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THE MECHANISMS OF COASTAL EROSION IN NORTHEAST BALI

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ABSTRACT

Marine tourism sector in the Northeast Bali, Indonesia, experienced rapid development in the last decades. However, severe coastal erosion in some parts of the area has threaten the industry. Unsuccessful mitigation measures have been carried out by authorities by constructing seawalls along the coastline. The objective of the study is to understand the physical processes related to coastal erosion in the area and to assess the effectiveness of seawall along the coastline. To achieve the objectives, a GIS approach was carried out to investigate general changes of the coastline since 1944 until 2013. Hydrodynamics analyses and sediment transport simulations were also conducted and validated by the data from field measurements. The role of Mount Agung (a volcanic mountain) to the coastal dynamic system was also investigated. Moreover, the data from cGPS measurements in the island were also used for the analysis of possible land subsidence in the area. From social aspects, the history of USAT Liberty Shipwreck in Tulamben Village supports the analyses and provides information on the evolution of coastline in the area. We conclude that coastal erosion in North-east Bali has long been occurred and strongly affected by the dynamics of hydro-oceanography, volcanic activities, geological dynamics, and human interferences. Finally, the mechanism of coastal erosion in the area was also proposed.

Keywords: coastal erosion, volcanic eruptions, bali, seawall, land subsidence.

INTRODUCTION

Bali Island, especially in the Southern part of the island (e.g. Sanur and Kuta Beaches) is one of tourist destinations in the world. The Northern part, however, is by far neglected by tourists due to lack of tourism attractions. The economy of the locals has long been relied on the available natural resources such as agricultures, fisheries, and mining of river-bed sands. In 1980's, the discovery of USAT Liberty shipwreck in Tulamben, Karang Asem has transformed the traditional closed-society of Tulamben into an international open society due to the increase of both local and international tourists. The site of USAT Liberty shipwreck in Tulamben was once declared as the most popular diving site in Bali and in Indonesia by UNWTO (Hasanah, *et al.,* 2013). Moreover, UNWTO also named Tulamben as the number one marine tourism destination in Indonesia. In 2011, the number of tourists in Karang Asem reached 416.363 or 1140 tourist per day. For the diving site of Tulamben, the number of divers reached 100 -150 divers a day (Hasanah *et al.,* 2013). The growing number of tourists in Tulamben has led to the growth of local economy. The statistic in 2002 showed that marine tourism in Tulamben contributes Rp. 29.392 Billion a year (USD 2,5 Mil) to the local government income (known as PAD) or the second after river-bed sand mining industries.

The explosion of Mount Agung Volcano in 1963 provided abundance of high quality sands in the North-east Bali and its surrounding. Since then, river-bed sand mining industries have been the backbone of the local economy for decades. In the 90's, the industries were legalised and modernised (known locally as "Galian C") resulting in a massive exploitation of sands dedicated not only for local consumptions but also for exports to the neighbouring islands. Meanwhile, the

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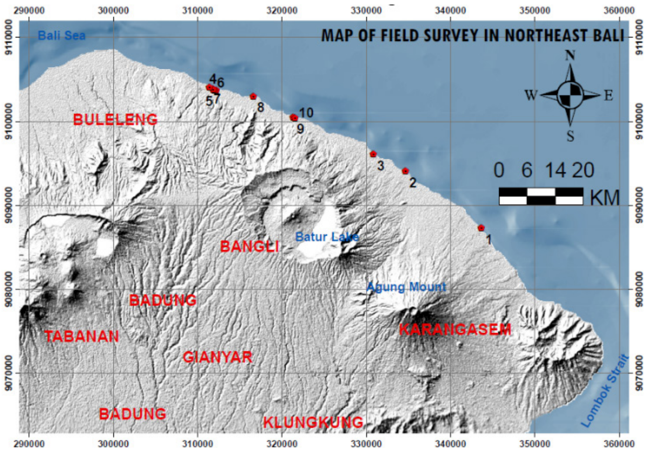

Figure 1. Research location in Bali. Large arrow indicates the location of the shipwreck (USAT Liberty).

locals also observed environmental damage to the environment, i.e. severe coastal erosion along the coastline of Northeast Bali. Continuing coastal erosion in North-eastern Bali, including in the diving site of Bali has threatens the existence of USAT Liberty shipwreck and the tourism industries in the area. The USAT Liberty shipwreck has been threatened to slide down into deeper water due to the gravity and the loss of sands in the beach. Therefore, this paper has an objective to understand the mechanisms and the driving forces of coastal erosion occuring in North-eastern Bali and to provide recommendation for mitigation measures (Figure 1).

METHODOLOGY

The flowchart of general research methodology is shown in Figure 2. Research started with literature review of available data and information on the internet, scientific publications, newspapers, technical reports, etc, to obtain knowledge on the environmental conditions of Northeast Bali such as oceanographic, geology, hydrology and other environmental conditions. Primary data are also needed. Thus data collections have to be carried out by interview and direct field measurements at the location to measure sediment transport, and oceanographic characteristics. Secondary data were also collected such as wind, hydrometeorology, satellite images, and hydro-oceanography of the region from previous reports/ publications. Once the data are all collected, the analyses was first carried out by using GIS tools. GIS technique is very helpful to identify general trends of the coastline over time. Physical processes in coastal area have been investigated by analysing the wave, tide and current data. Wave data are obtained from hindcasting processes of the wind while the tides and currents were measured directly in the field. Hydrodynamic simulations using MIKE21 Flow Model FM-Hydrodynamic Module from DHI was then carried out to see further influence of the currents to the characteristics of coastal oceanography of the region. The governing equations of the model are the continuity equation and momentum equation in -x and -y component, respectively (DHI, 2013):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \quad \text{...(1)}$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial P_a}{\partial x}-\frac{g}{\rho_o}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(V_t\frac{\partial u}{\partial z}\right)+u_s S \quad \text{...(2)}$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial P_a}{\partial y}-\frac{g}{\rho_o}\int_z^\eta \frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(V_t\frac{\partial v}{\partial z}\right)+v_s S \quad \text{...(3)}$$

where: u, v, w: three component of the velocity; x, y, z: space coordinates, S: Magnitude of dischage, P: Pressure, F: Diffusion term, t: time, ρ: density, η: surface elevation, g: gravity

Shoreline changes due longshore transport in Northeast Bali for a long period of time were estimated numerically using a one line model, GENESIS (GENEralize model for SImulating Shorline change) (Hanson, 1989). The bathymetry data used in the model is similar as the one used for hydrodynaimc model with MIKE21. The wave data was estimated from the wind data in the region using the data from the Indonesian Agency for Meteorological, Climatological and Geophysics (or BMKG) from 2004 – 2014. The hindcasting method from the Shore Protection Manual 1984 (USACE, 1984) was implemented to get the wave characteristics in the region for the input of the model. The (D50) was measured from the collected sand samples in the region during the field surveys. The domain model along the coastline of Northeast Bali stretches over 40 km long. Once the analyses completed, the understanding of coastal erosion processes can be made based on the validation of the models to the field findings and measurements. The models can be used to evaluate the alternatives of

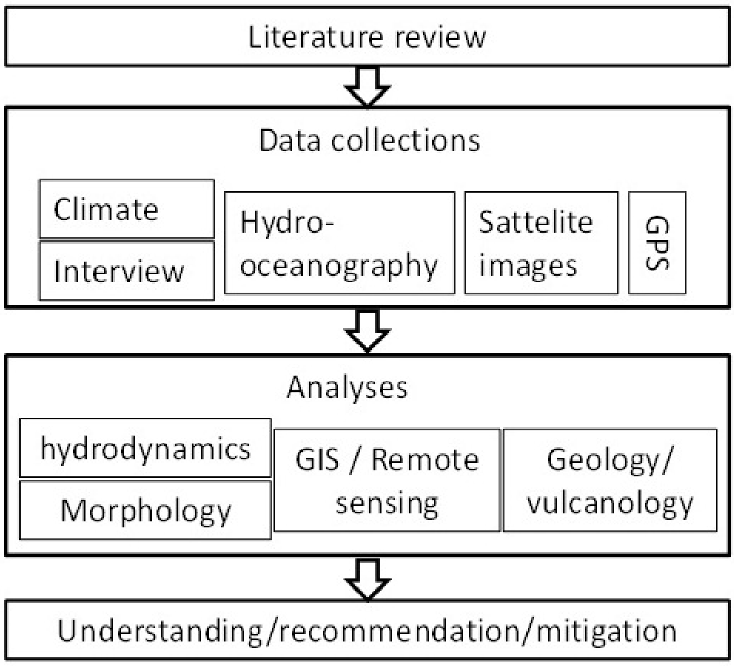

Figure 2. Research methodology.

coastal erosion measures in the region and the USAT Liberty Shipwreck protection systems.

RESULTS AND DISCUSSION

Field observations

Direct observation in the field was carried out to see the latest conditions of the coastline up to 45 km. Interview with the locals provided significant information related to the changes of the coastline over time. Points of observation were selected based on the recommendation of the locals. Generally, the 45 Km of the coastline experience coastal erosion from small degree up to severe conditions. Seawalls have been constructed to protect many public facilities and villages from wave attack during the storm seasons. Stones were almost observed along the coastline as the results from the volcanic eruption. Some of the lands has been lost due to coastal erosion in the last decades. Table 1 shows description of the stations for beach observations. Figure 3 shows some figures of coastline conditions in Northeast Bali.

Based on the information from the locals around the village of Tulamben where the USAT Liberty shipwreck is located, in 1940's there were 10 (ten) coconut trees in the beach with 10 m distance in between. Sands were everywhere and the sandy beach was wide enough. Now, there is only one coconut tree standing and the remaining 9 coconuts trees have gone eroded by the waves. Much of the sands on the beach have also gone. From this information, coastal erosion in the area where USAT Liberty is located has reached ~100 m considering the number of lost coconut trees and the distance between individual coconut trees (9 trees x 10 m = 90 m) and the width of the beach (~10 m).

GIS Analyse

In order to see an overview of coastline changes over time, a GIS analyses was carried based on the data from old map from the US Army 1944 (1:250000) and LANDSAT satellite images from 1972, 1989, 1995, 1997, 2003, 2005, 2009, 2013. There are ten points of validation location similar as the points of field observation. Coastline changes were measured based on the observed changes for each image referring to the initial condition in 1944. We found that the coastal erosion in Northeast Bali has already occurred prior the establishment of river-bed sand mining industries in 1990's. This means, unlike to the conclusion made San-nami *et al.* (2013), river-bed sand mining activities may have small influence to the coastal erosion in the Northeast Bali. There should be other physical aspects significantly contribute to the coastal erosion in the area.

From the GIS analyses, the erosion rate reaches 2 m/year in Station 6 (Desa Tembok II) in which severe erosion was observed from the field survey (Figure 3). In Station 3 where the Pura (Hindu's temple) is located, an accretion was observed. This location actually experiences dynamic conditions and the coastline is now well protected by seawall. Based on field observations, this area experience around 50 m of shoreline erosion from the existing seawall. The

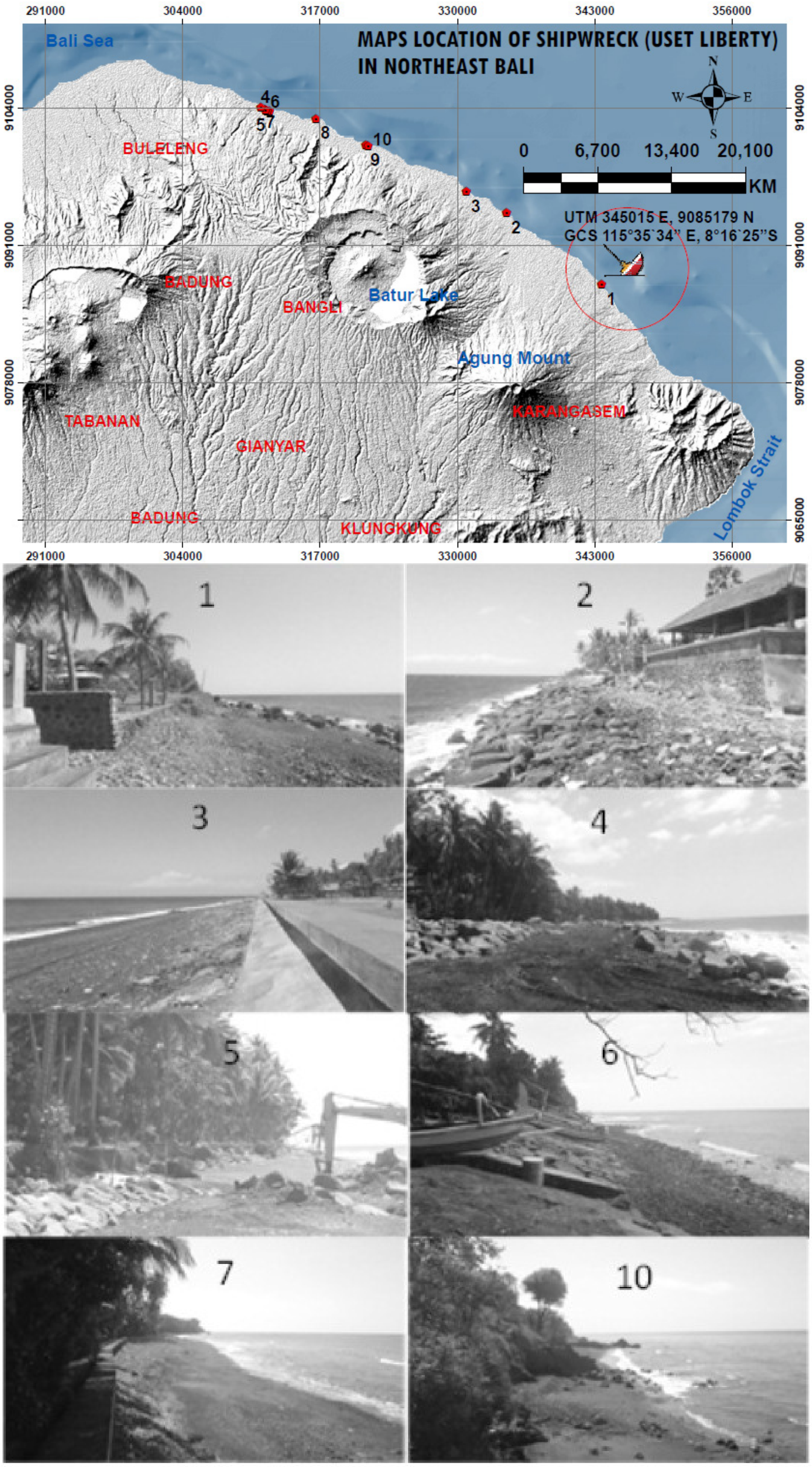

Figure 3. Coastal erosion problems in Northeast Bali from field observations in 2014 (see Table 1).

Table 1. Field observation results

No	Lat. (S)	Long. (E)	Notes
1	08°16'25.7"	115°35'23.5"	Many hotels. The beach behind the hotels was protected by a 1 m sea wall.
2	08°16'23.5"	115°35'29.8"	Many stones, few sands observed, the location of Liberty shipwreck, seawall 1-1,5 m, coastal erosion around 100 m, steep beach slope
3	08°15'07.1"	115°34'37.1"	Pura Dalem, coastal erosion ~50 m, there was a sea wall with concrete. A diving location. The Pura was built when the beach was still wide some 40 years ago.
4	08°11'31.8"	115°29'53.2"	Severe coastal erosion > 100m, milder beach slope than St.02, mixed of stones and sands, a Pura was protected by a 2 m seawall.
5	08°09'27.8"	115°26'29.8"	Severe coastal erosion > 100m, sandy beach with stones, black sands observed, mild beach slope, the construction of new seawall was observed.
6	08°09'26.9"	115°26'24.4"	Severe coastal erosion > 100m, black sand beaches mixed with stones, mild beach slope, seawall construction observed, coconut trees are dominant, Eroded cliff 1 – 2 m observed.
7	08°08'16.1"	115°23'36.5"	Protected by 2 km long of seawall, sands come and go depend on the climate, the beach has lots of stones with steeper slope compare to St. 3 and 4.
8	08°05'20.7"	115°15'56.4"	Cliff beach, corals, black sands, small erosion observed.
9	08°05'37.1"	115°16'18.5"	The location of a Pura located on top of the cliff reinforced concrete. Stone armoured for coastal protection
10	08°05'47.0"	115°16'34.0"	The border between cliff and mild beach slope, protected by 2m high seawall. Black sand with stones, small erosion observed.

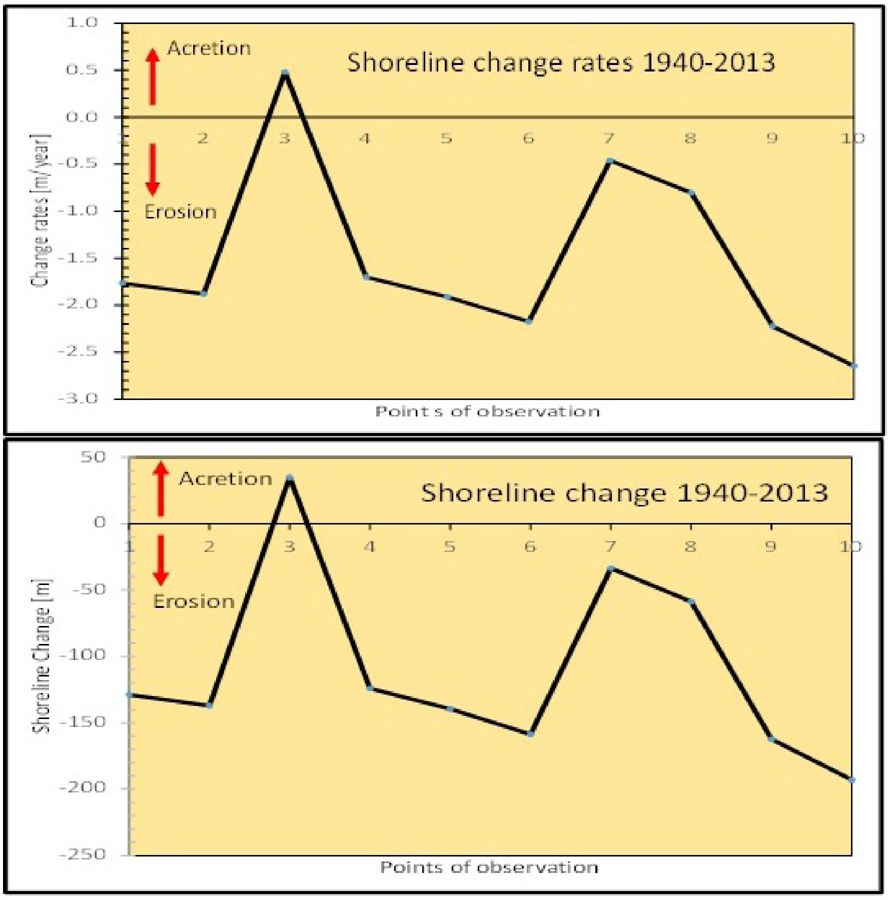

Figure 4. The rate of coastal erosion (m/year) and shoreline changes (m) in Northeast Bali (see Table 1 and Fig. 3 for the points of observation).

coastal erosion observed from the analyses is around 50 - 200 m. The findings confirm the information from the locals that around 100 m of the beach has gone in the last 50 years.

Hydrodynamic Analyse

Current measurement off-shore the Tulamben Village using Aquadopp Acoustic Doppler Current Profiler (ADCP) from Nortek was carried out for 26.9 days started from 29 August 2013 – 25 September 2013 with 10 minutes interval. The scatter plots from water depth 5m, 10m, and 15m show that the currents move generally parallel to the coastline or in Northwest-Southeast directions. In the surface, the current direction is predominantly going Northwest with current velocity reached 0.58 m/s (Figure. 5). In order to understand the characteristics of hydrodynamics in the region, a numerical simulation using MIKE21 was carried out for the duration of the measurement of ADCP. The bathymetry data was obtained from the National Agency of Disaster Mitigation (or BNPB) which has a resolution of 90 m. The simulation confirms the field data measurement with validation error (RMSE) around 4% (Figure 6). Moreover, the simulation results show that surface currents obviously move along the coastline in Northeast-Southeast directions (Figure 7).

Volcanic and geological activities

Volcanic eruption of Mount Agung in 1808, 1821, 1843 and 1963 are believed to play important role in shaping the characteristics of the beach in Tulamben (Volcano Discovery, 2013). The eruptions in 1800's obviously have supplied sands into the beach of Northeast Bali and the surroundings including in Tulamben. In the following years, the volcano erupted once more in 1963 which was eruption till these days. Sands in the beach may have reduced over time naturally or eroded by the waves. In addition to that, the tremor from the volcanic eruptions may also cause the earth to shake and causing the stranded USAT Liberty to slip down into deeper water due to the gravity force (Figure 8). This assumption was also mentioned

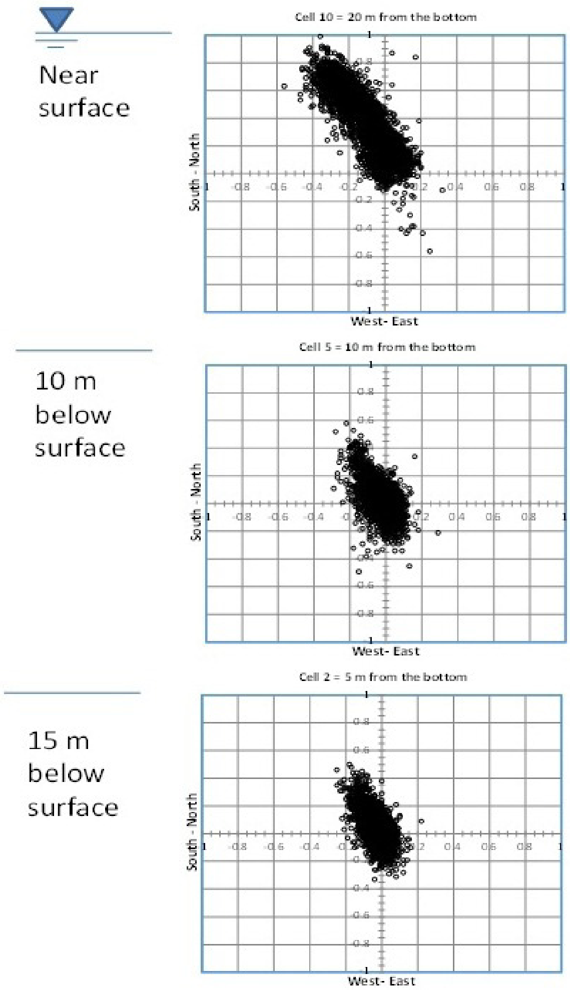

Figure 5. The scatter plots of current based on the ADCP measurement near the site of the shipwreck in Tulamben.

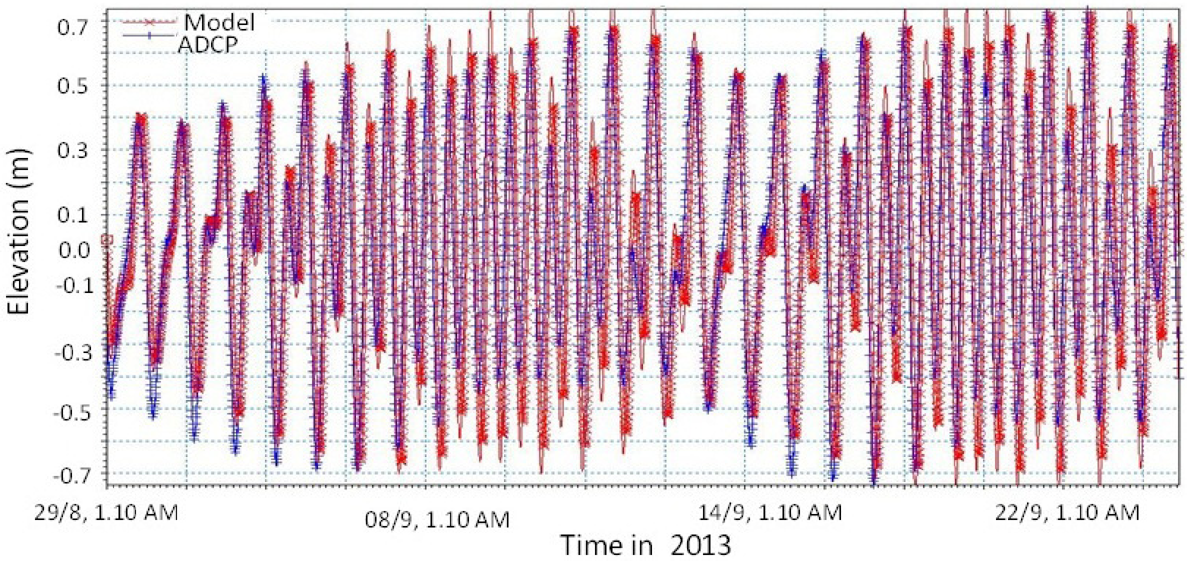

Figure 6. Validation of numerical simulation by the elevation data from the ADCP measurement (RMSE error 4%).

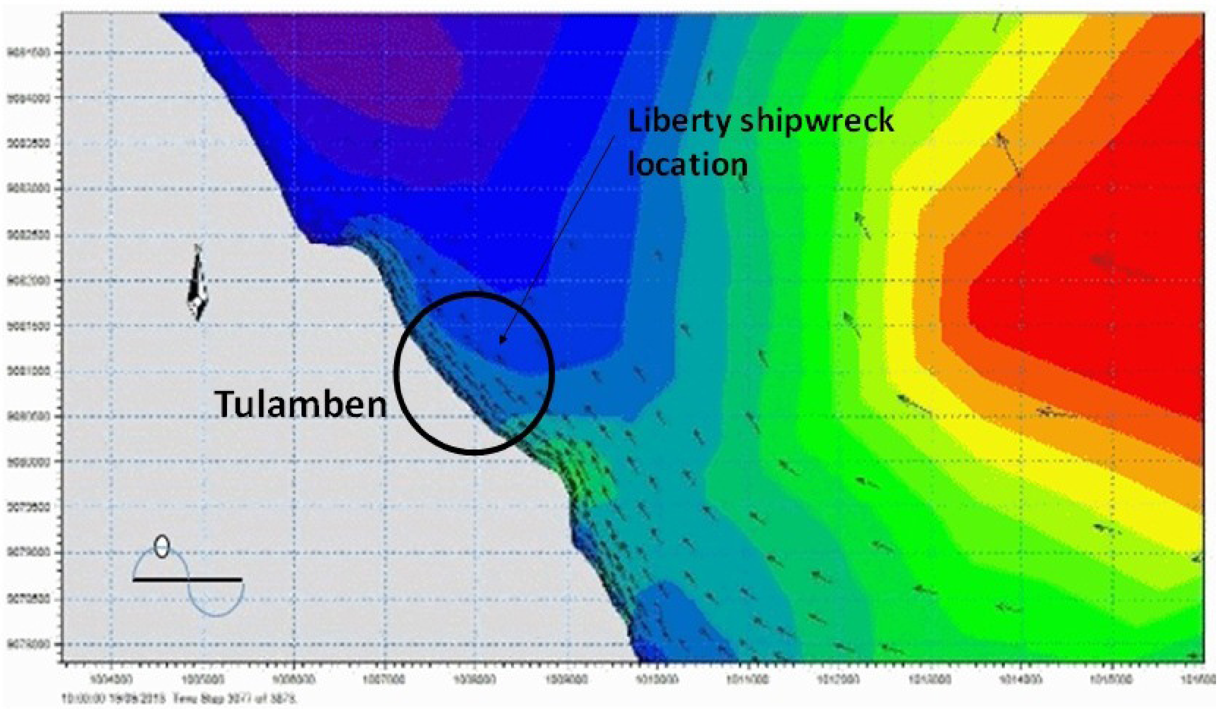

Figure 7. A snapshot of surface current simulation during high tide around the location of Tulamben Shipwreck.

by many locals who believed that the sinking of USAT Liberty shipwreck into deeper water was due to the volcanic eruption of Mount Agung in 1963. However, in 1963 volcanic eruption was not the only natural disaster occurring in the area. In 1963, two large earthquakes (6.9 and 6.1 RS) hit the area and causing severe damage in the region. The earthquakes have bigger change to cause the shipwreck to slide down into deeper water than volcanic eruption. Earthquakes are common in the region due to the existence of subduction zone in the South of Bali and the back-arc in the North of Bali. Land deformation, particularly land subsidence occurring in the area has been triggered by the subduction zone activities in the South of Bali as shown by the data from the latest GPS measurements all over the island (Figure 10). Based on satellite measurement (ALOS – InSAR time series 2007 - 2009), land subsidence of about 12 cm was observed from the Line of Sight (LOS) displacement of the peak of Mt. Agung. (Chaussard & Amelung, 2012) (Figure 9). The effect of land subsidence was clearly play an important role in coastal erosion in the Northeast Bali.

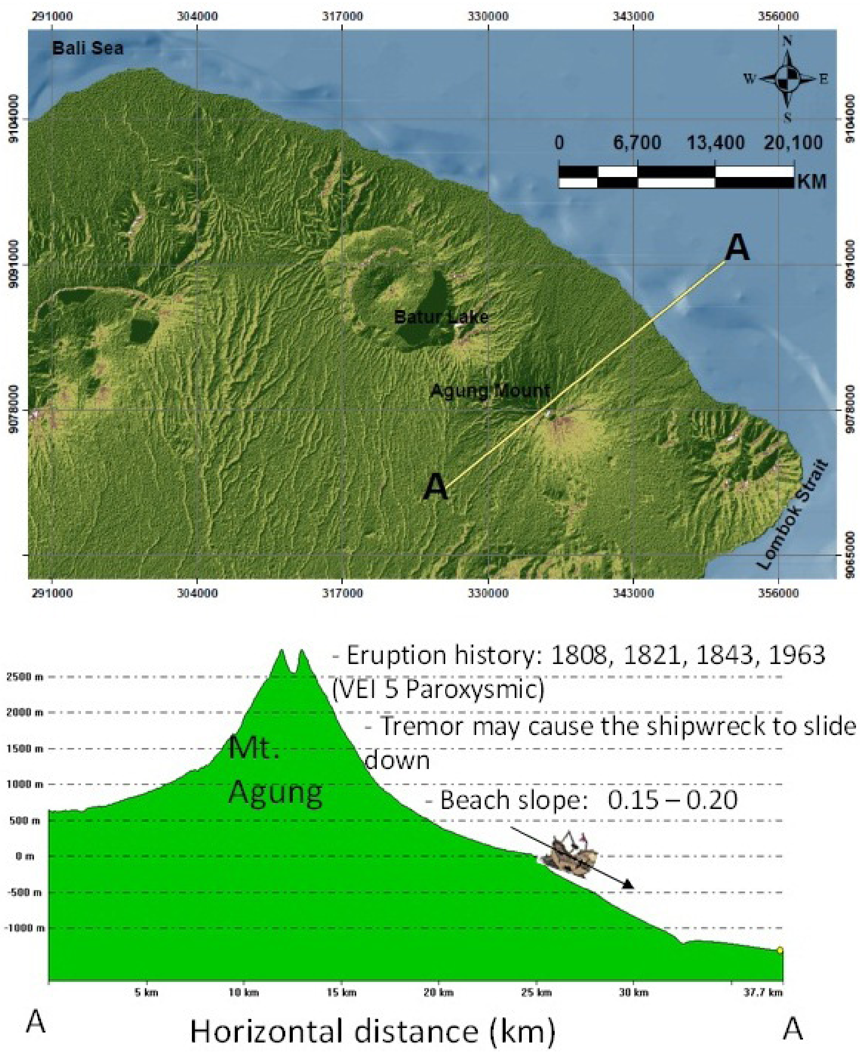

Figure 8. Role Mt. Agung as sand supplier to the beach after the eruptions and to the processes of sliding down of the shipwreck to the deeper water.

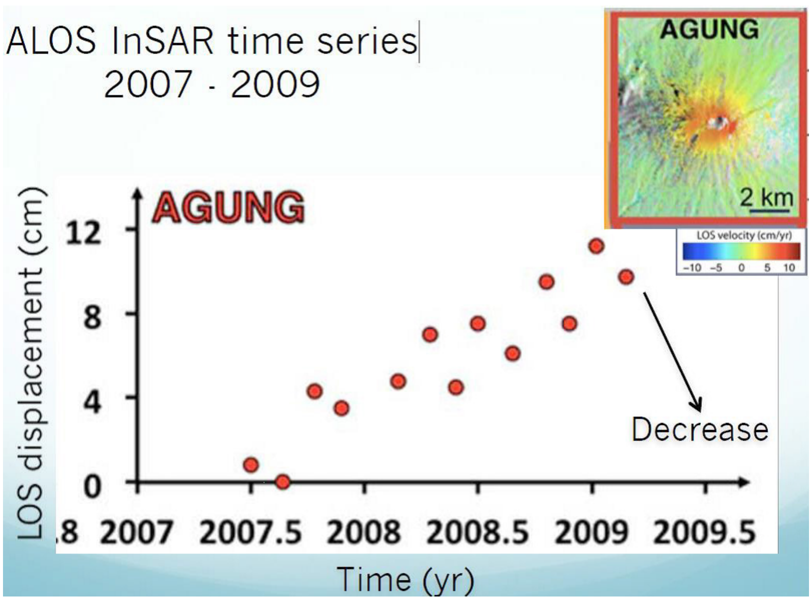

Figure 9. Land subsidence observed from the measurement of LOS displacement of Mt. Agung (Chaussard & Amelung, 2012).

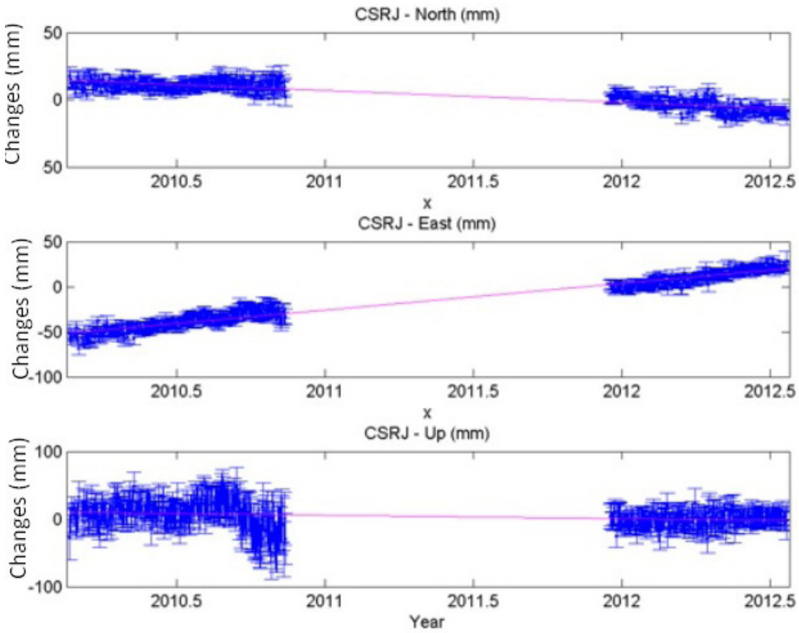

Figure 10. Land deformation and subsidence observed from cGPS measurement in Singaraja (CSRJ).

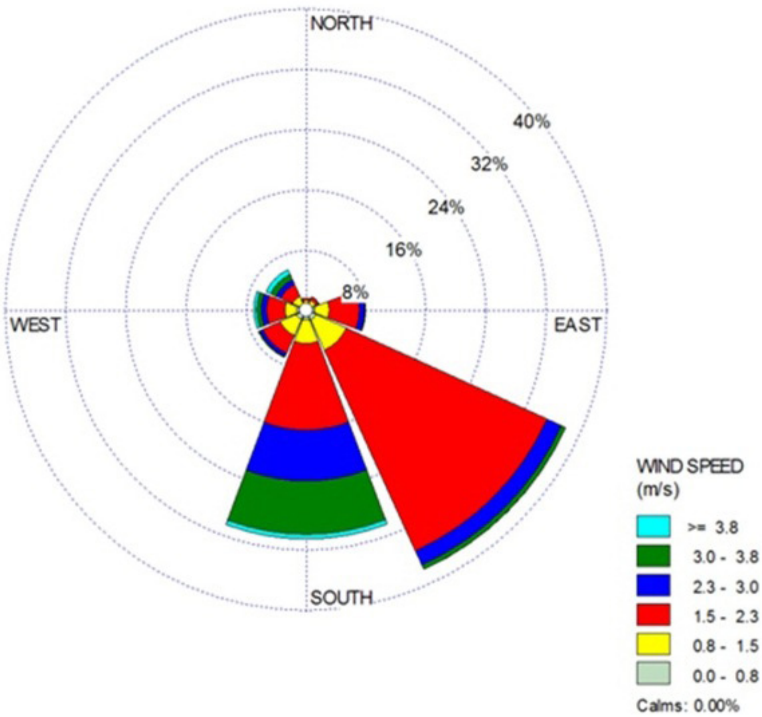

Figure 11. Wind rose in the Northeast Bali (2004 - 2014).

Sediment transport model

One of the key parameter in the simulation of shoreline change is the wave characteristics generated by the wind. Wind in the region is dominated by the wind blowing from the Southeast and from the South (Figure 11). This means the waves are also dominant from the same directions. Prior the simulation, model calibration was carried out by taking series of simulation for smaller model domains from field data. Shoreline data for calibration is from year 1989 (initial condition), while year 2007 was used as the reference of the shoreline (19 years). Model calibration was done by comparing simulated and observed shoreline conditions in 2007 (Satellite data/GIS Analyses). Model calibration parameters K1 = 0.1 & K2 = 0.05 were found to be the most suitable indicated by the smallest relative error. The erosion distance in Tulamben area in 19 years was around 11.98 m or 0.66 m/year. Other model domains based on the field survey were also

Table 2. Simulation results

Stations	Erosion / Acretion distance (m)	Model Sumulation 1989 - 2007 (m/yr)	GIS Analyses (m/yr)	Relative Error (%)
1	-11.98	-0.66	-0.68	3%
2	-6.61	-0.37	-0.37	0%
3	-4.56	-0.25	-0.13	48%
4	-4.98	-0.27	-0.18	33%
5	-3.05	-0.17	-0.13	24%
6	-11.65	-0.65	-0.30	54%
7	-2.12	-0.12	-0.11	8%
8	-7.19	-0.40	-0.40	0%
9	08.62	-0.48	-0.50	4%
10				
Averaged relative error				19%

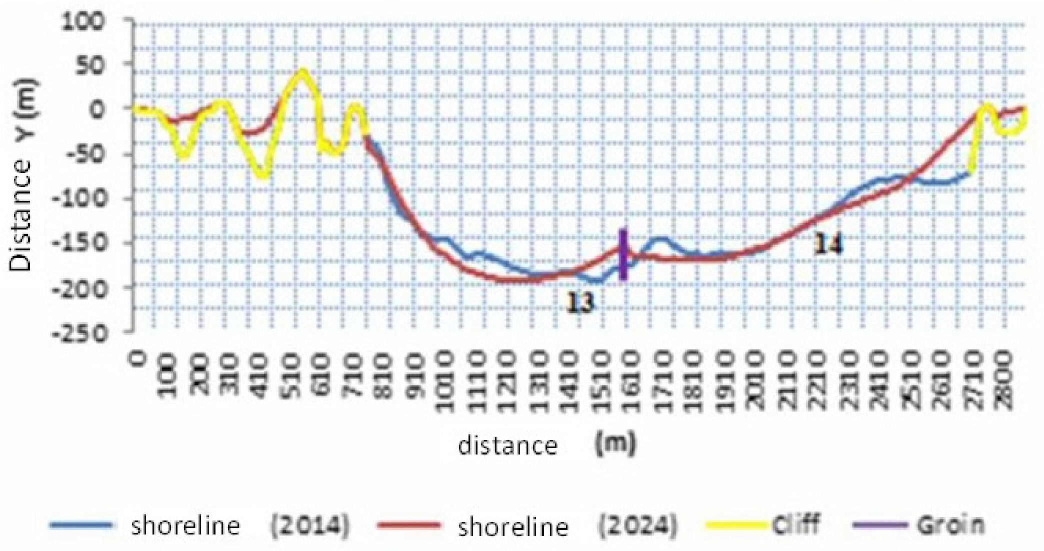

Figure 12. Sediment transport model around the Tulamben.

considered in the calibration processes. The averaged relative error of the model is 19% (Table 2). This result indicates that longshore transport also contributed to the erosion of the coastline in Northeast Bali.

After the calibration, model scenario to see the effectiveness of existing seawalls and other coastal protection system can be carried out for the future, e.g. between year 2014 – 2024 (ten years). Alternatives for better protection systems can also be considered in certain area where residential area (or tourism area) are observed. An example of the simulation for stations around Tulamben (residential area) are described in more detailed in Pratama (2015). The longshore sediment transport coastline around Tulamben was simulated for ten years by the placement of an additional protection in the form of a groin. Since longshore sediment transport is dominant, a groin can provide better protection along the coastline as shown in Figure 12. The area behind the groin experience sedimentation (accretion) up to 20 m after 10 years. Other alternatives can also be considered for the simulation such as beach fills. However, the alternatives shown in the simulation did not consider socio-economic aspects of the locals which is very important in the implementation processes of any measures.

The mechanism of coastal erosion

From the discussion above, coastal erosion in the Northeaster Bali seems to be part of a cycle or beach cycle evolution. The existance of Liberty shipwreck in Tulamben village helped the analses by providing significant clues since the ship was stranded in 1940's. Four aspects may have contributed to the cycle of Tulamben beach. They are hydrodynamic characteristics (wave and currents), volcanic eruptions, land subsidence and human intervention (sand mining activities). Sand mining activities from the riverbeds in

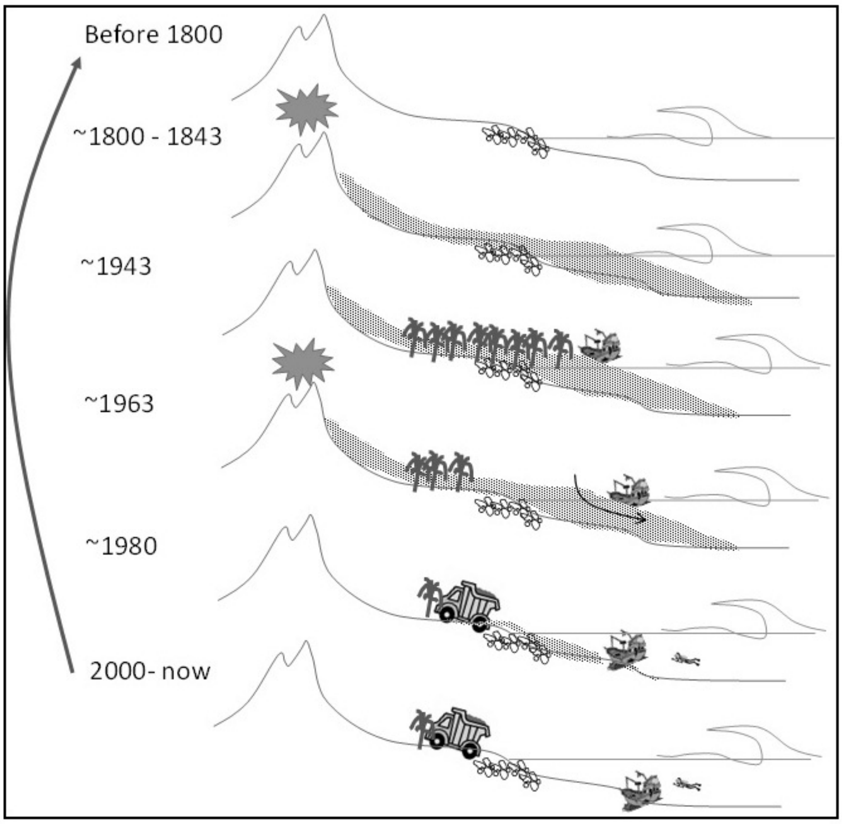

Figure 12. The mechanism of coastal erosion in Northeast Bali.

the region however were difficult to measure because there were hardly any data to estimate the amount of sands taken in certain time. By considering those aspects, the cycle of Tulamben beach can be explained as follows (Figure 13):

- Stage 1: Shingle beach of Tulamben (pebbles). This is the initial condition of the beach in Tulamben. There was no sands. This situation might have seen in early 1800's.
- Stage 2: Eruptions of Mt. Agung covered the beach with sands. This situation occurred between 1800-1843 where Mount Agung erupted three times. Wide beach was observed along the coastline.
- Stage 3: In 1943, USAT Liberty stranded in sandy beach of Tulamben, 10 coconut trees observed by the locals
- Stage 4: Between 1943 – 1963, currents, coastal erosion, volcanic tremor, earthquakes and land subsidence slided down the wreck into deeper water. Mount Agung erupted again. Some coconut trees may have already gone.
- Stage 5: in 1980's, Mining activities started, sands keep disappearing, diving activities started. Waves and currents keep eroding the beach.
- Stage 6: In 1990's, Large scale mining activities started and diving industry is getting bigger. Sands in the beach has gone and leaving pebbles in the beach or the situation has returned to its original condition in 1800's. Land subsidence in the region and sand mining in the riverbed may accelerate the coastal erosion.

CONCLUSION

Some important aspects related to coastal erosion in Northeast Bali and the existence of the diving site in Tulamben (USAT Liberty) can be drawn as follows:

- Coastal erosions in the region has long been naturally occurred. From GIS analysis, coastal erosion reaches up to ~2.5 m/year or ~200 m since 1940. For similar timeframe, the GIS and numerical analyses are in agreement. The 10-year numerical simulation shows coastal erosion reach 0.68 m/year or almost 12 m for 10 years.
- The existence of shipwreck provided valuable information for the study of coastal erosion in the region.
- Hydro-meteorology, geology, volcanic and topographic conditions play important role on the cycle of Tulamben beach. However, the most significant parameter still needs further investigations.
- Human activities speed-up the erosion along the coastline
- Other alternatives for coastal protection other than seawalls are possible for future mitigation purposes

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