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Wave Attenuation Service By Intertidal Coastal Ecogeosystems In the Bay Of Mont-Saint-Michel, France: Review And Meta-analysis

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Abstract: The wave attenuation service (WAS) literature review over the Bay of Mont-Saint-Michel encompasses saltmarshes, mudflats, seagrasses, shelly cheniers, oyster, honeycomb worm and sandworm reefs, which all together will be named “ecogeosystems” in this review due to their combination of biogenic systems, ecological systems and geomorphological systems (Mury et al., 2018). It provides a comparative meta-analysis of the various measurements of wave attenuation induced by “ecogeosystems” across different studies focusing on wave height monitoring. The array of “ecogeosystems” included in this review was firstly identified through a fine-scale mapping of the Bay of Mont-Saint-Michel, then literature research was led using several keywords related to ecosystem services and coastal protection. A total of 32 studies was compiled over six countries. The majority of studies was located on North-Atlantic Ocean coastlines. According to their specificities, “ecogeosystems” were synthetically split into two categories, surface (saltmarshes, mudflats, seagrasses and oyster reefs) and punctual (shelly cheniers), for the sake of the WAS comparability. WAS associated with surface saltmarshes, mudflats, seagrasses, and oyster reefs ranged from 0.25 to 7.86%/m, from 0.01 to 4%/m, from 0.03 to 0.77%/m, from 1 to 64%/m, respectively. The punctual shelly chenier was monitored from 70 to 98%. Honeycomb worm and sandworm reefs have no data about WAS according to our literature review.

Key words: Protection Ecosystem Service; Coastal Hazards; Coastal Management; Mega-tidal Environment.

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1. Introduction

A consequence of global change might be an increase in coastal risks (Temmerman et al., 2013). Indeed, sea-level rise conjugated with spring tides, can lead to hazardous sea-levels, in worldwide coastal areas subject to unprecedented demographic densification (exposure), thus risks. Coastal “ecogeosystems” such as tropical coral reefs, have the potential to alleviate hazards by reducing wave energy due to their topographic complexity (drag coefficient, Harris et al., 2016, 2018). However, studies focusing on the wave attenuation service (WAS) of natural barriers remain spatially discrete and scattered, as well as not harmonized. Moreover, the WAS of some barrier types remains poorly known, or even unknown.

A comprehensive view of the ensemble of coastal “ecogeosystems” is needed to help stakeholders tasked with coastal risk reduction and coastal protection. The Bay of Mont-Saint-Michel (BMSM, France) suitably matches this objective, given its mega-tidal regime and the large panel of natural barriers (Collin et al., 2018a) facing hazards and protecting human assets.

The WAS literature review over the BMSM encompasses saltmarshes, mudflats, seagrasses, shelly cheniers, oyster, honeycomb worm and sandworm reefs. It offers a comparative view of the various values of wave attenuation by “ecogeosystems” observed across different studies through wave height monitoring. Ecological parameters acting as wave height attenuation factors have also been evaluated. Beyond the comparative results, the main objective of the study is to give an overview of the existing knowledge of WAS evaluation and identify the gaps hindering an efficient implementation of ecogeosystem-based solution to sustainably cope with coastal risks. Therefore, this work will be an opportunity to bring new data on the WAS of shelly cheniers, honeycomb worm and sandworm reefs, three types of “ecogeosystems” still under-considered for their role in coastal protection (only two studies: Jeanson et al., 2016; Mury et al., 2018).

2. Methods

The first step of this review work consists in the identification of the various “ecogeosystems” of the intertidal environment, which may take part in the wave mitigation process and thus which have to be considered in

an integrated vision towards the management of coastal risks.

In so doing, five different “ecogeosystems” of the intertidal domain, which can possibly take part of the WAS, were able to be identified from a mapping of the BMSM

(saltmarshes, mudflats/sandflats, shelly cheniers, honeycomb worm and sandworm reefs) (Figs 1, 2, 3), and two others were identified in the literature (seagrasses, and oyster reefs) to have a more complete view of the intertidal “ecogeosystems” of temperate coastal areas.

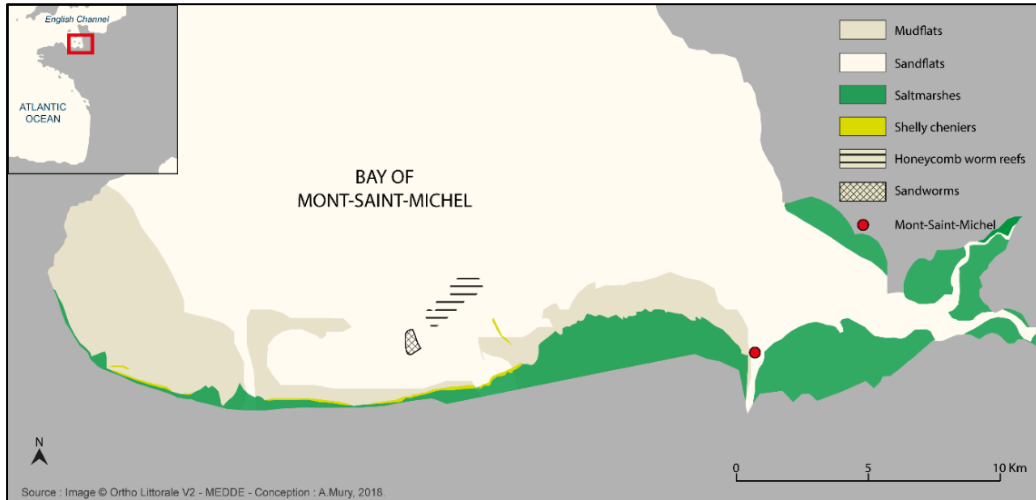


Figure 1. Location map of the "ecogeosystems" observed in the Bay of Mont-Saint-Michel, France



Figure 2. Illustration of the "ecogeosystems" concerned by the WAS review

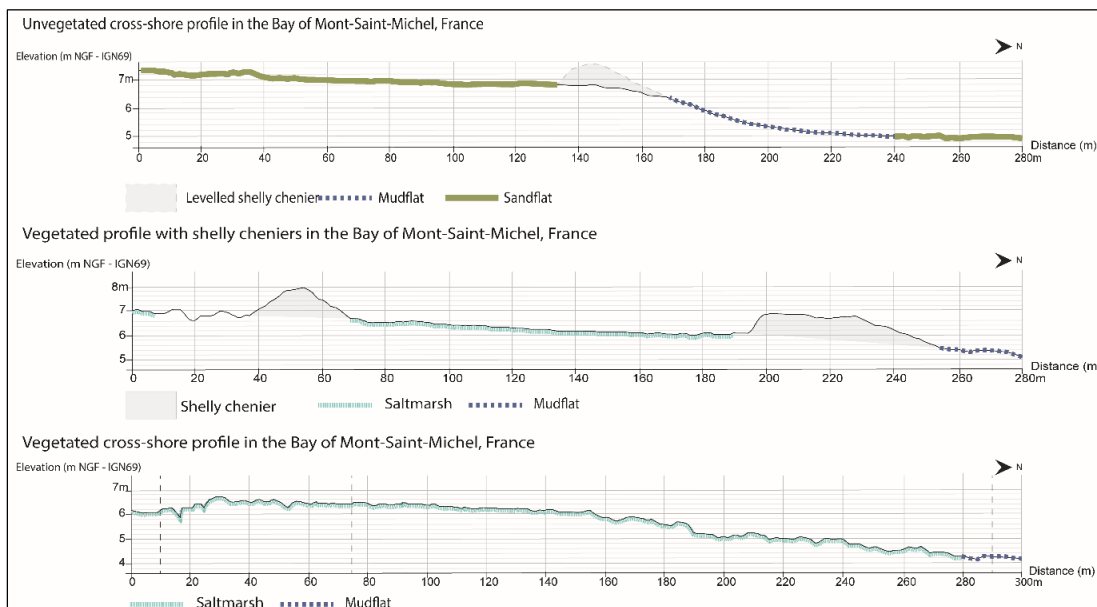


Figure 3. Cross-shore profiles in the Bay of Mont-Saint-Michel, France

These “ecogeosystems” can be separated in three categories depending on their nature: (1) plant ecosystems (saltmarshes, seagrasses), (2) geomorphological structures (mudflats/sandflats, shelly cheniers), and (3) biogenic structures (honeycomb worm, oyster and sandworm reefs).

Concerning the screening method for scientific articles on WAS by coastal “ecogeosystems”, the attention was focused specifically on the wave attenuation through the wave height attenuation data (WHA) (neither the velocity nor flow), due to its recognized representativeness of the submersion hazards. We examined the temperate intertidal natural features (what excluded the mangroves and coral reefs, which are tropical ecosystems as well as artificial seagrasses). We searched for the literature using research portals like Google Scholar, Web of Sciences and BibCnrs

(Database of CNRS research teams) to target articles dealing with coastal protection, wave attenuation, ecosystem services and nature-based solutions for wave mitigation.

To achieve this literature review, several keywords were used, from generic keywords (i.e., ecosystem services, coastal protection service, coastal protection) to more detailed terms, in the form of *feature* + wave attenuation (or mitigation or reduction) or *feature* + wave height attenuation or *feature* + protection service (e.g., saltmarsh wave attenuation, saltmarsh wave height attenuation, saltmarsh protection service). Subsequently, were selected articles mentioning a percentage of attenuation by the whole selected features or a percentage per unit of distance (%/m) for the sake of data comparisons.

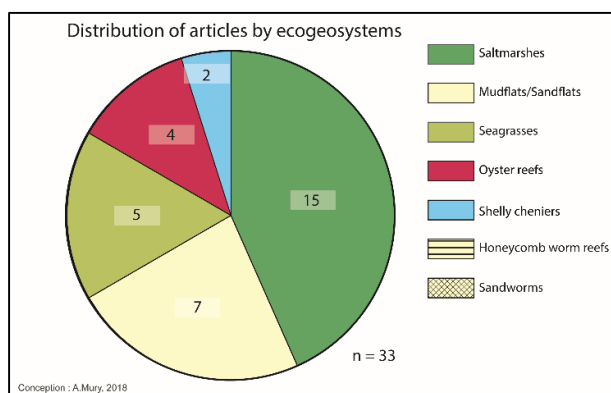


Figure 4. Diagram of the distribution of the papers

3. Results

A suite of 33 articles corresponded to the mentioned research criteria: 15 concerned saltmarshes WAS, 7 mudflats/sandflats, 5 seagrasses, 4 oyster reefs, 2 shelly cheniers, 0 dealt with honeycomb and sandworm reefs WAS. Some of the identified “ecogeosystems” like honeycomb worm reefs were not considered for their WAS yet, thus were not mentioned in the literature (Figure 4). Some “ecogeosystems”, such as oyster reefs, are well known to act as natural breakwaters, but their WAS is seldom assessed. Most studies, extracted in this literature review, took place on the margins of the Atlantic Ocean, especially along the European and North-American coastlines (Figure 5).

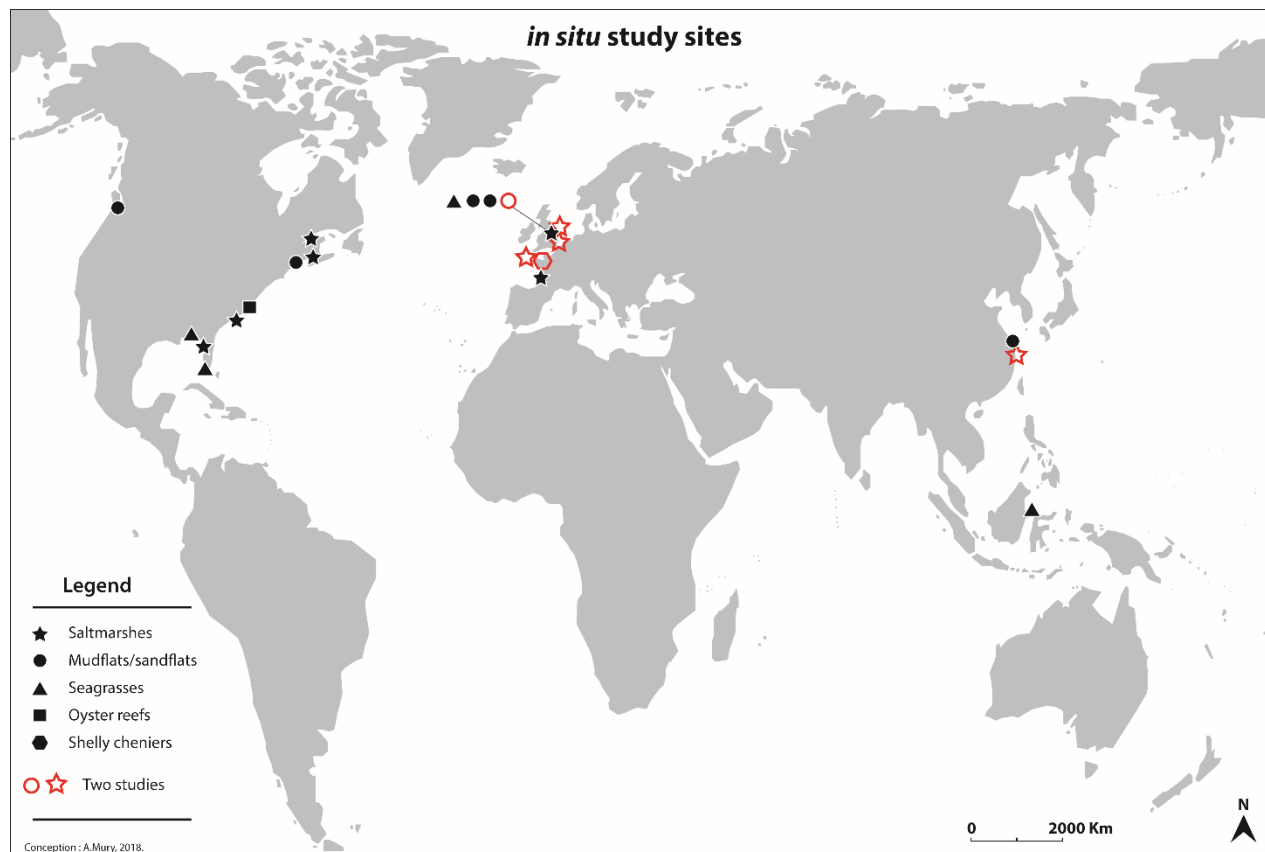


Figure 5. Location map of the in situ study sites, from the review

Saltmarshes

About the saltmarsh review, fourteen studies dealing with the WAS were selected (Table 1). Considering the diversity across the different sites and the discrepancy in measurement methods in the literature dataset, we had to implement methodological choices to analyse the distinct study results. First, we decided to compare the studies by using the wave height attenuation (WHA) value, expressed as a percentage of attenuation per meter, to obtain a common unit between studies. When the WHA value was not directly provided by the authors, we calculated it (see shaded boxes). Even though the influence of the distance from the shore, of the foreshore and seabed characterization, the hydrodynamic conditions and water depth, underlying the studies was not accounted for, the calculated values offer a first-level comparison set. Second, we carried out a classification based on ecological criteria and more specifically on the plant length, to compare the

WAS across the studies. In this way, we retrieved plant communities with a higher length range (*Spartina alterniflora*, *Spartina maritima*, *Scirpus mariqueter*, *Spartina patens*), which corresponded to the fringing marsh of the lower mixed marsh communities (North-West European mixed saltmarsh, *Elymus athericus*, *Puccinellia maritima*, *Salicornia*, *Suaeda maritima*, etc.).

Regarding the higher plant community studies (Wayne 1976; Knutson et al., 1982; Morgan et al., 2009; Yang et al., 2008; Yang et al., 2012; Lechevalier, 2016), the WHA ranged from 0.95 to 7.86 %/m (mean: 3.3%/m).

These findings differed considerably from those observed for the lower mixed saltmarshes (Moller et al., 1996, 1999, 2002, 2006, 2014; Cooper, 2005; Collin et al., 2018). Indeed, the WHA measured bottomed at 0.3 and topped at 1.8%/m (mean: 0.52%/m) range.

Table 1. Synthesis table of Saltmarshes wave attenuation service studies (WHA: Wave Height Attenuation; WEA: Wave Energy Attenuation; * grey literature, PS.: pressure sensors)

Reference	Study Location	Tidal Category	Materials	Site Characteristics	Wave Attenuation				
					WHA		WEA		
					Whole	%/m	Whole	%/m	
Wayne, 1976	Adams Beach, Florida, USA	Micro-tidal	NC	<i>S. alterniflora</i>	71%/20m	3.6	92%/20m	4.6	
				<i>T. testudinum</i>	42%/20m	2.1	67%/20m	3.4	
Knutson et al., 1982	Chesapeake Bay, Virginia, USA	Micro-tidal	Wave gage	<i>S. alterniflora</i>	40%/2.5m 57%/5m 65%/10m 87%/20m 94%/30m	3.1	64%/2.5m 72%/5m 88%/10m 98%/20m 100%/30m	3.33	
Moller et al., 1996	North Norfolk, UK	Macro-tidal	PS.	North-West European mixed Saltmarsh	53.6%/180m	0.3	79%/180m	0.44	
Moller et al., 1999	North Norfolk, UK	Macro-tidal	PS.	North-West European mixed Saltmarsh	60.96%/180m 63%/200m	0.34	82%/180m	0.45	
Moller and Spencer, 2002	Dengie Peninsula, Essex, UK	Macro-tidal	PS.	North-West European mixed	Shallow slopping edge	87.37%/163m	0.54	98.92%/163m 99%/310m (whole transect)	0.61 – 0.3 (whole transect)
					Cliffed edge	43.81%/10m	4.38	79.13%/10m	7.91
Cooper, 2005	The Wash, Eastern England, UK	Macro-tidal	Buoy and PS.	Wrangle flats transect	90.7%/300m	0.3	97.1%/300m	0.32	
				Butterwick Low transect	63.5%/250	0.25	71.9%/250m	0.29	
				Breast Sand transect	78%/110m	0.7	91.3%/110m	0.83	
Moller,	Dengie	Macro-	PS.	North-West	2-7%/10m	1 – 1.8	/	/	

2006	Peninsula, Essex, UK	tidal		European mixed salt marsh				
Yang et al., 2008	Eastern Chongming, China	Macro-tidal	Wave recorder / PS.	<i>S. mariqueter</i> , <i>S. alterniflora</i>	16%/16.5m	0.95	29%/16.5m	1,80
Lambert, 2009	Saint Laurent Estuary, Canada	NC	PS.	<i>S. alterniflora</i> , <i>S. patens</i>	/	/	37-88%/566m	0.7-0.16
Morgan et al., 2009	Northern New England, USA	NC	/	<i>S. alterniflora</i>	55%/7m	7.86	/	/
				<i>S. patens</i> , <i>J. gerardii</i> , <i>D. spicata</i> and <i>P. maritima</i>	52%/7m	7.43	/	/
Yang et al., 2012	Eastern Chongming, China	Macro-tidal	PS.	<i>S. alterniflora</i>	30%/7.5m 51%/20m 79%/51m	2.34	/	/
Moller et al., 2014	ex situ	/	PS.	Mixed saltmarsh of <i>E. athericus</i> , <i>P. maritima</i> , <i>A. prostrata</i>	20%/40m (high energy conditions)	0.5	/	/
Lechevalier, 2016*	Moëze, France	Macro-tidal	Wave sensors / PS.	<i>S. maritima</i>	/	1.9	/	/
				<i>H. portulacoides</i>	/	4.6	/	/
Collin et al., 2018b	Bay of Lancieux, France	Mega-tidal	PS.	Lower marsh of <i>S. anglica</i> and <i>S. europaea</i>	5-10%/100m	0.05-0.1	/	/
				Medium marsh of <i>H. portulacoides</i> and <i>T. maritima</i>	10-20%/100m	0.1-0.2	/	/
				Upper marsh of <i>H. portulacoides</i> , <i>T. maritima</i> , <i>P. maritima</i> and <i>F. rubra</i>	>20%/100m	>0.2	/	/
Mury et al., 2018	BMSM, France	Mega-tidal	PS.	North-West European mixed Salt marsh	>78%/100m	>0.78	/	/

Mudflats/Sandflats

The second part of the review work was dedicated to the WAS of mudflats and sandflats, in which seven studies were selected (Table 2). The majority of these studies indirectly dealt with the wave attenuation process by mudflats or sandflats. Indeed, mudflat transect measurements were mainly used as samples for comparison

with the other “ecogeosystems” WAS (only Houser and Hill, 2010, focused on the mudflat WAS).

The WHA recorded in these various studies were generally found between 0.23%/m (modest increase) and 0.2%/m (with the exception of the Morgan et al., 2009, study data that reached 4%/m, a relatively high percentage due to the low distance between recording stations).

Table 2. Synthesis table of Mudflats and Sandflats wave attenuation service studies (WHA: Wave Height Attenuation; WEA: Wave Energy Attenuation; * grey literature, PS.: pressure sensors)

Reference	Study Location	Tidal Category	Materials	Site Characteristics	Wave Attenuation			
					WHA		WEA	
					Whole	%/m	Whole	%/m
Moller et al., 1996.	North Norfolk, UK	Macro-tidal	PS.	/	13.5%/197m	0.07	26%/197m	0.13
Moller et al., 1999.	North Norfolk, UK	Macro-tidal	PS.	/	15.29%/197m	0.08	29%/197m	0.15

Moller and Spencer, 2002.	Dengie Peninsula, Essex, UK	Macro-tidal	PS.	Marsh edge : shallow slopping	20.57%/147m	0.14	35.25%/147m	0.24
				Marsh edge : cliffed edge	+23.91%/102 m (+0.23	+55.06%/102m	+0.54
Cooper, 2005.	The Wash, Eastern England, UK	Macro-tidal	Buoy / PS.	Wrangle flats transect	10.1%/330m	0.03	15.9%/330m	0.05
				Butterwick Low transect	23%/390m	0.06	35.8%/390m	0.09
				Breast Sand transect	36.4%/180m	0.2	56.2%/180m	0.31
Yang et al., 2008.	Eastern Chong-ming, China	Macro-tidal	Wave-tide recorder / PS.	/	11%/185m	0.06	21%/185m	0.11
Morgan et al., 2009.	Northern New England, USA	NC	NC	/	28%/7m	4.0	/	/
Houser and Hill, 2010.	Fraser River Delta, Canada	NC	Current profiler / PS.	/	42%/4500m	0.01	62%/4500m	0.014

Seagrasses

Concerning the review work allocated to seagrasses WAS, an important methodological choice has been made by excluding all studies dealing with artificial seagrasses (Table 3). Indeed, considering the relative fragility of seagrasses in their natural environment, a plethora of studies focused on artificial seagrasses. The exclusion of artificial seagrasses from this review is justified by primarily targeting the natural components of the intertidal domain and their responses to meteorological and wave

forcing. Considering the studies dealing with WHA, a great variability has been recorded, from 0.03%/m to 0.77%/m. This variability in results can be explained by the fragility of this kind of ecosystem and his dependence on the experimental conditions. Furthermore, another explanatory factor of this variability is the diversity of the morphological characteristics (e.g., root system, leaf morphometry) of the various species.

Table 3. Synthesis table of Seagrasses wave attenuation service studies (WHA: Wave Height Attenuation; WEA: Wave Energy Attenuation; * grey literature, PS.: pressure sensors)

Reference	Study Location	Tidal category	Materials	Site characteristics	Wave attenuation			
					WHA		WEA	
					whole	%/m	whole	%/m
Fonseca and Cahalan, 1992	ex situ - wave flume	/	Wave flume	<i>Halodule wrightii</i> , <i>Syringodium filiforme</i> , <i>Thalassia testudinum</i> , <i>Zostera marina</i>	/	/	20-76%/1m (mean 40%)	
Prager and Halley, 1999	Calusa Key, Florida Bay, USA	NC	PS.	<i>Thalassia testudinum</i>	/	/	>80%/2500 m	0.03

Paul and Amos, 2011	Ryde Sand, Isle of Wight, UK	Macro-tidal	PS.	<i>Zostera noltii</i>	High shoot density	20% /30-95m	0.66-0.21	/	/
					Low shoot density	<10%/30-95m	0.33-0.11	/	/
Bradley and Houser, 2009	Santa Rosa Island, Florida, USA	Micro-tidal	PS.	<i>Thalassia testudinum</i>	+20%/5 th m then decrease of 30%/39m	0.77 (39m)	/	/	
Christian-en et al., 2013	Derawan Island, Indonesia	NC	PS.	<i>Halodule uninervis</i>	18%/667m 30%/450m 11%/200m	0.03-0.07	/	/	

Oyster reefs

Oyster reefs are deemed as natural breakwaters since several centuries and are currently utilized in ecosystem restoration programs. Their value as a protective ecosystem is attested, but there are surprisingly not so many studies, which aimed at quantifying their WAS value. Among the retained studies, three out of four are ex situ studies (Table 4). Data from these studies were difficult to harmonize because of the discrete shape of the oyster reefs, thus an

attenuation percentage per meter (i.e., surface metrics) could be inappropriate to estimate it. A punctual metric would be more likely to capture the WAS of these reefs. The only value we could find stemmed from Garvis (2012): 23% attenuation for a three-metre transect, that is to say 7.6%/m. Noteworthy was the absence of consideration of the non-linearity of the attenuation and the possible shoaling effect.

Table 4. Synthesis table of Oyster Reefs wave attenuation service studies (WHA: Wave Height Attenuation; WEA: Wave Energy Attenuation; * grey literature, PS.: pressure sensors)

Reference	Study Location	Tidal category	Materials	Site characteristics	Wave attenuation			
					WHA		WEA	
					whole	%/m	whole	%/m
Garvis, 2012*	ex situ	/	PS.	Dead reef	<1%/3m		/	/
				Natural reef	23%/3m		/	/
				Restored reef	25%/3m		/	/
Taube, 2013*	Delmarva Peninsula, Virginia, USA	Micro-tidal	Wave recorder – Acoustic Doppler	<i>Crassostrea virginica</i> reef	/	/	49%	/
Manis et al., 2015	ex situ	/	PS.	Newly deployed oyster shell	10.3%	/	18.7%	/
				1-year established oyster	10.5%	/	44.7%	/
Godfroy, 2017*	ex situ	/	Model	/	9-64%	/	/	/

Shelly cheniers

The capacity of shelly cheniers to alleviate wave energy is also accepted, although it is little documented. Shelly cheniers are besides relatively rare geomorphic structures worldwide, resulting in a few studies about their WAS. To date, we listed only two articles about this attenuation aspect (Table 5). The first study showed a very

high WEA rate, around 98% for healthy cheniers, whilst the second study, focused on the WHA, showed a rate around 61% for the whole well-developed chenier, and around 39% for the degraded one. It is also advocated to use a global punctual rate for the whole reef, since the attenuation percentage per meter looks inappropriate (discrete aspect).

Table 5. Synthesis table of Shelly Cheniers wave attenuation service studies (WHA: Wave Height Attenuation; WEA: Wave Energy Attenuation; * grey literature, PS.: pressure sensors)

Reference	Study Location	Tidal category	Materials	Site characteristics	Wave attenuation			
					WHA		WEA	
					whole	%/m	whole	%/m
Jeanson et al., 2016	BMSM, France	Mega-tidal	PS.	Well-developed shelly cheniers	/	/	98%	/
				Degraded shelly cheniers	/	/	70%	/
Mury et al., 2018	BMSM, France	Mega-tidal	PS.	Well-developed shelly cheniers	61.1%/100 m	0.61	/	/
				Degraded shelly cheniers	39.3%/100 m	0.39	/	/

Honeycomb worm and sandworm reefs

To our knowledge, WAS of honeycomb worm (*Sabellaria alveolata*) and sandworm (*Lanice conchilega*) reefs were not studied yet. Nevertheless, literature references evoke a potential mitigation process by the honeycomb colonies, which might significantly increase the surface roughness (Collin et al., 2018a) and so reduce wave energy. This lack of consideration of engineer-ecosystems into their protective role could be explained for several reasons. These biogenic structures are overall poorly known due to their relative rarity in comparison with some others features like saltmarshes or seagrasses. In addition, their location at the bottom of the intertidal zone (remote from the coastline) drives scientists to consider them as some marginal elements in the WAS of the entire intertidal zone, especially in a mega-tidal environment.

4. Discussion

This review of the existing literature about the WAS of the intertidal “ecogeosystems” in temperate areas allowed us to highlight several elements.

Indeed, it appears that WAS of some “ecogeosystems” are well documented, as it is the case for saltmarshes (Table 1). Contrariwise, some features, rarer worldwide or located lower in the intertidal zone, are poorly known, particularly shelly cheniers, honeycomb worm and sandworm reefs.

Thus, by a quantitative and qualitative analysis of the different papers, we can deduce one pattern: the more we go away from the coastline, the more we observe gaps in the WAS knowledge. The distribution of the reviewed papers along a cross-shore transect could be used to illustrate this finding (Figure 6).

Another element we drew from this review is the difficulties to harmonize the various data across studies. These difficulties are due to several factors. The first one is about the structural heterogeneity of study sites and

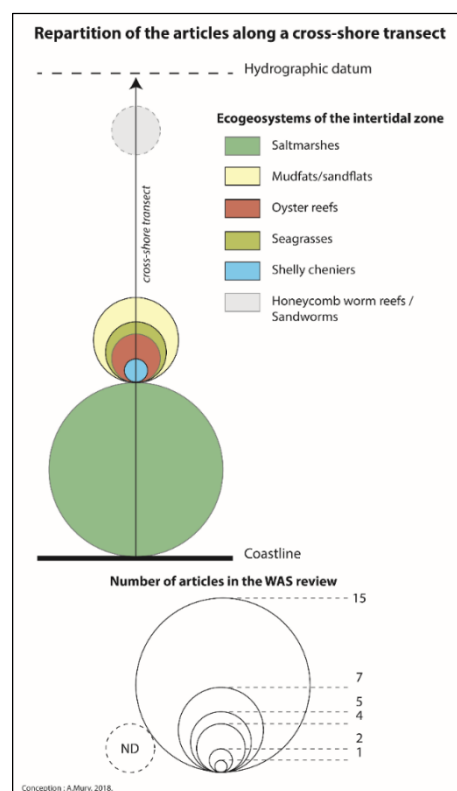


Figure 6. Scheme of papers' distribution along a conceptualized cross-shore transect

“ecogeosystems”: their shape (punctual features as cheniers versus surface features as saltmarshes), and their inherent composition (i.e., different vegetation communities for saltmarshes studies, various length measurement transects and various measurement conditions: weather, seasons, tidal category, water levels). The second reason is about the published datasets: some technical information might miss; foreshore and seabed morphometry and features backing the natural barriers, hydrodynamic regime and distance from the coastline are often not specified, thus introducing

biases in the data harmonization due to the ignorance of the influence of these elements on the WAS. The third reason concerns the heterogeneity of measurement methods between the different studies (pressure sensor, buoy, wave recorder), which complexify and even impede the comparison between studies. Moreover, significant wave height calculation methods are overshadowed, because of the absence of specifications in papers.

As a single variable based on significant wave height WHA might appear as a simplistic methodological choice in this review. Not considered in this review were the characteristics linked to the tidal regime (infragravity waves) and the flow velocity, taking probably part of the marine flood hazards. Moreover, in most cases, WHA is mathematically approached as a linear process along the study section while it is obviously a non-linear process in the complex real world (Koch et al., 2009). The wave reduction decreases from the start to the end of the section, i.e., the shoaling effect, which is rarely investigated in the research studies. This simplified linear approach of the mitigation process could be explained by the methodological and material contingencies. Indeed, frequently the data used for the calculation of the wave attenuation arise from punctual and fixed stations, at the beginning and the end of the study section. This approach does not allow to observe the process in its entirety. Several technical processes, in on-going development, should correct for this problem, in particular by the contribution of the high-resolution satellite imagery (Collin et al., 2018b).

Table 6 synthetizes results obtained from the papers reviewed. Despite its plain design, the table gives a first overview of the WAS value for every studied “ecogeosystem”.

Table 6. Synthesis table of WAS from the meta-analysis (WHA: Wave Height Attenuation, * Wave Energy Attenuation data were used for Shelly Cheniers)

Shape	Ecogeosystems	WHA
Surface	Saltmarshes	0.05-7.86%/m
	Mudflats	0.01-4%/m
	Seagrasses	0.03-0.77%/m
Punctual	Oyster reefs	1-64% (whole reef)
	Shelly Cheniers	70-98% (whole transect)*

To conclude, a work of harmonization of the results of the different studies is recommended by insisting on the transparency in the methods used. To leverage a generic model adaptable for all coastlines with their diversity of “ecogeosystems” and specificities, we propose to improve the knowledge about all the potential “ecogeosystems” WAS worldwide. To solve the problem of harmonization, a

robust approach would be to either find generic metrics across all “ecogeosystems” or ranking them through a table showing both range, mean and standard deviation values. This synoptic product holds great promise to be integrated into toolboxes of stakeholders tasked with nature-based mitigation of coastal risks.

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