MORPHOLOGICAL DYNAMICS ON TIDAL INLET SYSTEM BY GENERATING VARIABILITY OF TIDAL-WAVE ENERGY REGIMES; A PROCESS-BASED MODEL APPROACH OF TIDE DOMINATED CASE AND MIXED TIDE DOMINATED CASE

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ABSTRACT

A process-based approach of 2D morphodynamic modeling is an alternative technique to investigate the morphological evolution in the long-term period. In the conceptual model application, there is two methodologies of morphodynamic model; realistic-based model (short time scale model in days/months) and realistic-analogue model which is called process-based model (long time scale model in ~100 years). Realistic-based model is the representative of generating force with complexity of real condition model in the field, however process-based model is the simplification of forcing model by representing the major factor. In this study, the domain model is as the adaptation of Dutch Wadden Zee tidal inlet system. A couple model technique of Flow module (Delft3d) and Wave module (X-Beach) is implemented into the model system. The tidal forcing is based on one main harmonic tidal component of M2 and super harmonic tidal component of M4 and M6 from the analysis harmonic of ZUNO model. The wave forcing is 1.4 m and 330 deg as the representative wave climate condition in Wadden Zee. A process-based model shows that initially the morphological response leading into establish-state condition. Tidal wave propagation which leads to stronger cross-shore ebb-flow perpendicular to the coastline contributes in morphological evolution inside the basin and forming the outer part of the inlet (ebb-tidal delta). Wave induce current in mixed-tide energy case are as the major contribution of stirring up sediments from the sea bed, leads to transport sediment because of longshore currents process, undertow, mass transport.

Keywords: morphological dynamic, variability of tidal-wave energy, process-based approach

ABSTRAK

Pemodelan teknik Process-based dapat dipergunakan sebagai alternatif untuk mengidentifikasi respon morfologi dengan periode waktu panjang. Secara konsep aplikasi pemodelan, terdapat dua metodologi dalam pemodelan morfologi; model realistic-based dan model realistic-analogue yang selanjutnya kita sebut model process-based. Model realistic-based merupakan representative kondisi alam yang kompleks, sedangkan model process-based berbasis simplikasi factor mayor yang menyebabkan evolusi morfologi. Dalam makalah ini, konfigurasi model merupakan representative dari tidal inlet Wadden Zee. Coupling-model antara modul flow dan mode gelombang X-Beach digunakan dalam penelitian ini. Pembangkit model berupa komponen utama harmonik pasang surut M2 dan frekuensi turunan M2 berupa komponen super harmonic M4 dan M6 dari analis harmonic hasil simulasi model ZUNO. Pembangkit gelombang berupa tinggi gelombang 1.4 m dan arah 330 derajat sebagai representative kondisi iklim gelombang di Wadden Zee. Hasil simulasi menunjukan respon morfologi tidal inlet sangat dinamis pada awal periode simulasi kemudian dinamika morfologi mulai menuju pada kondisi establish-state. Propagasi pasang surut secara tegak lurus pantai menyebabkan pembentukan ebb-tidal delta di sisi luar dan pembentukan morfologi pantai di sisi basin dari system tidal inlet. Pengaruh adanya gelombang menyebabkan sedimen yang berada didasar bergerak ke atas akibat adanya proses arus sejajar pantai, pengaruh arus bawah, dan transport massa air.

***Kata kunci**: dinamika morfologi, variabilitas pasang surut-gelombang, pendekatan process-based*

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INTRODUCTION

One of the common features on coastal system is the tidal inlet system (Ranasinghe and Pattiaratchi, 2003). According to Kraus (2010) the typical characteristic of tidal inlet is a short, narrow waterway connecting a bay, estuary, or similar body of water with a larger water body such as a sea or ocean upon which the astronomic tide acts (Figure 1). In other words, tides are as the important parameter to generate the dynamic of tidal inlet system; even though waves induce current (e.g. longshore transport process) also contributes to the morphological responses of the system.

Tidal inlets have an essential role in the ecological system as well as the socio-economic activity (Dastgheib, 2012). As part of the ecological system, tidal inlets serve in exchanging water, nutrients, and sediment between the lagoon and ocean, as well as being a conduit for water-borne biomass exchange (Kraus., 2010). In the socio-economic perspective, tidal inlets often use as a place for recreational activity or marina harbor.

METHODOLOGY

A virtual laboratory by establishing numerical model scheme plays role as the proposed methodology in this study. Flow module of Delft3d model and Wave module of XBeach model are utilized to set up the schematised model. These two models will be coupled to generate flow field every time step and eventually it will yield sediment dynamic in morphological time scale.

Flow Model

Depth averaged (2DH) version of the Flow module in Delft3d is derived by the governing equation of momentum and continuity on a curvilinier grid, in which the schematization model is using differencescheme method. Lesser *et al.* (2004) extensively described the Flow module in Delft3d. Shallow water equations, consisting of the mass balance and the momentum equations, which is expressed respectively by the formula below:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} + g\frac{\partial \zeta}{\partial x} + C_f\frac{\bar{u}\left|\sqrt{\bar{u}^2+\bar{v}^2}\right|}{h} - u\left(\frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2}\right) = 0$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{v}\frac{\partial \bar{v}}{\partial x} + \bar{u}\frac{\partial \bar{v}}{\partial y} + g\frac{\partial \zeta}{\partial y} + C_f\frac{\bar{v}\left|\sqrt{\bar{u}^2+\bar{v}^2}\right|}{h} - v\left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2}\right) = 0$$

Where ζ is Water level (m), $\bar{u}$ and $\bar{v}$ are velocities in cartesian coordinate of x and y direction respectively (m/s), g stands for gravitational acceleration, h is water depth, and v is eddy viscosity.

With $C_f = g\frac{n^2}{\sqrt[3]{h}}$

C_f is friction coefficient and n is manning coefficient.

Wave Model

Stationary wave simulation with directional spreading is utilized by using X-Beach model in this study (Roelvink, Reniers et al. 2009). Wave action balance formula is as the governing equation to derive the wave effect in the model. Delft3d and X-beach are coupled and the advantage of using X-beach in Delft3d; it can operate from the same grid size and domain in Delft3d and it is also able to avoid a lateral boundaries problem which is common in models such as SWAN. XBeach module considers a mean frequency in the directional space; local rate of change of action density in time, wave propagation, depth and current induced refraction and spatial dissipation of wave energy due to breaking. The wave action balance is then given by:

$$\frac{\partial A}{\partial t} + \frac{\partial C_x A}{\partial x} + \frac{\partial C_y A}{\partial y} + \frac{\partial C_\theta A}{\partial \theta} = -\frac{D}{\sigma}$$

Where, C_x and C_y are Celerity of wave propagation speeds in x- and y-direction, θ is wave direction, D is dispersion coeficient. With the wave action:

$$A(\theta) = \frac{S_w(\theta)}{\sigma}$$

Where, $A(\theta)$ is wave action, S_w is wave energy density in each directional bin

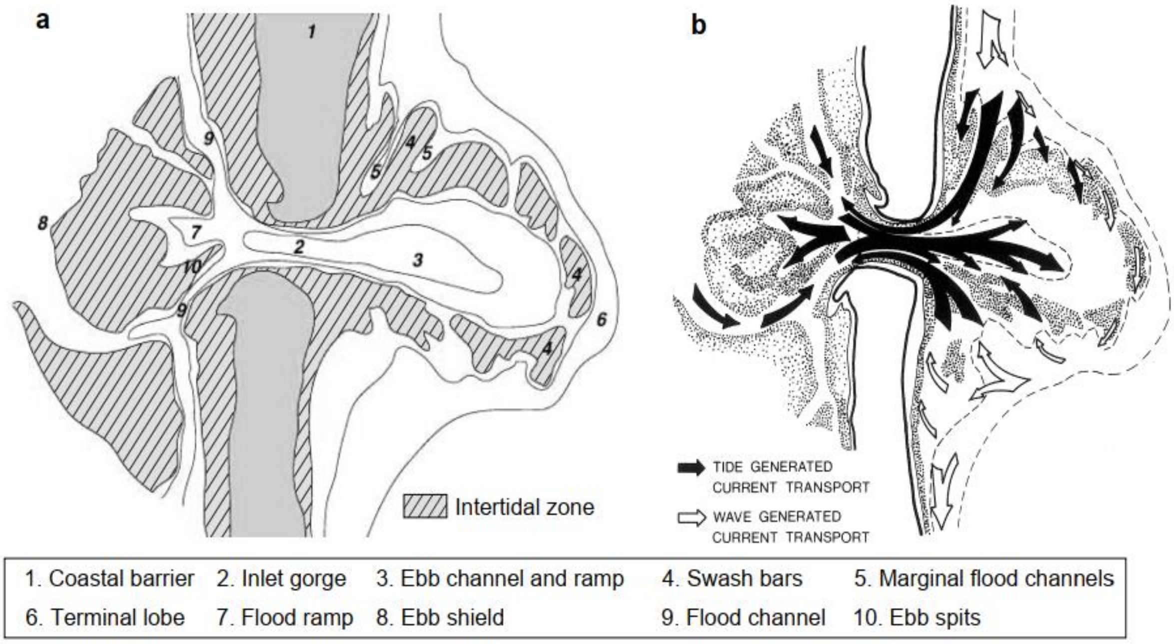

Figure 1. a) Schematic illustration of the morphological units that compose a tidal inlet; b) Wave and tide generated current transport pathway around and over the flood and ebb deltas. [adapted from Smith, 1987].

Coupling Model

A couple model technique of Flow module (Delft3d) and Wave module (XBeach) is implemented into the model system (Figure 2). In principle, the flow computation over tidal cycle is evaluated for a certain iteration time step, while the computation of Wave model is executed. The ouput of wave model is stored in the communication file every time step. Sediments are transported by the Flow field (combination of waves and tidal) and it induces bed level update. MORFAC (Morphological Factor) is defined to accelerate the bed level update (Lesser *et al.,* 2011), which is shown by the formulation below:

$$\Delta t_{morphology} = f_{mor} + \Delta t_{hydrodynamic}$$

Where $\Delta t_{morphology}$ is time step for morphology, f_{mor} is morphological factor, and $\Delta t_{hydrodynamic}$ is time step for hydrodynamic. This factor n increases the depth change rate by a factor, so that after simulation over one tidal cycle we have modeled the morphological changes over n cycles. Factor for erosion of 1.0 is applied in the model set up, it means that the adjacent coastline/wet cell can be eroded due to the flow field action.

Sediment Transport Model

Non-cohesive sediment simulation is simulated in the coupled model. Grain diameter for sediment size (D50) is 200 μm. Sorting and armoring considerations are neglected in the model. Sediment transport computation is based on Soulsby - Van Rijn formula (Soulsby 1997). Soulsby - Van Rijn formula is an empirical relationship for the independent prediction of both bedload and suspended load under the influence of current and wave action. Both waves and currents play important role in sediment dynamic of coastal and basin. Waves and current interact hydrodynamically with each other and to combine the behavior of these two factors can not be sum up linierly.

RESULTS AND DISCUSSION

Modeling philosophy

The traditional morphodynamic modelling philosophy is to calibrate and validate a model using laboratory and/or field measurements and then use the calibrated/validated model in hindcast or forecast mode to obtain quantitative estimates of system response to forcing. Depending on model accuracy, quality of data, and the accuracy of forcing conditions used for the hindcast/forecast, this traditional approach (i.e. virtual reality) may provide quantitatively accurate morphological predictions over relatively short time scales (~days/months). The present application is, however, a qualitative long term morphodynamic modelling exercise (~ 100 years) for which this traditional 'virtual reality' approach is not ideally suited due to several reasons. First, it is well known that a calibrated/validated model is quite likely to depart from the 'truth' the farther the simulation progresses past the calibration/validation period (Figure 3).

The deterministically chaotic nature of numerical models (Lorenz, 1972) is another phenomenon that places significant uncertainties on the quantitative accuracy of long term morphodynamic model predictions. Secondly, significant input reduction is required for long term simulations (i.e. present computational costs do not allow multiple long term brute force simulations). Therefore, even a model that is perfectly calibrated/validated (i.e. representing real forcing/response relationships), cannot be expected to predict future system response accurately due to the highly schematised nature of future forcing that is unavoidable in long term morphodynamic simulations. For the long term forecasts necessary in this study, therefore, a different modelling philosophy ('Realistic analogue' (Roelvink and Reniers, 2011)) is adopted. The 'Realistic analogue' to represent Process-based model essentially commences the simulation with a highly schematised initial bathymetry and allows the model to gradually produce the morphology that is in equilibrium with the main forcing that is to be used in forecast mode. The level of schematisation in the initial bathymetry is extreme in that while the geometry of the coastal system under investigation is very broadly represented, the initial bed is assumed to be more or less flat (i.e. flat bed morphology). Once this initial 'establishment simulation' produces a near-equilibrium morphology that is sufficiently similar to the observed system in terms of channel/shoal patterns and typical morphometric properties, the simulation can be extended into the future with slightly varied forcing, for example tidal forcing and slow sea level rise, to qualitatively investigate future system behaviour.

Model configurations

Model configuration in this study is the model which was set up by Dastgheib (2012) in the study of switching channel for long-term process-based morphological modeling of large tidal basins (Figure 3). This model is an adaptation of Ameland tidal basin in Dutch Wadden Zee through realistic analogue approach. In the backbarrier basin and in the gorge, the bathymetry grid resolution is finer 3 times to get more detail result. The bathymetry profile is flat, which consists of a 25 x 15 km basin with uniform depth of -3 meter. The basin is connected to the offshore through an inlet 3 km long and 1 km wide. The banks of the inlet are erodible therefore the inlet can expand in width. At the sea side, the seabed profile is a concave profile from 0 meter to -20 meter depth.

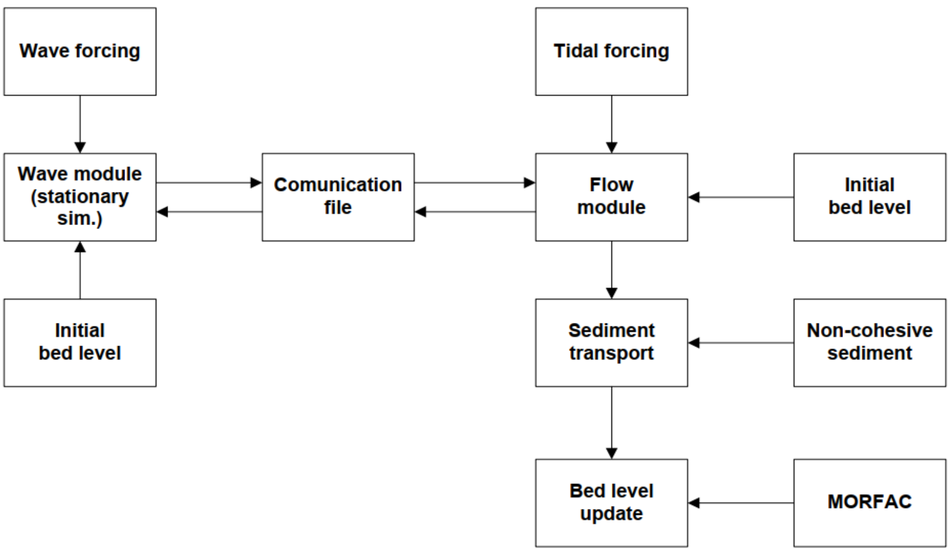

Figure 2. Coupling model scheme of tide model and wave model

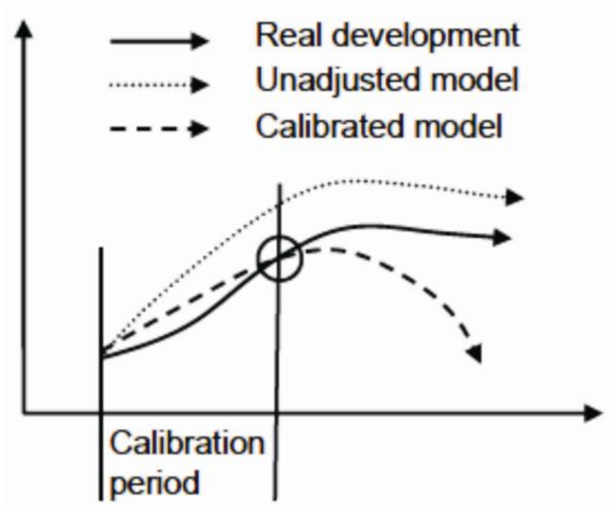

Figure 3. Pessimistic scenario for effect of calibration: real development, unadjusted model and calibrated model (Virtual reality) (after Roelvink and Reniers, 2011)

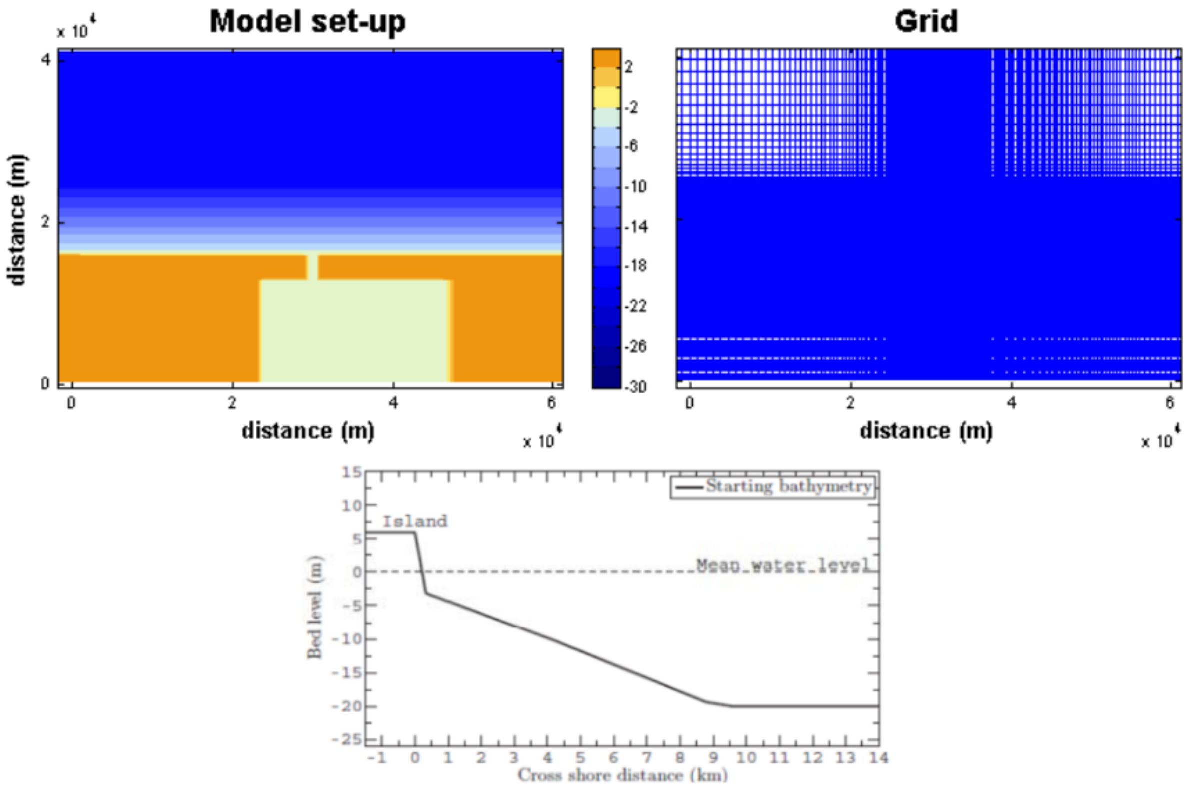

Figure 4. Flat bathymetry and model grid setup

Forcing model

Tides and wave effects will be applied as generating force in the model. These different energy regimes will be classified based on the recommendation of Davis and Hayes (1984). Tide dominated case and mixed tide dominated case are scenarios that will be investigated in this study (Figure 5 with red circle). The tidal components are simplified by only considering M2 and overtides components (M4 component and M6 component). This forcing is applied as water level boundary on the offshore side. For lateral boundary, in this case for east and west boundary, Neumann boundaries are applied (Roelvink and Walstra, 2004). Neumann boundary is a condition where the boundary is imposed as an alongshore water level gradient. Wave condition in the Dutch coast is represented by wave height of 1.4 m and northwesterly wave direction 330 deg (Dissanayake, 2011).

Establish-state condition

Defining establish-state

The objective of defining establish-state condition is to determine in which period the initial bathymetry will use for the next 100 years simulation ahead. Establish-state condition is defined as the state where the development of tidal inlet evolution is already in a well-developed situation and the morphological evolution relatively becomes slower in the certain period. The establish-state definition considers the calculation of sediment volume in the main element of tidal inlet based on their definition. In this case, the sediment volume of ebb-tidal delta and flood tidal delta sediment volume will be considered, because these elements have significant morphological evolution that began when the inlet was created (Dean and Dalrymple, 2001).

According to Walton and Adams (1976), the ebb-tidal is defined as the integration of sedimentation relative to an undisturbed coastal profile. Basin volume is defined as the sediment volume relative to undisturbed bathymetry Dissanayake (2011).

Tidal wave propagation and wave induce currents are as the main generator of the coastal dynamic in tidal inlet system. Tidal wave propagation which leads to stronger cross-shore ebb-flow perpendicular to the coastline contributes in morphological evolution inside the basin and forming the outer part of the inlet (ebb-tidal delta). Wave induce current in mixed-tide energy case are as the major contribution of stirring up sediments from the sea bed, leads to transport sediment because of longshore currents process, undertow, mass transport (Soulsby, 1997; Roelvink *et al*., 2009; Fitzgerald *et al.*, 2000; Dastgheib,2012).

Establish-state feature

The development of tidal inlet system from the flat bathymetry to the establish-state condition is extremely dynamic initially, whether the development in the ebb-tidal delta or in the flood tidal delta. Figure 5 and Figure 6 indicate the development of tidal inlet system through sediment volume calculation. In both figures (5 and 6), we can see that during the first period until the certain period before out of spin-up time, the morphological evolution, in this case sediment volume, is increasing tremendously. This process occurred, because initially the inlet is relatively narrow and shallow, so the velocity of tidal wave propagation is relatively high and this energy is sufficient to scour out the sediment from the gorge transported to the seaward (forming of ebb tidal delta) and to the basin (forming the flood tidal delta). In the certain period the inlet is relatively wider and deeper, in this situation the morphological evolution becomes slower and the forming of flood tidal delta and ebb-tidal delta are relatively well-developed.

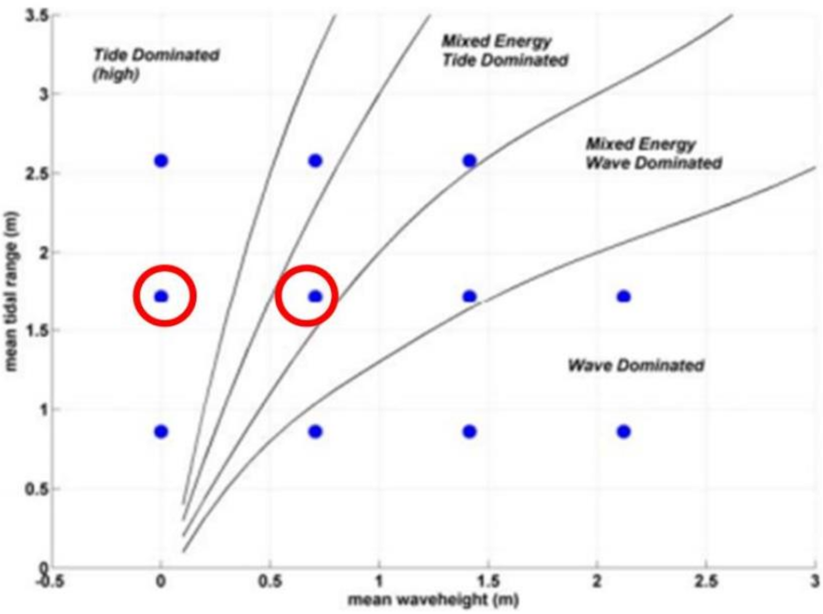

Figure 5. Generating force for tidal inlet system based on Davis and Hayes (1984); Red circle indicates scenario model used in this study

In the ebb tidal delta, the deposition process is increasing significantly after 60 years morphological time period. In the flood tidal delta, the sediment volume is dynamic but deposition processes are also occurred for both cases (tide dominated case and mix-tide case). Based on simulation result (Figure 6), in tide-dominated case the morphological evolution of ebb tidal delta was reached establish-state after 100 years simulation, in which morphological evolution of sediment volume in ebb tidal reached out of spin-up period. For mixed-tide dominated case, the sediment volumes in ebb tidal delta reached state after 80 years, where it is indicated by the small development compare to the volume development in the spin-up period.

Another interesting point in term of morphological evolution in ebb-tidal delta is that the amount of sediment volume indicates whether the tidal inlet system is already well developed or not reach the establish-state

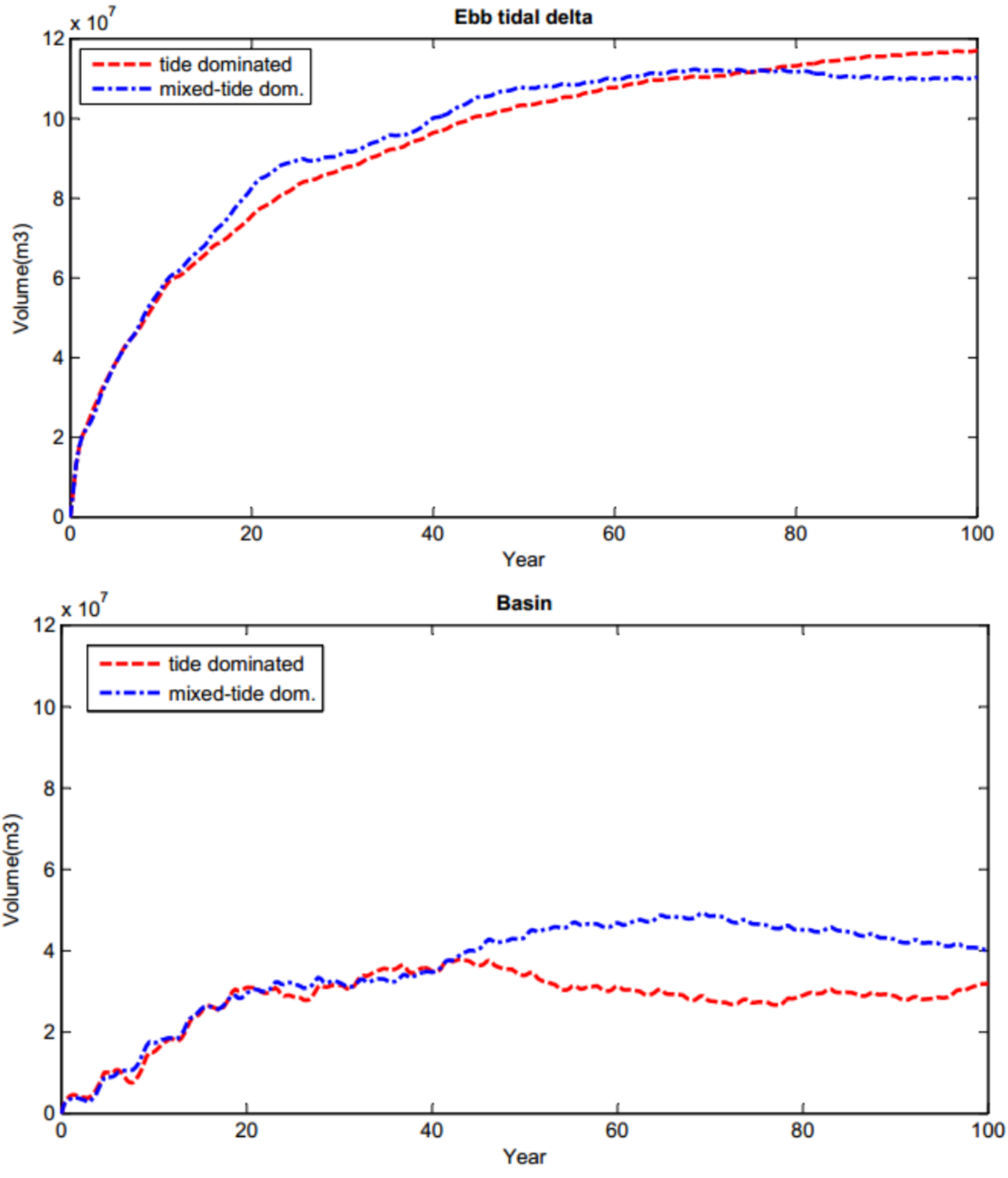

Figure 6. Sediment volume in ebb-tidal delta (top) and basin (bottom) during 100 years simulation

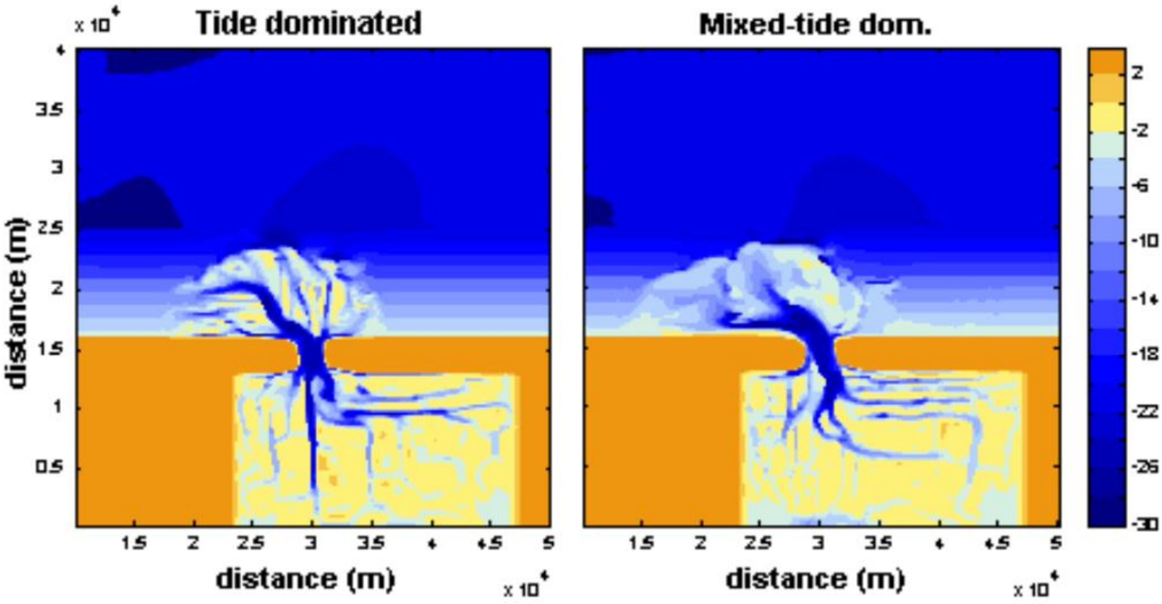

Figure 7. Bathymetry feature after establish state conditions; tide dominated case (left side) and mixed-tide dominated case (right side)

condition yet. Based on simulation result, tide-dominance case yields the highest sediment volume in ebb-tidal delta due to higher tidal range leads to higher cross-shore transport perpendicular to the barrier and hence ebb-tidal delta extends offshore. On the other hand, for mixed tide dominance case, the wave effect leads to increase of bed shear stress in the ebb tidal delta as well as wave induce current and hence the sediments are advected away. Therefore, sediment volume in mixed-tide case (110 Mm^3) has the lower volume of sediment budget compare to the tide dominated case (117 Mm^3).

Significant development of sediment volume in morphological time period is also pronounced in the flood-tidal delta initially (Figure 6). The sediment volume after 50 years for both cases is nearly the same, but afterward the sediment volume of mixed-tide dominated case becomes higher than tide dominated case. It indicates that waves contribute in the morphological evolution inside the basin, in which wave current interactions lead to sediment bypassing through longshore transport process as well as waves shoaling and breaking on the ebb tidal delta augment flood tidal currents and retard ebbtidal current. This process also lead to the contribution of transporting sediment onshore (Fitzgerald *et al.,* 2000).

Bathymetry features after reaches establish state condition are shown in the Figure 7. In tide dominated case, the ebb tidal delta expands seaward and the main ebb-channel is oriented to the updrift because of tidal wave propagation from West to the East side. For mixed-tide dominated case, the ebb tidal delta formation is less pronounced compare to the tide dominated case. This process occurred because the presence of wave affects the sediment in ebb tidal delta, which spread away the sediments (Fitzgerald *et al.*, 2000; Dissanayake *et al.*, 2012). The main channel orientation is also deflected to the updrift direction because of the same condition of tidal wave propagation. These bathymetry features are used as the initial condition of bed level for further investigation of SLR impact.

CONCLUSION

A process-based approach of 2D morphodynamic modeling is an alternative technique to investigate the morphological evolution in the long-term period. In the conceptual model application, there is two methodologies of morphodynamic model; realistic-based model (short time scale model in days/months) and realistic-analogue model which is called process-based model (long time scale model in ~100 years). A process-based model shows that initially the morphological response leading into establish-state condition. Tidal wave propagation which leads to stronger cross-shore ebb-flow perpendicular to the coastline contributes in morphological evolution inside the basin and forming the outer part of the inlet (ebb-tidal delta). Wave induce current in mixed-tide energy case are as the major contribution of stirring up sediments from the sea bed, leads to transport sediment because of longshore currents process, undertow, mass transport.

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