Tidal Flood in Pekalongan: Utilizing and Operating Open Resources for Modelling

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Abstract. The open resource materials are used in this research to construct a numerical model and study the tidal flood in Pekalongan City, including the impact of land subsidence. The area of interest is in 6 villages in the north coast of Pekalongan namely, Jeruksari, Pabean, Bandengan, Kandang Panjang, Panjang Baru, and Panjang Wetan. Delft3D, an open ware, is used for numerical modelling. While the input data are obtained from GEBCO for bathymetry, SRTM for topography, and TPXO for tidal constituent. The resulting model shows a decent agreement with field tidal elevation data from Indonesian Navy Tide Tables and GLOSS. After applying the annual land subsidence, compare to flood in May 2018, it is found that the inundation height increases for around 11, 36, and 132 cm in 2019, 2025, and 2050. In 2050, an extreme inundation over 2.5 m is found. Similar with Jakarta flood, to protect the land area, coastal dykes may be proposed. However, for long-term resilience, it is recommended to emphasize efforts in decreasing the land subsidence rate. This study indicates the threat of tidal flood in Pekalongan, thus further studies followed with field survey and more constituents in the modelling are strongly recommended.

1. Introduction
Land subsidence has been an important subject of studies in the past decades. Researcher across the globe has studied the subsidence rate [1], causes [2], impacts [3], and how to adapt to the threat especially in a coastal-front area at various countries [4]. In Indonesia, one of the sexiest topics is the capital city, Jakarta. Northern Jakarta has been regularly flooded in a certain time due to the tidal propagation intrusion and high precipitation. The land subsidence worsens the condition more significant than the sea level rise since it is declining the land elevation constantly so then the land is lower than the mean sea level [4].

However, Jakarta is not the only place suffered. Until the present time, some regions at the Northern Coast of Central Java are also threatened by the tidal flood, Pekalongan City for an instance [5]. National and local news reported that the city was severely flooded in the second half of May 2018 [6-9]. Tracking the history, the flood has been happening regularly years before. Meanwhile, Pekalongan can be described as one of the representatives of Indonesia batik culture [10]. Thus, to preserve human, culture, and assets in Pekalongan City, a study to understand and forecast the future scenarios of Pekalongan is needed.

This study aims to construct a reliable hydrodynamic model to simulate the tidal flood in Pekalongan City and its surrounding area. The highlight of this study is also the utilization of various kind of open data which freely accessible on the internet. Not to mention, the tool for numerical
mode
ling itself is also an open ware. In the end, this study will present the inundation forecast at 2019, 2025 and 2050.

2. Methodology
Study location is in the northern part of Java Island as shown in Figure 1, there are global domain, local domain and main area. Global domain covers West Java Province and Central Java Province. Local domain covers Pemalang Regency, Pekalongan Regency, Pekalongan City and Batang Regency, in Central Java Province. The main area is in the northern region of Pekalongan City. The illustration of study locations is presented in Figure 1.

The numerical modelling takes the main role in the study which performed to construct a reliable simulation of tidal propagation at Java Sea and its intrusion to the urban residential area in the northern coast of Pekalongan City. In this study, the only constituent included is the tidal, however, in the future, the involvement of wind and other forcing is promising. The modelling time frame is specified at the third to fourth week in May which is known as the worst period of the tidal flood in Pekalongan in 2018.

![Figure 1](image_url). Study locations and the three categories of area of interest, the (a) global domain, (b) local domain, and (c) main area

The study framework is given in Figure 2. The numerical model is set up few times before result in a forecast model. The steps are rough, initial, benchmark, and forecast model. The rough model is a
model defined by default value in the modelling tool and default input from open data. The initial model is a rough model validated with tidal elevation record. The benchmark model is a model which reliable to simulate the tidal propagation to land area, resulting in a correct value of inundation level. Finally, the forecast model is the future inundation model in Pekalongan City, set in 2019, 2025, and 2050.

![Figure 2. Framework of numerical modelling.](image)

2.1. Data compilation

As mentioned, open data and open ware combination is the highlight of this study. The numerical model is constructed using this widely available open resources. As in present, a large number of researcher have also applied these resources in their studies.

As shown in Figure 2, the required input to assemble the model are bathymetry, topography, and tidal boundary. Bathymetry data are essential for hydrodynamic modelling in the coastal environment since the water depth is one of the main variables in the shallow water equation. The bathymetry data used in this study is obtained from the GEBCO, which operates under the joint auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) [11]. While for land elevation, topography data is taken from the Shuttle Radar Topography Mission (SRTM) provided by the National Geospatial-Intelligence Agency (NGA) and National Aeronautics and Space Administration (NASA) [12]. Data resolutions for each data are per 30 and 1 arc second for the bathymetry and topography respectively. Tidal boundary is generated using TPXO 7.2, a tool for generating tidal constituent [13]. The program is developed by the Oregon State University in the United States.

Further for model validation, tidal elevation and inundation height record are gathered. There are two sources of tidal elevation data, they are the Indonesia Navy Tide Tables 2018 and GLOSS database. Tidal data at Semarang and Cirebon Station are obtained from the forecasted tide tables [14] which have been widely used in Indonesia. However, to present a recorded tidal data including the occurring abnormal tidal behaviour, GLOSS database is used which provides a dataset of tidal observation in Indonesia including in Semarang Station [15]. The comparison of tidal elevation at Cirebon and Semarang Station on May 15th – 30th, 2018 are shown in Figure 3 while the station locations are denoted in Figure 1.
Figure 3. Comparison between the three obtained tidal data, Cirebon Tide Tables (blue line), Semarang Tide Tables (orange line), and Semarang Tidal Record (grey line).

For inundation data of tidal flood, since there is no any document yet which provide solid data of inundation height and location, national and local newspaper are chosen as the sources. The data is obtained at the 6 villages around North Pekalongan District, in Pekalongan City, the inundation level is varied from 0.5 – 1 m on May 22nd and 23rd 2018 [6-9]. The location and inundation level are illustrated in Figure 1.

3. Numerical Model
Numerical model in coastal environment has been widely used by researcher around the world. The range of its utilization is about ocean renewable energy [16], coastal process [17], contaminant transport [18], and even for port planning [19] or other coastal infrastructure as well. For this study, the numerical modelling is proposed to show the impact of tidal propagation and intrusion in the north coast of Pekalongan City.

Some of well-known modeling tools at coastal environment are the MIKE [16], Delft3D [20], Telemac [20], SMS [18], and etc. Particularly in this study, Delft3D is chosen since it provides the open ware version for research activity and has a user-friendly interface.

3.1. Model description
Delft3D is one of the leading tools in hydrodynamic modelling for coastal, river, and estuarine areas. The tool is capable to simulate phenomena of flows, sediment transport, waves, water quality, and etc. Delft3D-FLOW which used in this study is a module in the Delft3D package. It uses and solves the Navier Stokes equations for an incompressible fluid, within the shallow water and the Boussinesq assumptions [21].

The modelling is set as a 2-dimensional model using flood scheme to able the tidal propagate into land area. The model is designed into two stages, the global and local domain. The global domain covers a large water area at northern part of West and Central Java. The local domain covers Pekalongan City and 3 other regencies. The global and local domain are presented in Figure 4. Each of Figures 4a and 4b correspond to Figures 1a and 1b.

The mesh of numerical model, both in the global and local model is design as a uniform rectangular grid from the boundary to the interest area. The mesh size of global domain is 1 x 1 km while the local domain is 5 times finer [20], which designed to be smaller to provide a more accurate model result. Overall, the model only applies the offline nesting, leaving the online nesting out. The transition of global and local domain is driven by the nesting 1 and 2 features in Delft3D [21]. Further, to assure period for model to be stable, 2 – 3 days spin up time is applied to both domains.
Figure 4. Overview of (a) The global and (b) local domain, including bathymetry, land elevation, and boundary condition setting

The seabed and land elevations are obtained from the GEBCO and SRTM combination which also have been used in Takagi et. al. (2016) for a similar study in Jakarta, the capital city of Indonesia [3]. The resulted bathymetry and land elevation are shown in Figure 4. The tidal constituents at boundary conditions of global domain are generated using TPXO 7.2 [13] while the boundaries of local domain are from global domain output translated using nesting features. The northern boundary is set in current velocity (black line in Figure 4b) and western and eastern boundaries (red lines in Figures 4a and 4b) are in water level. This arrangement is adapted from A. A. Rahman et al. (2017) to result in a more stable model [20].

To result in a reliable rough and initial model (stated in Figure 2), the tidal constituent and topography data are required to be calibrated, respectively. Particularly for the topography calibration, an effort to correct the data is needed since the land elevation is the main variables to determine the inundation height. In addition, the modelling which including land area, the manning value used is 0.02 and 0.04 for water and land respectively [22]. The summary of the 4 models set up is presented in Table 1.

Table 1. Set up of the rough, initial, benchmark, and forecast model.

| Parameters            | Rough | Initial | Benchmark | Forecast |
|-----------------------|-------|---------|-----------|----------|
| Domain                | Global| Local   | Local     | Local    |
| Grid size             | 331 x 216 | 159 x 188 | 159 x 188 | 159 x 188 |
| Grid resolution       | 1 x 1 km² | 0.2 x 0.2 km² | 0.2 x 0.2 km² | 0.2 x 0.2 km² |
| Time step             | 4 minutes | 1 minute | 1 minute | 1 minute |
| Time frame            | May 9th – 30th, 2018 | May 11th – 30th, 2018 | May 11th – 30th, 2018 | Nov. 12th – 30th, 2019 Nov. 20th – Dec. 8th, 2025 Oct. 28th – Nov 17th, 2050 |
| Roughness (Manning’s n value) | Uniform 0.02 | Uniform 0.02 | Water 0.02 Land 0.04 | Water 0.02 Land 0.04 |
3.2. Scenarios
There are 4 modelling steps as presented in Figure 2. In the forecast model, land subsidence parameter is applied. The used annual subsidence rate is shown in Figure 5 which is adapted from Chaussard et al. [2], varying spatially along Pekalongan City and Pekalongan Regency [2]. The minimum and maximum values are approximately 0 and 8 cm/year at the highland area and Bandengan Village respectively. Models with different land elevation affected by the land subsidence are run in 2019, 2025, and 2050. The result is inundation level at the 6 investigated villages and the spatial distribution.

![Figure 5. Annual land subsidence rate, adapted from Chaussard, et al. [2]](image)

The forecast model is set in the highest tidal elevation to represent the most extreme inundation occurrence. To know the time frame of this high tidal elevation at those years, ErgTide, a software to predict tidal elevation is used. ErgTide also has been used in few studies [23-24]. ErgTide builds the tidal constituents from a known tidal dataset (at least for 14 days) using least square analysis and converts it again into elevation data at any time. As shown in Figure 6d, the predicted elevation by ErgTide is showing a decent agreement to both model and field data. After generated for full year in 2019, 2025, and 2050, the obtained maximum tidal elevations are 46 cm (November 22nd 2019), 48 cm (November 30th 2025), and 40.5 cm (November 9th 2050). Considering the spin-up time and to show a cycle of flood-ebb tide, the time frame for forecast models are determined as shown in Table 1.

4. Result and Discussion

4.1. Tidal elevation validation
The resulting model data are compared with the field data at the corresponding locations. The errors of model and field data are calculated using mean absolute error formula as defined in Eq. 1. There are two sites, Cirebon and Semarang. In Semarang, there are the Indonesian Navy (Dishidros) and the Gloss data. The comparison is given in Figures 6a – 6c for Cirebon Dishidros, Semarang Dishidros, and Semarang Gloss respectively. The obtained value are 6.4, 4.1, and 5.8% respectively. Thus, the simulation is concluded to be reliable to simulate the tidal propagation decently.

\[
\text{Error} = \frac{|\text{Model data} - \text{Field data}|}{\text{Tidal range}} \tag{1}
\]
Figure 6. Tidal elevation validation result for (a) Cirebon Tide Tables, (b) Semarang Tide Tables, and (c) Semarang Tidal Record also (d) the predicted tidal from Ergtide.

4.2. Topography calibration

Previously, inundation depths at 6 villages (see Figure 1) have been introduced as summarized in Table 2. With the validated tidal elevation model (in the initial model), the resulting inundation depth is found to be 0 meter at all districts (as given in Table 2). It indicates that the land elevation is overestimated which is reasonable since SRTM data accuracy is around 10 meters [25] and taken in 2000 [12]. To correct the data, elevation of 5 rail stations [26] in the global domain are taken as a benchmark. Further, the land elevation data in a region is reduced with the difference between the SRTM data with the rail stations and inundation level data in the corresponding region. Model equipped with land elevation corrections which resulting in a closer inundation value as shown in Table 2, is taken as a benchmark model.

Table 2. Inundation height comparison for field data vs initial and benchmark model.

| No | Villages     | Longitude (E) | Latitude (S) | Dates (May 2018) | Inundation (Meter) |
|----|--------------|---------------|--------------|------------------|--------------------|
|    |              |               |              |                  | Field Data | Initial Model | Benchmark Model |
| 1  | Jeruksari    | 109.65426     | 6.86999      | 22nd             | 1.0 [6]     | 0            | 1.02           |
| 2  | Pabean       | 109.66034     | 6.88022      | 22nd             | 0.5 [8]     | 0            | 0.52           |
| 3  | Bandengan    | 109.66449     | 6.87221      | 23rd             | 0.6 [6]     | 0            | 0.62           |
| 4  | Kandang Panjang | 109.67237   | 6.87015      | 22nd             | 0.6 [6]     | 0            | 0.67           |
| 5  | Panjang Baru | 109.67846     | 6.86198      | 22nd             | 0.7 [9]     | 0            | 0.72           |
| 6  | Panjang Wetan | 109.68042    | 6.87012      | 22nd             | 1.0 [7]     | 0            | 0.97           |

4.3. Future inundation and Solutions

As the forecast models have run in the mentioned time frame in Table 1, the resulting inundation height is given in Figure 7, which taken at the highest tidal condition. Clearly seen that in 2019 the inundation values around 1 – 1.5 meter then in 2025 and 2050 the range grows to 2 and 3 meters respectively.
To summarize the specific inundation heights at 6 observation points (marked as colored dots), Table 3 is presented. Compare to inundation in 2018 (given in Table 2), 2019’s model shows an increment around 8 – 14 cm. While in 2025, the increment rises to around 31 – 41 cm. It is also shown that if the existing rate of land subsidence is continuing to 2050, inundation in an extreme level is inevitable, over 2.5 meters at worst.

| No | Villages      | Inundation height (meter) |
|----|---------------|----------------------------|
|    |               | 2019 | 2025 | 2050 |
| 1  | Jeruksari     | 1.14 | 1.40 | 2.51 |
| 2  | Pabean        | 0.64 | 0.91 | 2.08 |
| 3  | Bandengan     | 0.73 | 0.93 | 1.82 |
| 4  | Kandang Panjang | 0.76 | 0.92 | 1.59 |
| 5  | Panjang Baru  | 0.83 | 1.06 | 2.04 |
| 6  | Panjang Wetan | 1.08 | 1.31 | 2.28 |

As observed in Figure 6, the maximum tidal elevation at Pekalongan Coast is around 45 cm or 60 cm (in the abnormal condition). Considering the existing inundation given in Table 2, it is certain that some area is already below the mean sea level (MSL). For instance, Jeruksari and Panjang Wetan are approximated to be 55 cm below the MSL since the 45 cm tide elevation resulting 100 cm inundation.

Exactly similar occurrence takes place in few cities around the world, namely Jakarta, the Capital City of Indonesia where 2 meters coastal dyke is built to protect the land area from tidal inundation. This coastal dyke can also be applied in Pekalongan. However, it is only for short term since the coastal dyke will subside along the land in the meantime caused by land subsidence. To fight tidal inundation, the core problem is the excessive groundwater extraction. So, it is strongly recommended to manage the groundwater consumption in Pekalongan coastal area and another coastal-front city in Indonesia.

5. Conclusion
Numerical hydrodynamic modelling using open ware Delft-3D is performed in this research. The input data are based on open data which are the GEBCO for bathymetry, SRTM for land elevation, and
TPXO 7.2 for tidal constituent. Open access tidal record data of GLOSS is also used to validate the constructed model. In addition, the Indonesian Navy’s tidal elevation data is used to ascertain the validity. The utilization of GEBCO and TPXO 7.2 is decent enough to result in a good tidal propagation model, as validated with the tidal prediction and record data. While SRTM data requires to be corrected to be used for tidal inundation model. Some landmarks elevation can be used to formulate the correction. With open data utilization, model accuracy may be an issue in this research. However, the result of this research can be taken as a basic evidence and in the future, it is crucial to conduct field survey (such as topography and tidal elevation) and compose an advance model to present the behaviour of flood in Pekalongan better. The involvement of other constituents like wave and river discharge is promising.

Model with corrected land elevation model shows that some area in Pekalongan is already below the mean sea level, most probably as an impact of land subsidence. Thus, after the land subsidence rate is applied in the model, it is shown that after yearlong, the tidal flood inundation height is increasing in the range of 8 – 14 cm. The further projection shows that in 2025, inundation height in Jeruksari closing down to 1.5 meters while in 2050, it may reach 2.51 meters. At this level, the flood may severely damage urban living in Pekalongan. As happened in Jakarta, the coastal dyke guarding coastal-front area is one of the proposed solutions. However, it is only for short term since the land subsidence will lower the dyke elevation. It is highly recommended to control the groundwater consumption to fight the land subsidence and the threat of tidal flood as well.

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