Salt marshes, as coastal defense systems against climate change

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Abstract

Salt marshes and tidal flats are present in the intertidal zone and are bordered by the dyke at the landward side and by low-tide at the seaside. Tidal flats are largely muddy and sandy areas that are inundated by the tide. Whereas, the salt marsh sites are sited at the higher intertidal zone and inundated less than tidal flat. Given their wave-damping capacity, salt marshes are becoming a crucial factor as coastal protection against long-term extreme weather conditions such as storms, tsunami, etc. Therefore, in this paper, the protective value of salt marsh sites is studied by analyzing short-term (5 years) datasets including grain size, water-levels, bed level changes and significant wave heights. To obtain those datasets, novel SED-sensors and wave gauge have been applied. Four research sites in Westerschelde estuary, in the Netherlands are researched. By combining the acquired datasets, the mean value and fluctuation of bed level change and significant wave height of tidal flats and salt marsh, could be studied in each season and during each extreme stormy period. Furthermore, the transition of significant wave height in each station on each site are analyzed. So, wave attenuation effect on tidal flat and salt marsh sites are compared on different circumstances. Moreover, various studies are reviewed on the more extreme hydrological natural events that would occur in coming years due to climate change and used to extrapolate the findings retrieved from the datasets to the coming years.

1. Introduction

A variety of studies showed that salt marshes provide vital ecosystem services in the coastal area (Balke, et al, 2015) and it plays an important part of coastal protection measures (Temmerman, et al, 2013) as a final terrestrial frontier facing the tidal flat. Furthermore, salt marshes can store a large amount of carbon. In recent years, the importance of salt marshes for a coastal ecosystem is becoming more prominent (Balke, et al, 2015). In this paper, the impact of salt marsh as a coastal protection strategy is the focus.

Historically, coastal protections have relied on hardened infrastructures such as dykes, sea walls, jetties, and groins, etc. (Christine, et al, 2011). However, conventional coastal defense measures are challenges due to the continual and costly maintenance fee. Furthermore, height and width of these measures have to be increased as flood risk and sea-level are becoming increased due to climate change (Temmerman, et al, 2013). In addition, after the two huge natural disasters such as the Indian Ocean tsunami and Hurricane Katrina, the interest of an ecosystem-based natural flood protection system has been increased (Christine, et al, 2011). On top of this, unpredictable extreme natural disaster would occur due to climate change and it would pose more threats to our society in the future. Therefore, the long-term investigation of salt marsh datasets along the coastal line is important to take actions against increasing natural disasters such as storms, hurricanes, etc. Therefore, highly tidal bed-level change research datasets on salt marsh areas are necessary to understand intertidal ecosystem development. But the present datasets are scarce due to excessive labor and cost. Therefore, a new sensor(see Figure 1) has been developed which is called Surface Elevation Dynamic Sensors (SED-sensors).

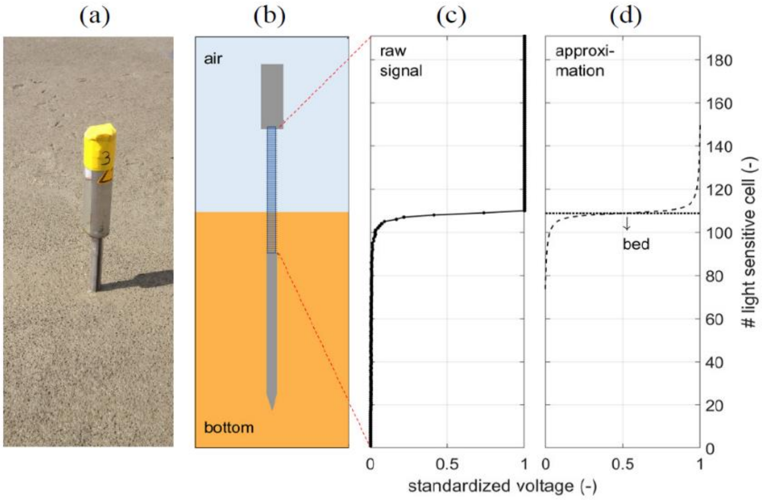

Figure 1 (a) represents picture of a SED-sensor, (b) represents schematization of a SED-sensor, (c) represents raw voltage signal from a SED-sensor and (d) represents voltage signal without noise

By applying this novel method, short-term(5 years) high-resolution daily bed-level change datasets are obtained from 2013 to 2017 in 10 salt marsh sites in the Netherlands, Belgium and British by the research team (by Zhan Hu, Pim W.J.M. Willemsen, Bas W. Borsje,..); (Zhan, et al, 2020). The salt marsh sites located in Westerschelde, Netherlands are analyzed and those datasets can be found in (https://doi.org/10.4121/uuid:4830dbc2-84b8-46f9-99a3-90j9jf01ab5b923). In this paper, the important role of salt marsh as a coastal buffer is studied and the relation between bed level change and wave height is the main focus of this study.

1.1 Description of system

The effect of salt marsh sites is analyzed based on given bed level change and significant wave height datasets. In order to analyze and determine the datasets, the bed level change and significant wave height datasets on tidal flat sites are compared. Further, the conventional coastal protection infrastructures such as dykes are studied to investigate the additional effect of salt marsh sites as coastal protection measure. Thus, coastal system (Figure 2) and conventional measures are described.

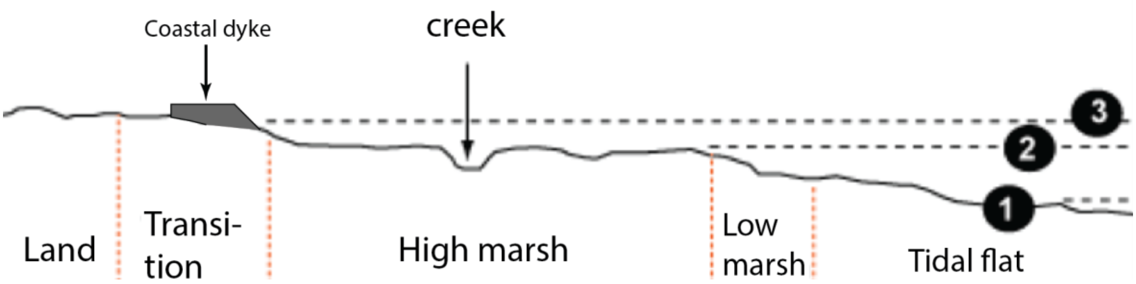

Figure 2 Topography of a salt marsh. 1. Normal low water 2. Normal high water 3. High water springs

1.1.1 Salt marsh definition

Salt marsh sites are located throughout the world. For the research, the salt marsh sites which exist in Westerschelde, the Netherlands are studied.

Salt marshes are coastal wetlands (Figure 4) that are flooded and drained by salt water brought in by the tides and these are intertidal halophytic vegetation distributed in mid to lower latitudes (National Ocean Services, 2019; Banerjee, 2017) and these are found in high tide and near-shore sublittoral zones along the coastlines (Vernberg, John, 1993). Also, the seawater periodically floods on marsh sites and the fine-grained sediments are deposited on salt marsh sites (Alma, Willem, 2013). Based on this process and principal, the valuable salt marsh sites are created. In addition, salt marsh sites provide species diversity, habitat to fauna, and fishes (Mariotti, 2010). Plants are a vital component of the salt marsh ecosystems (Figure 3).

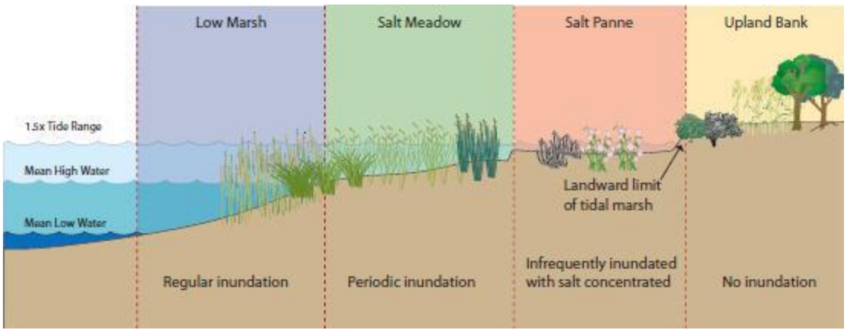

Figure 3 Plants for Salt Marshes and Upland Banks (Center for Coastal Resources Management, 2017)

Plants in salt marsh ecosystem have adapted to live in brackish and these plants have adapted in constantly changing water levels. Also, salt marsh provides the abundant habitat of various species of animals, especially invertebrates such as crabs, mussels, and oysters. And salt marsh serves habitats for fishes. In addition, by increasing the interests in natural or ecosystem-based coastal protection, salt marshes are seen as a coastal buffer (Christine, et al, 2011). Further, the plants reduce flow velocity and wave height, so that fine-grained sediment can be settled (Alma, Willem, 2013). Therefore, salt marsh sites are the crucial parts of coastline systems for coastal protection and natural development.

Figure 4 the salt marsh site in Westerschelde estuary, Netherlands (Glovanni, 2001)

1.1.2 Tidal flat definition

Tidal flats (Figure 5) are the transition between subaerial and submarine environment (Flemming, 2003). Tidal flat is important not only for environmental circulation, transformation, and conservation (Barranguet, 1997) but also for the coastal protection and flood defense (Reise, 2001). Tidal flats exist widely in the world coastlines and it plays an important role as a part of coastal wetlands (Amos, 1995). Tidal flats are normally formed in the area where the fine-grained sediment (e.g., clay, silts, and fine sands) are sufficiently supplied (Rechard, Davis, 1985).

Generally, two conditions are needed to form tidal flats. The first condition is being satisfied with all coastal environments: fully delivered fine-grained by rivers and discharged into the estuary and coastal sites, etc. The second condition is whether or not the fine-grained sediment will be accumulated in the tidal flat area. Mainly, three factors are influence these conditions (Shu Gao, 1995). Firstly, the tidal action should be significant. The tidal can be classified by the average tidal range(R). The tidal flat can be micro-tidal($R<2m$), meso-tidal($R=2-4m$), or macro-tidal(R>4m) (Davies, et al, 1964). Secondly, the wave action should not affect dominantly, even if the tidal range is large (George, 1985). Finally, storms can significantly modify the tidal environment (Ren, Zhang, Yang, 1985).

Figure 5 Tidal flats at Westerhever, schleswig-Holstein Wadden sea

1.1.3 Coastline dyke definition

The coastlines have environmental and economical valuable assets. However, coastlines are threatened by natural and anthropogenic factors. (Thai, 2019). Therefore, the conventional coastal protection structures are designed (e.g. coastal dykes, breakwaters, and sea walls) to protect the coastlines against storms (Figure 6), and these structures should be enough to withstand the natural disaster such as storms (Kazutaka, et al, 2016). However, hydrological structures only perform their functions well when the structures are constructed strong enough (Ravindra, et al, 2015). However, as the sea level rise thousand kilometers of European coastal dykes will be exposed to the waves with higher and stronger than the original designed plan. Therefore, reinforcement will be inevitable for the origin coastal dykes (Ravindra, et al, 2015).

Figure 6 The Sea dyke called Hondsbossche Zeewering, Netherlands

1.2 Salt marsh as a coastal protection service

As mentioned above, coastal salt marshes provide vital benefits to humans known as "ecosystem services" and it plays a very important role as a buffer in coastal line against storms, hurricanes, and tsunamis.

Historically, coastal line faces a variety of natural hazards (Christine, et al, 2011) and it is protected by hardened infrastructures such as sea walls, jetties, etc. However, these defense systems are challenged due to their continual and costly maintenance as well as their reinforcement (heightening and widening) to keep up with the increasing flood risk and sea-level rise. Contrary to conventional measures, flood protection by ecosystem can provide more sustainable, cost-effective and ecological alternatives (Temmerman, et al, 2013). Furthermore, after two huge natural disasters (Ocean tsunami and Hurricane Katrina), the interest of natural and ecosystem-based coastal protections are strongly increased (Christine, et al, 2011). Besides, according to researches, the salt marshes have significant positive effects on wave attenuation, shoreline stabilization and floodwater attenuation (Christine, et al, 2011).

2. Datasets

2.1 Data description

As described above, the important role of the salt marshes is recognized. To understand this intertidal ecosystem, high-frequency long-term research datasets in terms of bed-level change in salt marsh sites are needed. However, historically only a small number of these ecosystem-based researches have done since there have not been suitable methods to obtain dataset which is not expensive and excessive labor (Robert, et al, 2011). Therefore, a novel instrument is developed which is called Surface Elevation Dynamics sensors (SED-sensors). By using Surface Elevation Dynamics sensors (SED-sensors), high-resolution daily bed-level change data sets in each observation sites are obtained((Zhan, et al, 2020); 4TU Centre for Research Data) and this method reduces unit cost and labor cost. As measuring of this method depends on daylight, the sea-level change datasets are acquired only in the daytime during low tide. When SED-sensors are submerged during high tide, the data cannot be obtained (Willemsen, et al, 2018). On top of bed level change datasets, the significant wave heights on research sites are recorded. The significant wave height datasets are obtained using wave gauge from November 2014 to January 2017 (Zhan, et al, 2020).

Short-term (5 years) daily bed-level changes are monitored in 10 different marsh areas are observed by a research team (Figure 7). Collected data are obtained in the period 2013-2017 from 10 salt marsh sites in the Netherlands (Westerschelde and Wadden Sea), Belgium (Zeeschelde) and Britain (Thames and Humber Estuary). 7 sites from Netherlands, 1 site from Belgium and 2 sites from Britain (Belliard, et al, 2019). However, in this paper, only 4 marsh sites located in Westerschelde estuary, in the Netherlands are researched. And those collected SED-sensors datasets could be checked in 4TU Centre (https://doi.org/10.4121/uuid:4830dbc2-84b8-46f9-99a3-90f01ab5b923). In addition, the significant wave height and other datasets could be acquired in 4TU centre for Research Data as well. The bed-level change datasets are provided with synchronized hydrodynamic data such as water level, wave height, tidal current velocity, and medium grain size.

The Westerschelde estuary (51° 20'N; 4°E) is located in the southwestern delta of the Netherlands (Willemsen, et al, 2018). The prevailing wind direction is from the southwest. And it is measured by KNMI which is Dutch Royal Meteorological Institute.

As shown in Table 1, 6 sites in Westerschelde estuary, Netherlands have different tidal range, wave height mean, vegetation characteristics and sediment grain size. Multiple SED-sensors and wave gauges are set in each site to measure bed-level change and significant wave height. Real Time Kinematic Global Positioning System (RTK-GPS) is used to get the coordinates of sensors.

Table 1 acquired dataset in the Westerschelde estuary using SED-sensors and other methods

Country	Site name/ estuary	Latitude/longitude	SED sensor time period	D50 mean and [spatial variations] (μm)	Tidal range (m)	Significant wave height mean and [standard deviation] (cm)	SED-sensor deployments relative to the marsh edge (m)[a]	Vegetation species	Bio-physical measurements[b]
NL	1. Zuidgors A/ Westerschelde	51°23'15.61"N, 3°49'43.46"E	2013.10-2015.1	72.1 [23.4-202.1]	4.3	8 [8]	15, 64, 109, 150, 233, 308, 329, 346, 379	*Spartina anglica*, *Salicornia spp*	D_{50}, Hs, WL, Vel
	2. Zuidgors B/ Westerschelde	51°23'21.95"N, 3°50'7.51"E	2015.9-2016.9	[23.4-48.8]	4.3	8 [8]	-20, -.5, 5, 25, 60, 100, 155	*Spartina anglica*, *Salicornia spp*	D_{50}, chl-a
	3. Baarland/ Westerschelde	51°23"49.56"N, 3°52'51.63"E	2013.10-2015.1	26.8 [12.9-49.4]	4.1	1 [1]	12, 29, 38	*Spartina anglica*, *Salicornia spp*	D_{50}, Hs, WL, Vel
	4. Zimmerman/ Westerschelde	51°24'8.05"N, 4°10'32.15"E	2015.1-2016.5	[66.7-99.5]	4.9	10 [7]	-50, -15, -5, 5	*Spartina anglica*, *Salicornia spp*	D_{50}, Hs, WL
	5. Paulina/ Westerschelde	51°20'59.73"N, 3°43'3.37"	2014.12-2015.8	[27-42.4]	4.1	5 [3][c]	-42.5, -25.5, -17.5, -2.5, 22.5, 47.5, 127.5	*Spartina anglica*, *Salicornia spp*	D_{50}, chl-a
	6. Hellegat/ Westerschelde	51°21'59.33"N, 3°56'44.67"E	2015.1-2016.5	[113.4-131.8]	4.2	11 [8]	-50, -15, -5, 5	*Spartina anglica*, *Salicornia spp*	D_{50}, Hs, WL

The given dataset files comprise with coordinates of observation stations, observed bed level over each tidal cycle (cm, starting from 0), SED-sensors elevations measured by RTK-GPS over time (NAP in m), D50 at each SED-sensors stations over time (D50 in μm), tidal current velocity data from stations, water level data very 15 mins (in m and reference to NAP), significant wave height data very 15 mins (in m) and peak wave period data very 15 mins (in s).

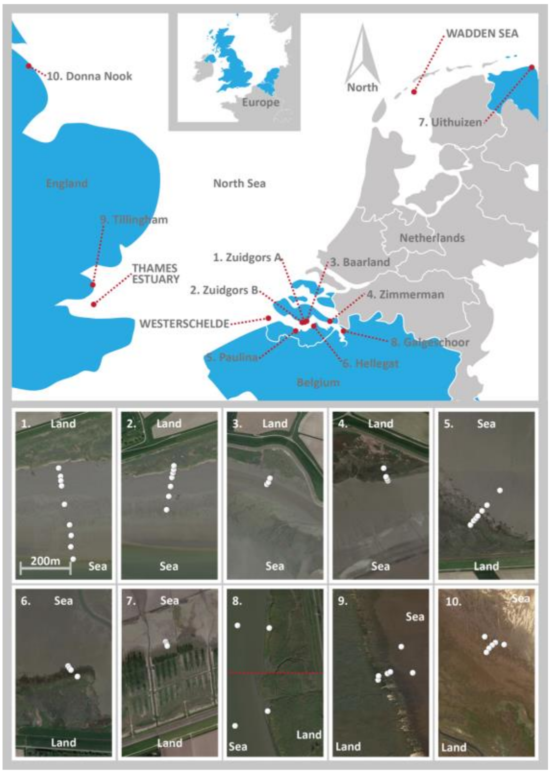

Figure 7 Locations of 10 observation sites in Netherlands, Belgium, and United Kingdom (Zhan, et al, 2020)

2.2 Given datasets

In order to study the bed level change data, datasets at site 2, 4, 5, and 6 are analyzed since there is only tidal flat's bed level change datasets at site 1 and 3.

Datasets only at site 4 and 6 are used to study significant wave height in salt marsh site. Since there are no wave height datasets at site 2 and 5. Besides, only tidal flat sites' datasets are analyzed at site 1 and 3 as the SED-sensors were set only in tidal flat sites. Thus, datasets site 4 and 6 are used to study significant wave height on tidal flat and salt marsh sites.

Therefore, given datasets at site 2, 4, 5, and 6 are chosen to study bed level change and site 4 and 6 are chosen to study significant wave height on tidal flat and salt marsh sites.

Table 2 Location of stations in salt marsh and tidal flat areas.

	Stations in tidal flat(distance from edge, m)	Stations in salt marsh(distance from edge, m)
Site 2	3(6.05), 4(25.60), 5(60.94), 6(99.65), 7(155.98)	1(19.66), 2(5.37)
Site 4	4(5)	1(49.66),2(14.65),3(4.74)
Site 5	5(22.08), 6(48.29), 7(128.41)	1(42.27), 2(25.56), 3(18.09), 4(2.50)
Site 6	4(4.58)	1(51.15),2(14.85),3(5.6)

2.2.1 Bed level change datasets analysis

The common bed level change observation period of site 4 and 6 is from Jan-2015 to May-2016. And from Sep-2015 to Sep-2016 and from Dec-2014 to Aug-2015 for site 2 and 5 respectively. And below Figure 8 shows the bed level and bed level change of tidal flats and salt marsh sites.

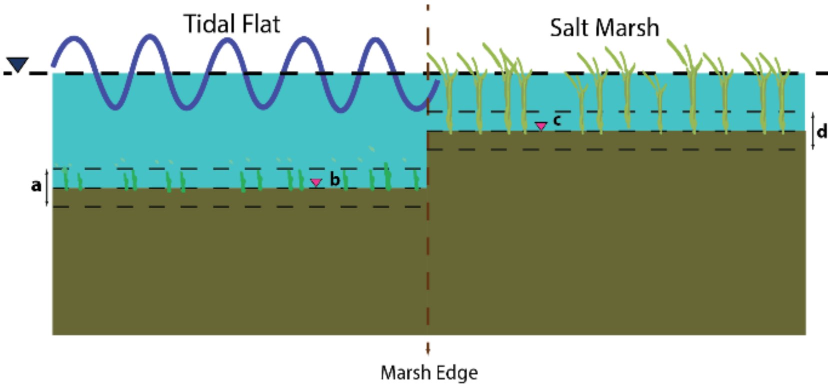

Figure 8 Schematic of the coastal basin, a) tidal flat bed level change, b) tidal flat bed level, c) salt marsh bed level, and d) salt marsh bed level change

In this research, the standard deviation values of bed level change datasets are calculated to determine the extent of fluctuation of bed level change. So, the bigger standard deviation value means the bigger fluctuation in the sites. As can be seen in below bar charts (Figure 9), except site 4, most sites show the tendency that the average standard value of all seasons and storm periods in salt marsh site are less than the tidal flat sites.

When site 4 is compared to the site 2 and 5, the biggest difference is the grain size (Table 3). The grain size in tidal flat of site 4 is more than twice bigger than site 3 and 5 in the year of 2015.

Table 3 Average grain size(d50 in µm) in tidal flat sites at site 2, 4, and 5

	Site 2	Site 4	Site 5
Average grain size in tidal flat(d50 in µm)	39.23	92	38.22

This means the tidal flat sites are more vulnerable in erosion due to waves than the salt marsh sites on the same grain size circumstances.

The standard deviation value of bed level in salt marsh sites is more stable in all seasons and during storms but contrary to salt marsh sites standard deviation in tidal flat sites is more fluctuated and bigger (see Figure 9). This shows the bed level change tendency in salt marsh sites are less affected by the circumstance such as weather than tidal flat sites.

However, the below graphs (Figure 9) show that salt marsh sites have a bigger standard deviation value than tidal flat sites during the most of stormy periods. Therefore, it can be concluded that the salt marsh sites are likely more erode than tidal flat sites during the stormy period. And the average bed level change in each season does not show any correlations. Also, the mean value of bed level change does not show any relation neither (See Figure 16 in Appendix 7.1)

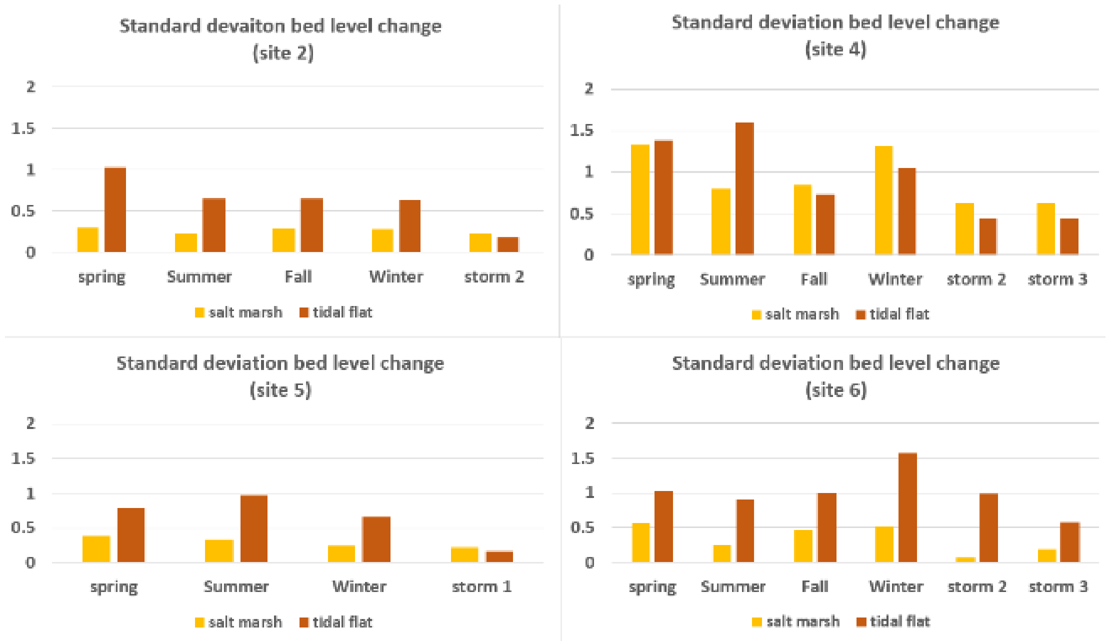

Figure 9 Bar chart of standard deviation bed level change data at site 2,4,5,6

The more detailed observed and analyzed data can be found in Appendix 7.1

2.2.2 Significant wave height datasets analysis

Wave attenuation is a crucial function of salt marsh and tidal flat sites. The significant wave height is significantly decreased in tidal flat and salt marsh sites (Figure 10). Therefore, in this section, the wave attenuation in both sites(4 and 6) are studied by analyzing the given datasets.

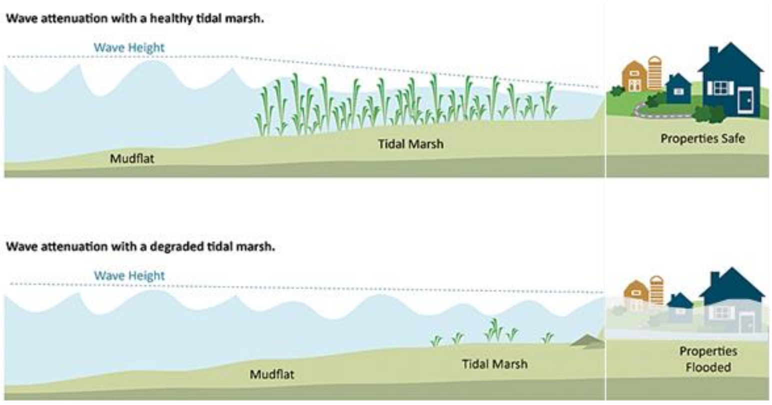

Figure 10 Wave attenuation with a healthy tidal marsh (Governor's office of storm recovery, 2016)

Datasets in site 4 and 6 are analyzed to study the protective value of salt marsh sites by attenuating the wave. The significant wave height data in site 4 and 6 are analyzed to study wave attenuating in salt marsh and tidal flat sites together. By using the given datasets, significant wave height change tendency in each season and storm surge periods are analyzed.

The observation period in site 4 and 6 is from Jan-2015 to May-2016 and the significant wave height datasets are collected on tidal flat and salt marsh sites. The first below graph shows that the mean wave height in salt marsh site is less than the mean wave height in tidal flat sites. Besides, wave height transition per m at salt marsh sites is bigger than tidal flat sites, except the autumn season. Therefore, the wave attenuation effect on salt marsh sites is more effective than the effect on tidal flat sites. Especially, as shown in Figure 12, the effectiveness of wave attenuation in salt marsh sites are between 1.5 to 6.5 times bigger than tidal flat sites during the stormy periods. Therefore, salt marsh as coastal protection in the extreme condition is more effective than during non-extreme condition.

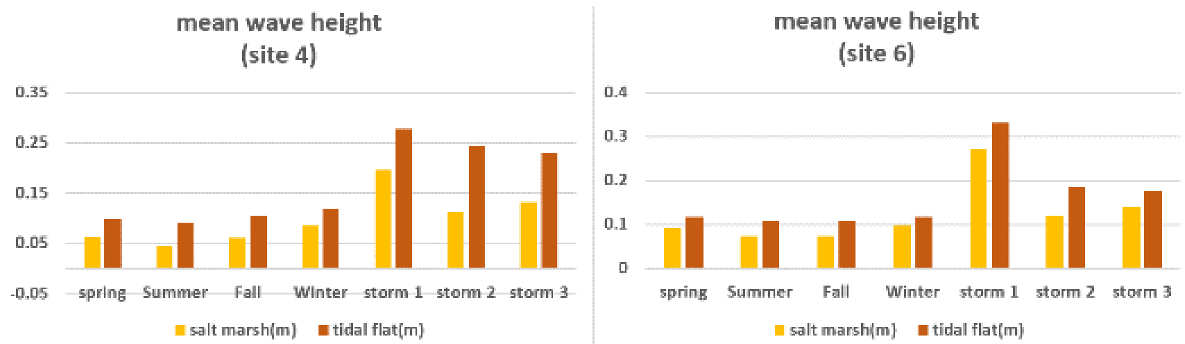

Figure 11 mean wave height at site 4,6

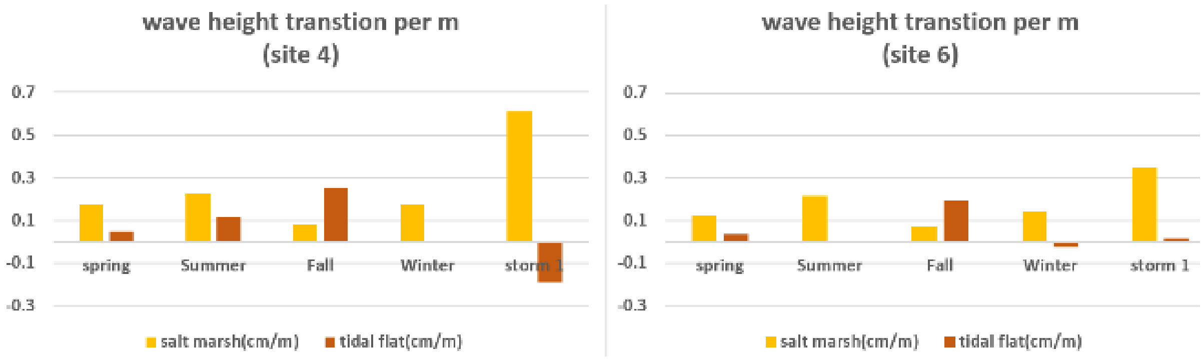

Figure 12 wave height transition per m at site 4,6

Detailed acquired and analyzed data can be seen in Appendix 7.2

3. Increasing natural hazards(Hydrological) due to climate change in the future

Due to various reasons, more extreme weather events are going to occur in the future. Most likely, the intensity and frequency of extreme natural events will be changed due to climate change (Sandra, et al, 2014). Additionally, human has a huge impact on climate change (IPCC, 2013). Especially, as shown in figure 13, global warming is clearly in evidence in Europe. Annual, summer, and winter temperatures are increasing with an average 0.95℃ rise since 1900 (EEA, 2004). Thus, evidence of global warming seems solid. Because of this temperature rising, Hurricanes may be getting more frequent and intense (Jason, Camilla, 2005)

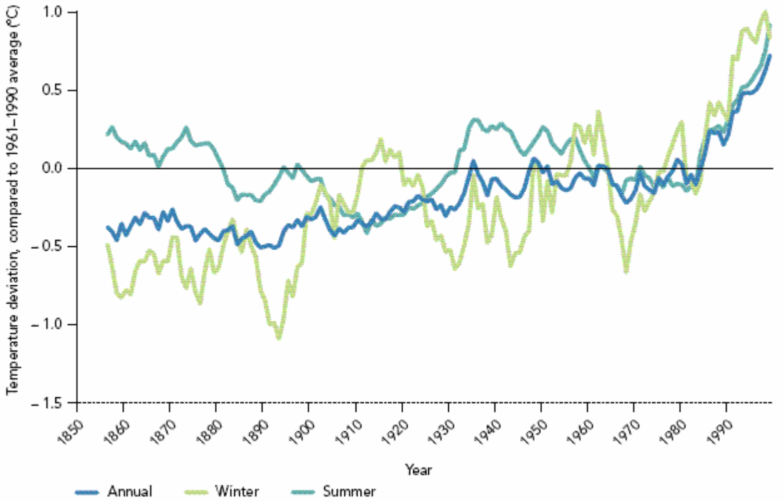

Figure 13 Mean annual, winter, and summer temperature in Europe since 1855 (EEA, 2004)

The frequency of natural disasters recorded in the Emergency Events Database (CRED, 2020) has soared in the last four decades. As shown in below Figure 14, especially hydrological (floods, storms, hurricanes, droughts, and other hydrologic threats) and meteorological (extreme heat and cold, ice or snow, etc.) natural events have sharply increased. Furthermore, the number of people who are affected by these natural events has been increased (Jason, Camilla, 2005)

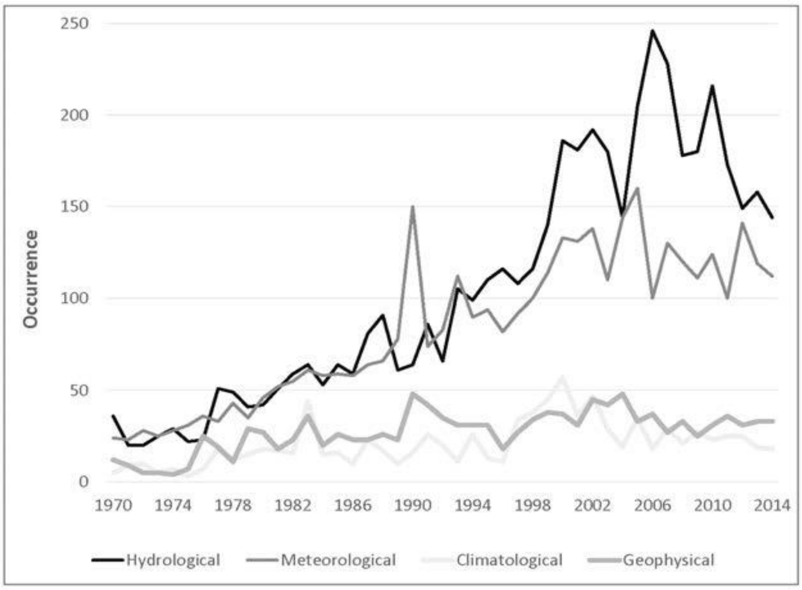

Figure 14 Global frequency of natural disasters by type, 1970-2014 (EM-DAT, 2015)

Below trendline graph (Figure 15) has been created based on the above Hydrological natural disaster occurrence graph (Figure 14). The red line represents the trend of hydrological natural disaster occurrence from 1970 and it shows that the hydrological natural disaster occurrence have been increasing from the past (1970). According to trendline, around 310 hydrological natural disasters would occur in 20 year (2040). This means that the hydrological natural disaster occurrence in 20 years is almost 2 times than 2000. Therefore, the action against this prediction is necessary

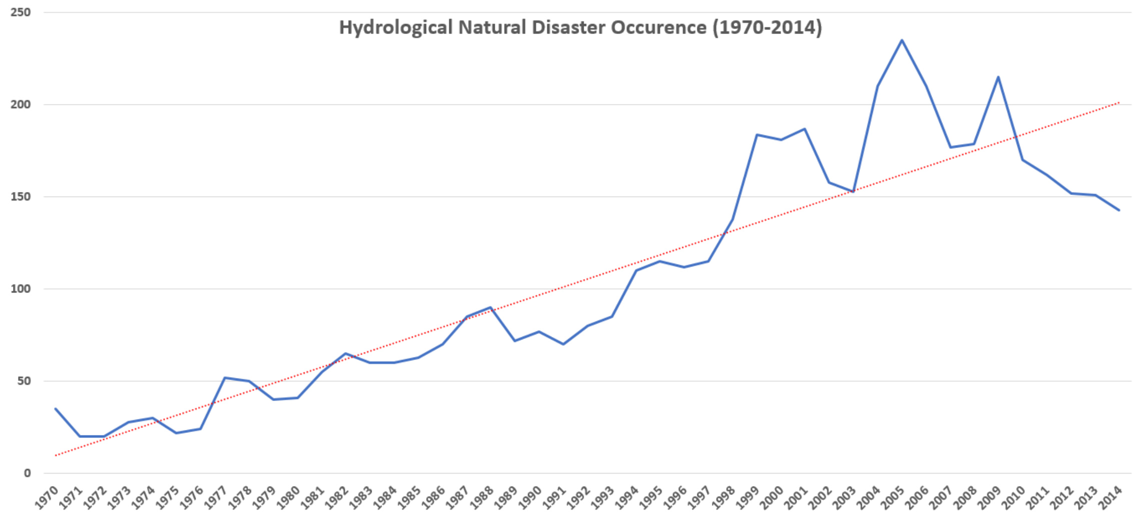

Figure 15 Hydrological natural disaster occurrence graph (1970-2014)

Conclusion

With the observed climate change effects, coastal protection against storms is important in coastal defense systems in the coming years. Up to now, conventional measures, such as dykes, are usually used to protect the coastal regions. However, coastal defense infrastructures task continuous and costly maintenance fee. In addition, frequency and intensity of hydrological natural disaster such as storms are becoming bigger. Therefore, many studies are conducted focusing on the main advantages of salt marsh sites against storms and how to adapt these salt marshes.

In this paper, different types of season and extreme weather condition such as storm are investigated mainly in two different coastal sites (tidal flat and salt marsh) by analyzing the obtained datasets.

In order to obtain the bed-level change and significant wave height datasets, a novel SED-sensors and wave gauge have been applied, respectively. Based on this given dataset, the bed level change and wave height in each seasonal and extreme weather (storms) conditions can be studied. The standard deviation values are calculated to determine the extent of fluctuation of bed level in salt marsh and tidal flat sites. So, it could be determined that the fluctuation of bed level change in tidal flat is relatively bigger than fluctuation in salt marsh sites under same circumstance(same grain size). Thus, the tidal flat sites are more vulnerable to erode than the salt marsh sites. However, same tendency cannot be seen during the stormy periods.

Wave attenuation is an important function of salt marsh and tidal flat sites. And the research results show that the significant wave height in tidal flat and salt marsh sites are gradually decreased. The protective value of salt marsh sites is much bigger than tidal flat sites. In addition, the effectiveness of wave attenuation in salt marsh sites are much bigger than non-stormy periods which is between 1.5 to 6.5 times than non-stormy periods. As a result, coastal protection value of salt marsh sites is much bigger than non-extreme condition periods such as storms.

The frequent of hydrological natural disaster such as storm has been increasing and it is predicted that in 20 years, the frequency of hydrological natural disasters will be almost 2 times larger than observed in 2000. So, it is expected that the salt marsh sites will play a very important role as a coastal protection system in the coming years to protect ourselves against more intense and frequent extreme storms.

Discussion

Four different research sites which are located in Westerschelde, the Netherlands are observed. However, the given datasets are short-term (5 years) datasets. Besides, some datasets, especially during the stormy period and autumn season are missing due to technical and environmental reasons. Thus, in this paper, the bed level change datasets, and significant wave height are studied only with these short-term datasets. But collected short-term datasets are not enough to ensure this can be proven that the derived result is reliable. Therefore, the more sufficient long-term periods bed level change datasets were expected to research in the coming future using novel SED-sensors with other data such as significant wave height, grain size, water level, and etc.

Due to above mentioned reason, it is assumed that the long-term and fully observed datasets would be observed in the coming year and those datasets will be used as a database for the coming future. And the results would be the same with the data analyzed in this paper. For instance, the grain size are compared to study the exception where the fluctuation tendency at site 4 . However, there are not enough datasets to compare all research sites in the same period year. Thus, grain size at only site 2, 4, and 5 are compared. Also, it is assumed that the obtained bed level and significant wave height datasets are calculated to determine the effect of salt marsh and tidal flat even if some periods' datasets were missing.

As described in the previous chapters, the storms are becoming more frequent and intense in the coming year due to climate change. Thus, the Netherlands have been trying to adapt the salt marsh site as a coastal protection together with man-made infrastructure such as dyke, levee, etc. Throughout this research, the more ecological coastal protection system (salt marshes) would be adapted against the more frequent and intense hydrological natural disasters in the coming future in Dutch coastal regions and then it will not necessary to reinforce the hydrological infrastructure which can save costly maintenance and reinforcement fee. Therefore, it is expected that combination of salt marshes and conventional coastal protections will play more effective role to protect the coastal regions in Dutch coastal regions.

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7. Appendix

7.1 Bed level change

7.1.1 Mean value data at research site 2, 4, 5, and 6

Table 4 Mean bed level change on each sites and periods

Site	Season / Station	Spring(cm)	Summer(cm)	Fall(cm)	Winter(cm)
2	1(salt marsh)	0.027745	-0.08029	0.597392	-0.21236
	2(salt marsh)	1.080061	1.520356	0.3675	-0.04853
	3(salt marsh)	0.967724	1.154963	-	0.402296
	4(salt marsh)	-0.33599	0.291981	1.175474	-0.46797
	5(tidal flat)	-3.1375	-5.00136	-1.36131	0.679289
	6(tidal flat)	-2.4504	-3.9182	-2.14029	-1.16825
	7(tidal flat)	-5.53289	-8.16719	-0.91083	-2.28179
4	1(salt marsh)	1.553674292	1.696927716	3.219548333	1.553674292
	2(salt marsh)	-0.578040048	1.100400959	2.288562484	-0.578040048
	3(salt marsh)	-0.022740162	1.974108723	4.05602425	-0.027740162
	4(tidal flat)	1.417443934	2.703975225	1.861728186	1.410841001
5	1(salt marsh)	-0.16723	0.032951		0.597392
	2(salt marsh)	0.153207	1.303843		0.3675
	3(tidal flat)	0.571926	1.018581	-	-
	4(tidal flat)	-0.48421	-0.14002	-	1.175474
	5(tidal flat)	-0.10928	-3.9464	-	-1.36131
	6(tidal flat)	-1.21882	-3.11241	-	-2.14029
	7(tidal flat)	-2.68094	-6.84278	-	-0.91083
6	1(salt marsh)	0.076827	0.599326	0.48213	0.08933
	2(salt marsh)	-0.41341	-0.02873	0.564635	0.117833
	3(salt marsh)	0.448549	1.276332	0.713219	0.117464
	4(tidal flat)	-1.09604	0.485797	1.597716	-0.15411
	Storm / Station	Storm 1(cm) (30-31 March 2015)	Storm 2(cm) (13-17 Nov 2015)	Storm 3(cm) (27 Nov – 1 Dec 2015)	
2	1(salt marsh)		0.341405		
	2(salt marsh)		0.516815		
	3(salt marsh)		-		
	4(salt marsh)		1.333496		
	5(tidal flat)		-1.82469		
	6(tidal flat)		-2.2832		
	7(tidal flat)		-		
4	1(salt marsh)		3.379901525	3.348803167	
	2(salt marsh)		0.767180126	-1.34087198	
	3(salt marsh)		-	-	
	4(tidal flat)		2.1937683	3.628513767	
5	1(salt marsh)	-0.10109			
	2(salt marsh)	-0.02576			
	3(tidal flat)	0.374836			
	4(tidal flat)	-0.12716			
	5(tidal flat)	1.129762			
	6(tidal flat)	-0.89027			
	7(tidal flat)	-2.37214			
6	1(salt marsh)		0.590928	0.35955	
	2(salt marsh)		0.510463	-0.32089	
	3(salt marsh)		0.773201	1.071154	
	4(tidal flat)		2.787897	0.646636	

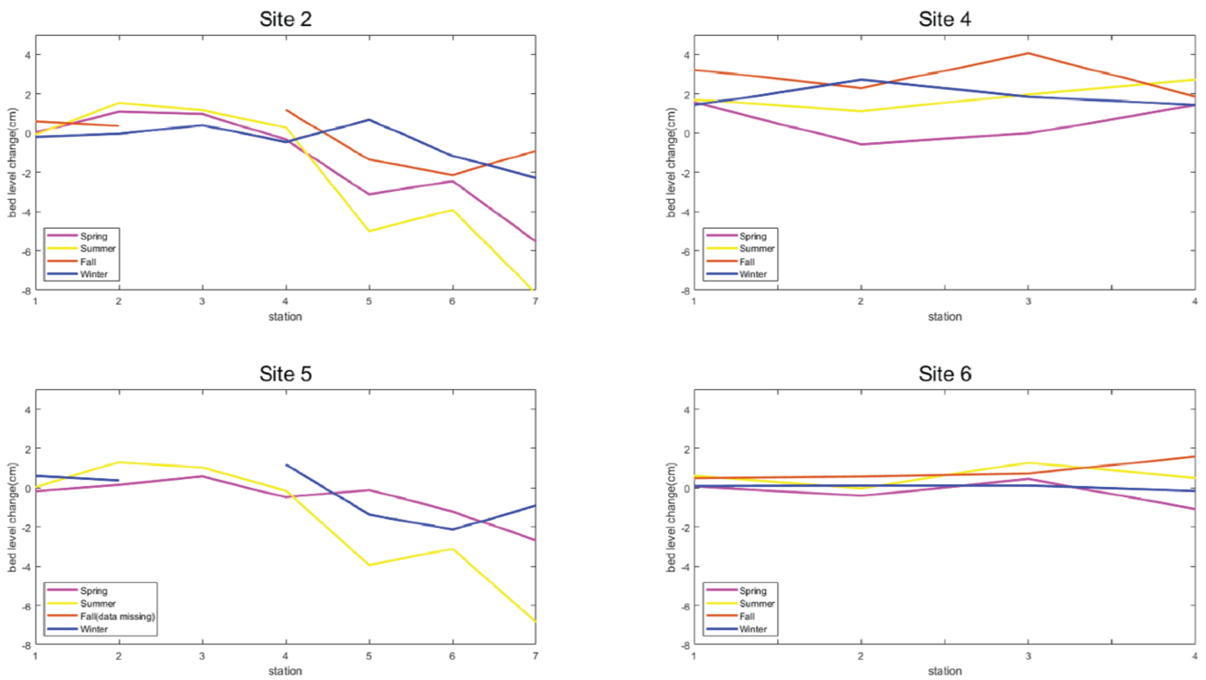

Figure 16 Seasonal mean bed level change graphs at Site 2, 4, 5, and 6

7.1.2 Standard deviation values at research site 2, 4, 5, and 6

Table 5 Standard deviation of bed level change on each sites and periods

Site	Season / Station	Spring(cm)	Summer(cm)	Fall(cm)	Winter(cm)
2	1(salt marsh)	0.372711	0.252505	0.280654	0.315726
	2(salt marsh)	0.388491	0.187443	0.201651	0.371799
	3(salt marsh)	0.337082	0.184687	-	0.254092
	4(salt marsh)	0.557556	0.237948	0.417424	0.319754
	5(tidal flat)	1.042924	0.969509	0.660216	0.937524
	6(tidal flat)	1.432052	1.171058	0.768459	0.700045
	7(tidal flat)	1.771874	0.702229	0.766128	0.96893
4	1(salt marsh)	1.313528	1.016949	0.274135	1.762749
	2(salt marsh)	1.343088	0.581099	1.40081	0.873561
	3(salt marsh)	0.496935	0.980883	0.330497	0.653337
	4(tidal flat)	2.258069	2.2112804	1.141067	1.4455367
5	1(salt marsh)	0.308823	0.375137	-	0.280654
	2(salt marsh)	0.460544	0.287587	-	0.201651
	3(tidal flat)	0.377886	0.316573	-	-
	4(tidal flat)	0.305776	0.602734	-	0.417424
	5(tidal flat)	1.455323	1.028643	-	0.660216
	6(tidal flat)	0.742213	1.402071	-	0.768459
	7(tidal flat)	1.066549	1.500393	-	0.766128
6	1(salt marsh)	0.529482	0.211756	0.36994	0.452892
	2(salt marsh)	0.542875	0.185424	0.493643	0.51841
	3(salt marsh)	0.610518	0.361524	0.556295	0.567843
	4(tidal flat)	1.030491	0.900676	1.001219	1.56986
	Storm / Station	Storm 1(cm) (30-31 March 2015)	Storm 2(cm) (13-17 Nov 2015)	Storm 3(cm) (27 Nov – 1 Dec 2015)	
2	1(salt marsh)		0.251798		
	2(salt marsh)		0.199705		

	3(salt marsh)		-		
	4(salt marsh)		0.315862		
	5(tidal flat)		0.104709		
	6(tidal flat)		0.118241		
	7(tidal flat)		-		
4	1(salt marsh)		0.20426	0.204472	
	2(salt marsh)		1.032721	0.291686	
	3(salt marsh)		-	-	
	4(tidal flat)		0.441278	0.423675	
5	1(salt marsh)	0.126549			
	2(salt marsh)	0.303414			
	3(tidal flat)	0.17155			
	4(tidal flat)	0.127426			
	5(tidal flat)	0.159801			
	6(tidal flat)	0.022174			
	7(tidal flat)	0.320492			
6	1(salt marsh)	-	0.077065	0.127693	
	2(salt marsh)		0	0.10949	
	3(salt marsh)		0.130246	0.306301	
	4(tidal flat)		0.984515	0.569237	

7.1.3 Bed level change graph

The two stations are shown in below figures that are located at the most landward and seaward salt marsh and tidal flat sites.

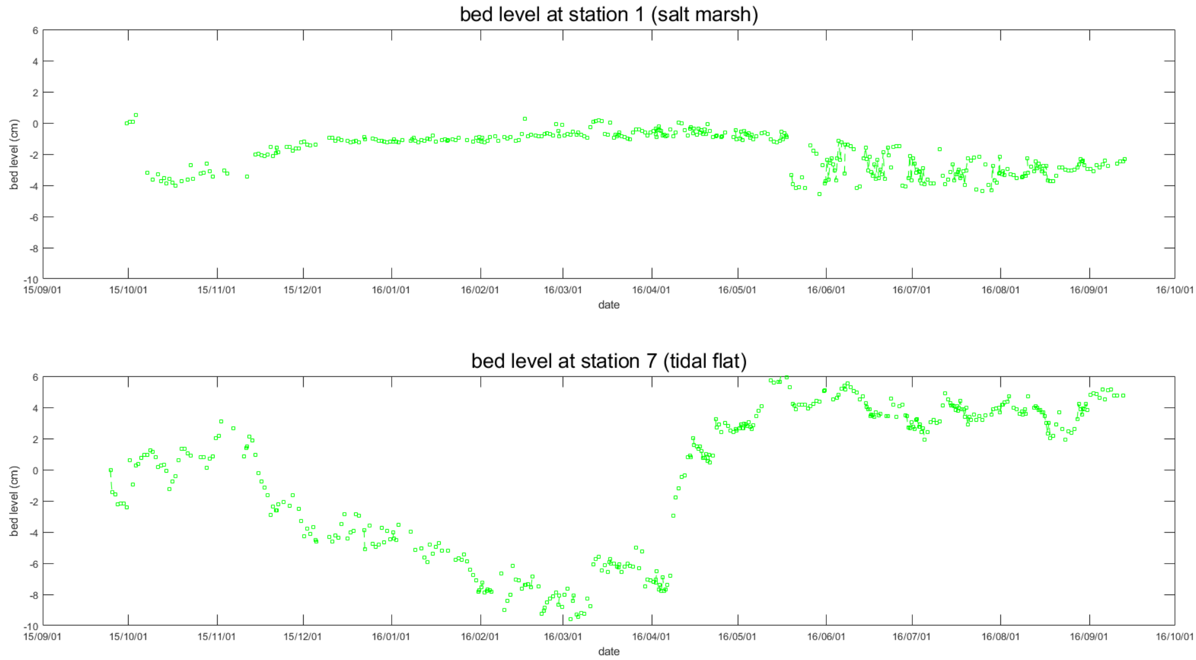

Figure 17 bed level change graph at each station in Site 2

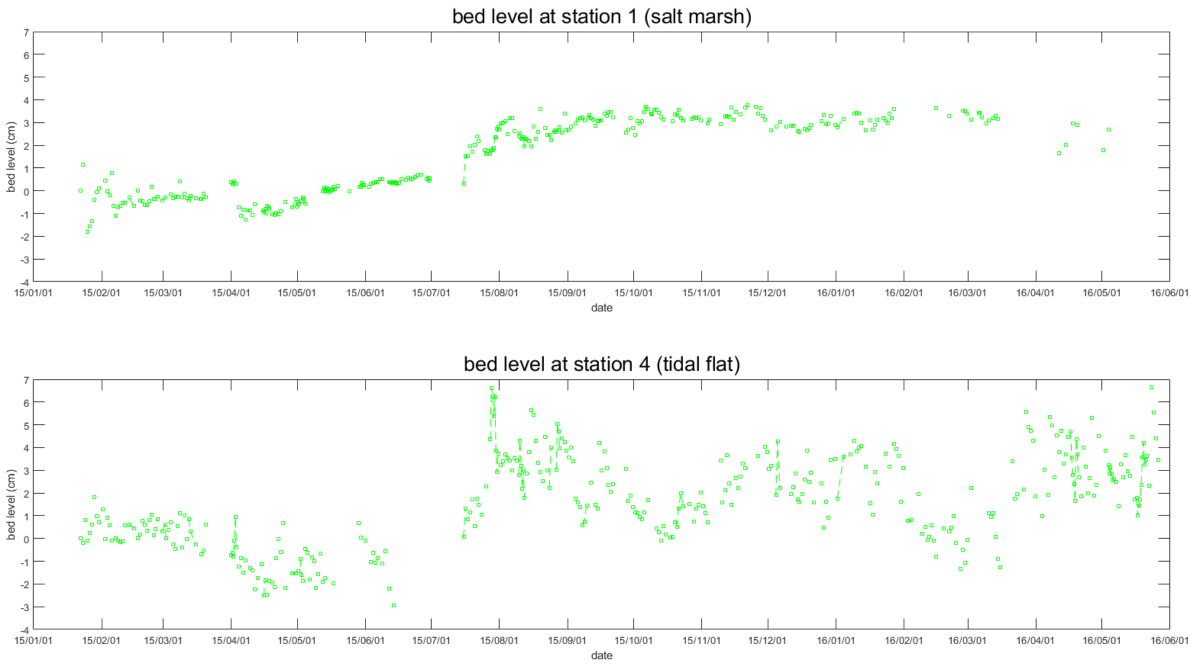

Figure 18 bed level change graph at each station in Site 4

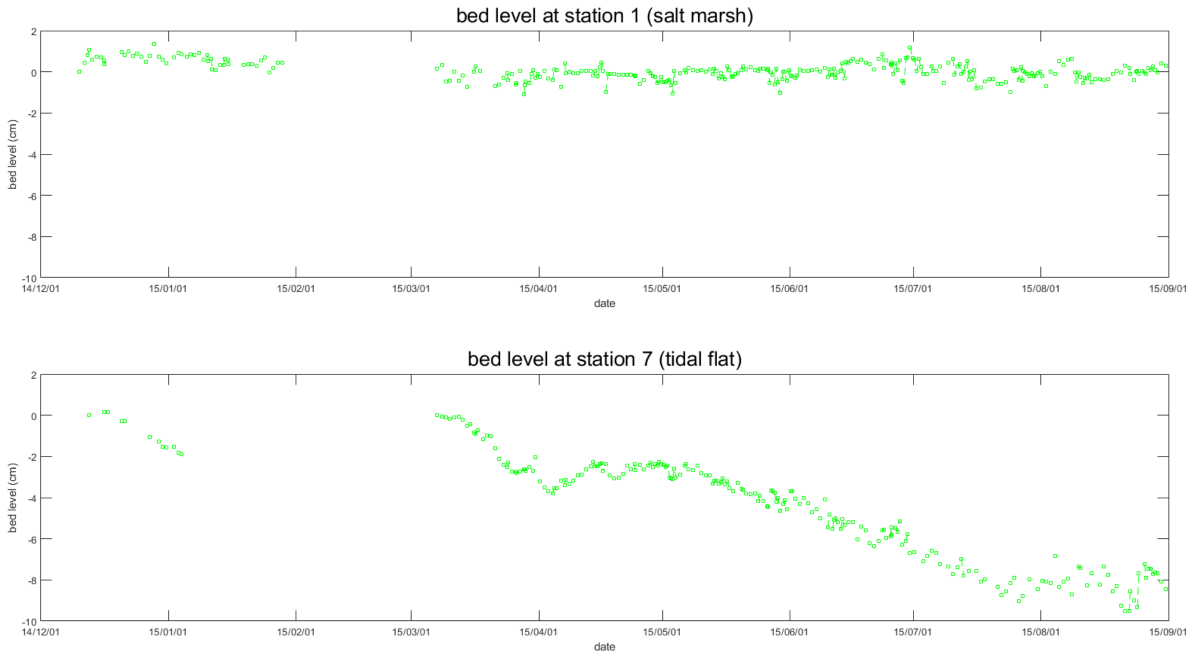

Figure 19 bed level change graph at each station in Site 5

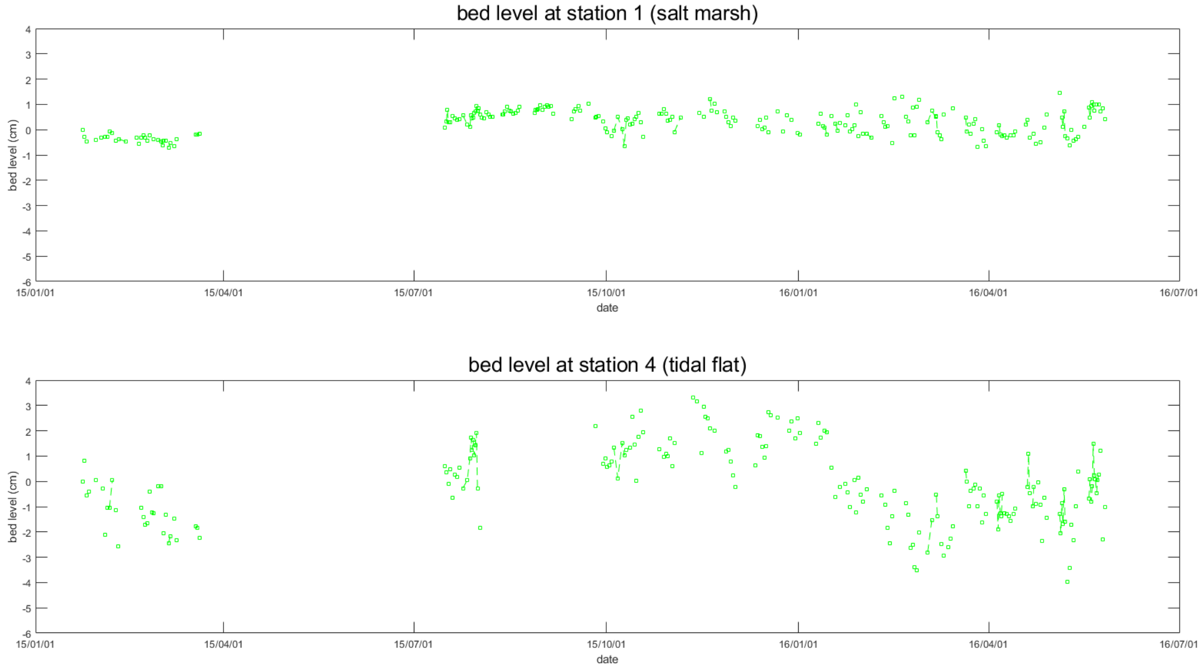

Figure 20 bed level change graph at each station in Site 6

7.2 Significant Wave Height

7.2.1 Mean significant wave height value at research site 4, and 6.

Table 6 Mean significant wave height at research site 4 and 6

Site	Season / Station	Spring(m)	Summer(m)	Fall(m)	Winter(m)
4	1(salt marsh)	0.025772	0.006865	0.019444	0.04031
	2(salt marsh)	0.069623	0.046391	0.082544	0.101439
	3(tidal flat)	0.091904	0.080644	0.08014	0.119252
	4(tidal flat)	0.096852	0.091733	0.105104	0.119086
6	1(salt marsh)	0.057720038	0.027595727	0.046286486	0.070888524
	2(salt marsh)	0.103675498	0.082612601	0.085488013	0.102122412
	3(salt marsh)	0.115288891	0.108227877	0.088731316	0.119852141
	4(tidal flat)	0.118689282	0.108441118	0.108137107	0.117282191
Site	**Storm / Station**	**Storm 1(m) (30-31 March 2015)**	**Storm 2(m) (13-17 Nov 2015)**	**Storm 3(m) (27 Nov – 1 Dec 2015)**	
4	1(salt marsh)	0.081025	0.041189	0.075798	
	2(salt marsh)	0.212218	0.184757	0.188976	
	3(tidal flat)	0.296522	-	-	
	4(tidal flat)	0.277902	0.244984	0.229682	
6	1(salt marsh)	0.193925263	0.08484385	0.116675133	
	2(salt marsh)	0.290415333	0.155208232	0.162476304	
	3(salt marsh)	0.329517576	-	-	
	4(tidal flat)	0.330977949	0.18463254	0.177695817	

7.2.2 Significant wave height change per meter towards inlands from sea at research sites

Table 7 Significant wave height change per meter towards inlands from sea on each season and storm surge periods (m/m)

Site	Station gap	Spring(m/m)	Summer(m/m)	Fall(m/m)	Winter(m/m)
4	1-2(salt marsh)	0.0012525	0.001129	0.0018023	0.001746
	2-3(salt marsh - tidal flat)	0.0022483	0.0034564	-0.0002426	0.0017975
	3-4(tidal flat)	0.000508	0.0011385	0.002563	-0.0000017
6	1-2(salt marsh)	0.001266	0.0015156	0.0010799	0.0008604
	2-3(salt marsh)	0.0012555	0.0027692	0.0003506	0.0019167
	3-4(salt marsh - tidal flat)	0.000334	0.0000209	0.0019063	-0.0002525
	Storm / Station	**Storm 1(m) (30-31 March 2015)**	**Storm 2(m) (13-17 Nov 2015)**	**Storm 3(m) (27 Nov – 1 Dec 2015)**	
4	1-2(salt marsh)	0.0037473	0.00410077	0.00323273	
	2-3(salt marsh - tidal flat)	0.008507	-	-	
	3-4(tidal flat)	-0.001912	-	-	
6	1-2(salt marsh)	0.0026581	0.00193841	-0.0031131	
	2-3(salt marsh)	0.0042273	-	-	
	3-4(salt marsh - tidal flat)	0.0001435	-	-	

7.2.3 Significant wave height graph at the most landwards and seawards station at site 4 and 6.

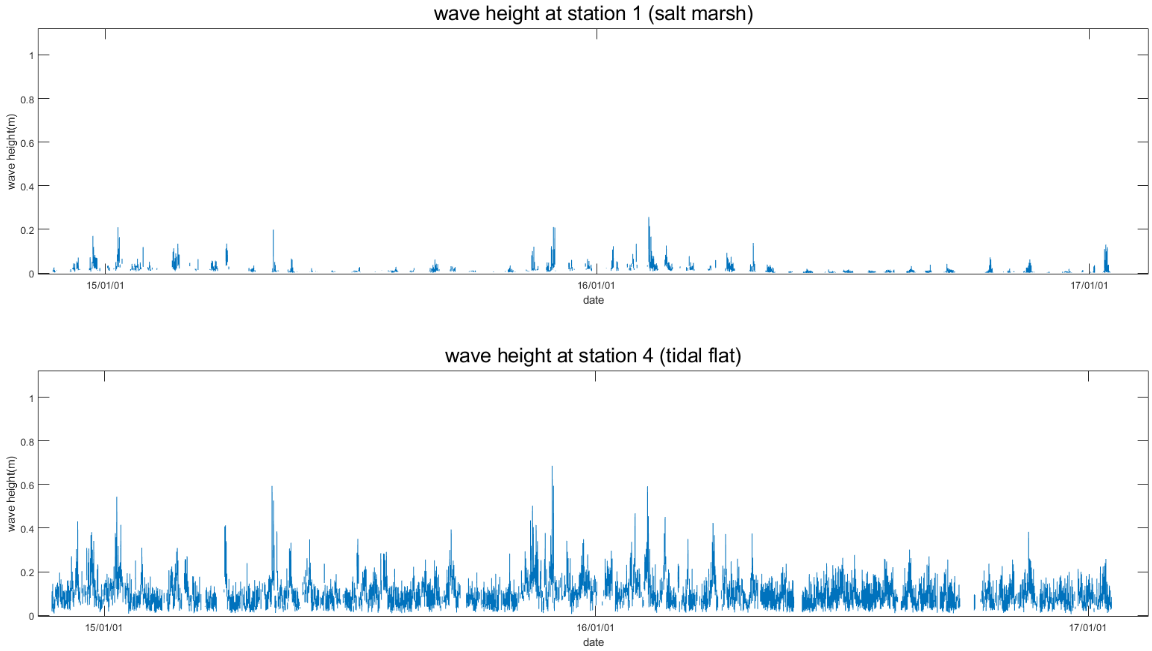

Figure 21 Significant wave height graph at each station in Site 4

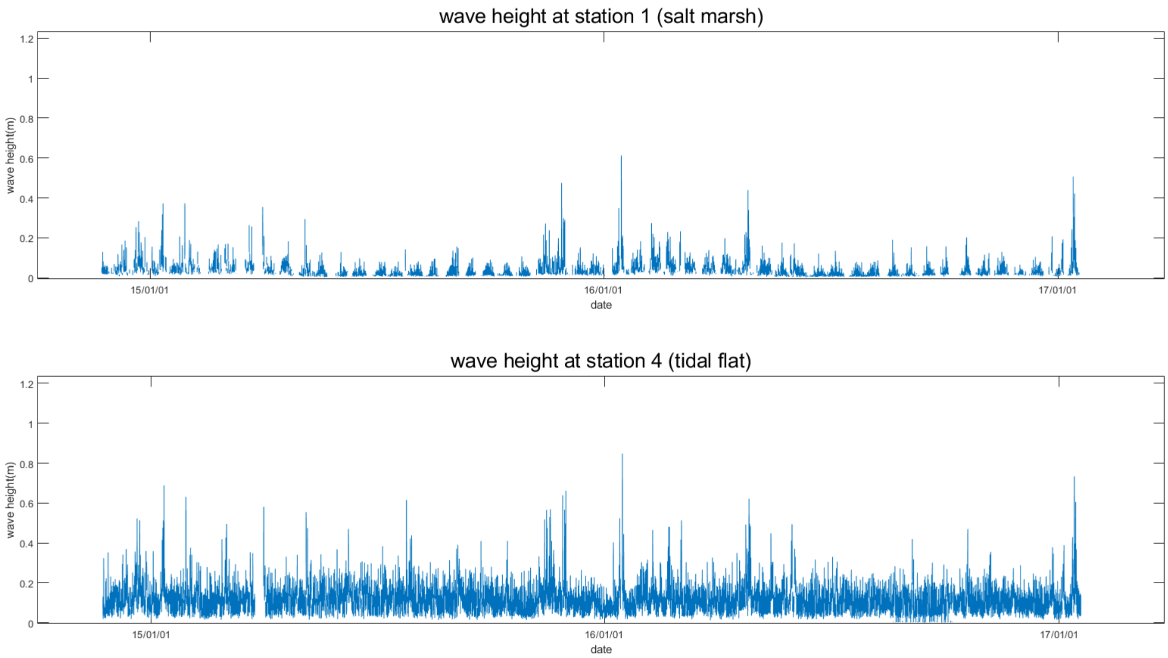

Figure 22 Significant wave height graph at each station in Site 6

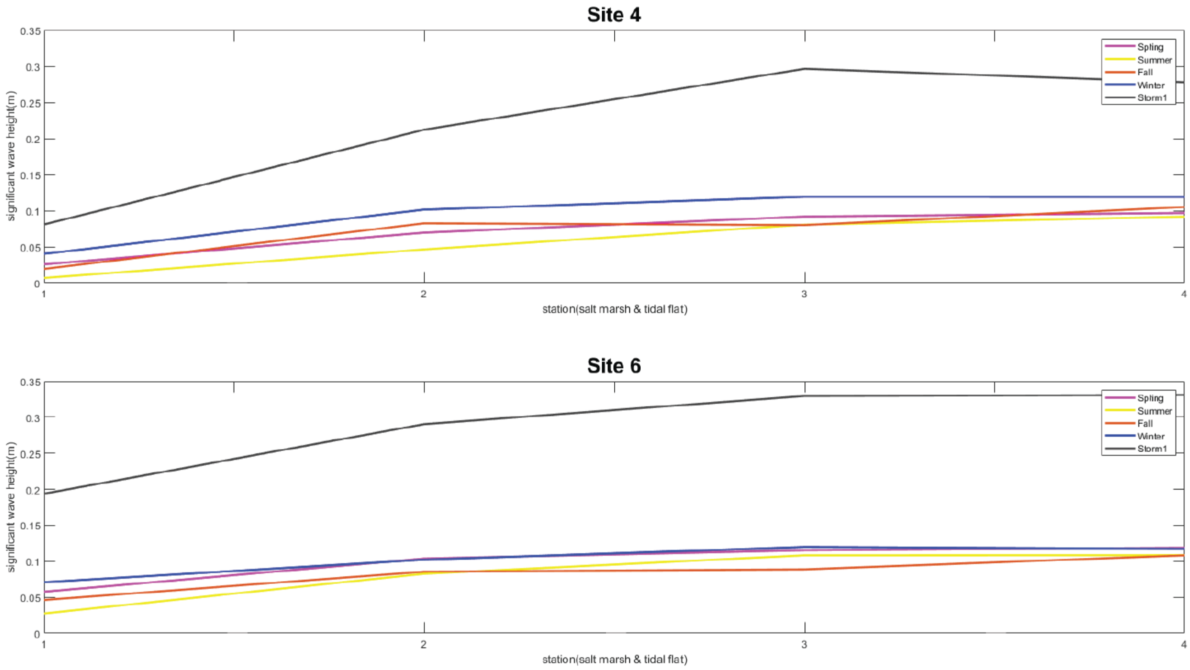

Figure 23 Significant wave height during each season and stormy period (Site 4 & 6)