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COASTAL LANDFORM AND ITS INDICATIVE RISK OF CHANGES THROUGH INTEGRATED SATELLITE AND ON GROUND OBSERVATIONS FOR COASTAL DEVELOPMENT AND REVITALISATION IN PATI, CENTRAL JAVA

BENTANG ALAM PESISIR DAN INDIKASI RISIKO PERUBAHANNYA MELALUI INTEGRASI STUDI CITRA SATELIT DAN PENGAMATAN LANGSUNG UNTUK PENGEMBANGAN DAN REVITALISASI PANTAI DI PATI, JAWA TENGAH

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ABSTRACT

An appropriate foreshore management should take into account coastal processes based on physical and biological features of the particular coastal environment. This study aims to determine the coastal landform and its instability and susceptibility through satellite study, thematic map, and groundtruth checking. The coastal landform of Pati is typified by the muddy coast with ~1 km tidal mudflat moving seaward and coastal plain moving landward. Mangrove ecosystem, mainly Avicennia, intermittently occurs along the coast of Pati resting on muddy substrates where tributaries drain off water from the hinterland. The coastal plain is largely occupied by salt and/or fish ponds. Considering the geological condition, coastal characteristic, and oceanographic processes, the coast of Pati has medium to high-risk level of landform changes with shoreline changes greater than 1 m/yr and 5 to 10 yearly coastal inundation driven by the erosion and sedimentation. The study provides insight in recognising time and space scale of an indicative risk of landform changes and its driving processes for the coastal management and planning purposes.

Keywords: coastal landform, Landsat images, coastal revitalization, Pati, Central Java.

ABSTRAK

Pengelolaan pantai yang tepat harus mempertimbangkan proses pantai berdasarkan kondisi bio-fisik lingkungan pesisir tersebut. Penelitian ini bertujuan untuk mengetahui bentang alam pesisir dan ketidakstabilan serta kerentanannya melalui penafsiran citra satelit, peta tematik, dan pengamatan lapangan. Bentang alam Pantai Pati sebagian besar dicirikan oleh pantai berlumpur dengan ~1 km rataan lumpur pasang surut maju ke arah laut dan dataran pantai mundur ke arah darat. Ekosistem mangrove, terutama jenis Avicennia, menempati sebagian Pantai Pati yang tumbuh pada substrat lumpur terutama pada muara cabang-cabang sungai yang mengalirkan air dari daratan. Dataran pesisir sebagian besar digunakan untuk tambak garam dan kolam ikan. Berdasarkan kondisi geologi, karakteristik pantai, dan proses oseanografi, Pesisir Pati memiliki tingkat risiko perubahan bentang alam sedang hingga tinggi dengan perubahan garis pantai lebih dari 1 m/tahun dan 5 hingga 10 tahunan genangan pantai yang ditimbulkan oleh proses erosi dan sedimentasi. Penelitian ini memberikan dasar pemahaman dalam menilai skala waktu dan ruang dari indikasi proses penyebab perubahan morfologi pesisir untuk tujuan perencanaan dan pengelolaan wilayah pesisir.

Kata kunci: bentang alam pesisir, citra Landsat, revitalisasi pesisir, Pati, Jawa Tengah.

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INTRODUCTION

Coastlines are among the most rapidly changing and dynamic landscape features. A combination of seawaves and currents erosions, sediment depositions, activities of living organisms such as coral, crustal movements, and sea-level variations due to climate changes is the factor governing coastline formation (Dolan, 1975; Komar, 1976; Bird & Ongkosongo, 1980; Solihuddin *et al*., 2011; Moechtar *et al*., 2013). The coastline of Pati has been utilised as a centre of salt and fish pond activities located alongshore, stretching from the north of Dukuh Seti to the south of Batangan. Consequently, the coast protection of Pati is essential for sustaining those commercial activities. In addition, preventing mangrove ecosystem degradation along the coast of Pati may ecologically contribute to the mitigation and adaptation of global climate change and related potential impacts such as sea level rise (Krintensen *et al*., 2008).

The need for this research arise when coastal managers are planning to manage the coastal area with regard to the existing and potential coastal landform changes both in short-term (annual) and long-term (centennial) scale. In determining the coastal foreshore reserve, it is important to recognise time and space scales in which the coastal landforms and their driving processes operate for the planning timeframe (Hesp, 1986). The long-term variation in processes determines the coastal morphology upon which the effects of short-term variability are superimposed. Long-term scales encompass broad-scale changes occurring to the land system over a planning horizon of 100 years or longer. Conversely, short-term changes are apparent at individual landforms and changes to them. The short-term changes are apparent at site planning scales and time intervals of less than a decade (Hesp, 1986).

This research aims to provide a greater understanding of the coastal system in terms of coastal landform and evolution through satellite study, thematic map, and on ground observations. Studies and researches related to coastal hazards have previously been conducted on the north coast of Java discussing primarily coastal vulnerability to tidal inundation (Andreas *et al*., 2017a, 2017b), coastal erosion (Astjario, 2006; Setiadi & Usman, 2008; Marfai, 2012; Achiari *et al*., 2015), coastline changes (Ongkosongo, 1979; Heriati & Husrin, 2017), land subsidence (Budiono & Rahadjo, 2008; Abidin *et al*., 2011, 2013), and sea level rise due to climate change (Yuwono *et al*., 2016). Coastal sediment cell as a compartmentalisation of net sediment transport boundaries on the north coast of Central Java has also been generally recognised by Khakim *et al*. (2005), providing an overview of a utilisation of coastal sediment cell for coastal management.

However, this coastal region has been considered to be a “stable” shoreline and consequently disregarded by the coastal researchers. Thus, the overall objectives of this study include: 1). Identification of coastal landform consisting of geology, geomorphology, and coastal characteristic, 2). Description of the coastal evolution, 3) Hydro-oceanographic patterns, and 4). Assessment of the indicative risk of coastal landform changes based on susceptibility and instability of the coastal landform. The study is also projected to be suitable and applicable for many other coastal management and research purposes in the future.

Field setting

The coastal geology of Pati is entirely alluvial deposits consisting of gravel, sand, silt, and clay (Kadar & Sudijono, 1993). The coastal morphology has generally low relief contours (<25m) with river systems drain off into the Sea of Pati (width of estuary <50 m). The Pati coastline and adjacent waters provide a range of habitats for species including mudflats and mangroves. The supratidal coastal plain is largely utilised for salt and/or fish ponds beside residential area used by the local people. The coastal waters of Pati are turbid due to high terrestrial input, peaking during the wet season. The mangroves ecosystem intermittently occurs along the coastline especially in the estuary environment where fresh water drains off the island and rests on the silty substrates.

The oceanography of the Java Sea and along the coast of Pati is significantly influenced by the monsoonal drift prevailing easterly flow of surface current during the northwest monsoon from November to March. The southeast monsoon current sets westward from May to September (Gordon *et al*., 2003; Wyrtki, 1961). This monsoonal reversal of surface currents is responsible for major changes in the sea surface salinities, ranging from 31 PSU (Practical Salinity Unit) during the northwest monsoon to 35 PSU during the southeast monsoon. The bathymetry of the region is relatively shallow, rarely exceeding 60 m deep. The 5 m isobath lies generally about 2 km offshore of Pati. The average tidal range is 1 m along the coast with diurnal tide type. The prevailing wind direction is from the northwest with wind speed up to 6 m/s during the wet season. Whilst, during the dry season, the wind direction is predominantly from the southeast with wind speed up to 4 m/s (see Figure 1).

METHODOLOGY

Coastal landform mapping

Coastal landform was investigated following methodology described by Sharples *et al*. (2009). The method is practical for the local coastal zone analysis

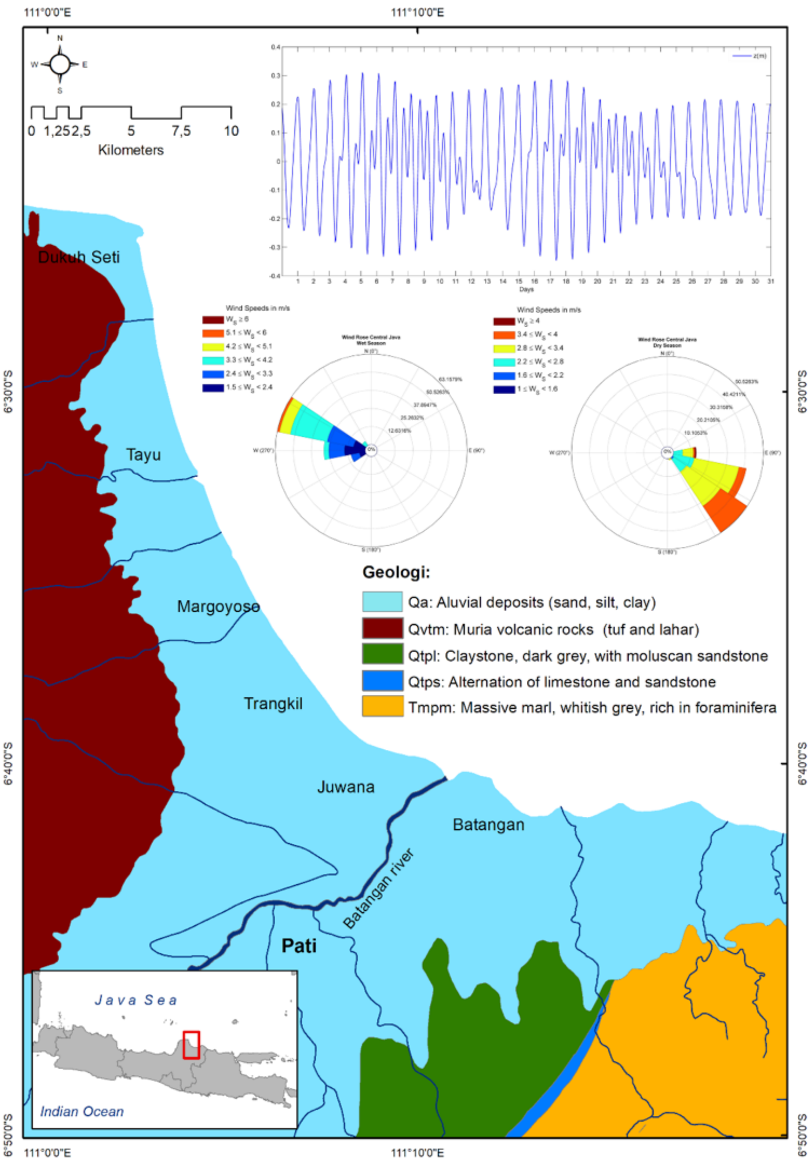

Figure 1. Map of study area showing geological setting, tidal pattern, and windrose diagram of average windspeed in Pati.

because of the essentially linear (alongshore) nature of the coasts by which information such as geology (rock resistance), relief (morphology), and shoreline characteristic are included. The surveys were conducted in 2016 and 2019 covering whole region of the Pati Coast. Identification of substrate types were characterised by a visual assessment with an aid of magnifying lens. Groundtruth locations were photographed with a built in camera-global positioning sytem (GPS) unit. The coastal characteristic units are named based primarily on their form and fabric (constituents) such as “rocky”, “sandy” or “muddy” and secondarily described by the genetic or morphodynamic descriptors such as “cliff”, “beach”, “shore platform”, etc.

Satellite image and topographic map

Study was based on Landsat TM/ETM+ image (path 119, row 065) which is available for this following years: 1989, 1998, 2008, and 2018. Army Map Service (AMS) topographic map scale 1:50.000 printed out by the Netherland in 1944 was also used to describe the shoreline back to 75 years ago. The images were corrected geometrically to the universal transverse mercator (UTM) zone 59 coordinate system and world geodetic system (WGS) 84 reference datum. The three visible bands of Landsat TM/ETM+ i.e. band 1 (0.45 - 0.52 µm), band 2 (0.52 - 0.60 µm) and band 3 (0.63 - 0.69 µm) as well as band 4 (0.76 - 0.90 µm) which is useful in differentiation of land from water, used in land-masking workflow. Groundtruth checking of the coastal landform status was assigned to the corresponding Landsat 30 x 30 m pixels. Multi-temporal Landsat TM/ETM+ images and AMS topographic map were analysed to assess coastal evolution following the procedure described below:

- Shoreline digitisation

Shoreline digitisation was performed from the georeferenced satellite images and AMS topographic map to obtain a vector dataset which subsequently used for coastal evolution analysis. The dataset analysed in this study includes 2 (two) periods i.e. 1944-1989 and 1998-2018.

- DSAS shoreline modeling

The Digital Shoreline Analysis System (DSAS) extension from ArcGIS toolkit (Thieler *et al.*, 2008) was employed for quantifying the rate of coastline advance or retreat over time. Once the coastline vectors have been merged, they can be utilised by the DSAS extension in order to assess the rate of change and total movement of the coastline over time. The net shoreline movement represents the total distance between the oldest and youngest rates described in this paper represent the distance of shoreline movement between the oldest and the most recent shoreline.

Hydrodynamic model

The model used in this study was two-dimensional (2-D) Hydrodynamic Model following Finite Volume Method (FVM) from Mike 21 developed by Danish Hydrolic Institute (Anonym, 2007). Bathymetry with 5-minute resolution (~9.25 km) generated from General Bathymetric Chart of the Oceans (GEBCO) and on-screen digitated shoreline from Landsat imagery were used to generate the model. In addition, wind and sea surface elevation data represented by east monsoon (August 2018) and west monsoon (January 2019) were also employed as model data input. The wind data was derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) with 6-hour interval and 15-minute resolution. Whilst, the sea surface elevation data was obtained hourly from Mike21 tools Tidal Prediction of Height for August and January dataset. The mean sea level pressure, however, was assumed to be uniform at 1013 hPa. The detail of the hydrodynamic model set-up is shown in Table 1.

RESULTS AND DISCUSSION

Results

Coastal landform

In general, the coastal landform of Pati is thoroughly classified as coastal lowland with alluvial deposits composed of sand, silt, and clay. The deposits spread from the north of Dukuh Seti to the south of Batangan. The low-relief coastal plains are mostly ocupied by salt and/or fish ponds with a few other of milkfish and shrimp. Alluvial deposits are geologically loose materials that have low resistance to the wave erosion and sea currents. The rivers draining off to the sea of Pati are generally small (width estuary <50 m). The biggest river is Batangan located on the southernmost of Pati and is part of Juwana watershed with approximately 154 km^2 area. The coastal landform of Pati is delineated of 2 (two) distinct characteristics: (1) mangrove and (2) muddy coast (Figure 2).

Mangrove

Mangrove occurs as narrow basins in the tidal reaches of rivers and streams discharging directly onto the coast of Pati, particularly the seasonally flowing streams of the Pati coastal plain. Alluvial flats adjoining the swamp water bodies were originally vegetated by mangroves to the water's edge (Figure 2). They are subject to marine inundation when the river mouth is open and to river flooding during high fluvial discharge following periods of intense of protracted rainfall. In most swamp environments, the alluvial flats are vegetated by mangrove such as in Tayu, Trangkil, Ngurenrejo, Juwana, and Batangan (Figure 2). Mangrove ecosystems grow on mud substrate,

Table 1. Set-up for hydrodynamic model

Parameter	Implemented in simulation
Simulation time	Number of time step = 720 (east monsoon), 744 (west monsoon) Time step interval = 3600 second Start and stop simulation date = 01/08/2018 17.00 – 30/08/2018 16.59 (east monsoon) 01/01/2019 17.00 – 31/01/2019 16.59 (west monsoon)
Mesh boundary	Bathymetry = GEBCO 5-minute resolution Coastline = Landsat Image on-screen digitation
Flood and Dry	Drying depth = 0.005 m Flooding depth = 0.05 m Wetting depth = 0.1 m
Boundary condition	Tidal forecast for coordinates: 1. Longitude: 110.970083°; Latitude: 6.695002° 2. Longitude: 111.233666°; Latitude: 6.214235°

Source : (Data Processing, 2019)

especially in estuary areas where tributaries drain off fresh water from the terrestrial. The most widespread and densely distributed of mangrove area is in Tluwuk, Ngurenrejo with a width of up to ± 500 m perpendicular to the shoreline.

Muddy coast

Muddy coast or tidal mudflats are associated with the highly active river and are distributed at almost all coast section of Pati especially in the estuary areas. This coastal landform is comprised of unlithified or unconsolidated sediments that have accumulated in response to sea level changes and coastal processes, marine and fluvial. Muddy coast, together with landforms adjoining the tidal reaches of inland water is vulnerable to river flooding and marine inundation, separately and coincidentally. The frequency and duration of both processes, as well as their extreme events are important factors in the development of coastal lowlands that have to be considered in coastal planning and management. The morphology of muddy coast and tidal mudflats is exposed in the intertidal zone at low tide up to ± 1 km towards the sea (Figure 2).

Coastal evolution

Results of the shoreline analysis are shown separately for the periods of 1998–2018 (Figure 3a) and 1944-1989 (Figure 3b). Overall, the shoreline evolution encompassing the coast of Pati has remained relatively accreting with some minor erosion recorded. The shoreline from the north of Tayu to the south of Batangan is mostly accreting. Tayu Coast showed little accretion (±3 m a year) for the periods of 1944-1989 and ±5 m a year for the periods of 1998-2018, and is considering the lowest rate of accretion in this area. The highest accretion rate has shown at around

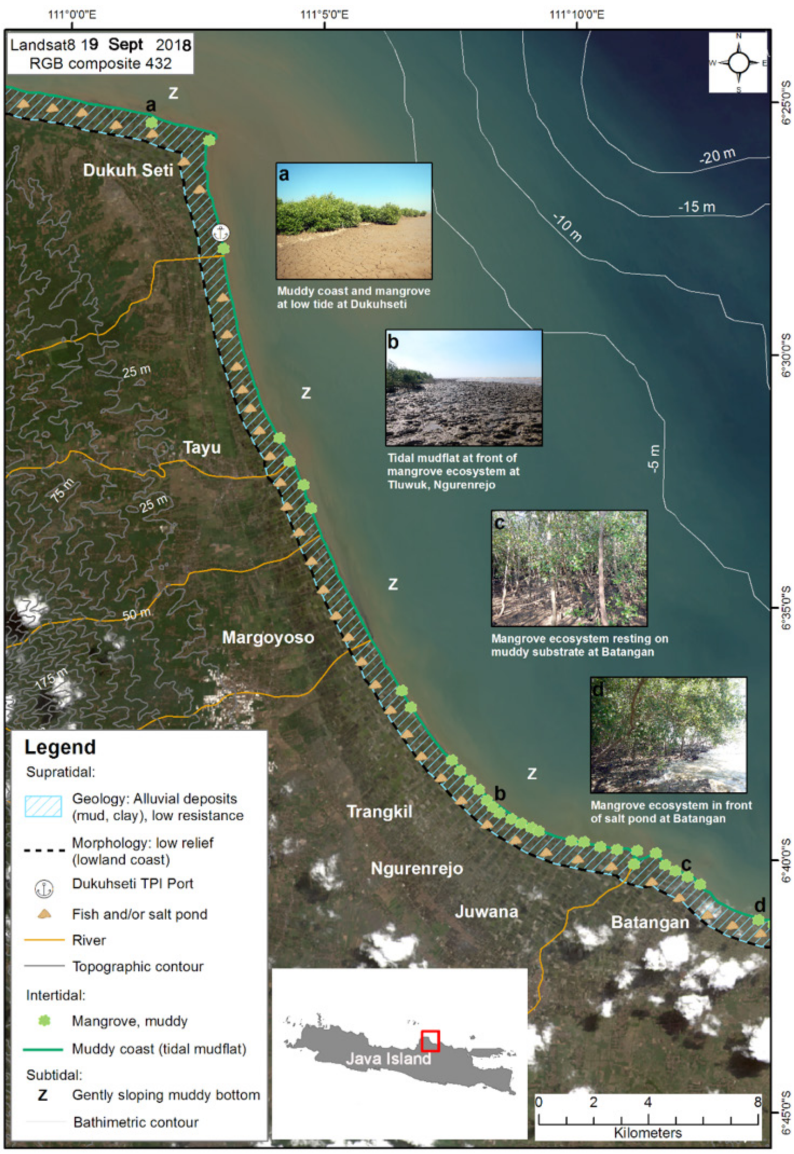

Figure 2. Map of coastal characteristic of Pati showing mangrove and muddy coast in the intertidal zone.

Table 2. Model simulation result of Pati (Diurnal tide)

East Monsoon					
High Spring tide condition (26 August, 2018)			**High Neap tide condition (5 August, 2018)**		
Current Speed	High Water Level (HWL) 07.00 wib	Low Water Level (LWL) 20.00 wib	Current Speed	High Water Level (HWL) 09.00 wib	Low Water Level (LWL) 21.00 wib
0.023-0.181m/s	0.442 m	-0.298 m		0.005 - 0.13 m/s	0.236 m -0.298 m
West Monsoon					
High Spring tide condition (21 January, 2019)			**High Neap tide condition (14 January, 2019)**		
Current Speed	High Water Level (HWL) 21.00 wib	Low Water Level (LWL) 09.00 wib	Current Speed	High Water Level (HWL) 21.00 wib	Low Water Level (LWL) 09.00 wib
0.014-0.225m/s	0.589 m	-0.578 m	0.03 - 0.114 m/s	0.294 m	-0.371 m

Source : (Data Processing, 2019)

Batangan Coast with ±380 m coastal progradation during 1942-1989 period (~8.5 m a year) and almost doubling (±15 m a year) over the last two decades (1998-2018). This indicates that there is a consistency of shoreline changes between the two periods showing the significant increase of coastal accretion in some areas including, in estimated order of rates: Batangan, Juwana, Ngurenrejo, Trangkil, Margoyoso, and Tayu. The reasons for this pattern are deemed to be linked to a natural sediment transport from the river and drainage system in Pati carrying sediments from terrestrial to the sea and facilitate sediment accumulation offshore. The sediment appears to be transported northwards from the Batangan river on the south side of Pati Coast.

Unlike in most areas of southern Pati Coast, Dukuh Seti on the north had an average erosion of approximately ±3 m a year from 1944 to 1989 with an almost fivefold of the average rate of erosion (±15 m a year) in the last two decades (1998-2018). This trend is attributed to the presence of eastward-oriented littoral currents eroding the coast. These currents are driven by the prevailing year-round eastward-oriented swell and wind waves during the wet season (November to

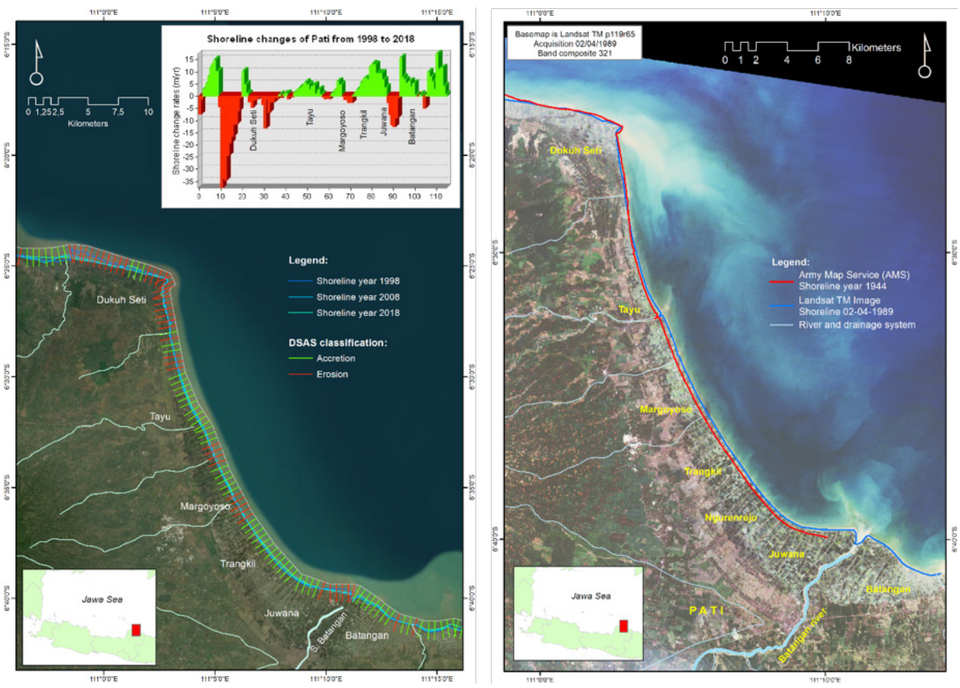

Figure 3. Map of shoreline changes of Pati: a) from 1998 to 2018 based on multi-temporal Landsat TM/ ETM+ images processed using DSAS in ArcGIS toolkit and b) from 1944 to 1989 based on Army Map Service and Landsat TM image.

March), with possible short-term reversal in dry season (May to September).

Hydrodynamic conditions

Hydrodinamic model performed at 4 (four) conditions including high spring tide, high neap tide, low spring tide, and low neap tide. Those conditions represent water flow dynamic around model area in Pati as shown in Table 2 and Figure 4.

Discussion

Assessment of indicative coastal landform change

The assessment of instability (existing change) and susceptibility (potential change) of coastal landform is essential for management purpose. The coastal managers must consider the coastal landforms and their indicative risk of landform changes over the last few decades to plan and manage the coastal areas in the future. Here, we describe the coastal landform, existing change, and potential change of Pati Coast and divide the coastline into modified Hesp's (1986) compartment by which estimated ratings of instability and susceptibilty are assessed (Table 3). This coastline compartment has been successfully used in Western Australia to assess Australia's coastal indicative risk of landform changes based on coastal characteristics and evolution to assess short to long term coastal instability and susceptibility (Hesp, 1986). The concept is also projected to be suitable and applicable for many other coastal management and research purposes in the future.

The coastal landform of Pati is thoroughly classified as coastal lowland (row 1) with alluvial deposits composed of sand, silt, and clay. These deposits are geologically loose materials, unlithified, and unconsolidated that have high susceptibility or potential change due to coastal processes; marine and fluvial. The coastline of Tayu, Margoyoso, Trangkil, Ngurenrejo, Juwana, and Batangan is characterised by mangrove and muddy coast (tidal mudflats) suggesting predominantly coastal accretion or progradation with rates from a low of ±3 m to a high of ±15 m a year since the last 7 decades (1944–2018). Hence, the indicative

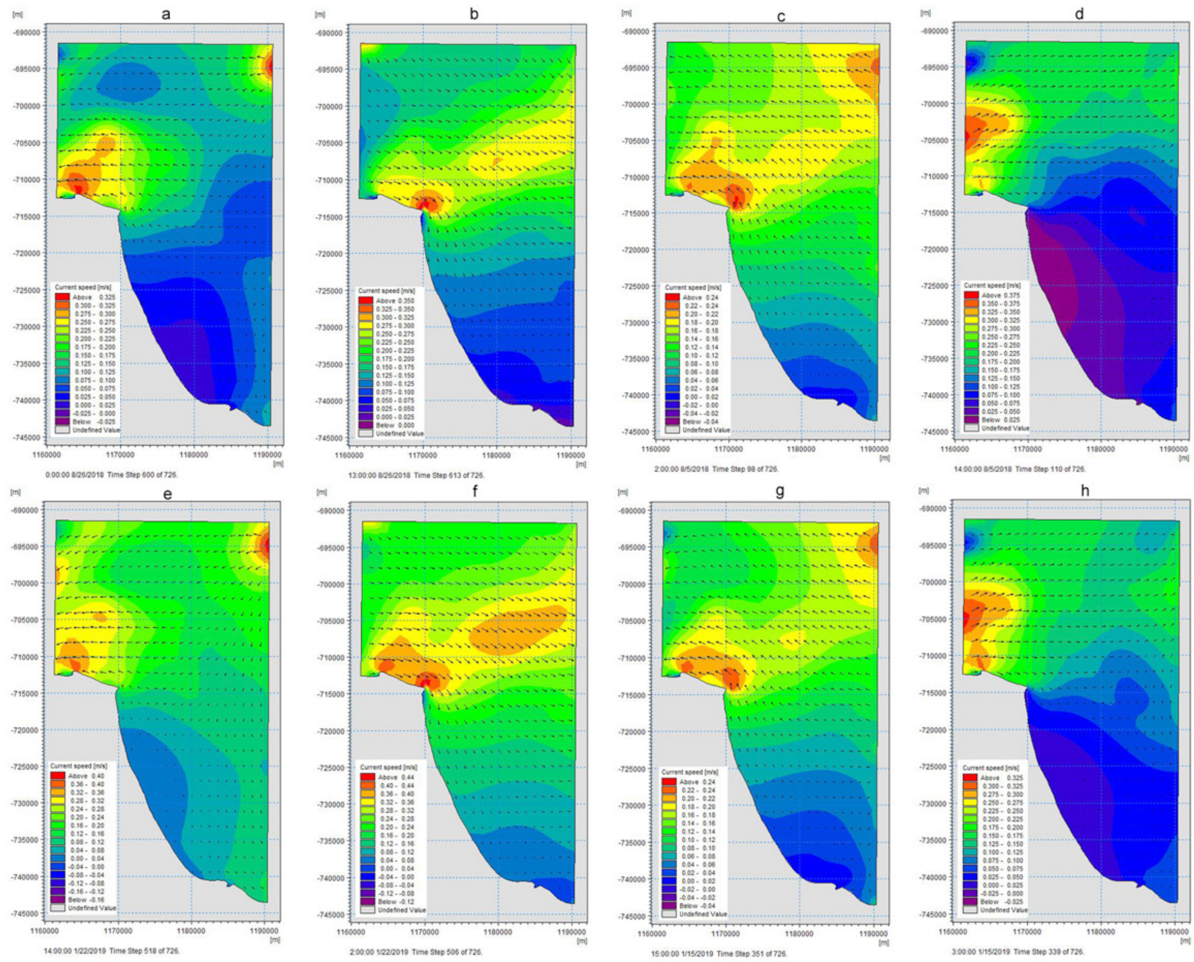

Figure 4. Current speed conditions along the coast of Pati at: East monsoon: a.High spring tide (0.0946 m/s) b. Low spring tide (0.181 m/s) c. High neap tide (0.131 m/s) d. Low neap tide (0.046 m/s) West monsoon: e. High spring tide (0.225 m/s) f. Low spring tide (0.079 m/s) g. High neap tide (0.054 m/s) h. Low neap tide (0.105 m/s).

risk of landform changes in these areas categorised from medium to high (class 4, row 1/column 2, pink colour).

Interestingly, although having similar coastal characteristic, the Dukuh Seti Coast is experiencing erosion with rates of ±3 m a year for the period of 1944-1989 and ±15 m a year for the last 2 decades (1998-2018). Hence, the indicative risk of landform changes in Dukuh Seti fall into medium to high (class 4, row 2/column 1, pink colour).

Looking at the hydrodynamic patterns particularly sea current speed (see Figure 4), it is apparent that the coastal landforms and evolution of Pati Coast are largely influenced by the hydrodynamic conditions showing the high current speed on the north coastal region (around Dukuh Seti) both in east and west monsoon. Thus, this will also affect the instability and susceptibility of the Dukuh Seti Coast.

Given the medium to high potential changes of the coastal landform of Pati, measures must be taken as an anticipative response to protect the coastline and associated economic activites such as salt pond and marine aquaculture. Moreover, as a consequence of the widespread awareness of the global climate change impacts such as sea level rise, storms, and extreme weather (intense rainfall or drought), response to such hazards must be taken immediatelly not just in terms of protection measures but also in terms of policy. Protection may include plantation and rehabilitation of mangrove ecosystem along thre coast of Pati which have been conducted by the Ministry of Marine affairs and Fisheries (KKP) since 2013, while policy may include institutional strengthening for climate-resilient coastal zone development and planning and/or capacity development at various scales to manage climate-related coastal risks.

CONCLUSION

The integrated coastal zone managament and planning can not be appropriately applied until there is a better understanding of the geomorphic and oceanographic processes; past and present. The significant finding of this study is that the coastline of Pati is predominantly accreting for the last 7 decades from the north of Tayu to the coast of Batangan ranging from a low of ±3 m to a high of ±15 m a year. Massive erosion also recorded at Dukuh Seti Coast with different rates of ±3 m a year for 1944-1989 and ±15 a year for 1998-2018. When this existing change combined with the potential change, the indicative risk of landform changes in Pati, Central Java is throughly categorised as medium–high risk compartment. This indicates that the coast of Pati has medium to high instability and susceptibility due to erosion and

Table 3. Indicative risk of landform changes modified from Hesp (1986)

			1	2	3
			INSTABILITY (Existing change)		
	SUSCEPTIBILITY (Potential change)		**High (Actively eroding)**	**Moderate (Apparently unchanging)**	**Low (Apparently unchanging)**
1	Coastal lowland	High	(5) Annual to 5 yearly inundation of: riverine floodplains, mudflats, and spits	(4) 5 to 10 yearly inundation of: riverine floodplains, mudflats, and spits	(3) Less frequency than 10 yearly inundation of: riverine floodplains, mudflats, and spits
2	Sandy coast	Moderate	(4) Shoreline retreat greater than 1.0 m/yr. Retreating barrier and cuspate foreland. Less than 20% vegetation cover on barrier	(3) Shoreline change from -1.0 to +1.0 m/yr. Stationary barrier. Between 20% and 80% vegetation cover on barrier	(2) Shoreline advance greater than 1.0 m/yr. Prograded and episodic transgressive barrier. More than 80% vegetation cover on barrier
3	Rocky coast	Low	(3) Weakly lithified rock (calcarenite) cliffs and rocky shore	(2) Soft rock (sandstone) cliffs and rocky shore	(1) Hardrock (granite) cliffs and rocky shore

Estimated ratings for susceptibility and instability of landform in compartment: (1) Low, (2) Low to medium, (3) Medium, (4) Medium to high, (5) High. The potential risks identify areas where more detailed analyses of environmental hazard and risk may be required.

sedimentation. Measures must be taken to protect the coastline and associated economic activities and to plan and manage the coastline in the future. Protection may include plantation and rehabilitation of mangrove ecosystem and institutional strengthening for climate-resilient coastal zone development and planning.

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