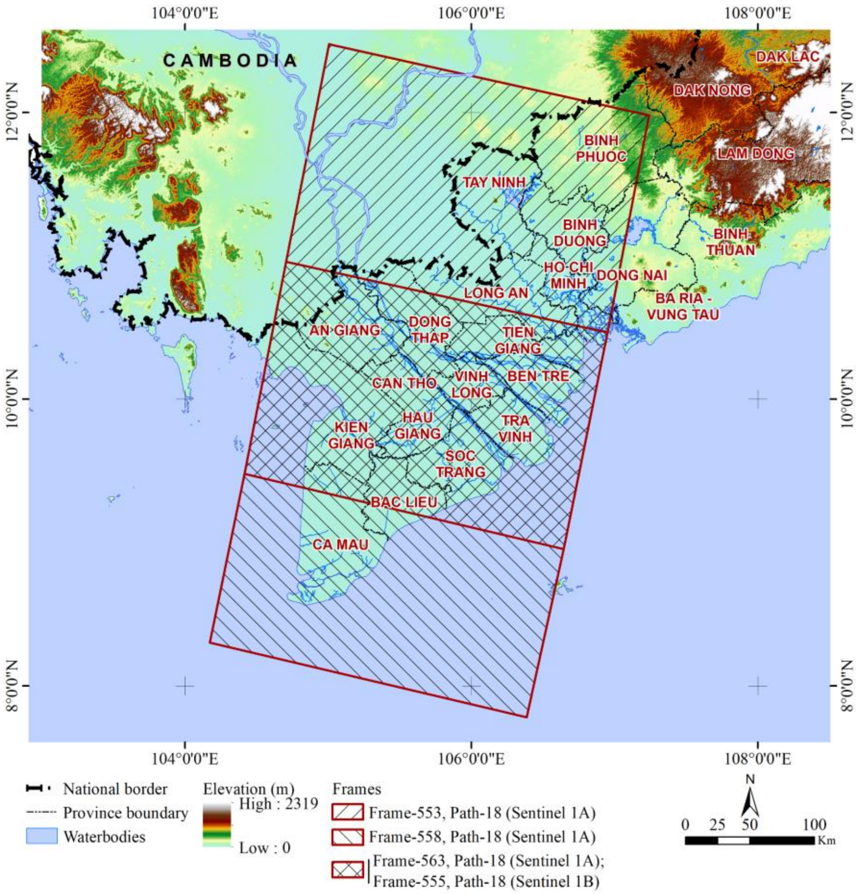

Figure 1. Map of Southern Vietnam with the location of the Mekong delta and the delimitation of 3 scenes for Sentinel-1A/1B satellites

The Mekong delta is mainly characterized by flat topography, the elevation gradually reduces from the North to the South and from the West to the East, on which there are only some mountainous summits in An Giang province with an elevation under 600 m. These mountains compose of igneous rocks or sedimentary rocks belonging to Deo Ca complex (K đc), Deo Bao Loc formation (J3 đbl), and Dau Tieng formation (T3 dt), respectively. The most exposed materials on the ground are unconsolidated sediments creating significant reserves of groundwater with eight aquifers, which distribute at a depth ranging from a few tens to 600 m. These aquifers are Holocene (Qh), upper Pleistocene (Qp3), upper Pleistocene (Qp2-3), lower Pleistocene (Qp1), middle Pliocene (N22), lower Pliocene (N21), and upper Miocene (N13) and mid-upper Miocene (N12-3). Land subsidence has principally occurred in the unconsolidated formations of which its composition is described in detail in the Lexicon of Geological Units of Vietnam [29]. The total potential reserve for exploiting the groundwater of the Mekong delta is 22.5 million m^3 day^{-1} and the total safe reserve for exploitation is 4.5 million m^3 day^{-1} [30]. The shallow groundwater in the Qh aquifer has poor quality because it is closely related to the phenomenon of salinity, alum, and microbiological intrusion. The groundwater in deep aquifers is complicatedly distributed in both space and depth; it is principally contained in the complex Pleistocene, Pliocene, Miocene aquifers [31]. These physical characteristics play an essential role in the occurrence of land subsidence because the degradation of surface water have ordinarily promoted the over-exploitation of groundwater, causing new situation with the downthrow of relief which has become stronger as recorded in many places of the Mekong delta and its surrounding areas such as Ca Mau, Long An, Bac Lieu, Can Tho, Hau Giang, etc. (Figure 2).

Figure 2. Occurrence of land subsidence at some provinces in dry season 2020 [32]

2.2. Method and use data

Sentinel-1A/1B satellites by ESA with a C-SAR sensor have many advantages in radar interferometry analysis because it regularly provides images (repeat cycle = 12 days) with the stability of image acquisition geometry, high coherence of the 12-day interferograms, and the reduced orbital tube, which is ideal for radar interferometry analysis [33]. In this research, four scenes in the descending track are used: three scenes of Sentinel-1A and one scene of Sentinel-1B of which footprints are presented in Figure 1. The study area is covered within three scenes of Sentinel-1A: first scene (path: 18; frame 553), second scene (path: 18; frame: 558), third scene (path: 18; frame: 563). For each scene, 40 radar images with the interval of 36 days between two consecutive images acquired from 7 October 2016 to 22 October 2020 are exploited for reducing processing volume and memory usage. A total of 120 Sentinel-1A images are processed using the procedure presented in Figure 3 for detecting the spatial distribution of land subsidence. Otherwise, the fourth scene (path: 18; frame: 555) of Sentinel-1B is used for validating the aforementioned InSAR analysis issued from the third scene of Sentinel-1A, because they overlap each other. The fourth scene is also composed of 40 images with the interval of 36 days between two consecutive images acquired from 25 October 2016 to 28 October 2020. Owing to a large number of images with the coverage of three radar scenes, these processing steps allowed to properly perform phase unwrapping and create a deformation map. The digital elevation model of the Aster Global Digital Elevation Model (resolution: 30 m), provided by the Japan Aerospace Exploration Agency (JAXA), is used to remove the terrain phase term in interferograms. Furthermore, precise orbital data (< 1 m) are provided online by ESA, which is exploited to eliminate the orbital phase term in the interferograms.

The utilization of radar interferometry to observe the Earth's surface has been successfully demonstrated over the years [34, 35]. The InSAR techniques have been developed to extract the phase difference between two SAR images taken from the same region at different moments [36]. Land displacement is quantified along satellite Line of Sight (LOS) direction, which depends on an angle between the incident ray and topography. This angle varies among radar beams and increases across from near to far range. However, this InSAR technique depends on the decorrelation level, which emerges either from a variation of the LOS direction for two acquisitions (different look and squint angles), or from a change of the scatterer position, or geometry within the resolution cell. If the decorrelation is too important, the obtained interferograms will not be suitable for analyzing the land deformation [34].

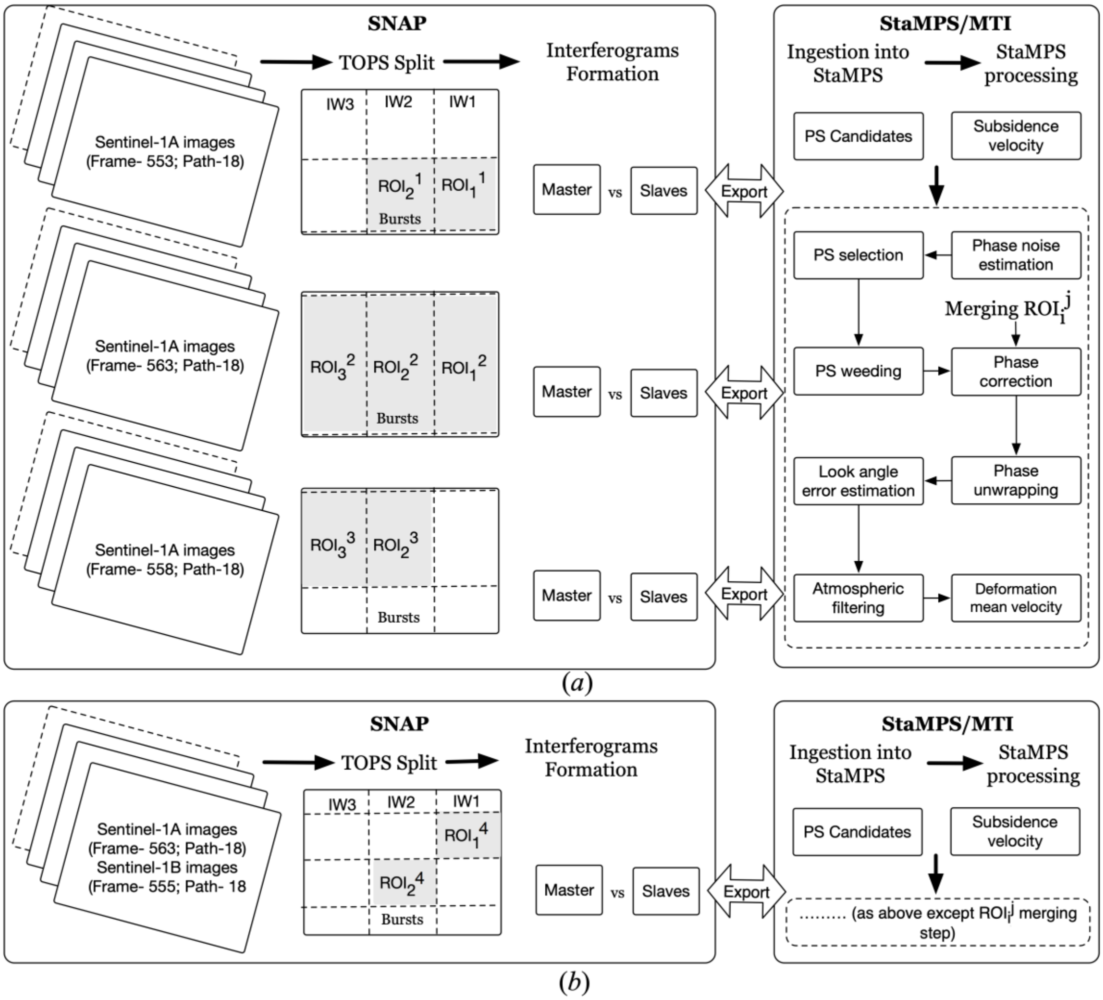

Figure 3. Processing procedure applied in the present study

To overcome the temporal decorrelation due to the change of scattering properties [37], to reduce the influence of the atmosphere [38], and to detect the transient motion [39], multitemporal interferometric synthetic aperture radar methods have been developed and improved since the last two decades. By analyzing multiple SAR images of an area, which are captured at different moments using time-space adaptive filters, the deformation phase is finally separated from other components. Based on that principle, multitemporal methods allow determining the most important information for each PS point: the average displacement velocity of the ground (mm year^{-1}) and time series of displacement during the period covered by SAR images [40].

The Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) is one approach of the multitemporal methods, that is well described in the works of [41-43]. This approach analyzes phase information of pointwise features with a stable amplitude backscattering behavior over time - Persistent Scatterers (PS). Instead of processing the entire image, they only analyze the PS with radar waves to determine their displacement. The PSInSAR is targeted at the resolution cells dominating single scatterers such as rock outcrops in a natural environment or man-made structures (buildings, towers) in urban milieux [36]. Due to its high sensitivity to vertical movement, the PSInSAR has become the main application to map out the spatial distribution of land deformation. This approach contributes to an assessment of geological hazards such as volcanic, tectonic activities, landslides, or land subsidence occurring anywhere on Earth [44, 45, 43, 46-48].

In this study, although Mekong delta and its surrounding areas expand on many landscapes with different types of land use/land cover including man-made features and natural features. However, a multitemporal interferometric method with the PSInSAR approach developed by [49], was chosen for selecting PS candidates using amplitude dispersion DA=0.4 because people build their houses along the rivers and canals which spread throughout the whole delta. They could become PS points in PSInSAR analysis and allow to improve the number of observation samples and to perform a better phase unwrapping process. With the utilization of this approach, deformation signals are separated from the PS candidates. Among the information that can be provided for each PS point, a three-dimensional (3D) phase unwrapping process using the statistical cost approach is initially applied and then the estimation of digital elevation model errors by correlating with values of the perpendicular baseline of each interferogram is estimated to unwrap taking into account these corrections [39].

2.3. Results

2.3.1. Spatial distribution of land subsidence

The obtained map shows that many places in the Mekong delta and its surrounding areas have been affected by land subsidence at different rates. In general, the subsidence patches do not concentrate in some specific places, but they randomly disperse all over the delta. These subsidence patches are grouped into eight main subsidence areas, of which the average velocity in LOS direction varies from 0.00 to -39.61 mm year^{-1}, which relates to the standard deviation ranging from 0.90 to 5.30 mm year^{-1}. On the one hand, warm colors are used to represent negative values, i.e. target objects which are moving away from the radar sensor. On the other hand, cold colors are used to represent positive values, i.e. target objects which are moving toward the radar sensor (Figure 4).

The subsidence velocity is a relative quantity, in which 0.0 mm year^{-1} refers to stable locations over the entire analysis period. If the Hau river is considered for delimiting two parts in which the Northern part is characterized by the clusters of dense PS points because of its developed milieux. However, PS points are much more dispersed in the Southern part due to the crucial disturbance of material in the natural milieux, causing a decorrelation in SAR interferograms.

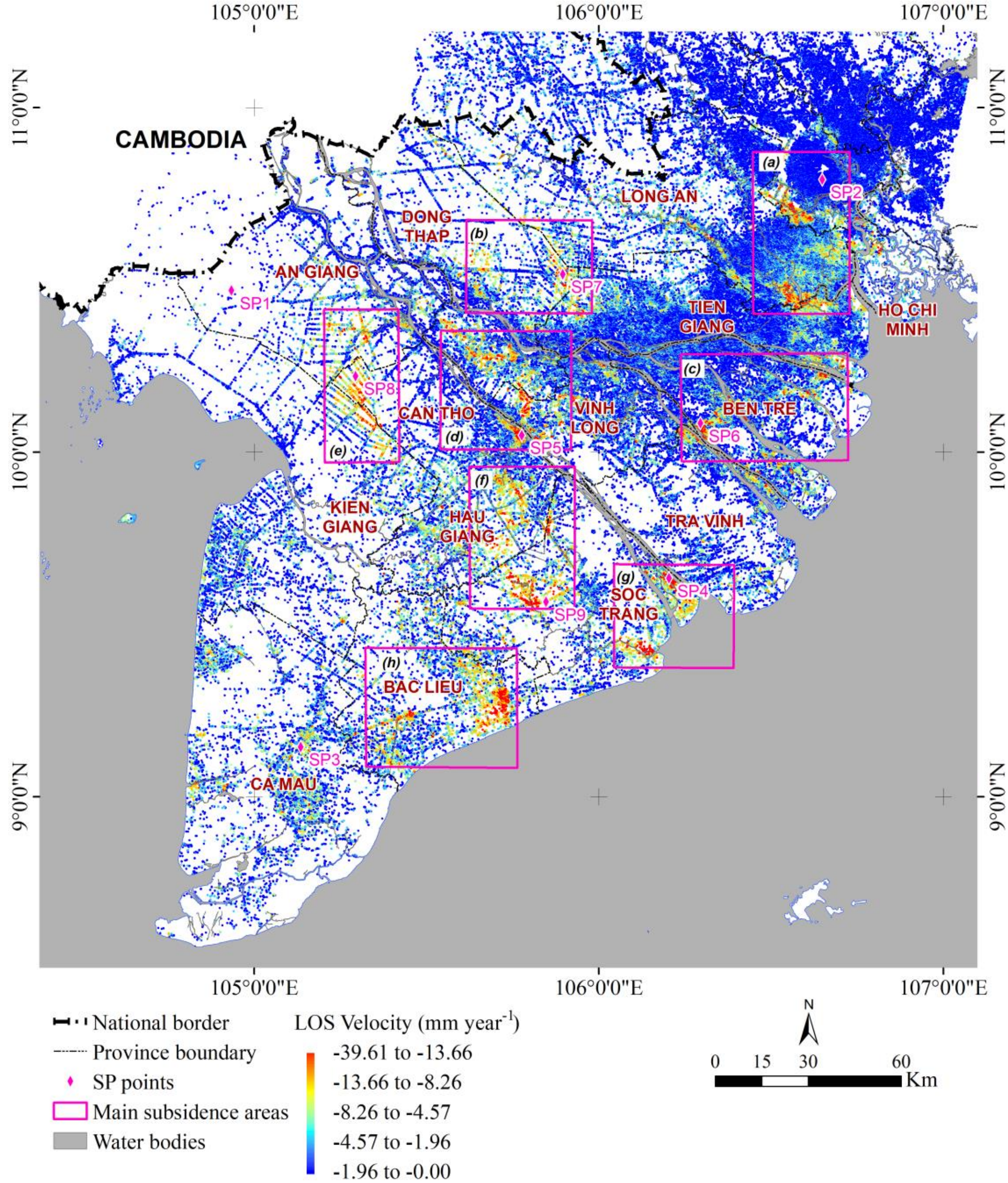

Figure 4. Distribution of land subsidence issued from Sentinel-1A images

In the Northern part, land subsidence has occurred in some prominent areas: the first main subsidence area partly includes the territory of Binh Chanh, Nha Be districts (Ho Chi Minh city), and Chau Thanh, Tan Tru, Can Duoc districts (Long An province). The patches cover a surface of about 29.0 km × 53.0 km, in which the LOS velocity ranges from -1.96 to -19.54 mm year^{-1}, and the maximum mean velocity reaches -22.52 mm year^{-1}. The second subsidence area partly occupies the territory of Cao Lanh, Thap Muoi districts (Dong Thap province), and Cai Be district (Tien Giang province). The patches of this area occupy an extent of about 40.0 km × 29.7 km, in which the LOS velocity ranges from -0.46 to -15.94 mm year^{-1}, and the maximum mean velocity reaches -19.33 mm year^{-1}. The third subsidence area partly includes the territory of Mo Cay, Giong Trom, Binh Dai districts (Ben Tre province), Tan Phu Dong (Tien Giang province), Cang Long district (Tra Vinh province). The patches of this subsidence area cover a surface of about 52.2 km × 34.3 km, in which the mean velocity in LOS direction varies from -0.10 to -19.79 mm year^{-1}, and the maximum mean velocity reaches -25.27 mm year^{-1}. The fourth subsidence area spreads to the territory of Lap Vo, Lai Vung, Sa Dec districts (Dong Thap province), Binh Thuy, Ninh Kieu districts (Can Tho city), Binh Tan, Binh Minh, Long Ho districts (Vinh Long province). This subsidence area covers the patches of about 42.0 km × 38.7 km, in which the velocity in LOS direction ranges from -0.23 to -17.45 mm year^{-1}, and the maximum mean velocity reaches -22.75 mm year^{-1}.

In the Southern part, some main areas have been threatened by land subsidence: The fifth subsidence area is partly composed of the territory of Chau Thanh, Thoai Son districts (An Giang province), Vinh Thanh, Tan Hiep, Giong Rieng districts (Kien Giang province), Vinh Thanh district (Can Tho city). This subsidence area encompasses the patches of about 23.5 km × 48.8 km, in which the LOS velocity ranges from -0.40 to -15.58 mm year^{-1}, and the maximum velocity is -19.27 mm year^{-1}. The sixth subsidence area partly includes the territory of Phung Hiep, Chau Thanh districts (Hau Giang province), My Tu district (Soc Trang province). This subsidence area covers the patches of about 32.5 km × 46.5 km, in which the LOS velocity reaches from -0.26 to -18.89 mm year^{-1}, and the maximum velocity is -22.56 mm year^{-1}. The seventh subsidence area corresponds to the territory of Cu Lao Dung, Long Phu, Vinh Chau districts (Soc Trang province). The patches of this subsidence area cover a surface of about 27.5 km × 33.9 km, in which the LOS velocity is measured from -0.14 to -28.54 mm year^{-1}, and the maximum velocity is -39.61 mm year^{-1}. The eighth subsidence area partly includes the territory of Bac Lieu city, Vinh Loi, Hoa Binh, Gia Rai districts, (Bac Lieu province). This subsidence area covers the patches of about 43.7 km × 38.8 km, in which the LOS velocity is measured from -0.05 to -18.17 mm year^{-1}, and the maximum velocity is -21.56 mm year^{-1}. Otherwise, some other small subsidence areas with the sparseness of scatterers appear blurred of which the dimension is about 4.0 km × 6.0 km such the case of Tran Van Thoi district, Ca Mau city (Ca Mau province), Tan An, Thu Thua districts (Long An province), Mang Thi, Long Ho districts (Vinh Long province).

2.3.2. Validation

It is necessary to use data from different sources (in-situ measurements, either images from another radar sensor, or image from the different track of Sentinel-1A) for validating the result derived from Sentinel-1A images by the PSInSAR approach [19]. Therefore, one scene of Sentinel-1A with 40 images in concordance with one scene of Sentinel-1B with 40 images has been independently analyzed at two different ROIs: Bac Lieu province and Ben Tre province. Table 1 describes the statistic parameters obtained from InSAR analyses for two zones under validation with Sentinel images. They demonstrate the identical subsidence velocity at two ROIs.

Table 1. Statistic parameters issued from PSInSAR results at two specific sites

Parameters	Sentinel-1A		Sentinel-1B	
	Ben Tre	*Bac Lieu*	*Ben Tre*	*Bac Lieu*
Number of PS points	210030	133236	209852	129838
Min value (mm year^{-1})	-28.20	-27.53	-31.76	-31.44
Max value (mm year^{-1})	0.00	0.00	0.00	0.00
Mean value (mm year^{-1})	-3.42	-5.47	-3.61	-5.49
Standard deviation value (mm year^{-1})	3.54	4.53	3.72	4.56

Furthermore, the differential values of subsidence velocity have been identified by subtraction operation between two results issued from Sentinel-1A and Sentinel-1B datasets. Figure 5 signifies that even though there are slightly different statistic parameters, obtained results are identical in terms of subsidence rate using similar parameters in PSInSAR analysis for two cases.

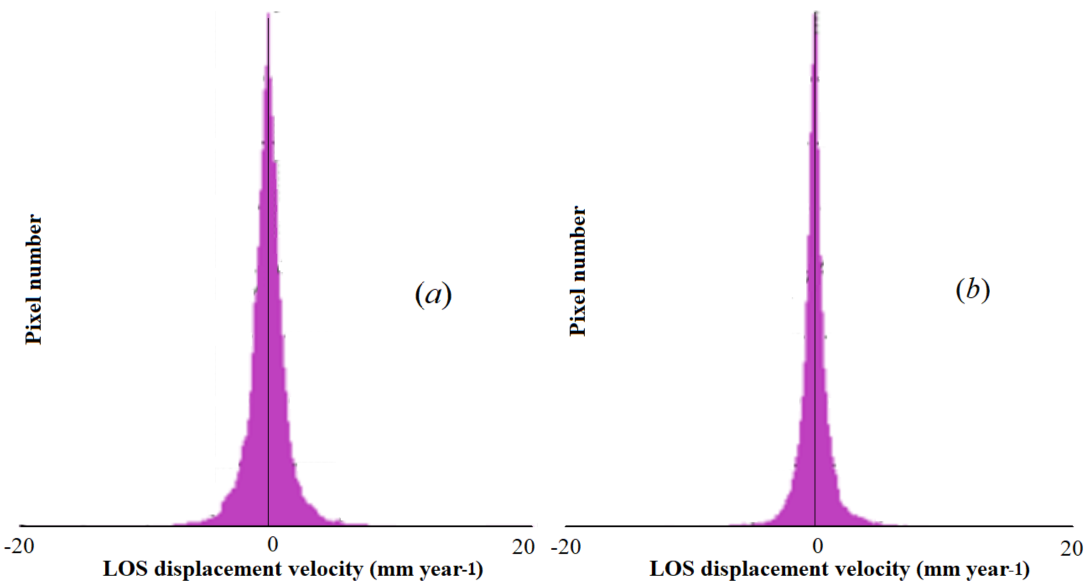

Figure 5. Histogram of differential values between results issued from Sentinel-1A and Sentinel-1B images at (a) ROI in Ben Tre province; (b) ROI in Bac Lieu province

The histograms in Figures 5 (a-b) show a normal distribution with a large number of pixel having zero value. It means that the subsidence velocity at Bac Lieu and Ben Tre provinces is approximately similar. However, there are also pixels of which its values differ from zero. It shows that many PS points represent the same features on the ground, but their positions are different due to improper co-registration between the images of Sentinel-1A and Sentinel-1B. Therefore, the subtraction operation exaggerates the differentiation causing the appearance of non-zero values.

Otherwise, a field trip was also conducted in November 2020 to collate with reality. In some residential settlements at Ca Mau city (Ca Mau province) and Bac Lieu city (Bac Lieu province), many damages were recognized at the wall and the foundation of structures. For instance, the pictures were taken on 22 November 2020 show that the walls of Tac Say catholic church (Gia Rai district) were split and the cracks were measured at a width ranging from 1.0 to 5.0 cm (Figure 6 (a)). Many houses at Ly Thai Ton street (Ca Mau city) have been inclined and the angle of inclination, ranging from 5° to 15°, can be recognized by emmetropic eye (Figure 6 (c)). In the urban milieu of Bac Lieu city, the fractures between the foundation house and pavement were observed on the ground surface. The picture, which was taken on 23 November 2020, shows that the ground has been ruptured at a width of 15 cm and a length of 30 m around the house (Figure 6 (b)). This fact proves that these structures have been suffered from impacts of land subsidence.

Figure 6. Recognized damage due to land subsidence: (a) cracks on the wall of Tac Say catholic church in Gia Rai district (Bac Lieu province); (b) inclined house at No 2 Ly Thai Ton street in Ca Mau city (Ca Mau province); (c) fractures between the house foundation and street pavement due to the motion of the ground surface at No 2/9, Hoa Binh street in Bac Lieu city (Bac Lieu province)

3. Conclusions

The obtained results proved that the InSAR technique for measuring the land subsidence seems to be significantly effective in comparison to in-situ methods in terms of time and cost. Indeed, radar images captured on band C of the Sentinel-1 satellites are an effective source for detecting the land subsidence in developed milieux using the PSInSAR approach. Nonetheless, this approach could be still applicable to rural milieux of the Mekong delta although it provided fewer PS points because of the presence of individual houses anywhere along the streams, on the one hand. The PSInSAR approach can provide complete spatial coverage of the study area and solve the decorrelation effect in rural milieux, on the other hand. The average velocity map shows eight main subsidence areas in the Mekong delta and its surrounding areas which have been affected in recent years with the maximum velocity of -39.61 mm year^{-1} and the cumulative displacement ranging from 60 to 100 mm in the Line Of Sight (LOS) direction over four years. The operation of radar satellites in ascending and descending orbits not only increases the probability of capturing an image for identifying land subsidence areas but also increases the ability to use complement images for validation procedures together with in-situ measurements. This capacity is even further enhanced with the presence of a constellation of two SAR satellites: Sentinel-1A and Sentinel-1B. Finally, the average velocity issued from the InSAR technique is a good reference for adjusting parameters of the land subsidence predicting model in further research.

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