TIDAL FLOOD MODEL PROJECTION USING LAND SUBSIDENCE PARAMETER IN PONTIANAK, INDONESIA

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ABSTRACT:
Land subsidence is a phenomenon that can exacerbate the impacts of tidal floods in coastal areas, such as disrupting citizen activities, and submerging settlements and public facilities. Therefore, research on tidal floods and their relation to land subsidence was widely studied in coastal areas of Indonesia. However, this study has not yet been carried out in the Pontianak, a dense urban area located in the Kapuas River Delta, West Kalimantan Province. This study aims to analyze the impacts of land subsidence on tidal floods in the city for disaster mitigation and long-term urban planning. We calculated the land subsidence by applying the DInSAR technique to Sentinel-1A imagery. Then, tidal floods were simulated by integrating the DELFT3D hydrodynamic and HEC-RAS hydraulic models. The results showed that the output water level of the DELFT3D model has good agreement with the observation data, which the Nash Sutcliffe Model Efficiency Coefficient (NSE) is 0.83. Furthermore, the maximum land subsidence in Pontianak is ± 1.03 cm/year, where the highest subsidence (between 0.48 - 1.03 cm/year) covers about 28.54% of the total area. Our results showed that shallow inundated areas (water depth less than 0.5 meters) decreased by 23.6%, while deep inundated areas (water depth more than 0.5 meters) increased by 16.9% over the next 50-year. Overall, the depth of the tidal floods within Pontianak that occur in the future will increase by 0.03-0.4 meters and varied in across locations. These analysis results can guide the local water manager in designing a mitigation plan.

Keywords: *Tidal flood, DELFT3D, HEC-RAS, Land subsidence, Pontianak*

1. INTRODUCTION

Tidal flood occurs due to the movement of sea water to lowland areas which cause inundation (Kurniawan et al., 2021). Tidal flood is detrimental and hampers population activities in coastal and rivers areas are still affected by tides. Inadequate information and analysis on this phenomenon cause delays in disaster mitigation, potentially causing serious problems (Zainuri et al., 2022). The risk factors of tidal flood include rainfall, drainage density, land use, distance to the river, soil type, elevation, slope, sediment transport index, distance to the estuary, and curvature (Chang et al., 2018; Panjaitan et al., 2021).

Pontianak is one of the cities in West Kalimantan Province, Indonesia which is often affected by tidal floods, especially in the riverbank areas (BPIW, 2017; Gultom et al., 2020). Previous studies (Kuntinah et al., 2021; Sampurno et al., 2022a; Sampurno et al., 2022b) have shown that tidal flood in Pontianak often occurs during the high tide seasons from December to February. During this period, the tides reach a maximum height because affected by Asian monsoon (Kästner et al., 2018).

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The monsoon influences the atmospheric dynamics and potentially causes storm surges and strong westerly winds that impact on the mass movement of estuary water to coastal cities with low-lying topography. The interaction between tides propagation and river streams in downstream area affects the river water level and creating two-directional currents propagation (Acreman, 1994; Pauta, 2017).

According to Sampurno et al. (2022a), the flood hazard along the Kapuas River is delineated into three regions. From the river mouth to 30 km upstream of the river (Pontianak) is the tide-dominated area, where discharge no longer controls the maximum water level, which is correlated to flood hazards. From 30 to 150 km is a transition region, where the flood is triggered by the interaction between tides, surges, and river discharge. Then, from 150 km upstream, the river-dominated area, where tides are no longer capable of triggering floods.

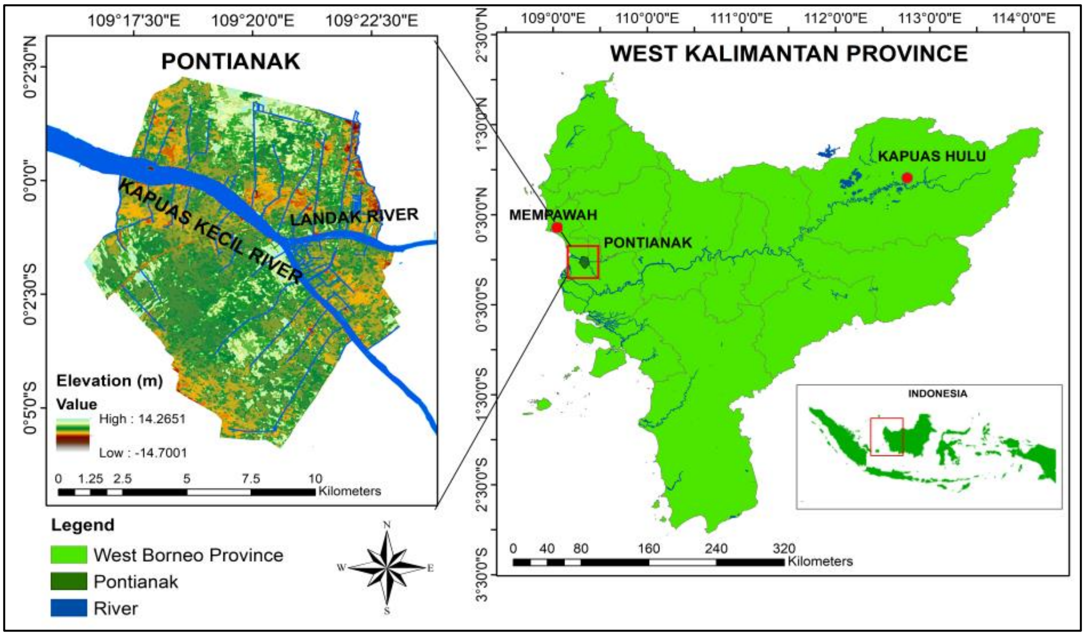

Fig. 1. The DEM of Pontianak, retrieved from the Geospatial Information Agency of Indonesia (BIG), within West Kalimantan Province, Indonesia. The province boundary and waterways maps retrieved from Geofabrik GmbH and OpenStreetMap Contributors | Map tiles: Creative Commons BY-SA 2.0 Data: ODbL 1.0.

The Kapuas River is the longest island river, with a length of 1143 km, stretching from the middle of Borneo Island (Kapuas Hulu Regency) to the western coast (Mempawah Regency). Its river branch stream (The Kapuas Kecil River) flows through Pontianak (Widjonarko et al., 2021). This Kapuas Kecil river stream meets the end of the Landak River in Pontianak, dividing the city into three parts (**Fig. 1**). The Kapuas Kecil River has a width of about 449 - 1977 meters (Lestari et al., 2017), with varying depths from 1 meter (river mouth) to 15 meters (middle stream) (Sampurno et al., 2022a). Potential inundation due to tidal flood within the city through the Kapuas River stream could reached 9.70 km^2 in Pontianak Kota and Pontianak Barat districts and 4.36 km^2 in Pontianak Selatan and Pontianak Tenggara districts (Purnomo et al., 2019; Kurnia et al., 2019).

Many factors, such as climate change, land subsidence, and sea-level rise, can exacerbate tidal floods in coastal areas. Those phenomena can increase inundation areas, destroy more infrastructures, and threaten coastal community activities (Takagi et al., 2016; Hidayat et al., 2020; Zainuri et al., 2022). Among those factors, land subsidence is vital in determining the severity of tidal flooding in the long term. Land subsidence is a major cause of environmental degradation (Hamdani et al., 2021).

Land subsidence is decreasing ground-level elevation against a stable reference field, which can occur suddenly or slowly over a long period (Khoirunisa et al., 2015; Islam et al., 2017). According to Whittaker and Reddish (1989) in Kasfari et al. (2019), land subsidence is caused by the extraction of groundwater, heavy loads from human settlement, mining activities, sedimentation of the basin area, and underground cavities that cause sink holes and natural subsidence. Characteristics of land subsidence need to be analyzed for area structuring and planning, including mitigation of tidal flood impacts.

Research on the correlation between land subsidence and the tidal flood has been carried out massively in several parts of Indonesia. In some study areas, they report that land subsidence's effect on tidal floods is more influential than sea level rise (Iskandar et al., 2020). The land subsidence has contributed to the expansion and depth of tidal floods (Marfai and King, 2008; Abidin et al., 2015; Adi and Wahyudi, 2018; Hidayat et al., 2020; Widada et al., 2020).

Unfortunately, tidal floods in the city of Pontianak are still less researched. However, some researchers have studied flood-related topics and the hydrodynamic processes within the city. Kuntinah et al. (2021) used the DELFT3D model to simulate water levels in several flood cases. Sampurno et al. (2022a) used the SLIM model to predict tide-surge-discharge interaction along the Kapuas riverbank. Therefore, this study attempts to simulate the current and the future tidal floods in Pontianak under land subsidence projection scenarios using the DELFT3D model integrated with the HEC-RAS (Hydrologic Engineering Center River Analysis System) model. The results of this study could help the local government prepare disaster mitigation strategies and long-term urban planning.

2. DATA AND METHODS

The land subsidence parameters in this study were calculated using the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique with Sentinel-1 SAR satellite imagery data (Aji et al., 2018; Hidayat et al., 2020). The DInSAR technique is a unique remote sensing approach that can map topography and measure surface changes (Mohammed et al., 2022). The data used was Sentinel 1-A satellite image data on 6 December 2020 as master image and 1 December 2021 as slave image obtained from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). Furthermore, the data was processed using the SNAP (Sentinel Application Platform) program (Serco Italia SPA, 2018). SNAP is a tool for processing and analyzing earth observation data developed by the European Space Agency (ESA) (https://www.esa.int/). The annual land subsidence is calculated with the formula (adapted from Iskandar et al., 2020) as follows:

$$LS = \frac{DV \; x \; 365}{T' - T} \tag{1}$$

where *LS* is land subsidence for one year, *DV* is the displacement derived from the differential phase in the line of sight of Sentinel-1 from DInSAR processing in SNAP Tools. $T' - T$ is the time-lapse of image pair acquisition (in days), here, 6 December 2020 to 1 December 2021.

This study uses the DELFT3D 4.0 model from Deltares (https://www.deltares.nl/) to perform flood simulations. DELFT3D is a model that can be used to simulate water dynamics on coasts, rivers, and estuaries (Deltares, 2014). It has been successfully applied to predict water level dynamics (Kuntinah et al., 2021; Madah and Gharbi, 2022). The meteorological data as the input for this model is retrieved from the Global Forecasting System (GFS), which was provided by the National Center for Environment Prediction (NCEP, 2015), with a resolution of 0.25° x 0.25° (data retrieved from t+0 to t+72 hours). The data comprises pressure and zonal-meridional wind components. Furthermore, the model's boundary conditions were the tidal components obtained from the TPXO 08 global tide model (Egbert and Erofeeva, 2002).

The bathymetry data were obtained from the Indonesian Navy (Kästner et al., 2019) with a resolution of 0.1 x 0.1 km, blended with data from the Geospatial Information Agency with a resolution of 0.18 x 0.18 km. The domain model was drawn from West Kalimantan's coast to the Pontianak to ensure that hydrodynamic and atmospheric phenomena were captured properly (**Fig. 2**). The average grid resolution was 0.25 x 0.25 km with a computational time step for 60 seconds.

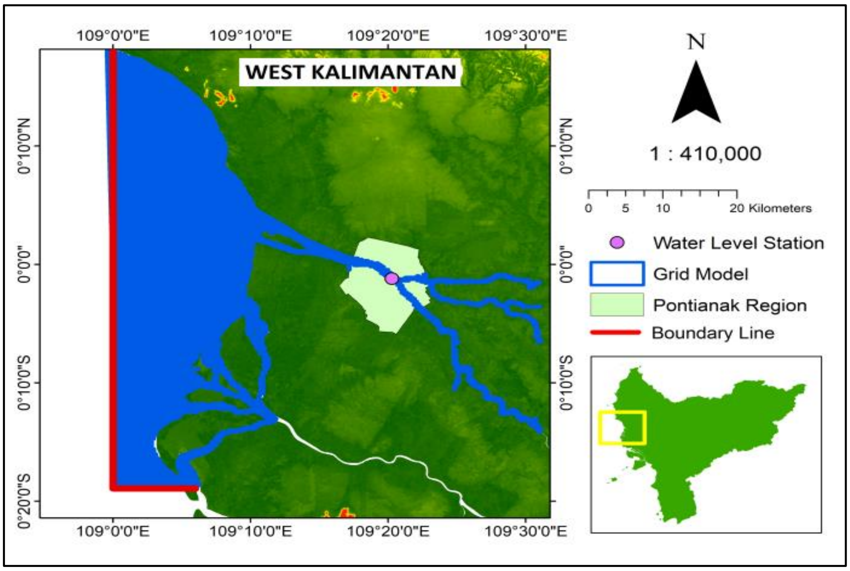

Fig. 2. Domain grid of the DELFT3D model.

The model outputs were validated using hourly observation data from the Pontianak Maritime Meteorological Station (PMMS), with the Nash Sutcliffe Efficiency (NSE) as the goodness of fit indicator. The NSE was developed by Nash and Sutcliffe (1971) and is widely used as a reliable statistic parameter for assessing the goodness of fit of hydrologic models (McCuen et al., 2006). The NSE can be calculated by the following equation:

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}(Q_0^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_0^t - \bar{Q}_0)^2} \quad (2)$$

where Q_m^t represents the model output, Q_0^t is the observation data, and $\bar{Q}_0$ is the mean of observation data. The NSE coefficient interpretation is based on the criteria put forward by Motovilov (1999): NSE greater than 0.75 means good, 0.36<NSE<0.75 means sufficient, and NSE less than 0.36 is assumed not sufficient.

The tidal flood inundation within the city was simulated using the HEC-RAS 6.1 model developed by the US Army Corps of Engineers (https://www.hec.usace.army.mil/). As the boundary conditions, the water levels and the discharges obtained from the output DELFT3D are imposed. The simulation period started from 6 December 2021 to 9 December 2021, both at 00 UTC, in 10 minutes time steps data. We chose the period because the historical rainfall data is 0 mm (based on data from the Pontianak Maritime Meteorological Station); therefore, the rainfall can be neglected, and the analysis can focus on the interaction of tides and land subsidence. The digital elevation model (DEM) used was provided by the Geospatial Information Agency of Indonesia (BIG) with a 0.27-arcsecond (8.1-meter) resolution. The DEM was corrected with Mean Absolute Error (MAE), retrieved from the benchmark point (yellow dot), which is also obtained from BIG (**Fig. 3a**). Next, the DEM over dense buildings located around the riverbanks was re-corrected again to remove the impacts of the buildings. Lastly, the river bathymetry was obtained from the Indonesian Navy (Kästner et al., 2019).

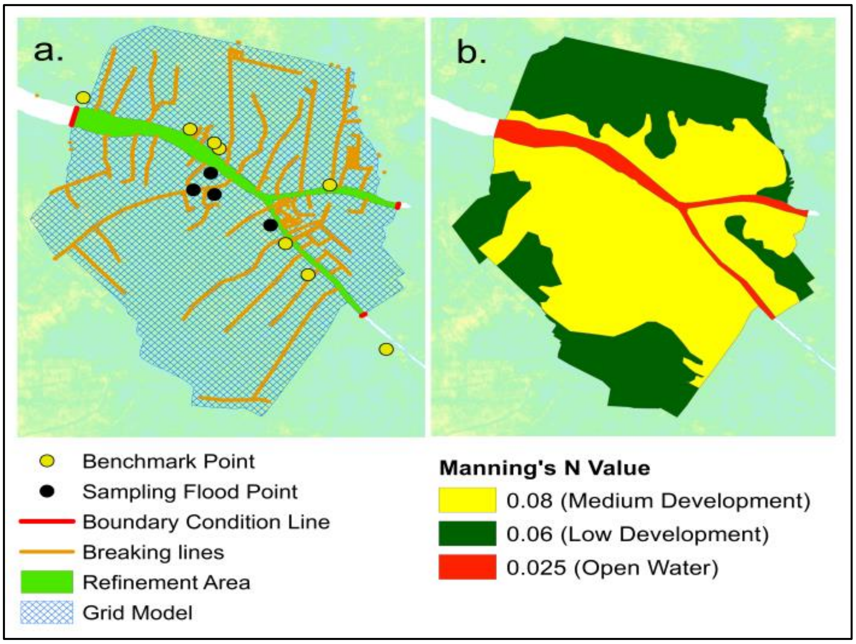

Fig. 3. a) The geometry of the HEC-RAS model. b) Manning's N Values.

The sensitivity of the flood event parameters completely depends on the flood boundary conditions, the DEM resolution, the roughness coefficient, and the 2D cell size (Pathan et al., 2021). Hence, appropriate boundary conditions and high DEM resolution will produce a more accurate model output. In addition, the roughness coefficient will affect the water propagation process. Therefore, the coefficient must be adjusted for every existing land cover. Then, the higher the grid resolution in the domain, the more detailed the model output represents the area. However, a higher grid will cost more computational resources.

The HEC-RAS model domain covered an area of 118 km^2 with varying resolutions between 10 and 8 meters (**Fig. 3a**). The model was run with a computing time step of 60 seconds. Next, the roughness coefficient was divided into three areas based on the type of land cover (**Fig. 3b**), including rivers (0.025), medium development area (0.08), and low development area (0.06). The coefficients are defined based on the roughness coefficient from the National Land Cover Database 2016 (Dewitz, 2019) and the recommended range of numbers in the HEC-RAS manual (HEC-RAS, 2021). The flood simulation was carried out four times on different DEM data (the current condition in 2021 and the projected conditions due to land subsidence in the next 10 years, 30 years, and 50 years).

3. RESULTS AND DISCUSSIONS

The water level extracted from the DELFT3D model output is close to the observation data (**Fig. 4**). However, there is a small difference where the peak tide's lag time in the model is one hour faster than the observation data, and the lowest ebb generated by the model is also lower than the observation data.

Furthermore, the NSE between the model output and observation is 0.83. It means that the output of the DELFT3D model meets the criteria of good conformity (against the observation) and can be used to represent the real processes. Therefore, we use those outputs as boundary conditions for the HEC-RAS model to estimate the city's tidal flood extent and depth precisely.

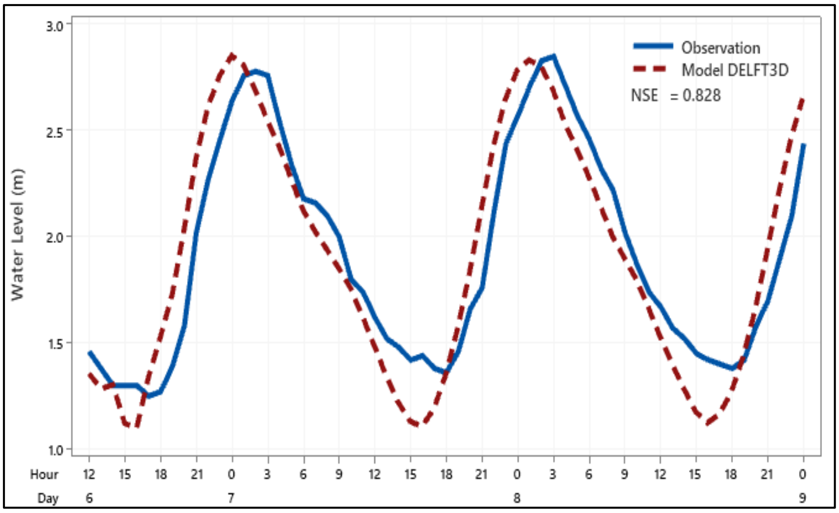

Fig. 4. Comparison between water level from the DELFT3D model output and the observation.

The output of the DELFT3D model shows that the discharge of the Kapuas Kecil ranges from 103 to 1403 m^3/s (**Fig. 5a**). However, the observation data from Kästner (2019) shows that from December 2013 to April 2015, the Kapuas discharge at Sanggau (285 km from the estuary, **Fig. 5b**) was between 1000 m^3/s (dry season) and 10,000 m^3/s (wet season). Then at Rasau (red dot in **Fig. 5b**), 17% of the discharge flows into Kapuas Kecil River (red line), and 83% flows into Kapuas Besar River (blue line). It means the discharge entering the Kapuas Kecil River was between 170 - 1700 m3/s. Since the output of our model is close to the observation, we concluded that the output data of the DELFT3D model is acceptable to represent the real discharge.

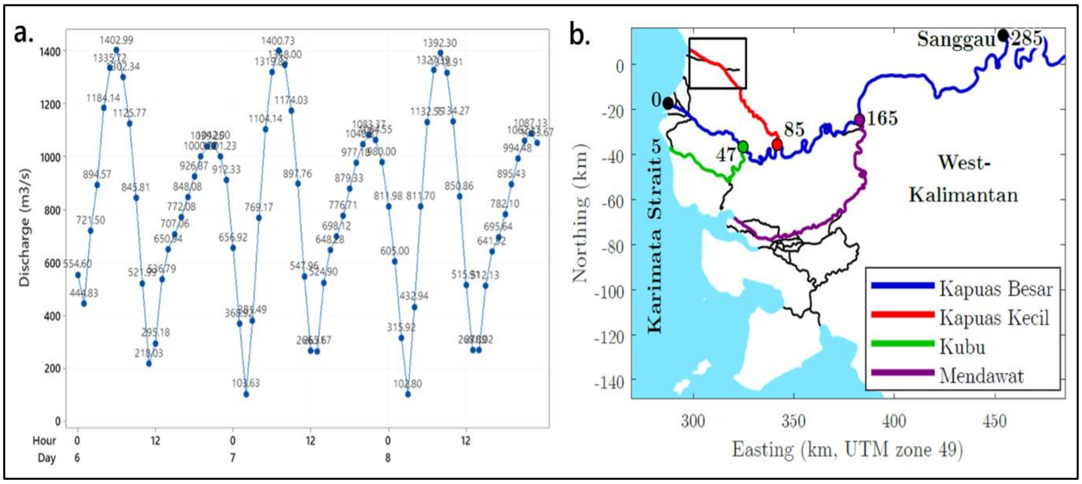

Fig. 5. a) Kapuas River discharge data from DELFT3D model output. The Kapuas River stream and its branches downstream (Kästner, 2019).

The annual land subsidence in Pontianak shows that the maximum is about 1.03 cm/year (**Fig. 6**). The extraction of the maximum land subsidence for each subdistrict in Pontianak: Pontianak Utara 0.71 cm/year, Pontianak Barat 0.89 cm/year, Pontianak Kota 0.99 cm/year, Pontianak Selatan 0.86 cm/year, Pontianak Tenggara 1.03 cm/year, and Pontianak Timur 0.86 cm/year.

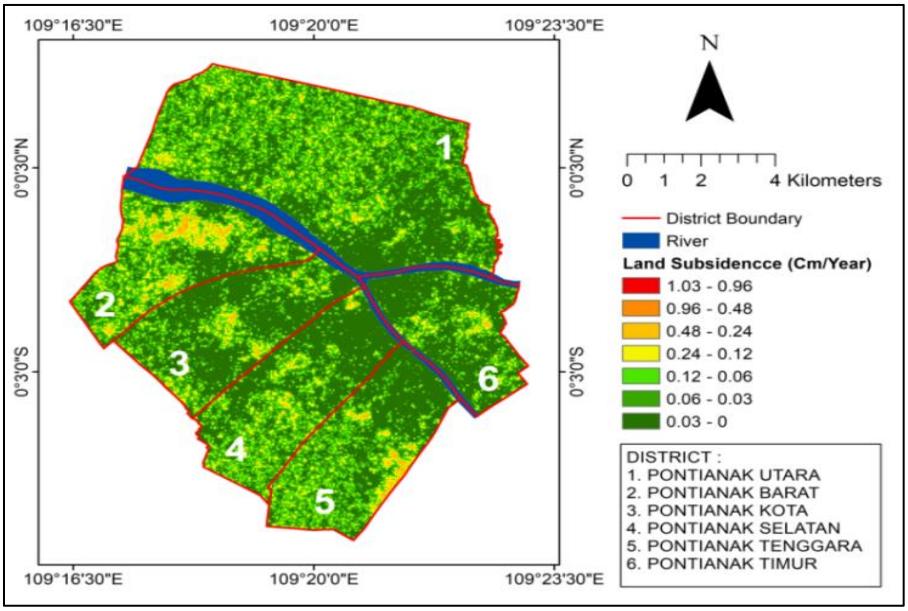

Fig. 6. Land subsidence velocity in Pontianak (cm/year).

Although southeastern Pontianak has high land subsidence, this section area is not directly connected to the river flow. Therefore, we suspect significant changes in tidal flooding for 50 years did not occur in this area. On the contrary, in the western Pontianak, land subsidence areas are directly connected to the river. Consequently, tidal flooding changes in the area will happen in the future. Land subsidence in Pontianak varies over an area of 112.11 km^2 (**Table 1**). If the existing domain model is 118 km^2, there are areas of 5.89 km^2 without subsidence. The significant land subsidence between 0.48 - 1.03 cm/year occurred over 32 km^2 (28.54% of the total area).

Table 1.

Land subsidence area of each subdistrict in Pontianak (km^2).

Subdistricts/ LS	**0 – 0.03 cm/year**	**0.03 – 0.06 cm/year**	**0.06 – 0.12 cm/year**	**0.12 – 0.24 cm/year**	**0.24 – 0.48 cm/year**	**0.48 – 0.96 cm/year**	**0.96 – 1.03 cm/year**
Pontianak Utara	14.76	0.01	0.34	3.35	9.34	10.81	0.00
Pontianak Barat	4.04	0.04	0.78	2.59	3.55	3.41	0.00
Pontianak Kota	9.11	0.00	0.01	0.21	1.11	2.31	3.01
Pontianak Selatan	8.23	0.01	0.19	1.36	3.08	3.42	0.00
Pontianak Tenggara	7.02	0.00	0.01	0.37	1.41	3.32	3.72
Pontianak Timur	6.98	0.00	0.11	0.67	1.44	2.01	0.00
Sub Total	**50.15**	**0.05**	**1.44**	**8.54**	**19.93**	**25.27**	**6.73**
Total Area	**112.11**						

The simulation of tidal flood projections due to land subsidence aims to see spatial changes over 50 years for existing flood cases. The results of the inundation projection in the scenario of tidal flood cases (**Fig. 7-8**) show changes in flood extent area and depth.

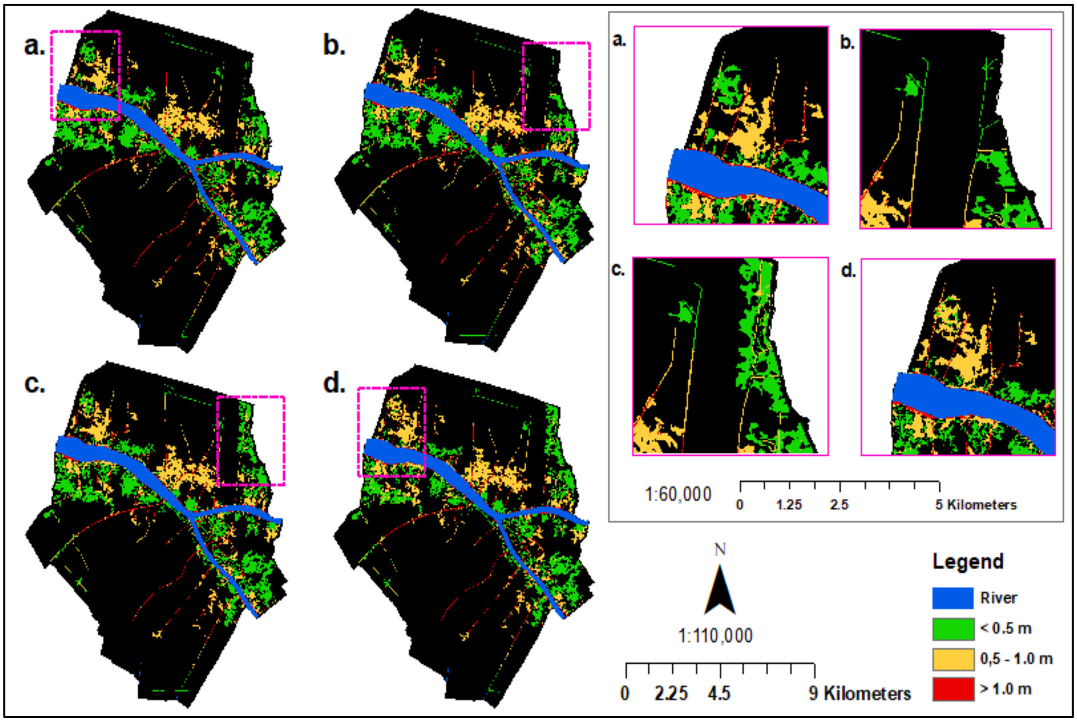

Fig. 7. The inundated areas at the flood's peak on 7 December 2021 at 02.00 UTC in a) current condition, b) 10 years, c) 30 years, and d) 50 years.

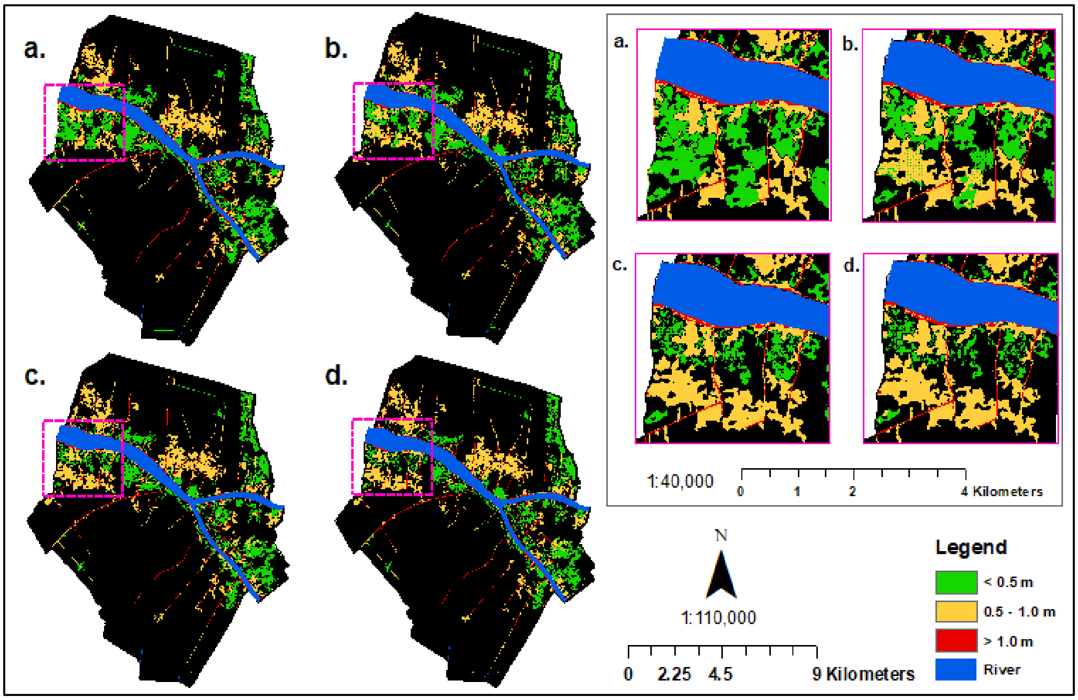

Fig. 8. The inundated areas at the flood's peak on 8 December 2021 at 03.00 UTC in a) current condition, b) 10 years, c) 30 years, and d) 50 years.

For example, northern Pontianak has not been inundated in the current condition and ten years simulations, and then it's become flooded in the next 30 and 50 years. Furthermore, the longer the projection period, the deeper the inundated area in western Pontianak, but its extent narrower (the map color changes from green to yellow).

Table 2.

Inundated areas for each flood's peak scenario (in km^2).

7 December 2021				
No.	**Simulation Period**	**Inundation < 0.5 meters**	**Inundation 0.5 – 1.0 meters**	**Inundation > 1.0 meters**
1.	Current (2021)	10.15	7.07	1.90
2.	10 years	10.01	7.07	1.90
3.	30 years	9.82	7.33	1.92
4.	50 years	8.71	7.68	1.95
8 December 2021				
No.	**Simulation Period**	**Inundation < 0.5 meters**	**Inundation 0.5 – 1.0 meters**	**Inundation > 1.0 meters**
1.	Current (2021)	10.37	7.93	1.99
2.	10 years	9.29	8.60	2.02
3.	30 years	7.97	8.86	2.16
4.	50 years	7.10	8.95	2.18

Generally, there is a dynamic flood area extent based on their respective depths (**Fig. 7-8**). Based on DEM, we suspect that land subsidence in Pontianak is uneven and clustered. If the land use is constant and the boundary condition is the same, then the inundation depth in some areas will be deepened. **Table 2** shows the inundation projection for the next 50 years based on the scenario of the 7 December 2021 and 8 December 2021 floods. Using the 7 December scenario, we project that the inundated areas with less than 0.5 meters depth decreased by 6.3%, while the inundated areas with a depth between 0.5 - 1.0 meters increased by 4.1%, and then the inundated area with a depth more than 1 meter increased by 1.2%. On the other hand, the flood projection based on the 8 December 2021 flood event shows that the inundated areas with depths lower than 0.5 meters decreased by 23.6%. Meanwhile, the inundated areas with depths between 0.5 - 1.0 meters increased by 10.4%, and inundated areas with depths deeper than 1 meter increased by 6.5% in the next 50 years.

The simulation results showed that the flood depth would be deeper in the future but impacts different sub-areas differently. Location A and D (**Fig. 9a** and **Fig. 9d**) showed that land subsidence increased the depth of the inundation by 0.1 - 0.4 meters. Location B (**Fig. 9b**) showed that in the next 10 years, the flood depth will increase to 0.4 meters, and dry areas in the current scenario will be inundated in future scenarios. Furthermore, for the next 30 and 50 years, while tidal floods subside, waters may remain within the area for two days. The flood dynamic in location C (**Fig. 9c**) is similar to locations A and B but has different depth changes. The simulation for the next 10 years shows that the depth increases by 0.03 meters. Meanwhile, for the next 30 and 50 years, the depth will increase by 0.1 - 0.18 meters.

Overall, we concluded that the impact of land subsidence on tidal flooding in Pontianak varied within each sub-area. The tidal flood depth will increase over the next 50 years due to land subsidence between 0.03 - 0.4 meters. The local government can use this information to plan mitigation strategies for each sub-area within the city.

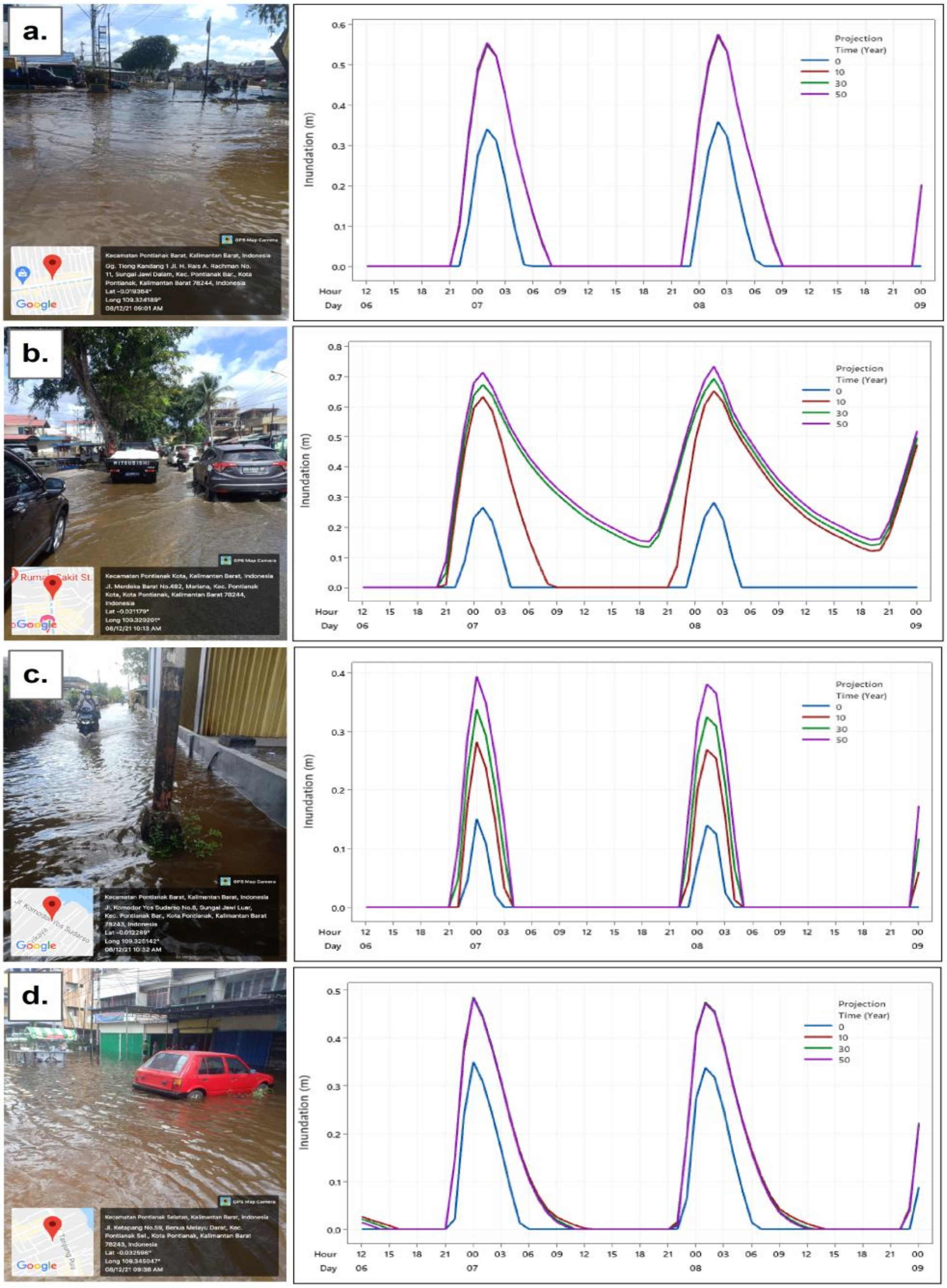

Fig. 9. (a-d) The tidal flood sample locations: documentation of flood events on 8 December 2021 at the different sample locations (left); time-series of flood depth dynamic in the current (0 years) and the future projections (right).

4. CONCLUSIONS

In this study, we successfully built a model that simulates the tidal flood projection due to land subsidence in the study area. The water level validation output of the DELFT3D model shows a good agreement with the observation data, with a NSE of 0.83 (good criteria). Our results showed that land subsidence in Pontianak, which reaches a maximum of ±1.03 cm/year, will decrease the shallow inundation areas (depth less than 0.5 meters) by 23.6% and increase the deep inundated areas (depth more than 0.5 meters) by 16.9% over a next 50-year. Although the southeastern area of Pontianak has high land subsidence, the area is not directly connected to the river flow. Therefore, tidal flooding in the next 50 years over the area will not be affected. While in the western Pontianak, where the areas are well connected to the river, land subsidence will exacerbate tidal flooding. Overall, the depth of the tidal floods within Pontianak that occur in the future will increase by 0.03 - 0.4 meters and varied in across locations. The local government can use the analysis results to plan proper mitigation to reduce the flood risk.

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