Numerical investigation of coastal sediment transport for assessment of coastal erosion of a Philippine coastline using a 3D hydrodynamic model

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Abstract. The Philippines, being an archipelagic country with at least 36,000 km of coastline, has been identified to have more than 20 areas that are at risk of coastal erosion. One of these areas, located in Ibajay, Aklan, was studied wherein a 3-dimensional numerical model using Delft3D was created in order to simulate and analyze the prevailing hydrodynamics and sediment transport. The model was calibrated using continuous water level and velocity data obtained from sensors deployed during two separate field surveys. Model results showed excellent agreement with observed data and sufficiently captures the existing tidally dominated hydrodynamics of the study area. The temporal variability of the hydrodynamics and transport of sediments was investigated by simulating flows during flood-ebb, spring-neap, southwest-northeast monsoon, and 2-year long conditions. Areas of erosion and deposition were identified based on the results of the long-term simulation. None of these areas were located along the coastline except on the area near the stream where local erosion and deposition happens. Based on this, it can be concluded that the study coast is stable under prevailing tidal conditions. The obtained results can be used as baseline data for managing future coastal developments of the municipality and the methodology conducted in this research can be applied on other erosion-prone coastlines nationwide.

1. Introduction
The coastal zone is a dynamically active region wherein several physical processes such as wave propagation, wave breaking, tidal flow, material transport, among others, interact with each other. Throughout the years, the emphasis on the coastal zone has been continuously increasing due to the rapid development of this region, as well as, the hazardous short-term and long-term effects of these natural processes [1]. One of the most prominent coastal process is the transport of sediments either towards, away, or along the coast. This phenomenon is driven by a large number of stochastic processes and has been the subject of several studies [2, 3, 4, 5, 6, 7]. Along with increasing coastal developments, the natural transport of sediments has caused coastal erosion which has become a serious problem in a high percentage of the world’s coastlines [8]. Because of its imminent environmental concerns, sediment transport and morphological studies have attracted great deal of attention especially in areas where there is development such as beach resorts, harbours, and navigation channels [9].
The Philippines, being an archipelagic country, has 50% of its municipalities, or at least 62% of the total population, located within 1 km of the coastal region [10]. Despite being surrounded with a vast amount of natural resources, the country is exposed to several disasters such as typhoons and earthquake, to name a few [11]. One prominent problem is coastal erosion in which at least 20 areas have been reported to be identified [12, 13, 14, 15]. Because of coastal erosion, the shoreline retreats inland causing major loss of land which translates to a number of adverse effects such as displacement of people, loss of livelihood, and destruction of property [16]. It is therefore necessary to assess the condition of the coastline with regards to coastal erosion in order to provide strategies to adapt or solve the problem.

In this study, a 3D numerical model using Delft3D was created in order to simulate the transport of sand in a reportedly coastal-erosion prone area. The temporal variability of the sediment motion was examined by simulating different scenarios, including flood-ebb condition, spring-neap condition, southwest-northeast monsoon season, and 2-year long simulation. Different flow patterns will be presented and the analysis will gear towards the assessment the coastal erosion problem of the study area.

![Figure 1](image_url)

**Figure 1.** (a) Locations of coastal erosion prone areas in the Philippines (b) Study site along Ibajay, Aklan coastline (c) Exposed tree roots and presence of scarps indicating possible erosion.

## 2. Study area

The study area for this research is located on the north western coast of Panay island in the Philippines. The coastline is within the 3rd class municipality of Ibajay, Aklan with fishing as the main source of livelihood of the residents. Fishing boats are regularly parked at several portions of the coast and houses are erected 5 to 10 meters from the beach face. An unfinished wharf is located on the left boundary of the study area and a small stream that passes through a natural mangrove forest discharges into the sea midway of the slightly concave coast.
The study area falls under Type III climate based on the Modified Coronas Classification [17]. There is no pronounced period of maximum rains and the dry season lasts only from one to three months, from March to May. Monsoon winds are also prominent in the area especially during December to February when the northeast monsoon is blowing. This causes increased wave heights propagating towards the shore. The tides are mixed semi-diurnal with maximum range of 2.2 m during spring tides. Sediments in the area are spatially uniform and made up primarily of sand that has an average grain size of 220 µm.

3. Methodology
3.1 Data Gathering
Two separate field surveys were conducted in order to gather primary data for this study. Last September 2017, a set of sensors that measure water level, current velocity and direction, and wave height, were deployed on a point 200 meters away from the coast (this point will be called O1). Long-term continuous data was recorded by the sensors and were successfully retrieved last February 2018. These data were used for calibration of the hydrodynamic parameters produced in the numerical model. A bathymetric survey using single beam echo sounder was conducted which covered up to 1 km offshore. A portable weather station which measures meteorological data, such as wind speed and direction, was deployed on top of a water tank near the coast for a duration of 1 whole year. Water samples were collected twice, at different times, at four different locations (called T1, T2, T3, and T4), about 100 m away from the coast. These samples were processed for instantaneous suspended sediment concentrations (SSC) and will be used for calibration of the sediment transport model.

3.2 Numerical model description
In order to investigate the transport of sediments in the study area, Delft3D FLOW was used. Delft3D is an open source, fully integrated computer software suite that can conduct 3D computations for coastal, river, and estuarine areas using a multidisciplinary, processed-based approach. FLOW is one of the several modules of Delft3D which calculates non-steady flow and transport phenomena caused by tidal and meteorological forcing. In this module, the models are solved numerically using finite differences on a computational domain that has curvilinear horizontal grid and a vertical grid that follow the bottom topography and the free surface (σ-coordinate system) [18].

The circulation model of Delft3D FLOW solves the unsteady shallow water equations in two (depth-averaged) or three dimensions along an orthogonal curvilinear grid. It is derived from 3-dimensional Navier-Stokes equations for incompressible free surface flow under the shallow water and Boussinesq assumptions. The system of equations consists of the horizontal momentum equations, the continuity equation, and the transport equation for conservative constituents. It accounts for the effects of tides, density gradients, river discharges, wind drag and waves. On the other hand, the sediment transport model of Delft3D FLOW solves the 3-dimensional advection-diffusion equation for cohesive or non-cohesive suspended sediments. For the bedload transport of non-cohesive sediments, different formulations from several researches can be used based on its applicability on the modelling condition. Updating of the bed morphology can be implemented in the model to account for sedimentation and can be used to predict the evolution of geomorphology of the study area [19].

3.3 Multi-scale computational domain
Three computational domains of varying size and resolution were created in this study. The first domain, called regional, is a 700 km by 200 km rectangular grid spanning from 11.21° to 13.10° N latitude and 119.34° to 126.34° E longitude. Astronomic tidal constituents from TPXO 7.2 global tide model from Deft Dashboard was used as boundary forcing. A second domain, called local, is a smaller, tilted, rectangular grid that covers the northern coast of Panay island. Both regional and local domains have bathymetries downloaded online from the global data set of GEBCO 2014. The third domain, called nearshore, is the smallest among the three which covers the study area. It is a curvilinear grid following the shape of the coast extending 2 km offshore. All three domains are nested within each other, meaning,
the results of the simulation of the regional domain was used as boundary conditions for the simulation of the local domain. Furthermore, the results of the simulation of the local domain were used as boundary conditions for the nearshore domain. Three observation points were set in the regional domain: O1, which is the location where the sensors were deployed, Capiz landing (CL), and Looc bay (LB). Capiz landing and Looc bay are International Hydrographic Organization (IHO) observation points which has forecasted water level data that will be used for calibration. CL and O1 were used as observation points for the local model while only O1 was used as calibration point for the nearshore model. The spatial resolution and time step simulation of each computational domain was selected in accordance with the limit prescribed by the Courant-Friedrichs-Lewy (CFL) number. The CFL number is a numerical parameter that defines the computational stability of the iterative solution of the governing equation. The value of the CFL number must be less than 10 for all of the nodes. The summary of the properties of all domains are shown in Table 1.

![Figure 2](image-url)

**Figure 2.** Nested computational domains (a) regional (b) local (c) nearshore models with observation points shown in red dots and boundaries highlighted with red lines.
Table 1. Properties of the computational domains

| Name of grid | Number of nodes | Spatial Resolution | Time Step | Dimensionality | Water Level Boundary | Observation points |
|--------------|-----------------|--------------------|-----------|----------------|----------------------|-------------------|
| regional     | 356 by 96       | 2 km x 2 km        | 15 s      | 2D             | astronomic           | O1, CL, LB        |
| local        | 236 by 107      | 500 m x 500 m      | 60 s      | 2D             | time-series          | O1, CL            |
| nearshore    | 72 by 102       | 40 m x 50 m 1 km   | 30 s      | 3D with 3 layers (25%, 50%, 25%) | time-series | O1       |
|              |                 | from the coast     |           |                 |                      |                   |
|              |                 | 25 m by x 50 m beyond |         |                 |                      |                   |

Important physical processes (i.e. wind and stream discharge) that might have an impact on the transport of sediments were incorporated into the nearshore model. Wind data were obtained from the measured wind speed and direction of the weather station while discharge and sediment data of the small stream came from long-term Soil and Water Assessment Tool (SWAT) simulation. Default values for the wind drag coefficients were used in the model. The depths used for the nearshore model came from the bathymetric survey. Uniform sand sediment with specific gravity of 2.65, size of 220 µm, and thickness of 30 m, was set throughout the entire domain. Equilibrium sand concentration profile was used on all boundaries due to the lack of measured sediment influx. Bathymetry updating is also set in order to identify areas of erosion and deposition. The effects of waves are not yet incorporated in the simulations so calibration of the model with sediment transport was postponed based on the assumption that waves have significant effects on the transport of sediments in open coastlines.

Figure 3. Inputs to nearshore model (a) wind data (b) monthly average flow rate and (c) monthly average sediment concentration at small stream

3.4 Model calibration and validation

3.4.1 Regional and local model. Water level measurements observed at station O1 and forecasted at CL and LB IHO tide stations from September 7 to 22, 2017 were used to calibrate the regional and local model. The calibration process involves adjusting iteratively the overall Manning’s bed roughness of the model domains in order to achieve excellent agreement between the simulated and observed water level values. Statistical parameters such as root-mean-square error (RMSE) and coefficient of correlation ($R^2$) were calculated to assess the goodness of fit for each observation point. The RMSE
value describes the accuracy of the simulation results while the R² value confirms the correlation between the simulated and observed water level values [20]. Validation was done by running the same calibrated properties of the model domains on a different time period. For this case, validation was done for the period of January 20 to February 5, 2018.

Calibrated model results showed excellent agreement with the observed and forecasted water levels on the observation points. The two models can capture the water level variation within these areas sufficiently and therefore can be used as input boundary conditions for the nearshore domain which is the main study area of this research.

**Table 2.** Computed statistical parameters for regional model calibration and validation

| Observation Point       | Calibration RMSE | Calibration R² | Validation RMSE | Validation R² |
|-------------------------|------------------|----------------|-----------------|---------------|
| Capiz Landing (CL)      | 0.0766           | 0.9824         | 0.0697          | 0.9863        |
| Looc Bay (LB)           | 0.0377           | 0.9830         | 0.0299          | 0.9964        |
| Station O1              | 0.0766           | 0.9904         | 0.0969          | 0.9820        |

**Figure 4.** Water level comparison after regional model calibration (a) CL (b) LB (c) O1 and validation (d) CL (e) LB (f) O1.
Table 3. Computed statistical parameters for local model calibration and validation

| Observation Point   | Calibration | Validation |
|---------------------|-------------|------------|
|                     | RMSE | R²   | RMSE | R²   |
| Capiz Landing (CL)  | 0.0718 | 0.9848 | 0.0766 | 0.9854 |
| Station O1          | 0.0775 | 0.9901 | 0.0903 | 0.9816 |

Figure 5. Water level comparison after local model calibration (a) CL (b) O1 and validation (c) CL (d) O1.

3.4.2 Nearshore model. In addition to water level, the nearshore model was also calibrated in terms of velocity. Aside from the Manning’s bed roughness, the horizontal eddy viscosity was adjusted in order to achieve good agreement between the simulated bottom (layer 3) velocities and measured near bed velocities. Due to the size of the model domain with “strong” boundary forcing from north, east, and west, the simulated water levels do not vary anymore with the bottom roughness. However, the magnitude and direction of the simulated bottom velocity are both sensitive with the Manning’s roughness value and horizontal eddy viscosity. The magnitude of bottom velocities significantly vary with the bottom roughness wherein higher bed roughness constitutes for lower bottom velocities. Variation of horizontal eddy viscosity, on the other hand, changes the behaviour and timing of peaks of the magnitude and direction of the bottom velocities. These two variables were adjusted simultaneously and iteratively during the calibration process. The calibration period for water level is the same as the regional and local model but for the bottom velocity, the calibration period is reduced to 3 days only which is from September 8 to 11, 2017 while the validation period is from January 30 to February 2, 2018.

Calibrated nearshore model results showed acceptable agreements between the measured and observed values of water level and bottom velocities. These indicate that the hydrodynamic model can capture the flow variations inside the domain and can be used in conjunction with the sediment transport model.
Table 4. Computed statistical parameters for nearshore model calibration and validation

| Parameter                  | Root Mean Square Error (RMSE) |
|---------------------------|-------------------------------|
|                           | Calibration | Validation |
| Water level               | 0.0745  | 0.0922   |
| Bottom Velocity Magnitude | 0.0244  | 0.0299   |
| Bottom Velocity Direction | 72.011  | 94.485   |

Figure 6. Comparison of hydrodynamic parameters at station O1 in the nearshore model after calibration: (a) water level (b) bottom velocity magnitude (c) bottom velocity direction and validation: (d) water level (e) bottom velocity magnitude (f) bottom velocity direction.

4. Results and Discussion

4.1 Hydrodynamics
The existing hydrodynamics in the study area is dominated by tidal variations. During ebb tide, the surface flow from the east and west boundary are directed towards the centre of the domain forming a rip current that exits on the north boundary. Small surface vortices are also formed at certain areas beside the rip current. On the other hand, the general direction of the flow reverses during flood tide. Current speeds at the surface during ebb tide varies up to 1 m/s with maximum values concentrated within 1 km of the west and east boundaries. These speeds decrease gradually during flood tide and increases again
during the next ebb tide. The magnitude of the velocity is higher during spring tide as compared to the speeds during neap tide as can be observed in Figure 7. During January-March, northeast monsoon winds cause an increase in magnitude of the surface velocities but not strong enough to induce change in the flow patterns during flood and ebb tide conditions.

**Figure 7.** Surface velocity patterns at (a) highest flood and (b) lowest ebb flow during spring tide and (c) highest ebb (d) lowest flood flow during neap tide for the southwest monsoon season.
Figure 8. Surface velocity patterns at (a) highest ebb and (b) lowest flood flow during neap tide and (c) highest flood and (d) lowest ebb during spring tide for the northeast monsoon season.

The bottom velocity is an important hydrodynamic parameter as the magnitude of the bed shear stress that will cause the motion of the sediments at the bed is a function of it. Naturally, the bottom velocity is smaller compared to the surface velocity since the effect of the bed roughness is felt more as you move closer to it. Figure 9 shows the variation between the surface and bottom velocity at one arbitrary instant in the simulation. It can be observed that the bottom velocity follows the general direction of the surface but its magnitude is lower by a value of about 0.1 m/s.
Figure 9. Variation of flow velocity at (a) layer 1 vs (b) layer 3 and vertically at section (c) 1-1’ and (d) 2-2’ at the instant Sept 19, 2017 09:00:00 of the simulation.

4.2 Sediment transport
Since the sediment transport model is not yet calibrated, only transport patterns will be described in this subsection. For the case of bedload transport, it can be observed that the general pattern follows the direction of the flow velocity which causes its motion. For suspended sediments, however, the transport shifts towards perpendicular to the coast in shallow waters while in deep waters, its direction is the same as the flow velocity similar to the bedload transport.
Figure 10. Bedload (b-subscript) and suspended sediment transport (s-subscript) patterns at (a) highest flood and (b) lowest ebb.

4.3 Morphology

Long term simulation using the calibrated hydrodynamic model with morphological updating was conducted in order to investigate the locations of erosion and deposition in the study area. Areas of active erosion were found near the west and east boundary where velocities are highly concentrated. During ebb flow, the sediments are transported towards the centre of the domain following the direction of the bottom velocity but during flood tide, only a fraction of the sediments are being brought back to its original location due to the lower magnitudes of near-bed currents. No significant change in the morphology near the coast was observed due to weak currents generated by tidal flows. Based on this, it can be inferred that the coast is stable under prevailing conditions.

4.3.1. Effect of stream discharge. The effect of the small stream discharging at the study area was investigated by doing a 2-year simulation with and without it. As the velocities near the beach area are weak, the sediment discharge from the stream are not being transported to other areas causing only a localized erosion and deposition as indicated in Figure 11. This phenomenon possibly explains the formation of a small pond on the west side of the channel mouth wherein a specific portion of it deepens and the area beside it is slightly elevated.
4.3.2. Effect of morfac. In modelling coastal morphodynamics, the time scale necessary to observe a significant change is usually 2nd order longer than hydrodynamic simulations. In order to solve this issue, Delft3D FLOW introduces a factor called “morfac” that accelerates the effect of hydrodynamic calculations to the morphology values. This morphological scale factor is a constant that scales up the erosion and deposition fluxes. In this study, the effect of this factor was investigated by simulating 1-year time periods with a morfac value of 1 and another with a morfac value of 5. Results indicate that greater values of erosion and deposition were present with a higher value of morfac. It is important to note, however, that increasing the morfac value to, say 5, does not multiply the erosion and deposition values to 5, but rather making the results of the morphodynamic simulation 5 times longer than the hydrodynamic simulation.
5. Conclusions and future works
A 3-dimensional model of the east coast of Ibaajay, Aklan, Philippines was created and calibrated in terms of water level and velocity. The hydrodynamics of the study area sufficiently captured the existing flow variations caused by tides. During ebb, velocities are stronger and directed towards the center of the domain while during flood, the flow reverses with smaller speeds exiting at the east and west boundaries. No change in flow pattern was observed during spring tides as compared to neap tides but magnitudes are increased when the water levels are higher and lower. Monsoon winds do not have significant effect on the hydrodynamics. No vertical flow is observed and near bed velocities follows the direction of surface velocities but with slightly lower magnitude. Bedload transport is directed in the same direction of the bottom velocity that causes its motion. In shallow waters, suspended transport is directed towards the coast but at deeper portions of the study area, the suspended sediments flows in the same direction as the velocity. Areas of erosion and deposition were identified using a long-term simulation. None of these areas are located at the coastline except near the stream mouth where a local erosion and deposition is happening so it can be concluded that the beach area is stable under prevailing tidal conditions. The exposed roots of the coconut trees along the coast that are the basis of tagging the area as a coastal erosion prone area may be attributed to short-term extreme conditions (i.e. typhoons) such as what happened last June 2008 when typhoon Fengshen hit the area.

Although the main limitation of this study is the uncalibrated sediment transport model, the assessment of the coastal erosion problem in the study area was still achieved by describing transport patterns and identifying areas of erosion and deposition. Prevailing waves will be incorporated soon in the model before calibrating the sediment transport model using measured suspended sediment concentration data. The obtained results from this research can be used as an aid by planners for environmental management and future development of the municipality. Finally, the methodology used in this research can be used to assess other coastal erosion prone sites nationwide.

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