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Research Article

Measuring land subsidence in Tra Vinh by SAR interferometry Sentinel–1

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Abstract: This paper presents the results of analyzing land subsidence in Tra Vinh province in the period of 2015–2019 by using InSAR interference from Big Data of Sentinel–1 satellite radar and ground measurement data to understand the impact of urbanization and groundwater exploitation on land subsidence in the area research. In the period from 2015 to 2019 in Tra Vinh city, there are areas with annual subsidence rate of about 1 cm/year while in Dan Thanh commune, Duyen Hai district subsidence rate is up to 3 cm/year. One of the reasons for such rapid land subsidence is the excessive exploitation of underground water in these areas, especially in Dan Thanh commune, Duyen Hai district.

Keywords: Mekong; Tra Vinh; Subsidence; InSAR; Sentinel–1.

1. Introduction

The countries in the Mekong region, and specifically Vietnam, are among the most affected by climate change. Consequently, the mean temperature is raised and the sea level has risen. One of the big environment impacts is the regional water–pumping induced land subsidence. Combined with the sea level rise due to global climate change, the land subsidence directly impacts a variety of hazards which can be associated with subsurface saline intrusion [1–2], and increases in the depth and duration of annual flooding [3]. In response to these challenges, besides climate change adaptation, the knowledge of the ground subsidence such as their spatial extent and their temporal evolution is essential.

Although traditional ground–based measurement methods such as Global Navigation Satellites System (GNSS such as GPS) and Geodetic Levelling can be made locally, remote sensing observations are essential for mapping spatial extent and temporal evolution of land subsidence over large regions. Large scale land subsidence can be measured using satellite–based SAR imagery processed by interferometry (InSAR) with high accuracy from space [3–7]. Since 2014, the Sentinel–1 satellite provides open access and systematic data (in Terrain Observation with Progressive Scan (TOPS) mode) with 6-day revisit and 20 m spatial resolution [8]. However, TOPS Sentinel–1A/1B phase is very sensitive to geometric errors. In case of a small misregistration error between a pair of images, this residual term leads to a phase jump in the interferometric phase. Due to this limitation, doing TOPS interferometry needs extremely high co–registration requirements (e.g., an accuracy of 0.001 pixel in azimuth direction) have to be met [9]. Thus, Although Sentinel–1 data offers the best opportunity for land subsidence monitoring, it is challenge to do InSAR processing.

In this paper, we will study on using InSAR techniques to determinate the land subsidence in the Mekong Delta. The work will be focused on the Tra Vinh, a typical coastal province in the delta, to demonstrate the feasibility of Sentinel–1 data.

2. Materials and Methods

2.1. Description of study site

Tra Vinh province, in the Mekong Delta, is one of the most biologically diverse and agricultural regions in the world, but sea level rise, land subsidence, upstream hydropower dam construction and rapid urbanization are the main causes affecting the hydrological, hydraulic, and sediment transport regimes of the whole area. Tra Vinh is located at the end of the island sandwiched between the Tien Giang and Hau Giang rivers. The terrain is mainly flat land with elevation of about 1m above sea level. In the coastal plain, there should be sand dunes, running continuously in an arc and parallel to the coast. The further to the sea, the higher and wider these mounds are. Due to the division by the hills and the system of roads and canals, the terrain of the whole region is quite complicated. Low-lying areas are interspersed with high hills, the slope trend is only shown in each field. Particularly, the southern part of the province is lowland, divided by bow-shaped sand varieties into many local low-lying areas, many places are only at an altitude of 0.5-0.8 m, so it is often flooded with salt water by 0.4 m per year -0.8 m for a period of 3-5 months. The average tidal amplitude of the east coast of Tra Vinh province fluctuates around 2m. Therefore, the delta of Tra Vinh is very vulnerable to land subsidence due to many reasons, in which special attention is paid to the causes of groundwater extraction, urbanization and change of shoreline due to the influence of the sea. The change of hydraulic regime, hydrology and sea level rise due to global climate change. More importantly, these two factors are directly responsible for many hazards such as saltwater intrusion on the surface and underground [1], increased altitude and timing of annual floods [3] and natural arsenic contamination [2]. This really causes concern for policy makers, managers and people living in Tra Vinh Province in particular and the Mekong Delta in general.

91% of Tra Vinh's water source for daily life and production is exploited from groundwater. Groundwater in the Mekong Delta including Tra Vinh is extracted from several aquifers ranging from Holocene to Miocene, in which deep aquifers are exploited the most [10]. When groundwater is extracted, the pore pressure decreases and the sediments undergo compression, which causes land subsidence. In order to determine the subsidence phenomenon as well as the subsidence speed, direct measurement methods such as geometric leveling, GNSS are used in small area, besides remote sensing methods such as: use LiDAR data from unmanned aerial vehicle (UAV) sensors or use radar remote sensing images to determine subsidence and its evolution over time for areas wide.

2.2. Methodology

Let $\varphi^n = \frac{4\pi}{\lambda} R_n$ represent the unwrapped interferometric phase, where R_n is the distance between the target and the n–th orbit acquisition, λ is the carrier wavelength. Then, φ^n is composed of the phase components related to deformation, residual topography, atmosphere, and noise [11]:

$$\varphi^n = \varphi^n_{defo} + \varphi^n_{topo} + \varphi^n_{atmo} + \varphi^n_{noise} + 2k\pi \quad (1)$$

where φ^n_{defo} is the deformation phase, φ^n_{topo} is the residual topographic phase, φ^n_{atmo} is the atmospheric phase, φ^n_{noise} is the phase noise, and k is an integer ambiguity number.

The goal is to estimate the deformation phase, which can be written as follows (assuming a constant velocity model):

$$\varphi^{n}_{defo} = \frac{4\pi\tau_{n}}{\lambda} v \tag{2}$$

where v is the mean deformation light of sight velocity of the target, and tn is the temporal baseline. The residual topographic phase is given as follows:

$$\varphi^{n}_{topo} = \frac{4\pi b_{n}}{\lambda \sin \theta R} \Delta h \tag{3}$$

where Δh is the residual topography, and θ is the local incidence angle, bn is the normal baseline. The atmospheric phase is the delay of the signal due to weather conditions. The phase noise is due to temporal decorrelation, mis–coregistration, uncompensated spectral shift decorrelation, orbital errors, and thermal noise.

In the conventional spaceborne InSAR, which uses two SAR acquisitions to calculate the interferometric phase, the technique has issues relative to atmospheric, spatial and temporal decorrelations [12]. These parameters can only be overcome by a specific analysis considering phase changes in a series of SAR images acquired at different times over the same region. In fact, multi–temporal Interferometry SAR approach [3–4, 6, 13,] is well–known for its ability to measure subsidence. Particular in [13], he proposed a Maximum Likelihood Estimator (MLE) approach which can jointly exploits all N(N–1)/2 interferograms available from N images, in order to squeeze the best estimates of the N–1 interferometric phases. In this fashion, we can exploit not only persistent scatters (PS) but also distributed scatters (DS) information for estimating the deformation. Such increased number of identified PS/DS points on the ground results at an increased confidence of the ground motion, compared to the previous PS algorithm [3]. The reader is referred to [3–4] for the full descriptions of the processing chain. The results are processed by the TomoSAR platform which offers SAR, InSAR and tomography processing [14].

2.3. Data collection

Tra Vinh is located in the delta area of the Mekong. The water for domestic and industrial use in Tra Vinh comes from wells located within and around the city. The heavy pumping of groundwater has produced a serious settlement problem, which in turn has affected surface structures in the city of Tra Vinh. Figure 1 reports our study area.

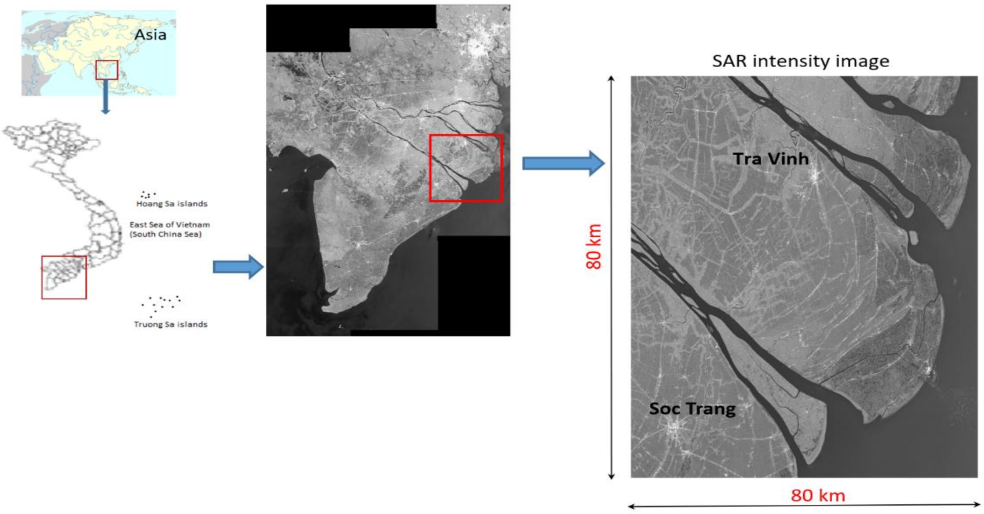

Figure 1. Tra Vinh study area coveraged about 80 km × 80 km. The background image is the SAR intensity.

The SAR stack is from Copernicus Sentinel–1 C–band 2015–2019. To reduce the dimensional of the computational data, we selected a good image for each month, resulting 55 images for PS/DS processing. The baseline distribution is shown in Figure 2.

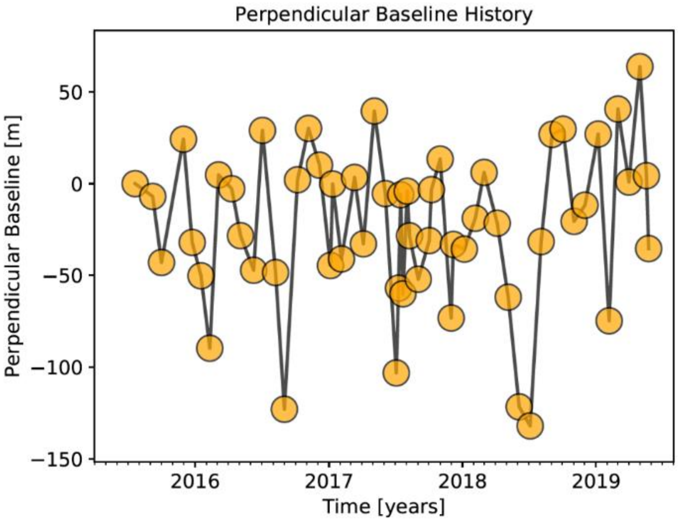

Figure 2. Baseline history of the 55 Sentinel–1 SAR images.

3. Results and Discussions

First of all, to provide better understand the presence of the stable points, we calculate the coherence of the stack and report in Figure 3.

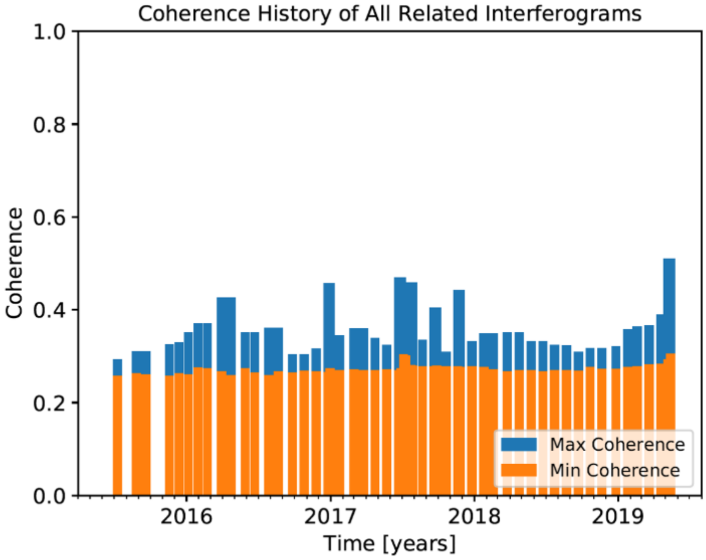

Figure 3. The average velocity trend: Positive velocities (green colors) represent movement uplift; negative velocities (red colors) represent movement subsidence.

The SAR data stack was then processed by using the MLE PS/DS approach. By exploiting the phase information at the PS/DS only, we are able to unwrap all the interferograms. In Figure 4, the unwrapped phase mostly varies from –2π to +2π. By inversion all the unwrapped interferogram, the average velocity (mm/yr) can be determined as in Figure 5. Positive velocities (blue colors) represent movement uplift; negative velocities (red colors) represent movement subsidence.

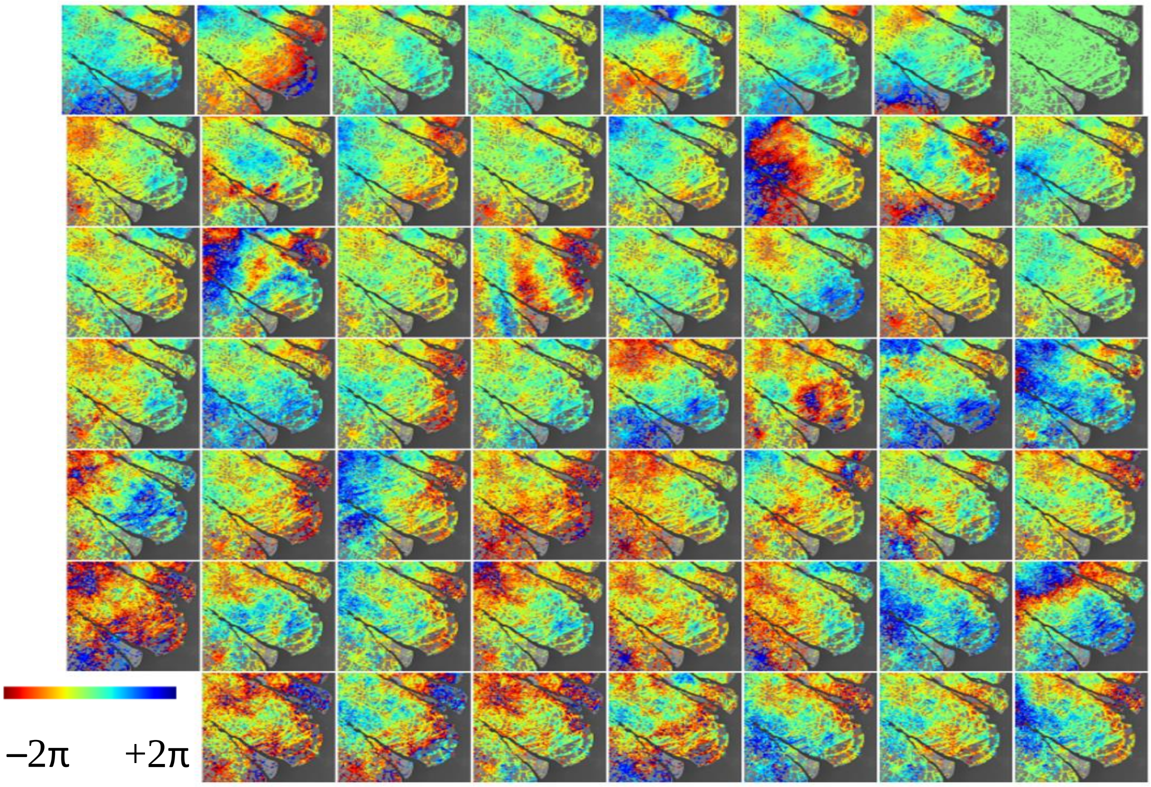

Figure 4. The unwrapped interferogram. The reference date of calculation is 21 July 2015.

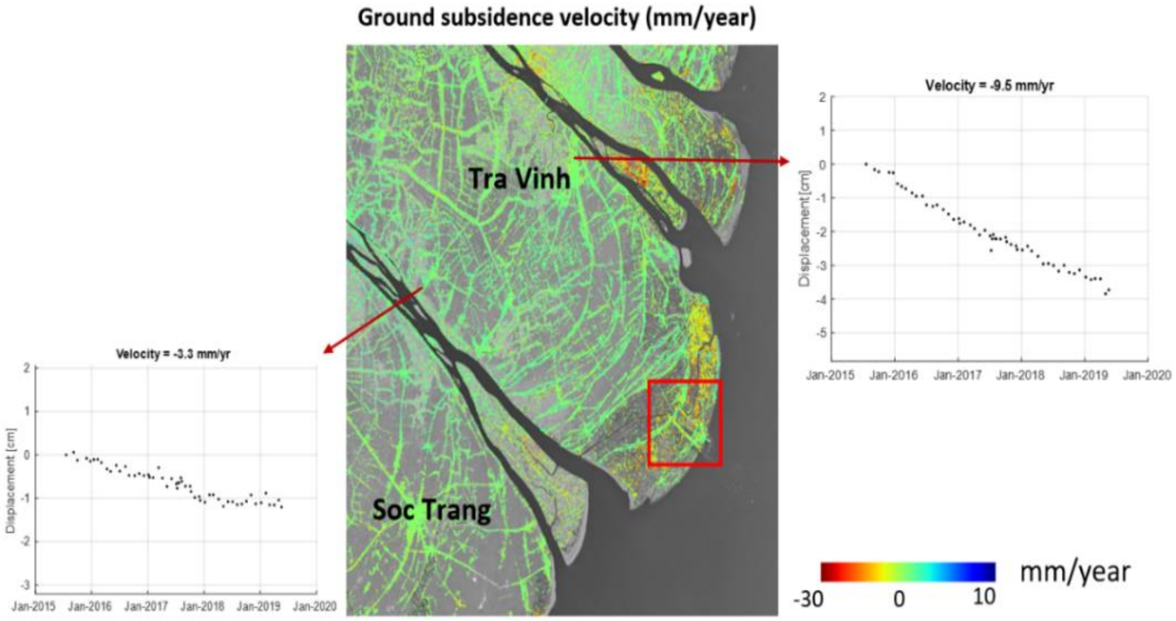

Figure 5. The average velocity trend. Positive velocities (blue colors) represent movement uplift; negative velocities (red colors) represent movement subsidence. The subsidence history is also provide to appreciation the displacement information.

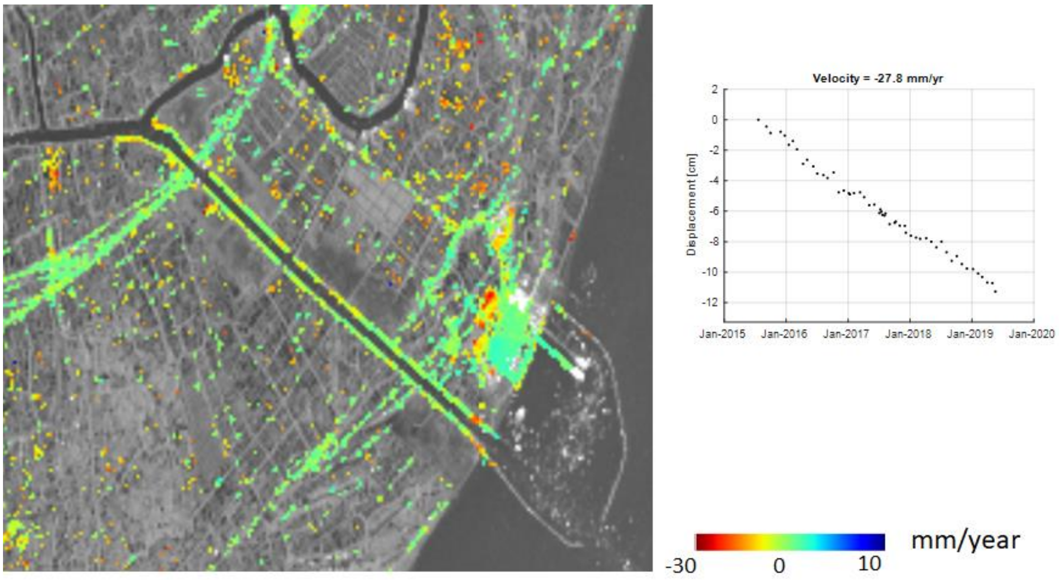

Figure 6. A zoom version of Figure 5 at the Quan Chanh Bo channel.

4. Conclusions

First of all, in figure 3, we can observe that the average coherence of each image ranges from 2.5 to less than 0.5. This indicates the areas is quite challenge for InSAR processing due to less stable measurement points and low coherent signals. However, as the culture of the Mekong, people habitant along the road and river channels, resulting in many scatters can be detected for InSAR processing. This phenomenon is very visible in Figure 5. Thus, we were able to map the subsidence for the whole Tra Vinh.

The average velocity varied from –30 to 10 mm/year. The subsidence phenomena were found mostly in the costal of the sea (the east of the province). Particularly, red pixels correspond to subsidence of nearly 12 cm, from 2015 to 2019, averaging 27.8 mm/yr (see the dots in Figure 6). For comparison, pixels near Soc Trang exhibit an average of 3.3 mm/yr (bottom left plot Figure 5).

The main reason of subsidence of Tra Vinh can be divided into two main kinds. The first kind is natural reason and the other one is artificial reason. Natural reasons include compact sediment, seasonal fluctuation of groundwater and soft soil layers. The artificial reasons include exploitation groundwater; loading capacity by building or levelling; dynamic loading by transportation or under construction building; and suffusion, quicksand negative skin friction. Related to artificial reason, exploitation groundwater pumping wells is most affected.

Groundwater in the Tra Vinh delta is widely pumped from several aquifers ranging from Holocene to Miocene age, where deep aquifers are the most heavily exploited [10]. When groundwater is extracted, pore pressures are reduced and sedimentary layers undergo compaction that can be measured as land subsidence. One of the reasons for such rapid land subsidence is the excessive exploitation of underground water in these areas, especially in Dan Thanh commune, Duyen Hai district.

To conclude, the ground deformation result from SAR of the period 2015–2019 in Tra Vinh describes exactly the subsidence area. This can help to identify hotpot subsidence areas. By using PS/DS processing, it can provide not only the average velocity of ground subsidence but also the subsidence history information. Future works need to focus on validation and also to evaluate the subsidence effects to sea–level rise due to global climate change. Finally, this work has a proof concept on the feasibility of measurement of subsidence for the Delta–wide based on Sentinel–1 data.

Author contribution statement: Conceived and designed the experiments: H.T.M.D., L.T.C.; Analyzed and interpreted the data: H.T.M.D.; Manuscript editing: L.T.C.; Performed the experiments: H.Q., B.T.V., T.V.H; contributed reagents, materials, analyzed and interpreted the data: H.T.M.D., L.T.C.; wrote the draft manuscript: H.T.M.D., L.T.C.

Competing interest statement: The authors declare no conflict of interest.

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