Alternatives of drainage engineering in tidal flood prone areas using eco-infrastructure approach in North Pekalongan

Laily Fadhilah Sabilal Haque[1] and *Wakhidatik* Nurfaida[1*]

[1]Civil Engineering Department, Vocational School, Universitas Gadjah Mada, Jl. Yacaranda Sekip Unit IV, Bulaksumur, Sleman, Yogyakarta, Indonesia

Abstract. Tidal flood is one of the the most persistent disaster in Indonesia. It often occurs during the high tide, which can be exacerbated by extreme tidal surges, land subsidence, and sea level rise. The coastal area of Pekalongan, especially in Panjang Wetan, is one of the impacted areas during the extreme tidal flood in May 2022. Data from Indonesia Geospatial Agency showed that maximum spring tides elevation reached + 0.4 to +0.5 m above the mean sea level. Currently, although sea dike has been installed in some parts, floods are still occurring. On the other hand, interest on the nature-based solution concept is globally increasing. Therefore, this study aimed to explore the possibility of eco-infrastructure applications in mitigating coastal flooding. The analysis was done through numerical simulation using HEC-RAS model which divided into three different scenarios: existing condition, grey infrastructure scenario, and a combination of grey and blue infrastructure scenario. The simulation results indicated that the existing drainage conditions in the area was not sufficient to accommodate the flood. The grey infrastructure could restrain the tidal overtopping, while the proposed eco-infrastructure could address this issue mainly by providing a buffer zone to prevent the water from entering the settlement areas.

1 Introduction

In several lowland areas, especially the beaches or the coastal area, tidal floods often occur [1]. Pekalongan is one of the most coastal flood prone area in Indonesia. The coastal area of Pekalongan and its surrounding areas are subject to flooding due to a combination of several factors, including high intensity rainfall, land subsidence, changes in the river cross-sections, and abnormally high tides. Besides, there has been a change in the shoreline of Pekalongan sea seen from the past few years [2]. It can be seen at Fig. 1. as a study area of this research.

On May 23rd, 2022, areas along the northern coast of Java, including Pekalongan, experienced an extreme tidal flood. The flood inundated more than 50% of the North Pekalongan area and two sub-districts in West Pekalongan. The extreme high tides which reached 1.2 meters had triggered a rise in sea water nearshore and had caused large floods. The settlements and roads were inundated in varying heights and some vital infrastructures were damaged, especially in the Panjang Wetan Village [3].

Local people tend to be adaptive in dealing with the flood by carrying out structural mitigations such as elevating the house terraces, build embankments, and installing parapets [4]. But it was not enough to overcome coastal floods in the long term.

Under these conditions, this research investigated the drainage condition around the area and proposed a mitigation scenario. In this study, a combination of blue and grey infrastructure was explored.

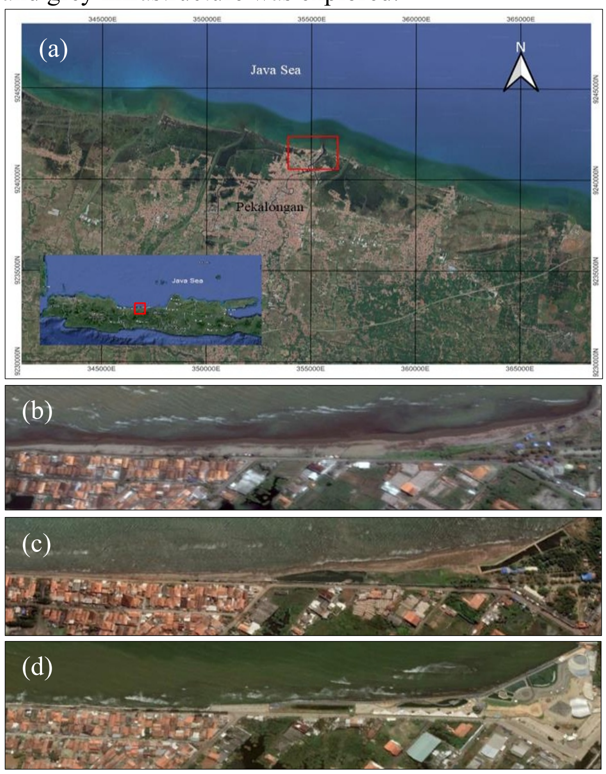

Fig. 1. (a) Map of study area; Shoreline condition in (b) 2003, (c) 2013, and (d) 2023.

*Corresponding author: wakhidatik@ugm.ac.id

Grey infrastructure, in the context of urban water resistance, could be defined as conventional rainwater management or commonly called conventional drainage [5]. This infrastructure is usually made of concrete or steel because its function to overcome the extreme events. The water will be more accelerated to flow from one location to another because its Manning value which lower than others.

Blue infrastructure is a component that aims at restoring the naturally oriented water cycle while contributing to amenity by bringing water management [6]. It usually relates to urban water infrastructure, including ponds, lakes, streams rivers and storm water provision. Blue infrastructure compliments the other infrastructure to overcome the extreme nature condition.

2 Data and Methods

This research was done in two main steps: field observation and numerical simulation. The field observation was carried out on August 2022 and January 2023, covering Jl. WR. Supratman, Pasir Kencana Beach, Jl. Kunti Utara, Jl. Pantai Sari, and Crematorium. Result from the site visit was then used to verify the numerical model. Therefore, the site description will be presented along with the model verification. The numerical model was carried out two dimensionally by using HEC-RAS 6.3.1.

The data used in the model consists of topographic data, satellite images, tide, and discharge data. The topographic data was downloaded from DEMNAS website, adjusted to the satellite images from Google Earth through terrain modification. Tidal data was obtained from the Maritime Meteorological Station Semarang, while the discharge data was assumed based on previous researches and field observation.

2.1 HEC-RAS Model Setup

The model has several important components to be set. First, the domain covers beaches, settlements, and rivers with a perimeter area of around 1.84 km^2 and 57065 computational grid cells as shown in Fig. 2. To obtain a good model, topographic detailing is crucial. Thus, terrain modification technique was greatly used in building the model. The terrain modification was done following the most recent Google Earth picture, and the result is presented in Fig. 3. The detailing includes the flood inundation prediction area which is depicted by the reddish-brown color in Fig. 2.

Runoff around the domain flows to Banger River which has two tributaries. Therefore, the model used two upstream boundary conditions (BC) and one downstream BC as seen in Fig. 2. Flow hydrograph and tidal fluctuation were assigned to upstream and downstream BCs, respectively. In this model, we mainly focused on coastal flooding. Thus, the river baseflow was estimated and assumed to be the input flow in the simulation. The discharge value for both branches were assumed as 0.56 m^3/s (Q1) and 1.63 m^3/s (Q2) [7]. This assumption was based on the flow measurement in dry season.

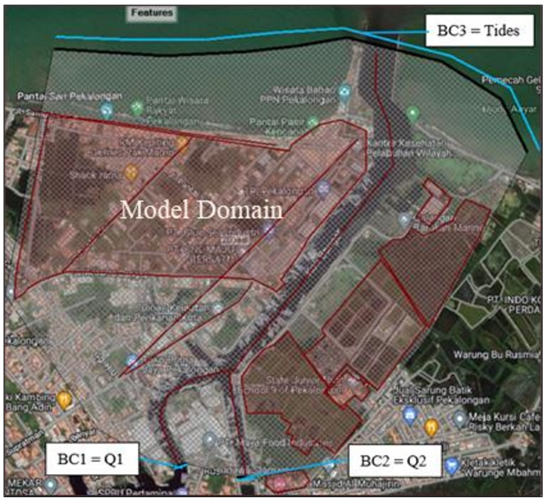

Fig. 2. Model domain.

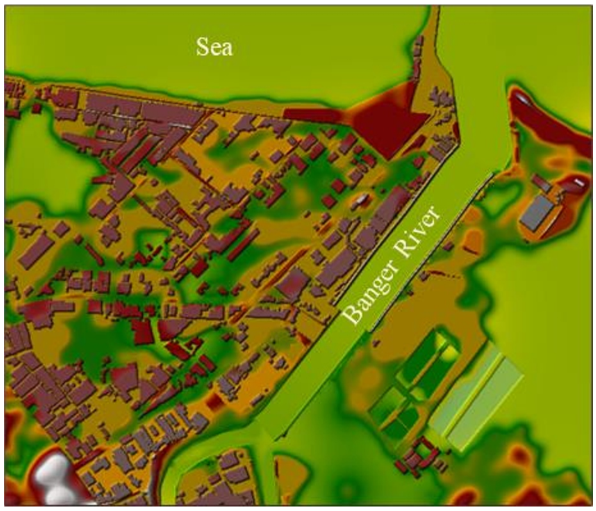

Fig. 3. Terrain modification.

Considering the various grid sizes, we used adjusted time step in the model control based on calculated Courant number. We set the computation interval in 30 seconds for unsteady flow analysis.

2.2 Topographic Data and Adjustment

Topographic data for the model was obtained from DEMNAS. However, this data has a low resolution around the area. Therefore, adjustment was a necessary process for this model using Terrain Modification feature in RAS Mapper. The final terrain result is shown in Fig. 3. The proposed eco-infrastructure was also created using this feature, after the design analysis.

2.3 Model Scenario

Three scenarios were simulated covering the existing condition and two design conditions. The existing scenario modeled the existing sea dike with a height of 0.8 m. The design conditions cover two model scenarios: one with full grey infrastructure (a 2 m sea dike), and one with the combination of blue and grey infrastructure. Sand nourishment with serial groins was selected as the blue infrastructure sample in this study. All scenarios were simulated under two tidal conditions: (1) the normal tide condition which was represented by tidal data in April 2022; and (2) extreme tidal condition which represented by the tide in May 2022 where the extreme coastal flood occurred.

These scenarios are summarized in the Table 1 and described in the Fig. 4.

Table 1. Model scenarios.

	Normal Tide (April 2022)	Extreme Tide (May 2022)
Existing condition (0.8 m sea dike)	Scenario A1	Scenario A2
Grey Infrastructure (2 m sea dike)	Scenario B1	Scenario B2
Blue and Grey Infrastructure combined (2 m sea dike and sand nourishment)	Scenario C1	Scenario C2

Fig. 4. Scenario sketch.

Fig. 4. illustrates the scenario condition**.** The existing condition and grey infrastructure (Scenario A and B) are represented by the brown line. Blue infrastructure is designed by the cyan area which will be combined with grey infrastructure as Scenario C. The cross-section sketch will be implemented as a HEC-RAS model.

2.4 Tide, Sea Level Rise, and Land Subsidence

Tide data was taken from the Maritime Meteorological Station, Semarang [8]. This data was used as the downstream BC in the model. Two tidal conditions were considered, namely normal condition and extreme condition. Normal condition was represented by tidal data in April 2022, while the extreme condition was in May 2022, as shown in Fig. 5.

Coastal flooding in Pekalongan was influenced not only by tide, but also by sea level rise (SLR) and land subsidence (LS). Based on data from the Geospatial Information Agency, the average sea level on Pekalongan Beach could reach 1.15 meters. It was exacerbated by the land subsidence since 2017 of around 24.13 cm/year for North Pekalongan [9]. This data was used as the assumption for tide elevation adjustment in 2022 which reached 1.2 meters. Based on that assumption, we then adjusted the normal high tides to 1.68 meters and the extreme high tides to 1.98 meters accordingly.

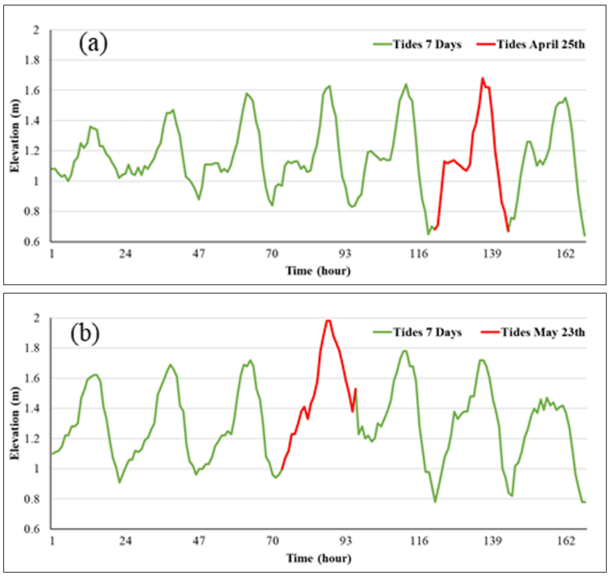

Fig. 5. (a) Tide Graph in April 2022, (b) Tide Graph in May 2022

3 Results and Discussion

3.1 Model Verification

Our model was validated by comparing the inundation pattern from the model to the actual condition in the field when the flood occurred. The model scenario used for the verification was the existing condition, both Scenario A1 and A2. Supporting figures for the model verification are presented in subsection 3.2 (Scenario A: Existing Condition). This subsection will describe the similarities and discrepancies between model result and field condition.

Based on the tidal flood case on May 23rd, 2022 (extreme high tide condition), most of Panjang Wetan area was submerged in water [3]. Modelling under this condition also gave inundation throughout the domain during peak hours. Some of the flood entrance points shown in Fig. 6. have been traced through digital track records as model validation materials.

In normal high tide condition, the area of inundated water was similar as in May 2022. However, this scenario gave a smaller inundation depth. These results were not quite in accordance with the conditions in the field, where no inundation was observed in normal tide condition. This discrepancy could be caused by the assumption of land subsidence accumulation at the beginning of the simulation [10]. The magnitude of LS is not necessarily the same at every point over the domain. Another possibility is that the value of land subsidence is different each year, so further analysis is needed to adjust the conditions of the location at that time [11]. However, the existing model is considered quite close to the field condition.

Fig. 6. Flooded locations: (a) Crematorium, (b) Bugisan Village, (c) Panjang Wetan condition on May 23rd, 2022.

In addition to tracing the tidal floods, sectional validation at the site was carried out by surveying the location. Some appearances of the locations included in the flood modelling can be seen in Fig. 7. The location conditions are quite suitable because in the modelling, the area tends to be low, so it was easily inundated by water.

3.2 Scenario A: Existing Condition

The coastal and settlement area along Panjang Wetan are only separates by small road. From the tourism area, Pasir Kencana Beach to the Crematorium was not fully protected by structures to prevent the tidal floods. The only barrier between the road and the beach is a small embankment as high as 0.8 meters which started from the west of the Pump House. The sides of the Banger River mouth were also not completely limited by protective buildings.

From the results of the flood modelling, runoff occurred in almost the entire Panjang Wetan area. The water inundated several roads such as Jalan Kusuma Bangsa, Jalan W.R. Supratman, Jalan Panjang Wetan, settlements, and the exact land on both sides of the Banger River.

Fig. 7. (a) Jl. WR. Supratman, (b) Jl. Mahoni Raya in January 2023.

In the normal high tide modelling, the entering water only came from the mouth of the Banger River which spread to residential areas. The coastal embankment is sufficient to keep the tide from entering the mainland. The highest water level in the region reached 1.68 meters. The modelling results at the 15th hour can be seen in Fig. 8.

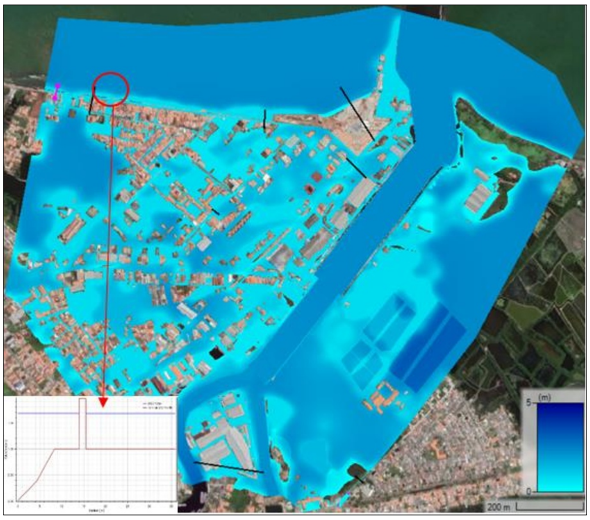

Fig. 8. Results of normal high tide existing condition.

The extreme high tide modelling shows water also originates from a 0.80 meters high embankment. This means that the tide goes beyond the existing embankment in the area and causes nearby settlements to be immediately submerged in water. The highest water level in the area reaches 1.98 meters. There was a difference of about 0.30 meters from the previous month. The modelling results at the 15th hour can be seen in Fig. 9.

The resulting floodwater elevation tends to be the same in one tidal period. However, the depth of the simulation results is relatively different depending on the type of land. It could be seen in Fig. 9. which has a darker colour of the impacted area rather than Fig. 8.

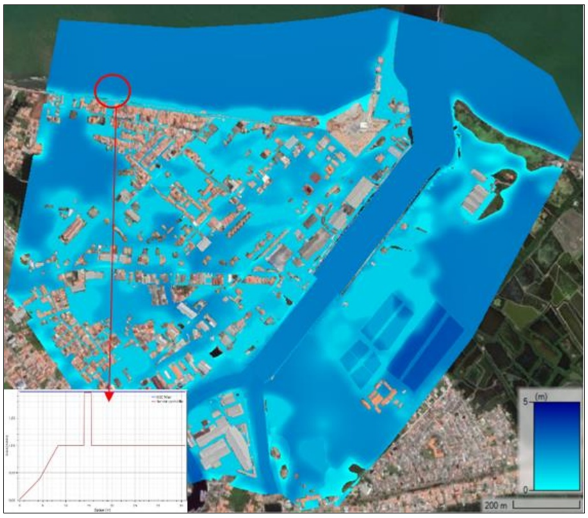

Fig. 9. Results of extreme high tide existing condition.

3.3 Scenario B: The Use of Grey Infrastructure

In this condition, the grey infrastructure was presented as a sea dike. The embankment functions to hold back seawater from entering settlement areas. In addition, the sea dike in North Pekalongan is a local government project to anticipate the tidal floods. It is planned to be constructed along Pekalongan Beach. Based on the calculation, the appropriate sea dike needs a design water level (DWL) and crest elevation of + 1.71 and +3.26 meters, respectively.

The levee elevation plan is close to the results of elevation measurements in the field, so the HEC-RAS model uses an embankment elevation of 3 meters. The modelling results in a condition where the tides are restrained and do not experience overtopping. The maximum water level in the area is still the same, reaching 1.98 meters. Even though it is still flooded, the incoming water comes from the mouth of the Banger River. The results of the embankment modelling at the 15th hour along with the field conditions can be seen in Fig. 10.

3.4 Scenario C: Blue and Grey Infrastructure

In addition to the sea wall, the modelling in this study is combined with blue infrastructure to create more environmentally friendly disaster management. The proposed blue infrastructure concept is sand nourishment. This component will help prevent tidal floods by raising the elevation of beach sand as a natural component. As the name implies, sand nourishment functions to prevent erosion by increasing the stability of beach sand.

The hydraulic modelling under these conditions operates the sea dike and sand nourishment simultaneously. Sand nourishment was designed by following the provisions of the Texas General Land Office [12] as sketched in Fig. 11. The designed elevation of the sand is around 1.80 meters parallel to the sea dike.

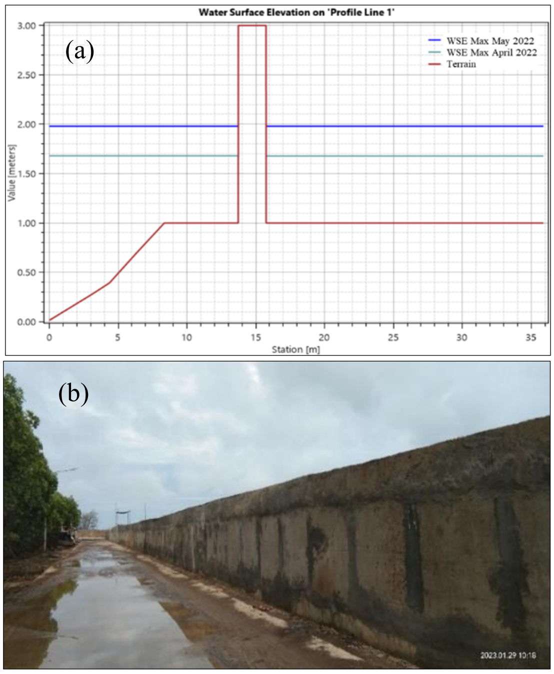

Fig. 10. (a) The cross section of grey infrastructure, (b) the field condition of Sea Dike in January 2023 (during normal condition).

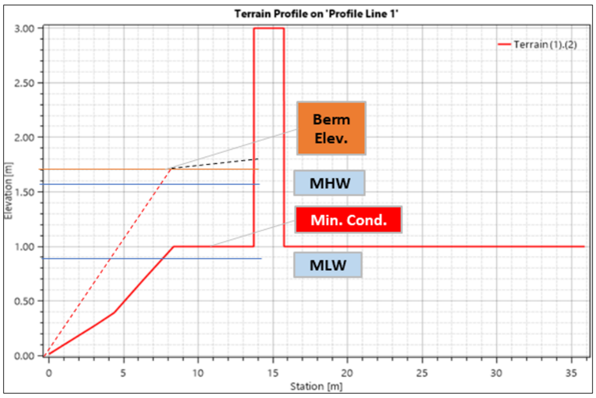

Fig. 11. Sand nourishment design.

With its design, the modelling results are not much different from the existing conditions, Panjang Wetan area is still inundated. However, there is a difference in the depth of the inundation in the area around the embankment. The difference in depth between the application of the embankment alone and the application of the combined infrastructure is 0.05 meters. The results of the combined infrastructure modelling at the 15th hour can be seen in Fig. 12.

Sand nourishment is a soft structure component. In this modelling, it could be concluded that the addition of sand is not too affected in reducing inundation as big as the sea dike. However, the addition of sand causes the water flow to decrease, so the sea water does not directly touch the embankment. It absorbed the tide and wave energies, slightly dissociate the shorelines [12]. Apart from preventing erosion, sand nourishment is sufficient to help maintain the natural structure of the embankment.

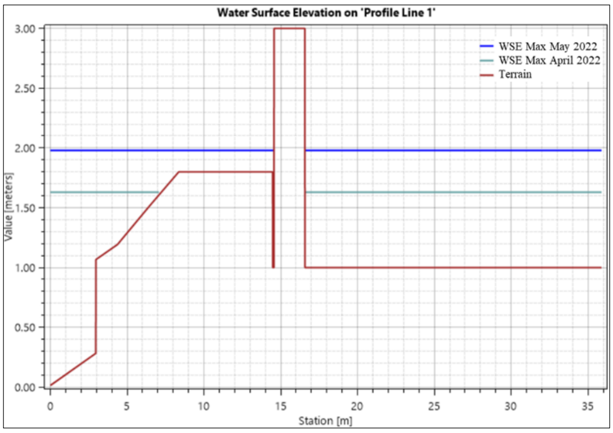

Fig. 12. The cross section of Blue-Grey infrastructure.

4 Conclusion

The simulations of tidal flood at Panjang Wetan are divided into two conditions, namely: normal high tides (April 2022) and extreme high tides (May 2022) where a 1.2 land subsidence was assumed. During the normal high tides condition, the sea level reached 1.68 meters. The model results show the current drainage conditions in the Panjang Wetan were not fully sufficient to accommodate runoff. At several points on the riverside, water enters the land, coupled with the condition of the residential drainage channels which are always wet so appropriate treatments are necessary to restore their normal functions.

Nevertheless, the existence of eco-infrastructure in the form of dikes and sand nourishment is sufficient to prevent seawater from directly entering residential areas. A sea dike as high as two meters can withstand sea tides and sand nourishment is useful in giving a buffer zone and stopping the flow of water before it hits the embankment. Even though the modelling of the simulated site is still inundated, the source of the inflow of water is no longer the sea or the beach.

Authors are wishing to acknowledge the Final Project Recognition Grant Universitas Gadjah Mada Number 5075/UN1.P.II/Dit-Lit/PT.01.01/2023 (*Hibah Rekognisi Tugas Akhir*/RTA *Tahun Anggaran* 2023) by Research Directorate of Universitas Gadjah Mada for the funding.

References

1 S. Nashrrullah, Aprijanto, J.M. Pasaribu, M.K. Hazarika, L. Samarakoon, IJReSES **10**(2), 76-83 (2013) http://dx.doi.org/10.30536/j.ijreses.2013.v10.a1845

2 S. Widada, A. Ismanto, I.B. Priambodo, H. Siagian, Tropical Marine Journal **25**(1), 121–130 (2022)

3 H. Setiyono, D.N. Sugianto, M. Helmi, G. Handoyo, I. Pratikto, R. Ario, IJAER **9**(1), 23–28 (2023) https://doi.org/10.53555/eijaer.v9i1.69

4 D.H. Bulanan, Z.I. Adlina, A.B. Sardjono, S.R. Sari, Jurnal Arsitektur ARCADE **3**, 21 (2019)

5 Conservation International, Green-gray community of practice (2020) https://www.conservation.org/projects/global-green-gray-community-of-practice

6 E.C. O'Donnell, N.R. Netusil, F.K.S. Chan, N.J. Dolman, S.N. Gosling, Water **13**(4), 544 (2021) https://doi.org/10.3390/w13040544

7 S.O. Yudowaty, W. Atmodjo, S.Y. Wulandari, Journal of Oceanography **1**(2), 197–204 (2012) https://ejournal3.undip.ac.id/index.php/joce/article/view/4692/4523

8 Stamar Semarang, Pasang surut 23 Mei 2022 (2022) https://www.ppid.maritimsemarang.com/

9 D.D.I. El-Fath, W. Atmodjo, M. Helmi, S. Widada, B. Rochaddi, Indonesian Journal of Oceanography **4**(1), 96–110 (2022)

10 R. Pujiastuti, S. Suripin, S. Syafrudin, Media Komunikasi Teknik Sipil **21**(1), 1-12 (2015)

11 S.A. Habibi, A.D. Pribadi, J.E. Sitorus, Geographica Pannonica **25**(2), 121–135 (2021) https://doi.org/10.5937/gp25-30852

12 R.G. Dean, T.J. Campbell, Springer Handbook of Ocean Engineering, 635–651 (2016) https://doi.org/10.1007/978-3-319-16649-0_29