Wave driven Setup across the North Coast Region of West Java

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Abstract. Wave energy dissipation on the surf zone is compensated with the increase of mean sea level, the so-called wave setup, within the area. This study used the numerical model Delft3D to investigate the dynamics of setup across the north coast region of West Java (Losari to Indramayu) influenced by monsoon variations. The wave forcing was obtained from previous field studies on Cirebon coastal region. The waves within the region were largely dissipated far from the coastline, mainly at the area between Babakan and Karangampel, due to the gentle slope of the North coast of Java. The waves approaching the shoreline were mainly influenced by the east monsoon associated with the longer fetch from that direction. The wave setup varied from ~0.03 to 0.15 m, with the maximum setup occurred near the coastline of the east (Losari) and west (Indramayu) parts of the model domain that consisted of steeper slopes. This, potentially inducing severe coastal inundation that became a serious problem across the coastlines. Meanwhile, the setup near the coastline of the middle area of the domain (Babakan to Karangampel) was very weak, which was correlated to the larger wave dissipation within the offshore area of that region.

1. Introduction

Coastal communities and ecosystems in low-lying areas are vulnerable to impacts resulting from flooding. The main source of coastal flooding could be from massive rainfall that exceed the capacity of natural watercourses or the increase of mean sea level due to offshore forcing higher than low-lying elevation. Among the offshore forcing, e.g., tides, storm surge or low frequency wave modulation, the increase of water level due to high incident wave that push the offshore water into coastline known as wave setup has been identified to significantly contribute to low-land inundation [1], [2].

The study was on the north coast of West Java from the east part of Indramayu to the east part of Cirebon (Figure 1). The region is well known as one of Indonesian most populated area with a wide variety of economic activities which prevail along the coasts. Facing the Java Sea, the coasts are exposed to the offshore waves with height sometimes exceeding 2 m [3] that is strongly influenced by east and west seasons in June-August and December-January, respectively [4]. Tides in the area are micro-tidal with a maximum tide range of ~1 m [5]). The bed is mostly composed of silt [5] with a gentle slope of ~0-0.27° (see Figure 1 and [6]).

The north coast of West Java is vulnerable to coastal flooding causing severe damage to infrastructures and economics [7]–[9]. Previous studies have identified the flooding were caused by the
astronomic tide and sea-level rise, land subsidence e.g., [10], [11]. However, the contribution of wave setup to the increase of sea level inducing flooding was rarely discussed. In this study, we estimated the spatial wave propagation patterns within the study area, and the resulting increase of mean water level, i.e., wave setup. Three different scenarios were applied, representing the possible incoming waves during the various seasons.

Figure 1. Bathymetry and the offshore boundary (red lines) super imposed on aerial image of the study area, see the insert for location within Java Island (the red dot). Coordinate is UTM 49 M WGS 84 (source of image: Google Earth Pro).

2. Methods

We applied a phase average model Delft3D-Wave based on the SWAN wave model e.g., [12]. The model solves the spectral action balance equation in which the two-dimensional evolutions of the wave spectrum are governed by

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_\sigma N + \frac{\partial}{\partial \theta} c_\theta N = \frac{S}{\sigma}.
\]

where \(x, y, t\) are the respective directions and time, \(\sigma\) is the relative frequency, \(N\) is the action density spectrum term which is equal to the energy density divided by the relative frequency: \(N(\sigma, \theta) = E(\sigma, \theta) / \sigma\). \(S\) is the source term in terms of energy density representing the effects of generation, dissipation and non-linear wave-wave interactions.

The numerical domain of the study area spanned between Losari to Indramayu (see Figure 1). The grid was curvilinear that covered around 2,620 km\(^2\) of the nearshore region with variable grid sizes consisting spatial grid of 352 (alongshore) x 244 (cross-shore). The bottom profile was a combined data
from global Shuttle Radar Topography Mission (SRTM) 30 and General Bathymetric Chart of the Oceans (GEBCO). The wave forcing was set to a single condition with \( h_s \) of 2.2 m and \( T_p \) 6.8 s [3], propagating from three main directions, i.e., northeast, north and northwest. In addition, wind forcing was uniformly imposed within the domain with a speed of 8 m/s [13] and the main directions parallel to the direction of the wave forcing. Furthermore, we also included three mechanisms in the wave dissipation processes, i.e., whitecapping [14], bottom friction [15] and depth-induced breaking [16].

The wave induced setup across the study area was calculated from an equilibrium between wave force and the hydrostatic pressure gradient.

\[
\frac{\partial}{\partial x} \left( F_x + g d \frac{\partial \bar{h}}{\partial x} \right) + \frac{\partial}{\partial y} \left( F_y + g d \frac{\partial \bar{h}}{\partial y} \right) = 0,
\]

In which \( F \) is wave force, \( g \) is gravity, \( d \) is depth, and \( \bar{h} \) is the wave setup (note the upper bar on the notation to distinguish the term to the instantaneous water level). In the calculation, the setup on the offshore boundary is assumed to be 0 (see detail on [17]).

3. Results and discussion

3.1. Wave propagation

The modelled wave propagation Figure 2 exhibited the patterns of wave deformation within Cirebon coastal region for three different scenarios. Near the offshore boundary, all models showed the waves were relatively uniform, where the depths were around 30-40 m. However, as the waves propagated more onshore, the patterns of wave dissipation were more vary depending on the depths. In general, at the west part of the model, the waves were more dissipated offshore at the area between E 230 to 240 km. Meanwhile, at the eastern part (E 250 – 270 km), the waves were more dissipated onshore, creating higher waves near the eastern part of the coastline.

Among the three models, the roughest wave occurred under the east direction scenario where higher wave energy penetrated most of the nearshore region with \( h_s \) may reach 1 m, see Figure 2a. In contrast, under the similar significant wave height and peak period, north (Figure 2b) and west (Figure 2c) wave models exhibited less wave energy (\( h_s <0.2 \) m) penetrated up to shallow water region mainly around Cirebon City where the coastline faces the east (E ~227-240 km). Moreover, although some research e.g., [18] exhibit more winds inducing energetic waves generated during the West season, the model showed weaker wave energy along the Cirebon nearshore. The difference in the amount of energy entering the nearshore was attributed to the sand spit and the elongated submerged barrier that span around 20 km eastward, creating a shallower region (depth <5 m) at the offshore (around S 9270 - 9290 km and E 230 - 250 km, see Figure 1) that dissipate most of the incoming wave energy from directions other than the east. In the study area, the submerged bar could be possibly developed through 2 combined main mechanisms. The first would be the river discharge, and sediment load into the ocean from rivers located nearby the onshore end of the bar, forming sediment plume that deposited over the years e.g., [19]. This was supported by the existence of rivers nearby the onshore end of the bar (at S 9280 – 9285 km, the Karangampel region) that would act as the main source of sediment. The second would be the longshore drift as waves approached in angles that generate sediment transport e.g., [20]. In our case study, the sand spit at the west part of the model domain would be caused by longshore drift during the west season.

3.2. Wave Setup
This section presented the spatial variability of the wave setup prediction across the study area for three different offshore wave directions. Spatial variations of the mean setup ($\bar{\eta}$) were presented in Figure 3. For a given wave height, $\bar{\eta}$ reached maximum near the coastlines and smaller at the deeper site. In general, the setup was largest when the waves propagated from the east, reaching 0.15 m, allowing more wave energy to approach the coastline. Meanwhile, the setup from other directions was much smaller, particularly when the waves came from the west with setup less than 0.05 m along the coastline. This is not surprising as the west part of the model domain is the extension of the Java coastline, with limited fetch, causing no large wave generating setup form e.g., [21].

![Figure 2. The patterns of significant waves propagating from (a) East, (b) North, and (c) West.](image)

Besides the amount of wave energy approaching the coastline, the magnitude of setup varied along the coastline of the model domain. The result showed the setup reached its maxima at the area with steeper slope, for example at the east (E ~260 km, the Babakan region) and west (E ~220 km, the Karangampel region) part of the domain. Meanwhile, at the area with gentle slopes, i.e., area between Babakan and Karangampel, the setup was relatively weaker (more than 50% than in Babakan region),
as depicted in Figure 3. The relation between beach slope and the resulting setup has been identified in some research e.g., [22]–[24], in which steeper profiles would force breaking with higher wave radiation stress gradient inducing higher setup.

Wave setup is higher during extreme wave events, and its existence may dominate the storm surge nearshore that leaded inundation along the coast [25]. In a longer time scale, the setup may induce topographic evolution [26] or the change of coastal currents pattern [27]. Even though the wave setup would only be on the order of centimetres, the east season setup interaction with high tides and other offshore forcing in Cirebon region, with low-lying zones and gentle slopes, may still give a significant contribution to frequent coastal flooding that severely impact human activities, e.g., shrimp or salt ponds and housing (Figure 4). Considering the potential disastrous consequences, comprehensive measures that combine structural protections (e.g., dikes or surge barriers) and non-structural measures...
(e.g., spatial planning and adaptation) would be essential. Yet, these need a good collaboration among all stakeholders for optimum results.

Figure 4. (a) shrimp ponds condition and (b) inundation in fishermen housing during coastal flooding in North West Java region. Source of Figure 4a:[28]

4. Conclusion

This study assessed the wave propagation and the resulting setup over a gentle slope bathymetry of the North coast region of West Java. The Delft3D wave model predicted variable spatial significant waves generated from 3 different main directions. In the study area, the east propagating waves mostly impacted the nearshore region that representing the east monsoon season in June to August. In contrast, waves travelling from west and north were largely dissipated suggesting the control of coastal bathymetry. Comparable to the result of the wave model, wave setup was also spatially varying that dependent on the offshore waves and the depths where near the coastline, the setup reached a maximum. The magnitude of wave setup also related the local slope. The region with steeper slopes for example Karangampel and Babakan exhibited a higher wave setup that potentially led to more inundation during extreme wave events.

References

[1] Wolf J, 2009 Coastal flooding: impacts of coupled wave–surge–tide models Nat. Hazards 49, 2 p. 241–260.

[2] Thompson D A Karunarathna H and Reeve D E, 2017 Modelling extreme wave overtopping at Aberystwyth Promenade Water 9, 9 p. 663.

[3] Kurniawanto A Sugianto D N and Purwanto P, 2017 Kajian karakteristik gelombang di Pantai Kejawanan, Cirebon J. Oceanogr. 6, 1 p. 79–88.

[4] Rachmawati R Ningsih N Ramadhan H and Nurfitri S, 2018 Analysis of ocean wave characteristic in Western Indonesian Seas using wave spectrum model in MATEC Web of Conferences 147 p. 5001.

[5] Nuraghnia A Windupranata W Hakim A R and Nusantara C, 2021 Modeling of tide in the Java sea coastal area between Jakarta and Cirebon, Indonesia: bathymetric data source and sensitivity tests due to bottom roughness and boundary condition in IOP Conference Series: Earth and Environmental Science 777, 1 p. 12034.

[6] Ismail M F A, 2014 Dinamika batimetri alur pelayaran Pelabuhan Cirebon, Provinsi Jawa
Barat DEPIK J. Ilmu-Ilmu Perairan, Pesisir dan Perikan. 3, 1.

[7] Nirwansyah A W and Braun B, 2021 Assessing the degree of tidal flood damage to salt harvesting landscape using synthetic approach and GIS - Case study: Cirebon, West Java Int. J. Disaster Risk Reduct. 55 p. 102099.

[8] Oktaviani A D Putri F A Pratiwi N T M and Setyaningsih I, 2020 Pemberdayaan Masyarakat melalui Program Desa Tangguh Bencana (DESTANA) Sebagai Upaya Mitigasi Banjir Rob di Kabupaten Cirebon J. Pus. Inov. Masy. 2, 3 p. 357–362.

[9] Triharto W, 2018 Reklamasi Pesisir Kota Cirebon Fakt. Exacta 11, 4 p. 386–399.

[10] Andreas H Usriyah Zainal Abidin H and Anggreni Sarsito D, 2017 Tidal inundation (“Rob”) investigation using time series of high resolution satellite image data and from institut measurements along northern coast of Java (Pantura) IOP Conf. Ser. Earth Environ. Sci. 71 p. 12005.

[11] Nirwansyah A W and Braun B, 2019, Mapping Impact of Tidal Flooding on Solar Salt Farming in Northern Java using a Hydrodynamic Model, ISPRS International Journal of Geo-Information , 8, 10.

[12] Booij N Holthuijzen L H and Ris R C, 1997, The" SWAN" wave model for shallow water, in Coastal Engineering 1996, p. 668–676.

[13] Hernawan U, 2016 Study of the Sedimentation Trend in the Prospective Area of Port of Marine Center, Cirebon Based on Remote Sensing Data Bull. Mar. Geol. 24, 1 p. 36–45.

[14] Komen G J Hasselmann S and Hasselmann K, 1984 On the existence of a fully developed wind-sea spectrum J. Phys. Oceanogr. 14, 8 p. 1271–1285.

[15] Hasselmann K F et al., 1973 Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Ergaenzungsh. zur Dtsch. Hydrogr. Zeitschrift. R. A.

[16] Battjes J A and Janssen J, 1978, Energy loss and set-up due to breaking of random waves, in Coastal engineering 1978, p. 569–587.

[17] SWAN-Team, 2010 SWAN Scientific and Technical Documentation, SWAN Cycle III version 40.81 Delft Univ. Technol.

[18] Siregar S N Sari L P Purba N P Pranowo W S and Syamsuddin M L, 2017 Pertukaran massa air di Laut Jawa terhadap periodisitas monsun dan Arlindo pada tahun 2015 DEPIK J. Ilmu-Ilmu Perairan, Pesisir dan Perikan. 6, 1 p. 44–59.

[19] Chikita K A Wada T Kudo I Saitoh S-I and Toratani M, 2021 Effects of River Discharge and Sediment Load on Sediment Plume Behaviors in a Coastal Region: The Yukon River, Alaska and the Bering Sea Hydrology 8, 1 p. 45.

[20] Petersen D Deigaard R and Fredsøe J, 2008 Modelling the morphology of sandy spits Coast. Eng. 55, 7 p. 671–684.

[21] Christakos K Björkqvist J-V Tuomi L Furevik B R and Breivik Ø, 2021 Modelling wave growth in narrow fetch geometries: The white-capping and wind input formulations Ocean Model. 157 p. 101730.

[22] Gourlay M R, 1996 Wave set-up on coral reefs. 2. set-up on reefs with various profiles Coast. Eng. 28, 1 p. 17–55.
[23] Zhang S, Zhu L, and Li J, 2018 Numerical simulation of wave propagation, breaking, and setup on steep fringing reefs *Water (Basel)* 10, 9 p. 1147.

[24] Melet A, Almar R, Hemer M, Le Cozannet G, Meyssignac B, and Ruggiero P, Aug. 2020 Contribution of Wave Setup to Projected Coastal Sea Level Changes *J. Geophys. Res. Ocean.* 125, 8 p. e2020JC016078.

[25] Nicolae Lerma A, Pedreros R, Robinet A, and Sénéchal N, 2017 Simulating wave setup and runup during storm conditions on a complex barred beach *Coast. Eng.* 123 p. 29–41.

[26] Hongo C, Kurihara H, and Golbue Y, 2018 Projecting of wave height and water level on reef-lined coasts due to intensified tropical cyclones and sea level rise in Palau to 2100 *Nat. Hazards Earth Syst. Sci.* 18, 2 p. 669–686.

[27] Wandres M, Pattiaratchi C, and Hemer M A, 2017 Projected changes of the southwest Australian wave climate under two atmospheric greenhouse gas concentration pathways *Ocean Model.* 117 p. 70–87.

[28] Hidayah N, 2018, Banjir rob hancurkan tambak di Indramayu, *Media Indonesia.* [Online]. Available: https://mediaindonesia.com/nusantara/139067/banjir-rob-hancurkan-tambak-di-indramayu. [Accessed: 06-Jul-2021].

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