Spatial diversity and time variability of erosion and accumulation processes on the unconsolidated cliffs of the Wolin Island (Southern Baltic - Pomeranian Bay)

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The rate of cliff recession depending on the geological structure

(Sunamura 1983)

- Granite cliffs – <1 mm/yr
- Limestone cliffs – < 1 cm/yr
- Chalkstone and sandstone – < 1 m/yr
- Unconsolidate cliffs – up to few m/yr

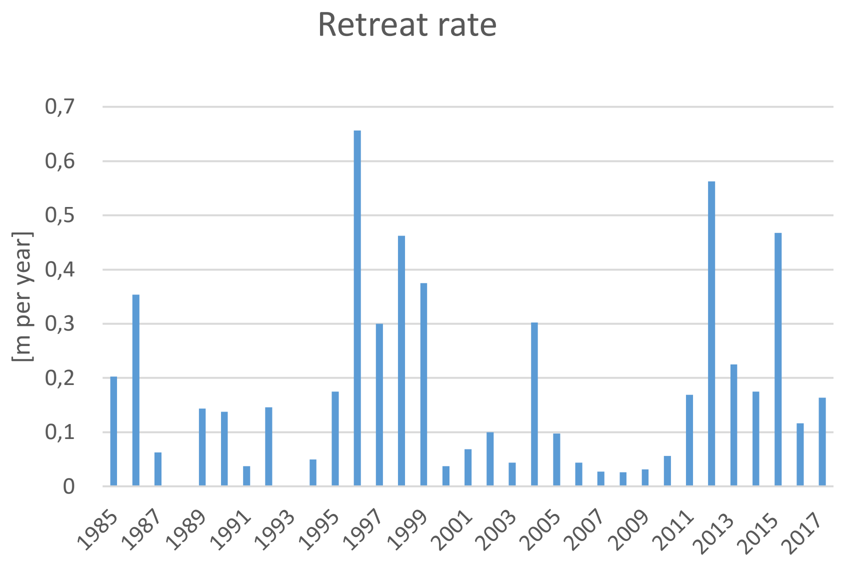
Main goal

Quantification of the sediment budget of unconsolidated cliffs of the Wolin Island in the years 2013-2019

Moraine cliffs (Wolin Island, Poland)

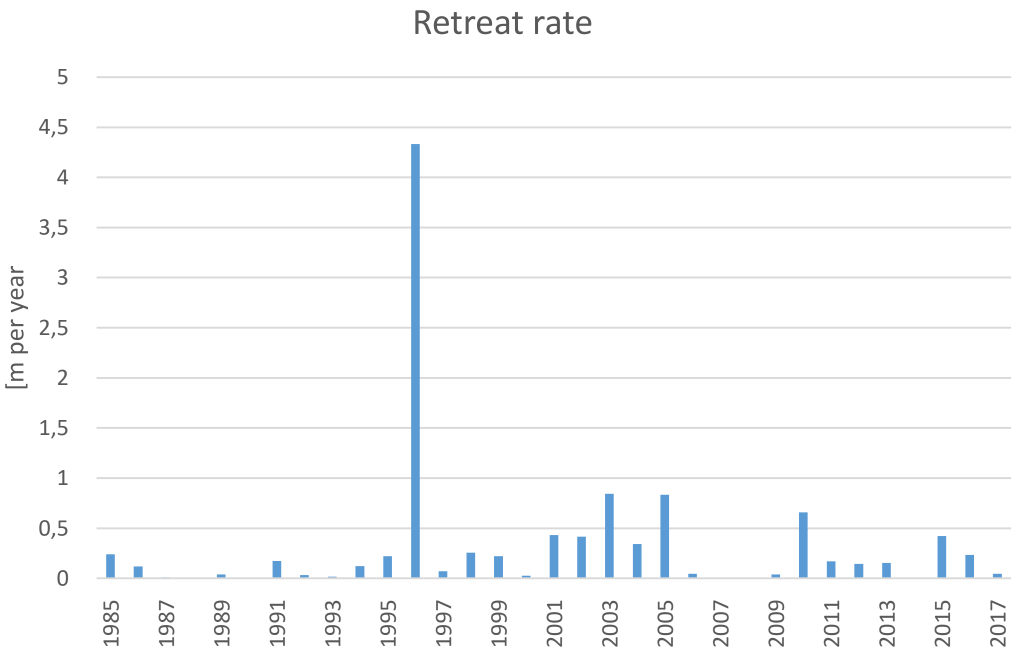
Clay cliffs

- Slope <80^{o}
- Resistance:
  - ✓ τ_{fu}-100-150kPa
  - ✓ ρ – 2,0-2,3 g/cm^3
  - ✓ W_P – 10-14%
  - ✓ W_L – 14-23%
- Low recession rate
  - ✓ 0,10 – 0,18 m/a
  - ✓ Long response time
- Weathering (30-40 cm):
  - ✓ Mechanical
  - ✓ Chemical
  - ✓ Biological
- Clay flacking– susceptibility to fall



Sandy cliffs

- Slope $<40^{o}$
- Low resistance:
  - ✓ τ_{fu}- 40-80 kPa
  - ✓ ρ – 1,7-1,8 g/cm^3
  - ✓ I_D – 0,2-0,6
- Short response time
- High recession rate
  - ✓ 0,30-0,35 m/a



Unconsolidated cliffs degradation types:

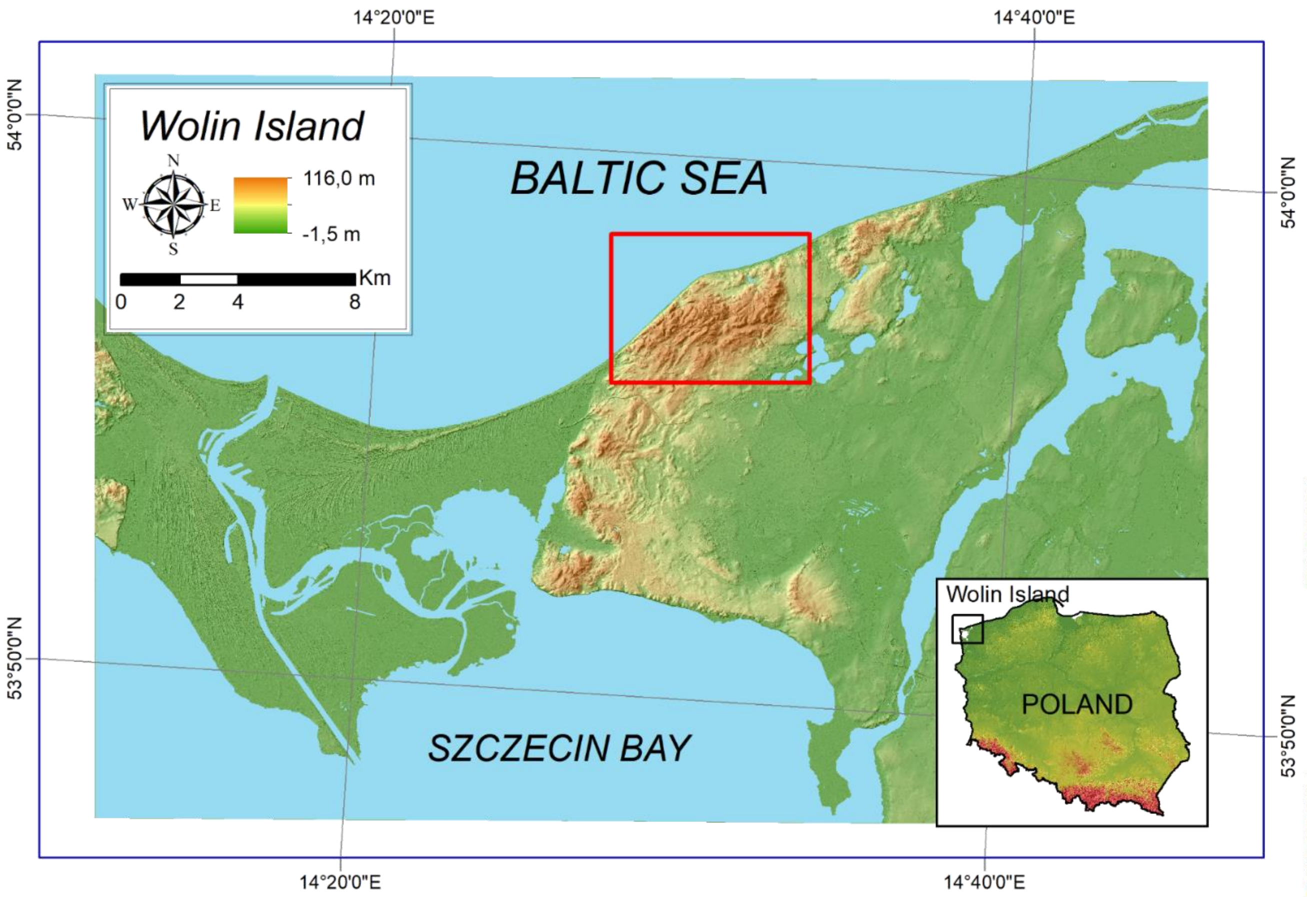
(Hall et al., 2002, Collins, Sitar 2008; Young et al. 2009; Furlani et al. 2011)

1. Slow and continuous erosion caused by hydrometeorological conditions with low and average morphogenetic potential,
2. Episodic and rapid erosion conditioned by factors with high morphogenetic potential (storm surges and heavy rainfall) dominated by sub-aerobic processes generating mass movements.

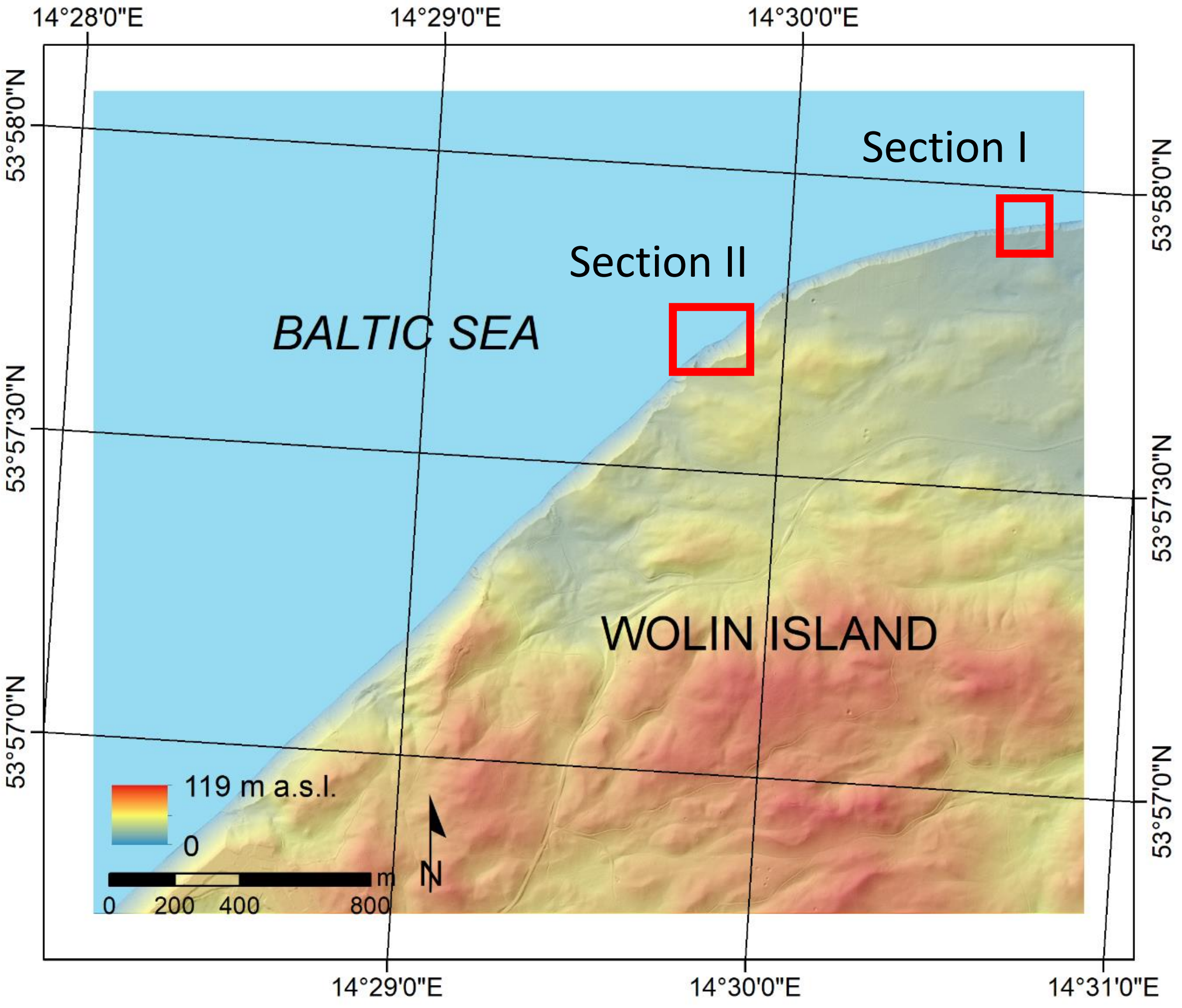
The dominance of degradation processes is conditioned by the time scale:

- short scale (annual, 10-year) - recession rate depends on weather conditions and sea dynamics,
- long scale (100-year, 1000-year) - the evolution of the coast is determined by eustatic and glacieustatic movements.

Study area



Wolin Island
116,0 m
-1,5 m
Km
0 2 4 8
BALTIC SEA
SZCZECIN BAY
Wolin Island
POLAND
14°20'0"E
14°40'0"E
54°0'0"N
53°50'0"N

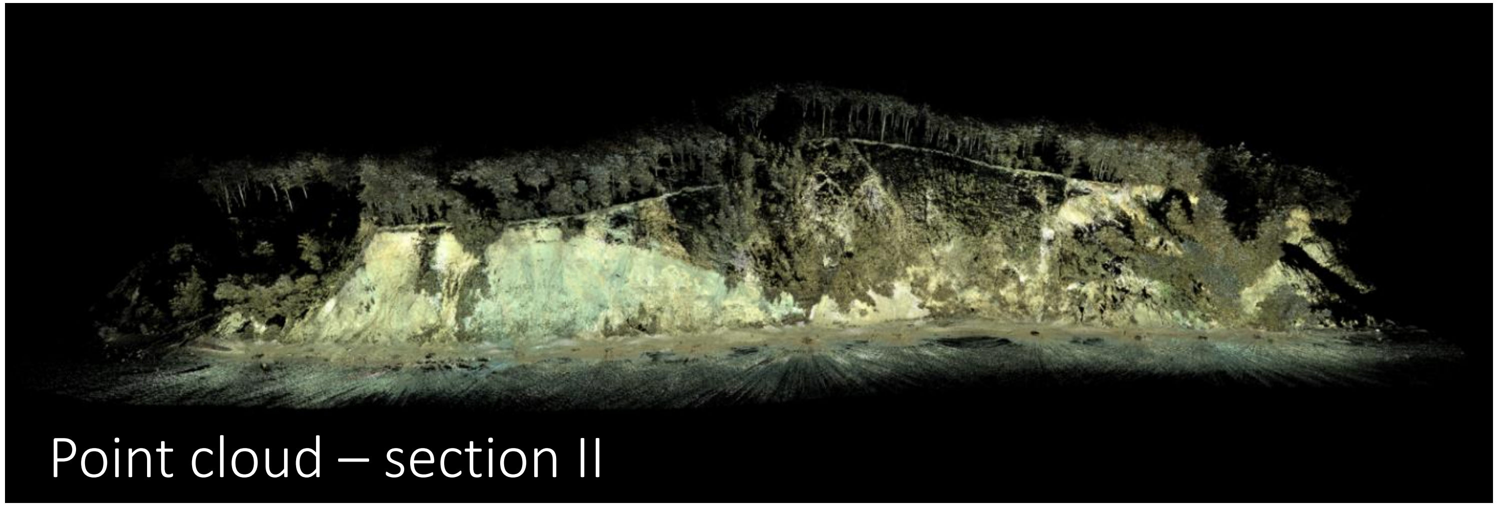


14°28'0"E
14°29'0"E
14°30'0"E
14°31'0"E
53°58'0"N
53°57'30"N
53°57'0"N
Section I
Section II
BALTIC SEA
WOLIN ISLAND
119 m a.s.l.
0
m
0 200 400 800
N

Methods

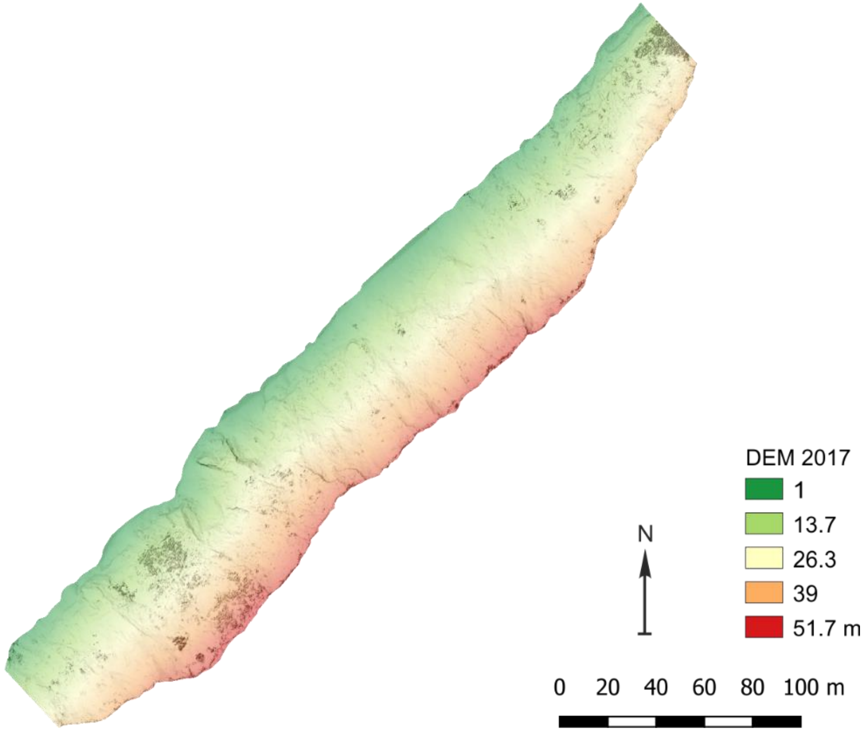
Field survey: Terrestrial Laser Scanning (TLS) (Geocartis sp. z o.o.)

Leica ScanStation c10

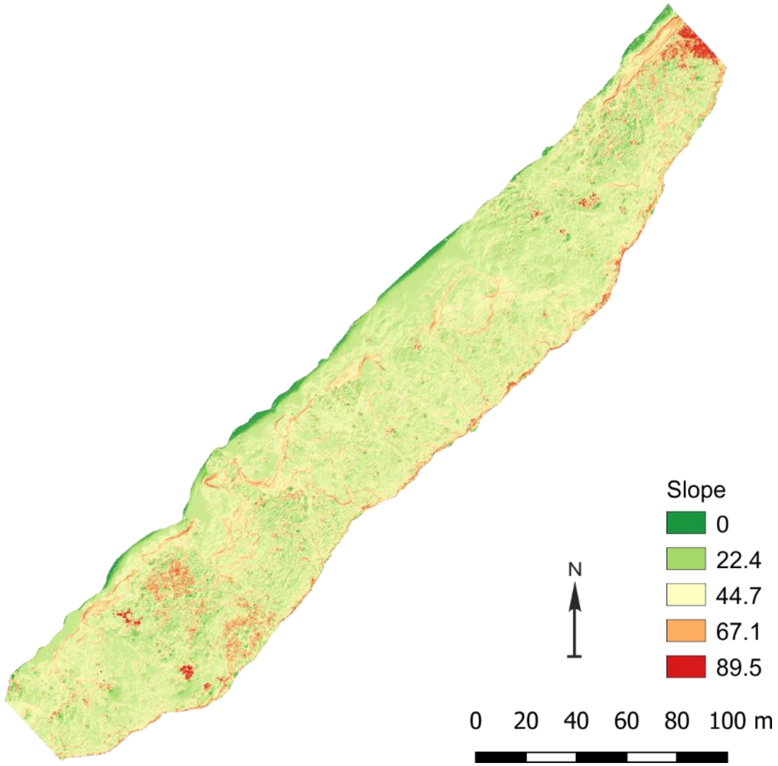


Methodology
GIS Analysis: Morphology and morphometry

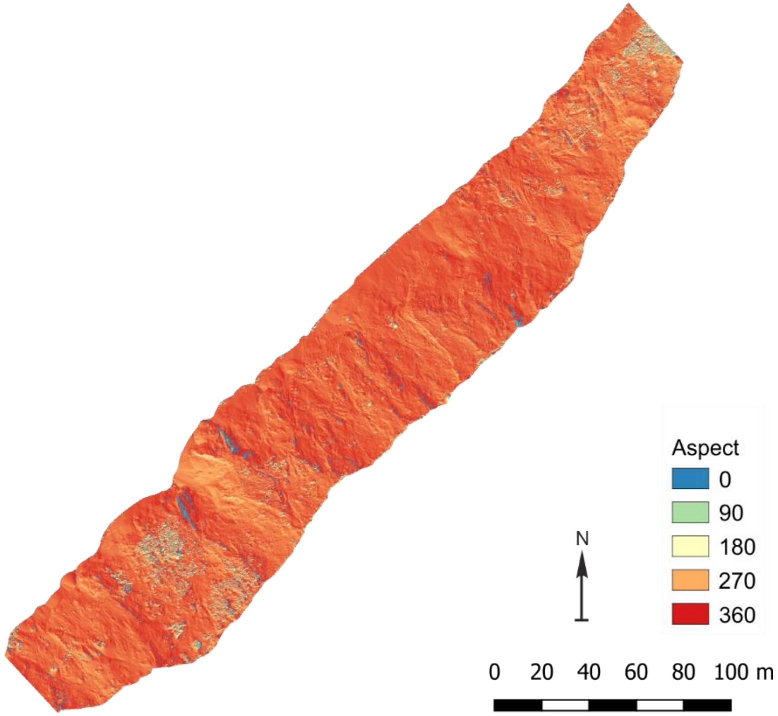
Digital Elevation Model



Slope model



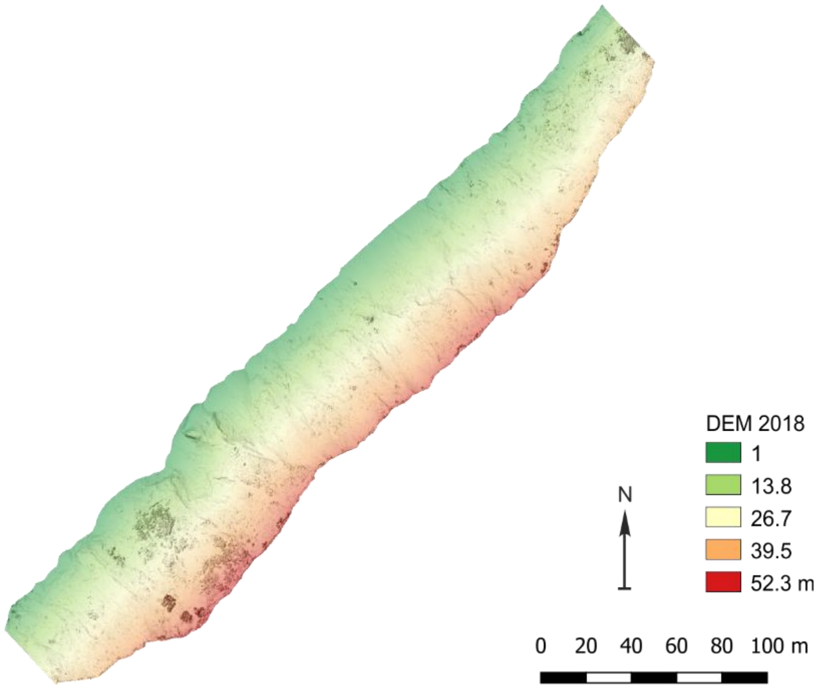
Aspect model

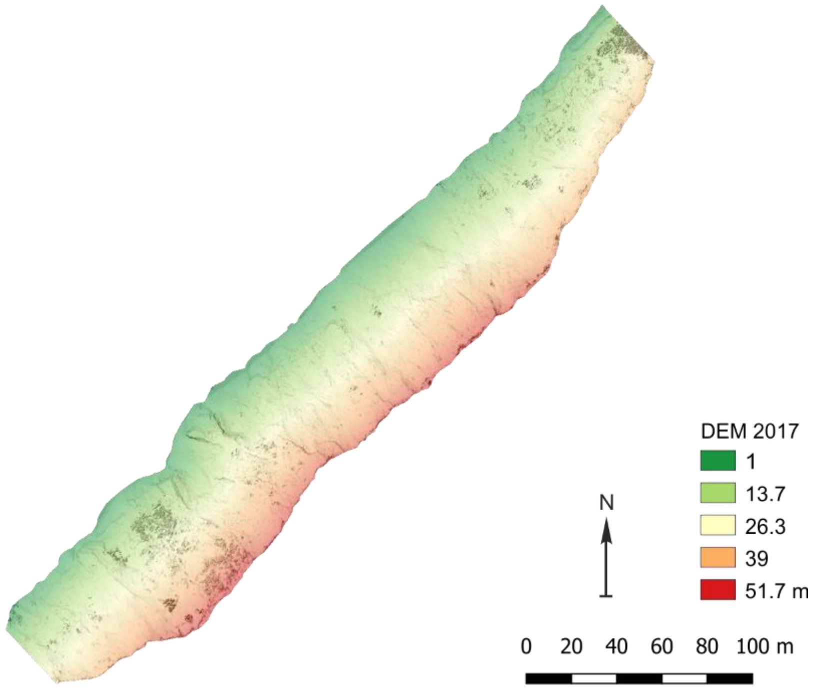


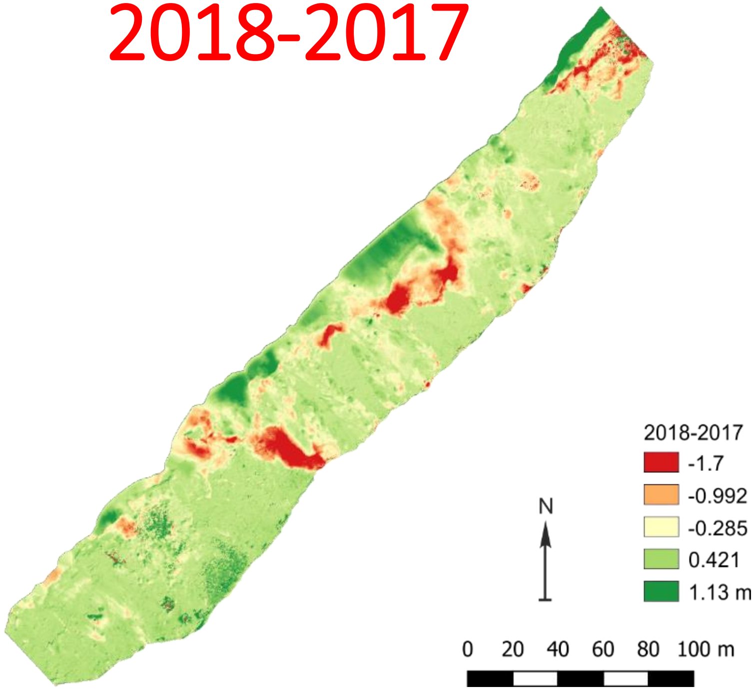
Methodology

GIS Analysis: Sediment budget

DEM 2018 – DEM 2017 = Differential elevation map (DoD) 2018-2017

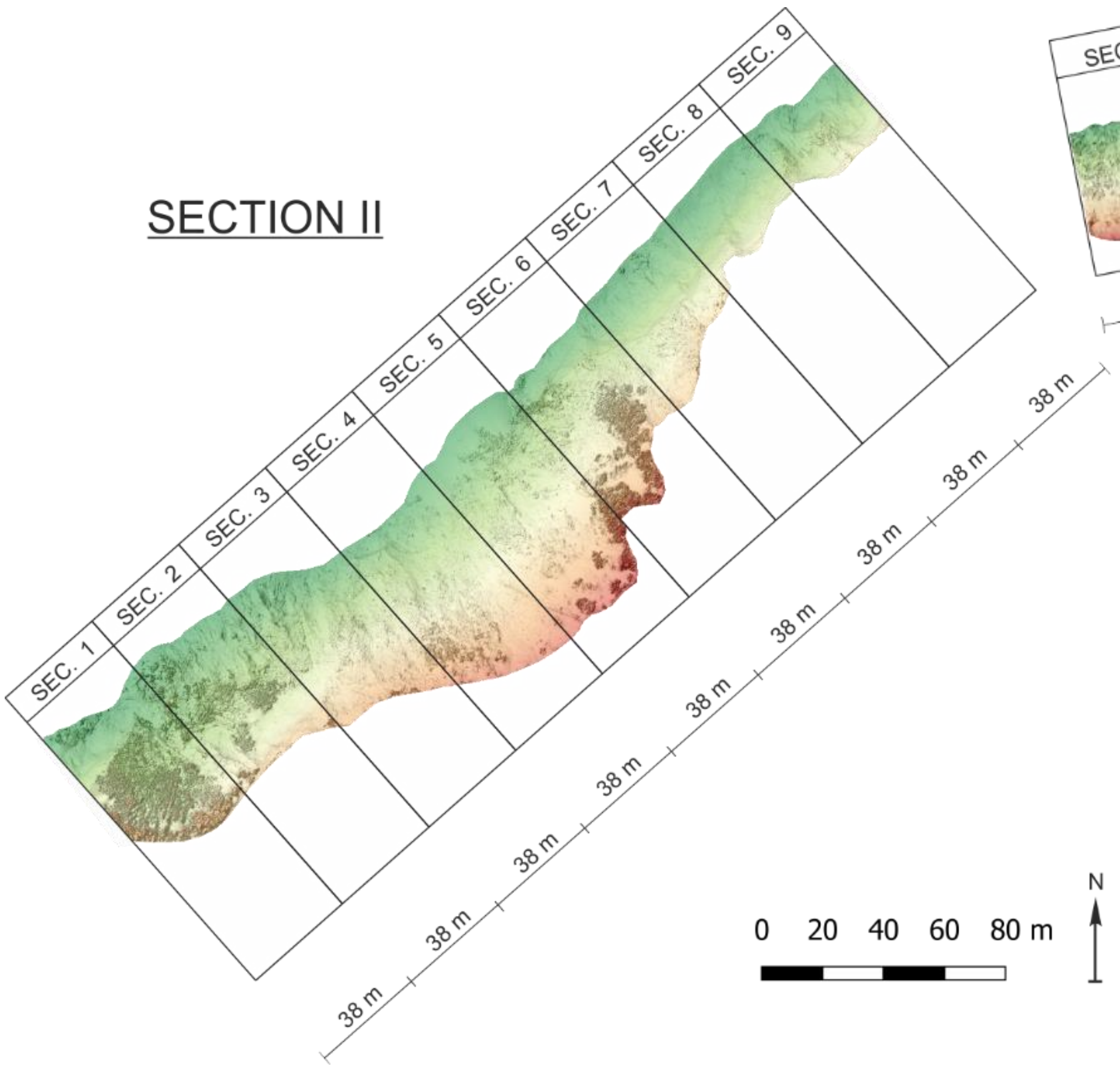


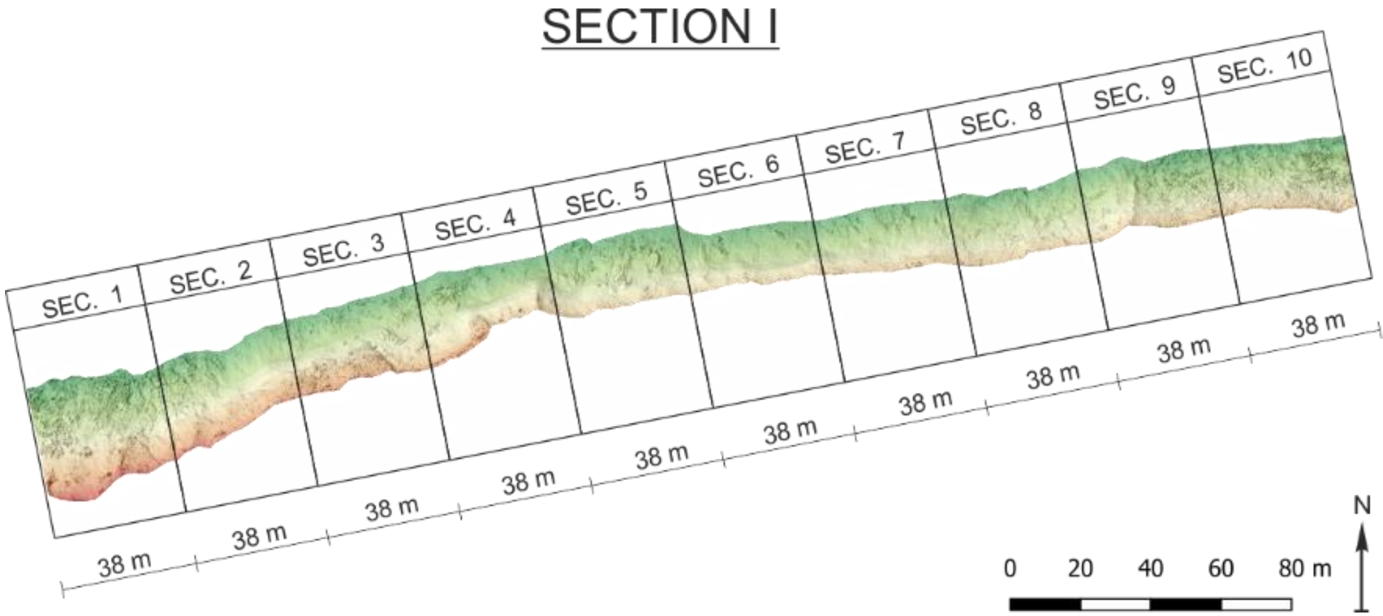




Work timeline:	1	2	3	4	5	6
• Section I –	2013.07	2015.04	2016.04	2017.04	2018.05	2019.04
• Section II –	2013.07	2015.04	2016.04	2017.04	2018.05	2019.04

Methodology
GIS Analysis: Section division





- Sections divided into equal sectors (38 m),
- Section I - 10 sectors
- Section II - 9 sectors
- **Possibility of spatial analysis of erosion and accumulation processes.**

Methodology
Sediment budget index

- Cliff efficiency index (nearshore supply)

$$E = \frac{V}{L}\ [\mathrm{m^3/m}]$$

  - E – Cliff efficiency,
  - V – volume (budget),
  - L – section lenght

- Cliff dynamics index

$$D = \frac{V}{P}\ [\mathrm{m^3/m^2}]$$

  - D – Cliff dynamics,
  - V – volume (budget),
  - P – section area.

Marine conditions of cliff denudation

Period I (07.2013 – 04.2015) – 643 days

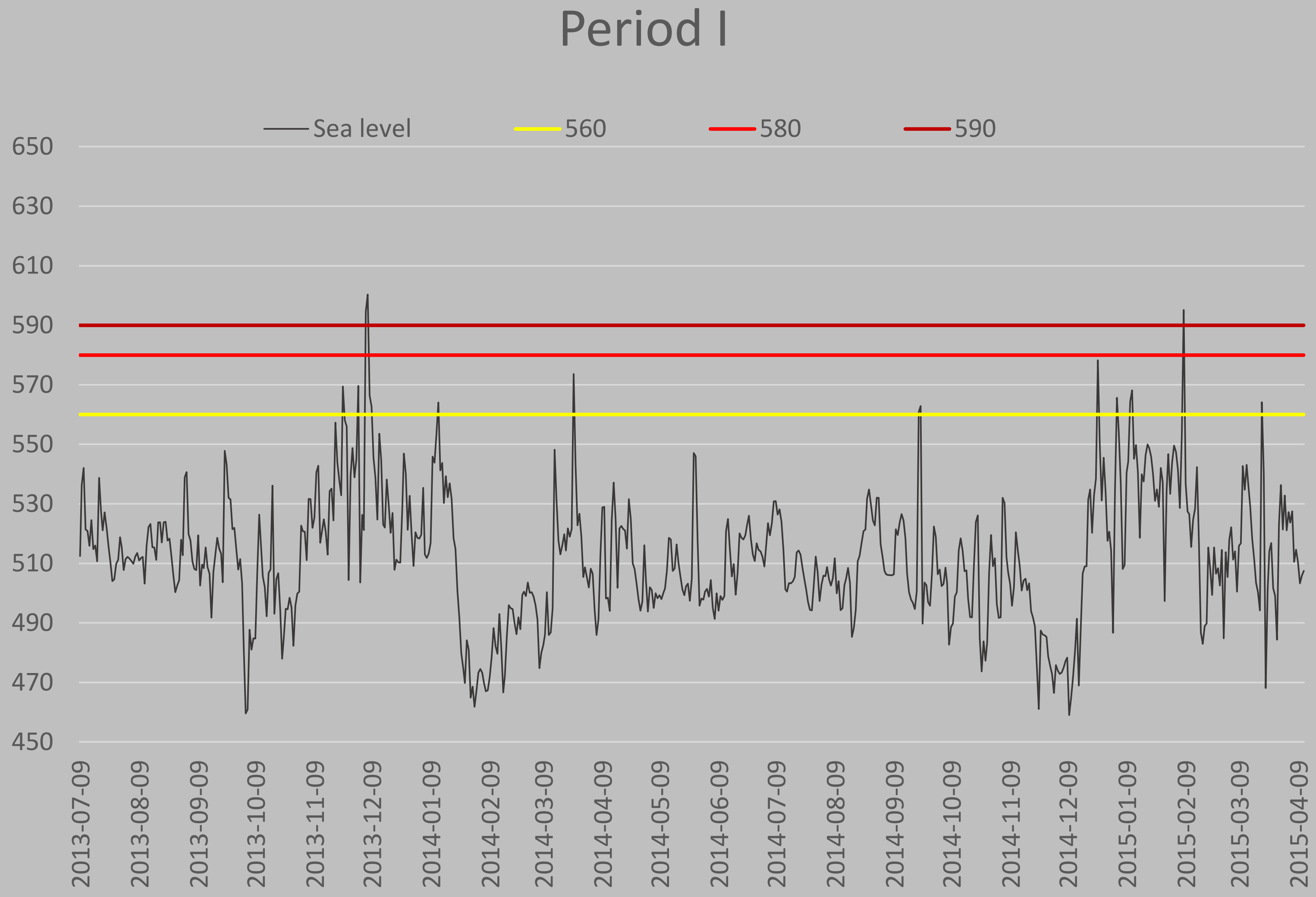
<u>2 storm surges</u>

Max sea level – 600 cm,

Max. height of significant wave – 3,44 m

Sea level duration:

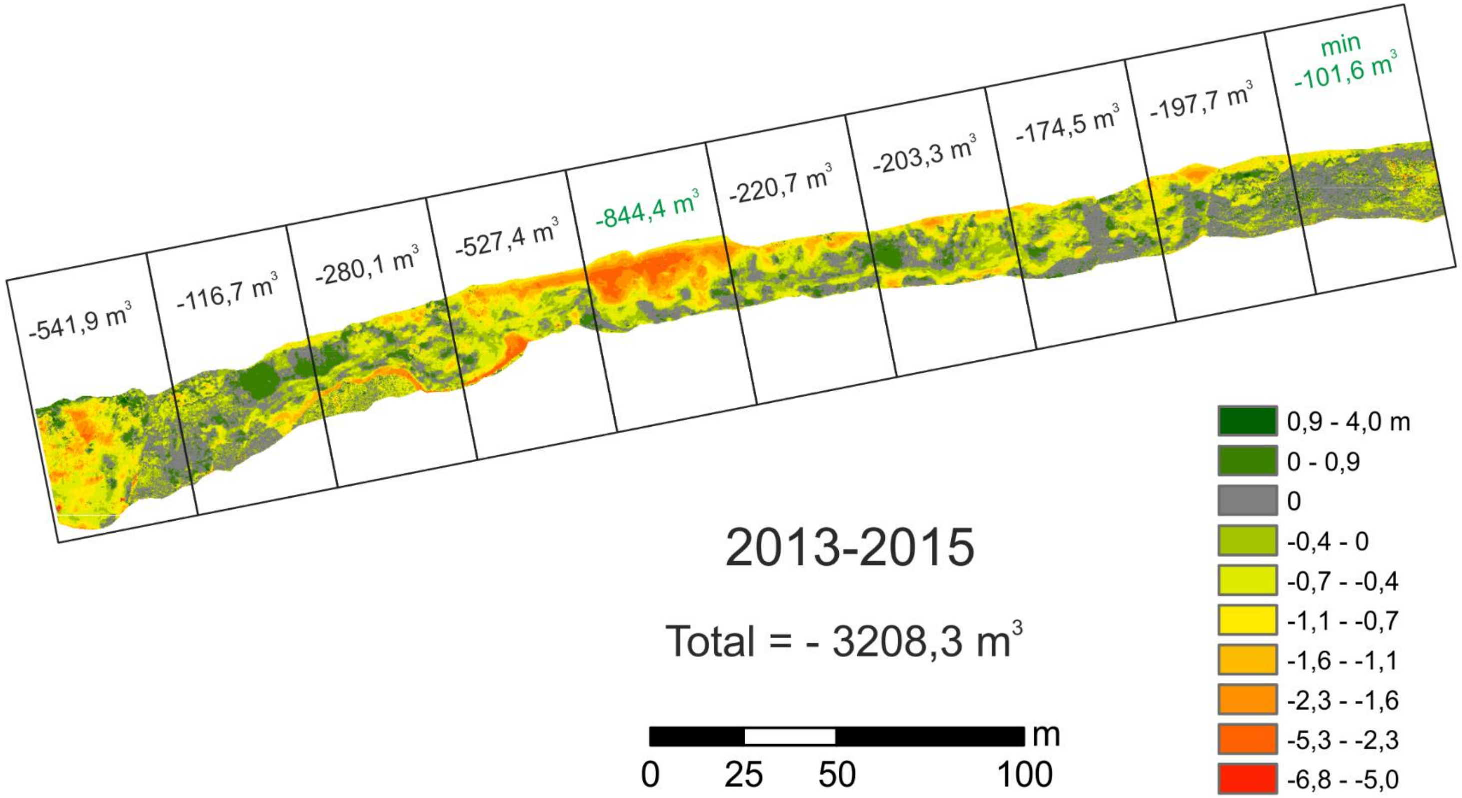
- 560-580 cm – 82 h,
- 580-590 cm – 15 h,
- > 590 cm – 16 h.

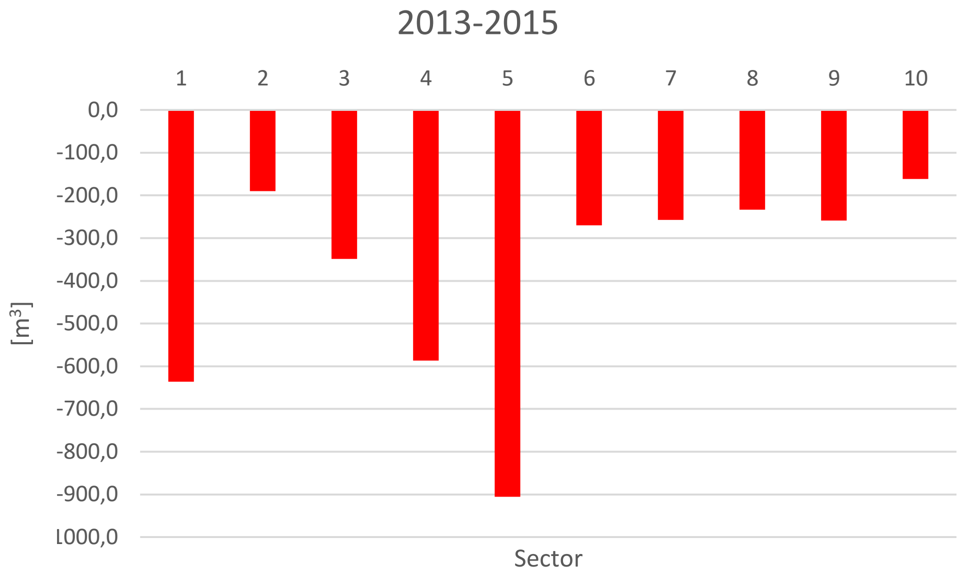


Results – Sediment budget

Section I

(Period I) - 07.2013 – 04.2015 - 643 days





Total sediment budget – **-3208,3 m³,**

- Max erosion - middle part of section
- Min erosion – eastern part of section

Erosion rate:

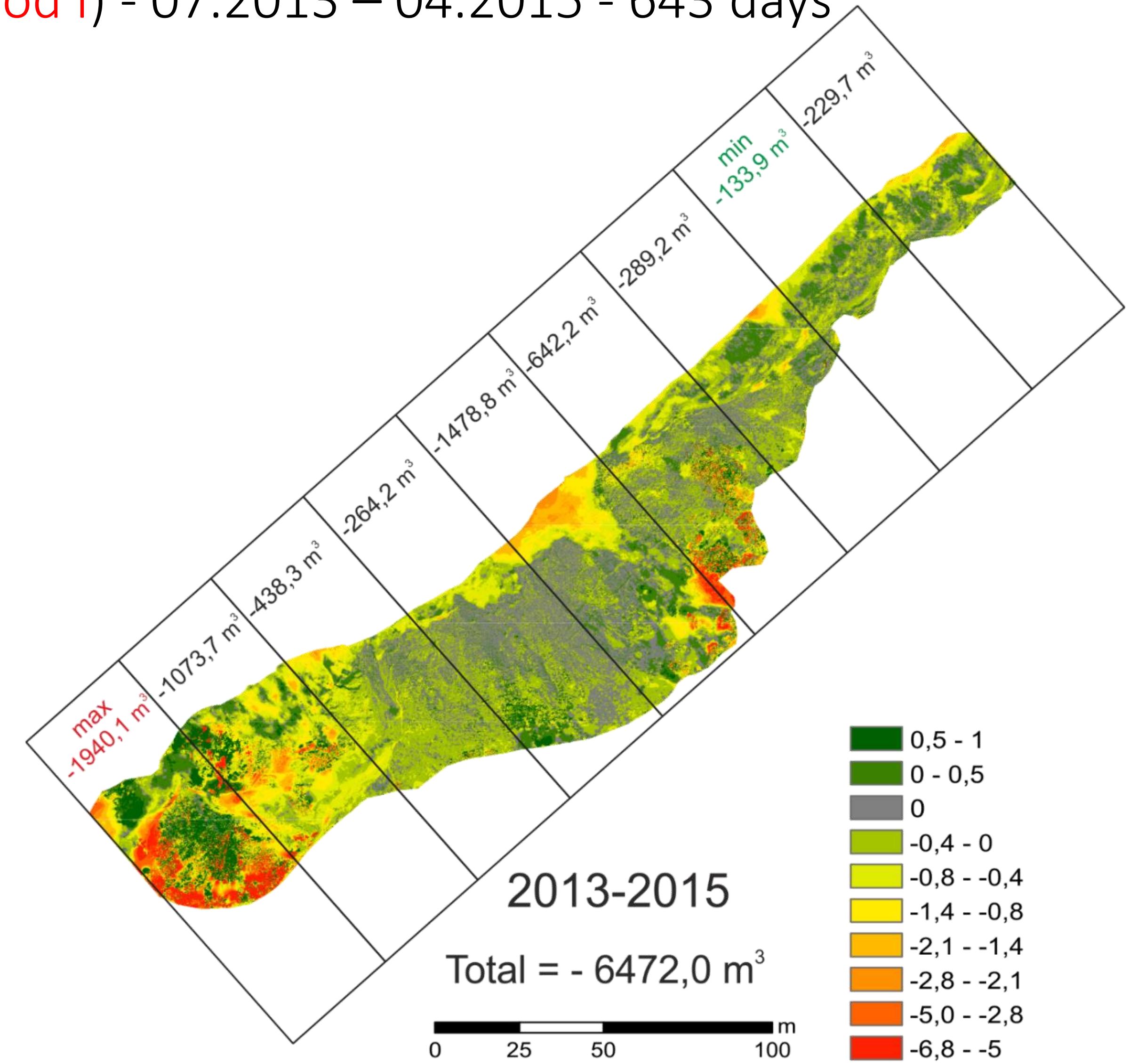
✓ **-8,44 m³/m,**

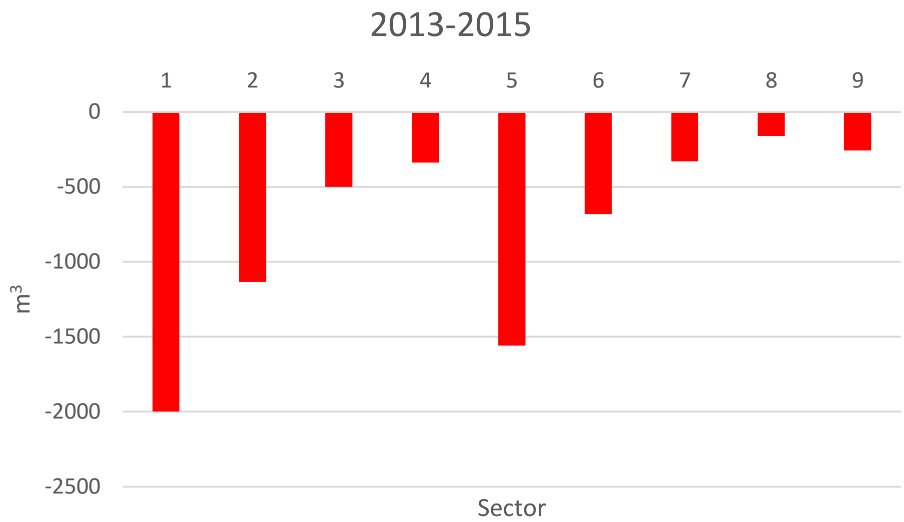
✓ **-0,40 m³/m²**

Results – Sediment budget

Section II

(Period I) - 07.2013 – 04.2015 - 643 days





Total sediment budget – - **6472,0 m³,**

- Max erosion - western part of section
- Min erosion – middle and eastern part of section

Erosion rate:

✓ **-18,92 m³/m,**

✓ **-0,37 m³/m²**

Marine conditions of cliff denudation

Period II (04.2015 – 04.2016) – 358 days

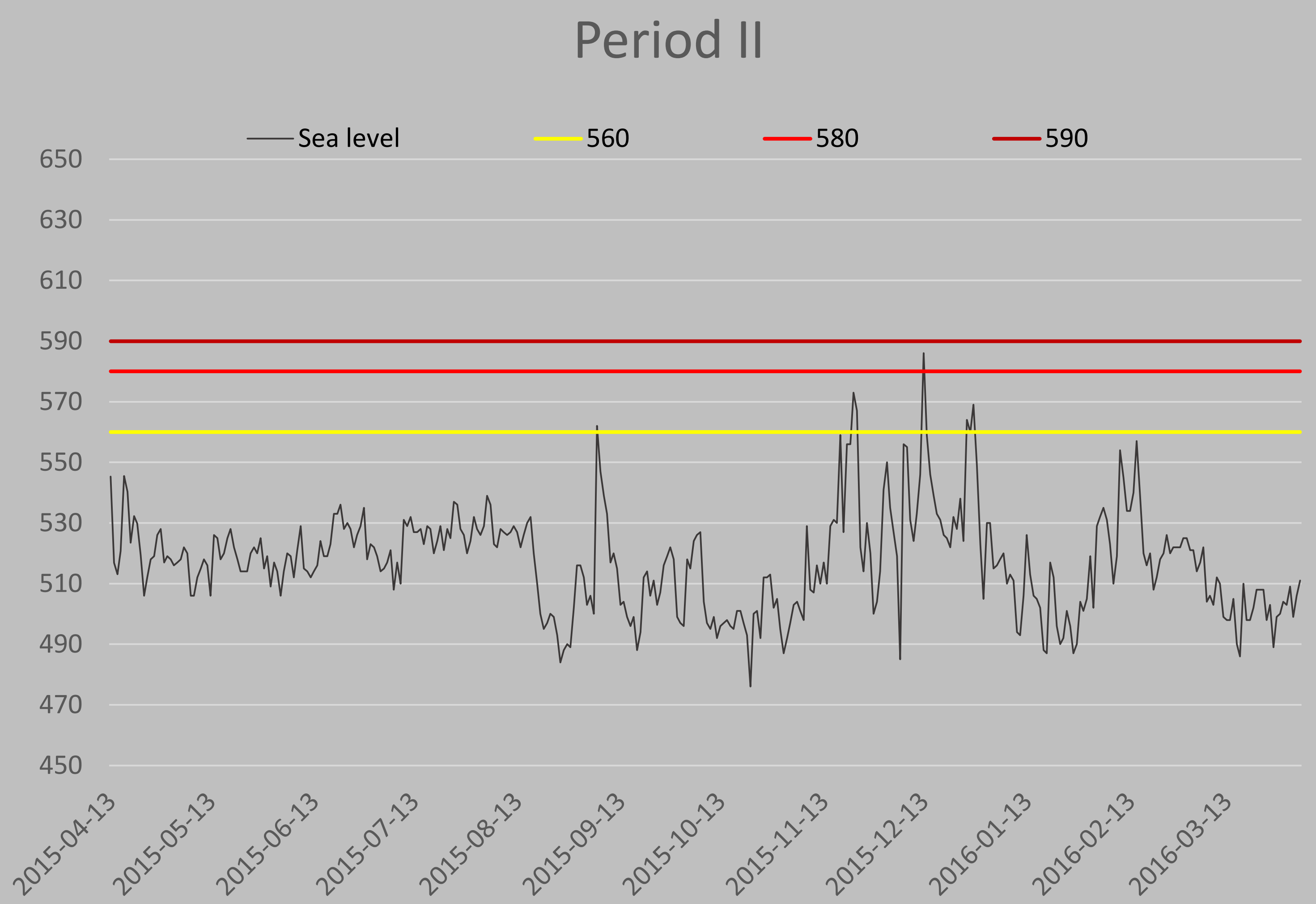
<u>1 storm surge</u>

Max sea level – 586 cm,

Max. height of significant wave – 1,3 m

Sea level duration:

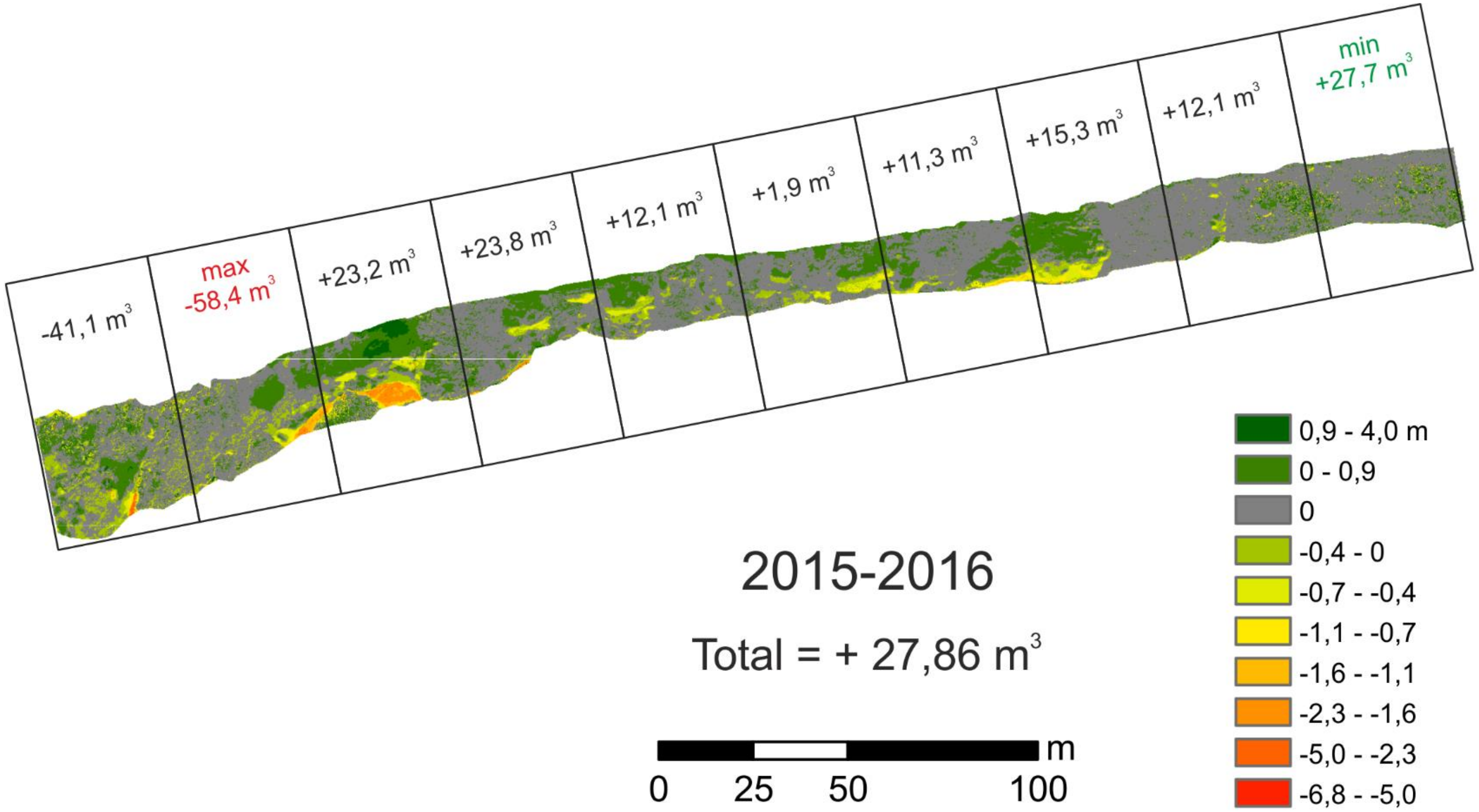
- 560-580 cm – 53 h,
- 580-590 cm – 2 h,
- > 590 cm – 0 h.

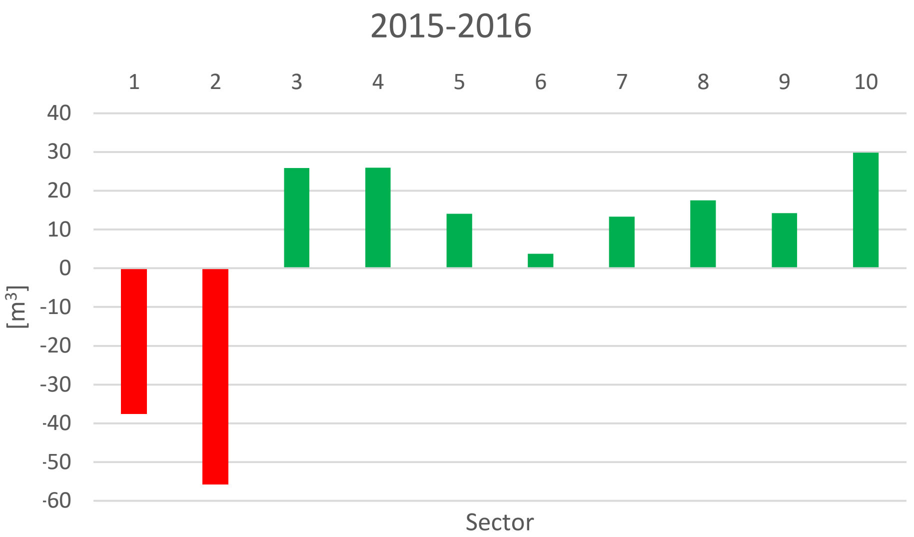


Results – Sediment budget

Section I

(Period II) - 04.2015 – 04.2016 – 358 days.





Total sediment budget – **+27,86 m³,**

- Max erosion - western part of section
- Min erosion – eastern part of section

Erosion rate:

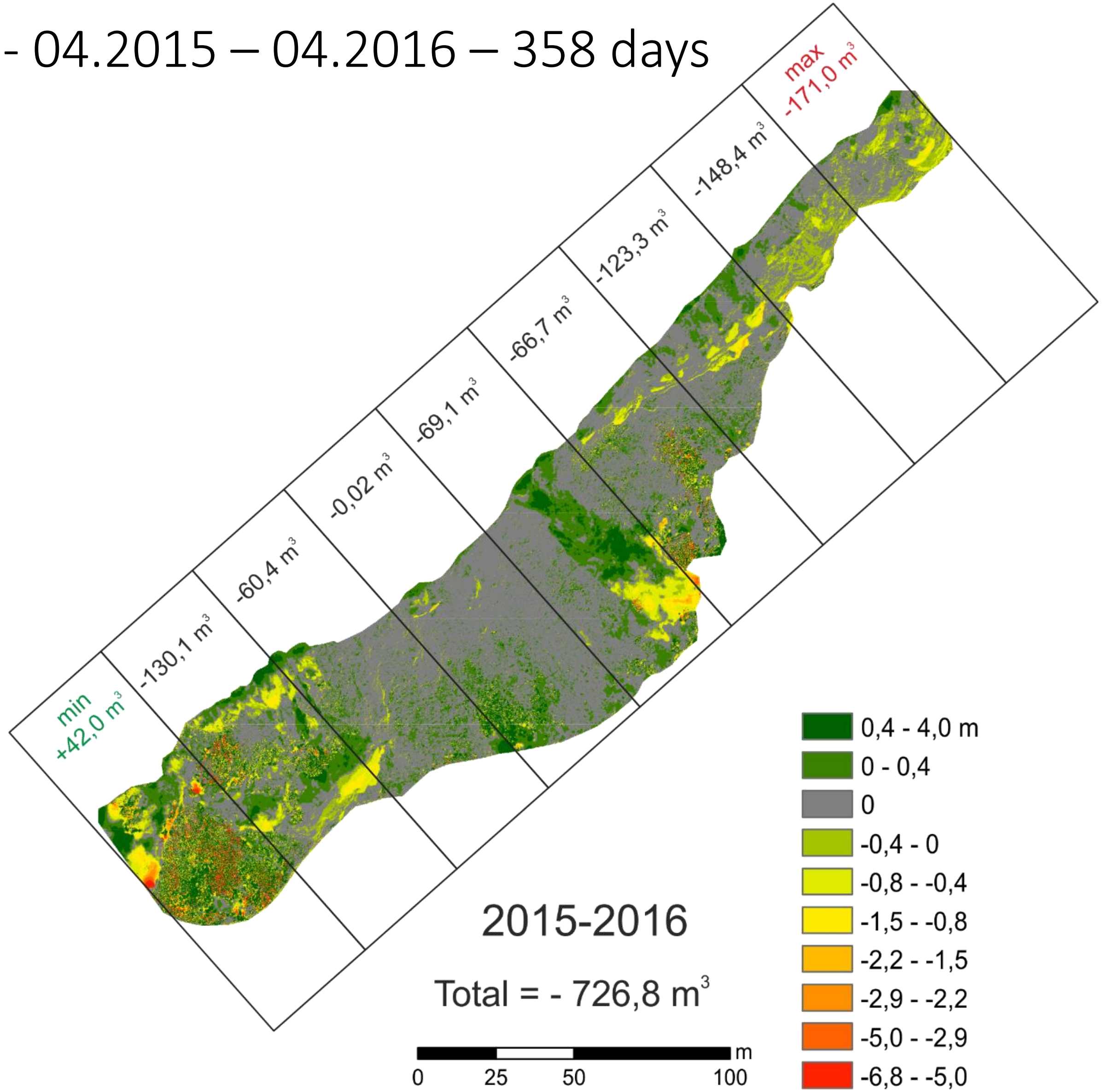
✓ **+0,14 m³/m,**

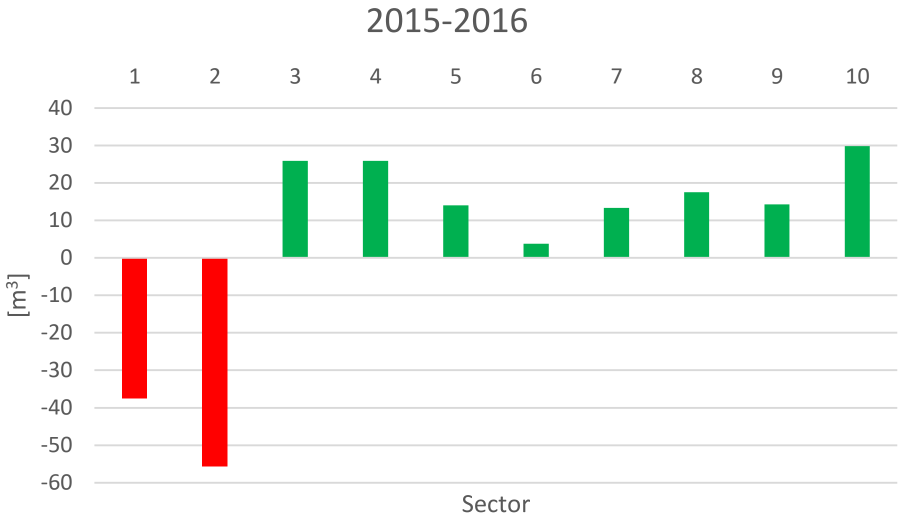
✓ **+0,01 m³/m²**

Results – Sediment budget

Section II

(Period II) - 04.2015 – 04.2016 – 358 days





Total sediment budget - **-726,84 m³,**

- Max erosion - western part of section
- Min erosion – eastern part of section

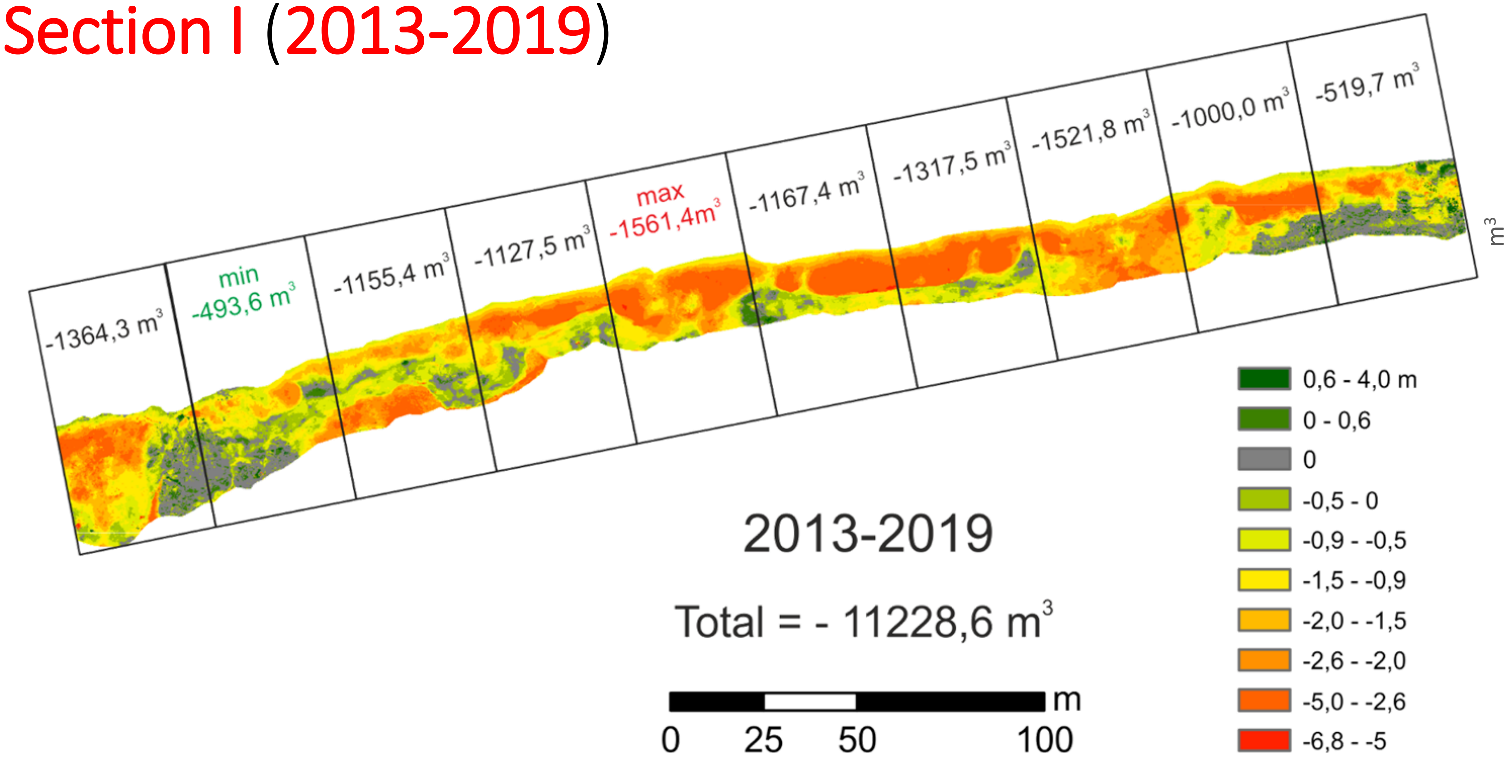
Erosion rate:

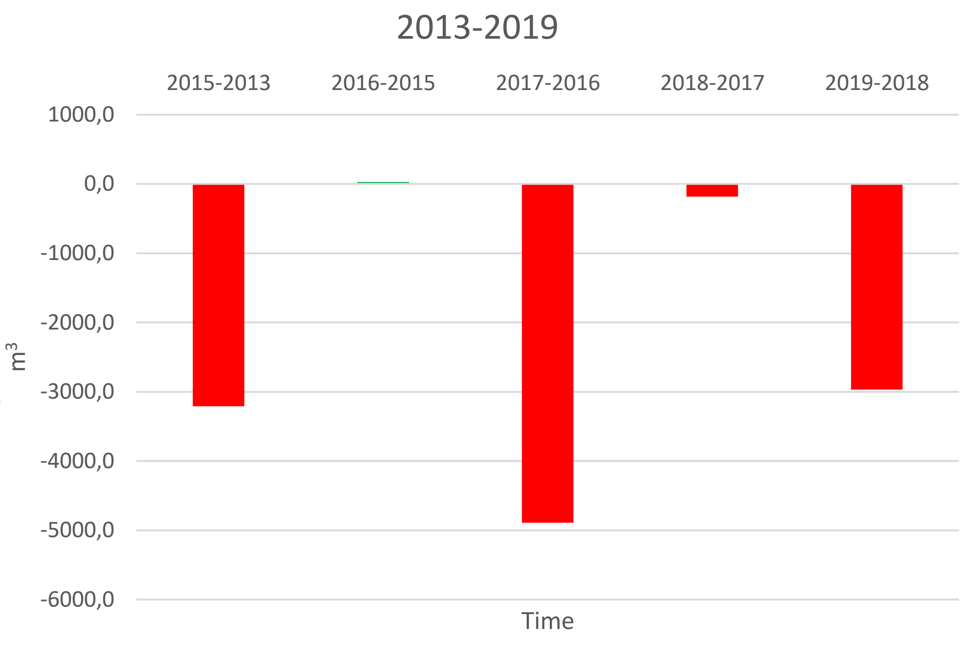
✓ **-2,12 m³/m,**

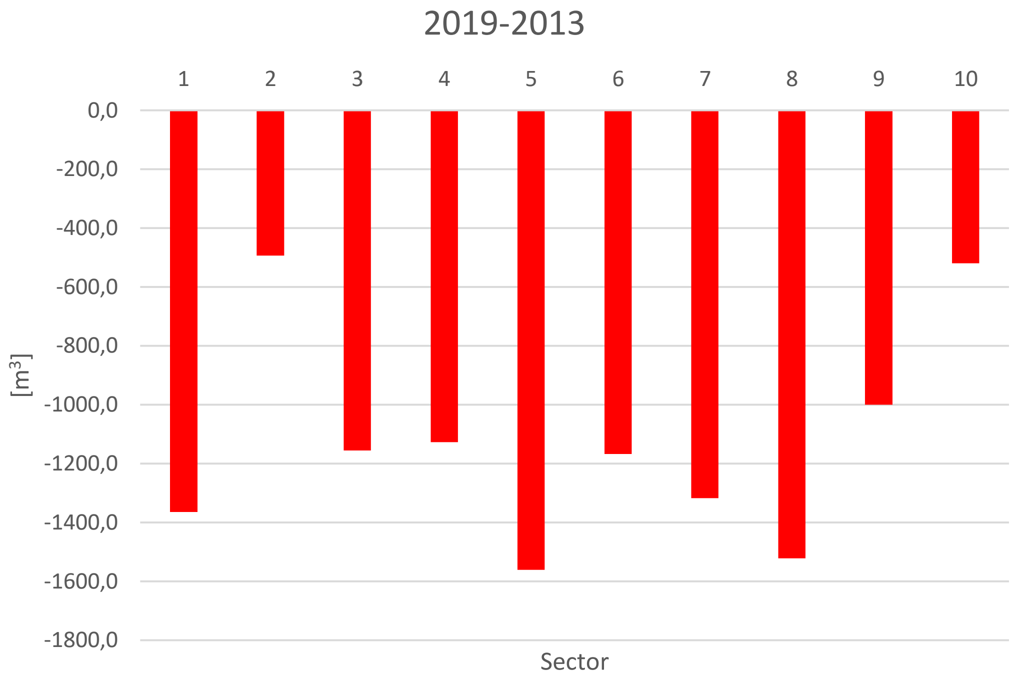
✓ **-0,06 m³/m²**

Results – Sediment budget

Section I (2013-2019)







Total sediment budget – **11228,6 m³,**

- Max erosion in 2016-2017 (III period) - - 4892,8 m³
- Min erosion in 2015-2016 (II period) - + 27,9 m³
- Evenly distributed erosion with 2 exceptions (2 and 10 sector)

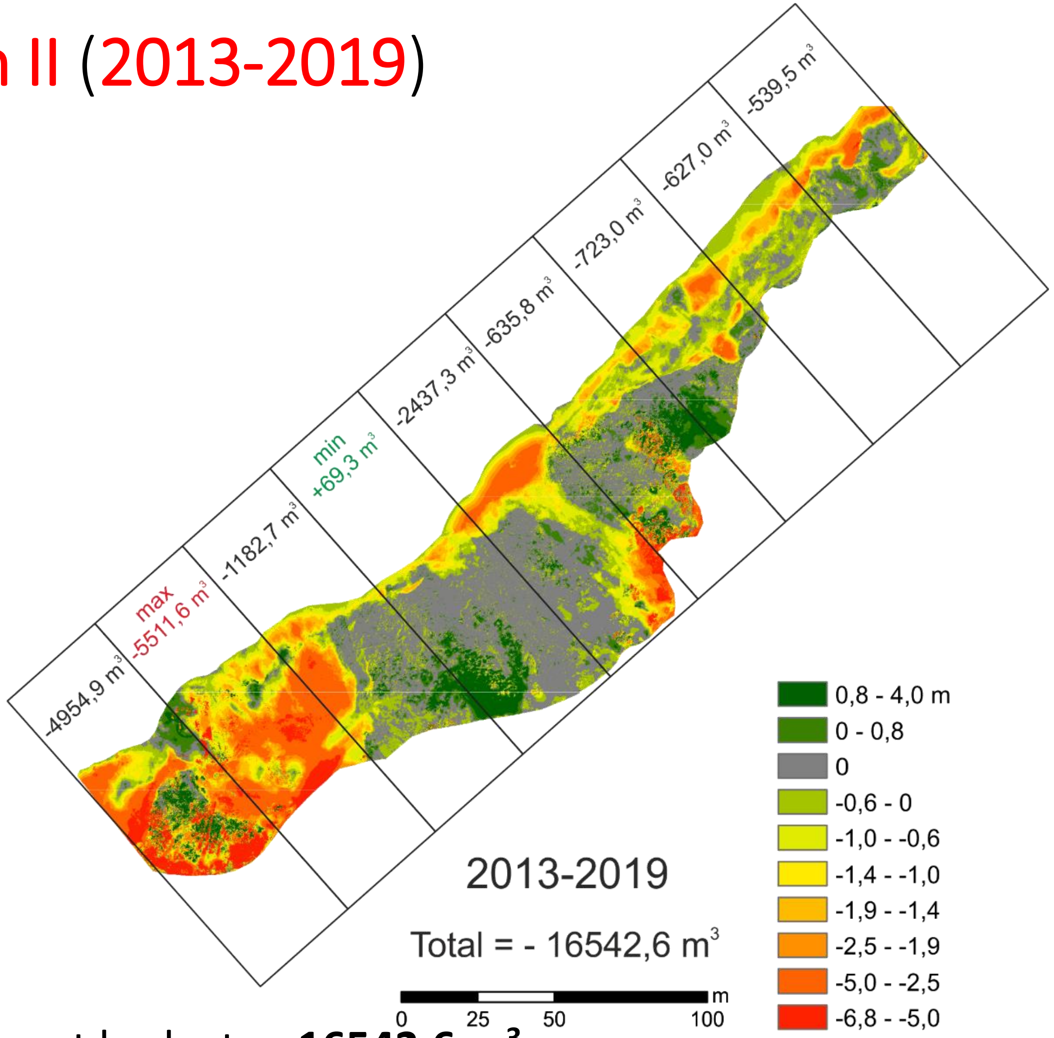
Total erosion:

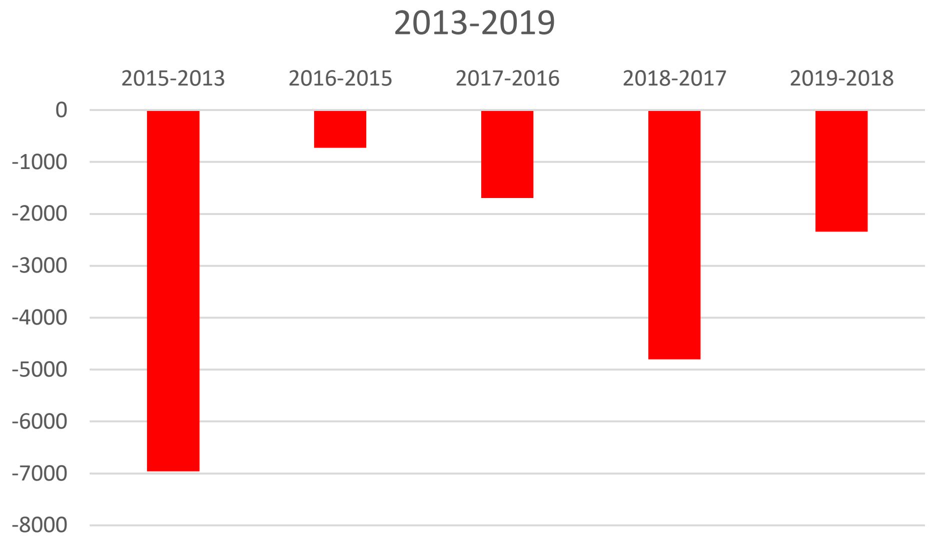
✓ **-29,55 m³/m; -4,90 m³/m/yr**

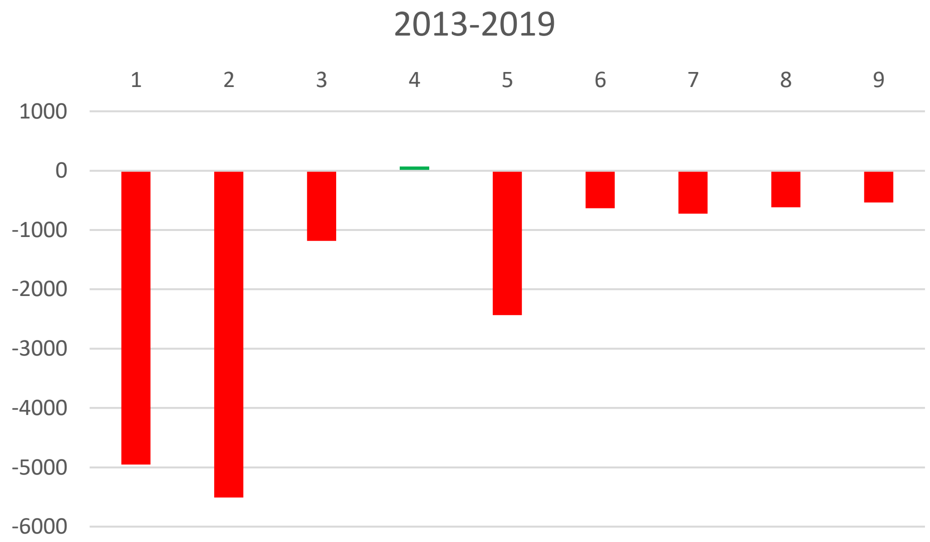
✓ **-1,46 m³/m²; -0,24 m³/m²/yr**

Results – Sediment budget

Section II (2013-2019)







Total sediment budget – **-16542,6 m³,**

- Max erosion in 2013-2015 (I period) - -6472,1 m³ (2 years)
- Min erosion in 2015-2016 (II period) - -726,84 m³
- Significant erosion – western part of section – big landslide
- Low erosion – eastern parto ofsection – resistant clay cliffs

Total erosion:

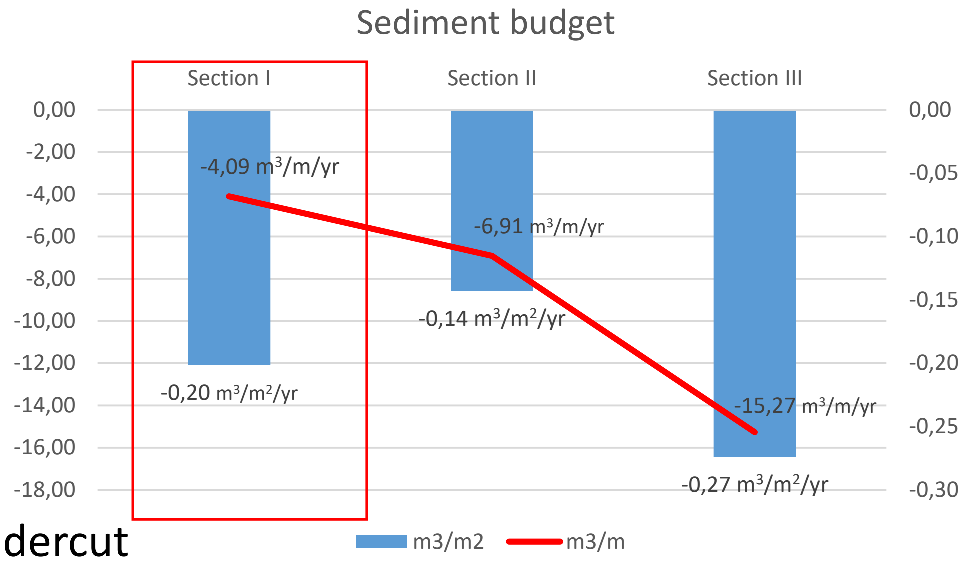
✓ **-48,37 m³/m; -8,06 m³/m/yr**

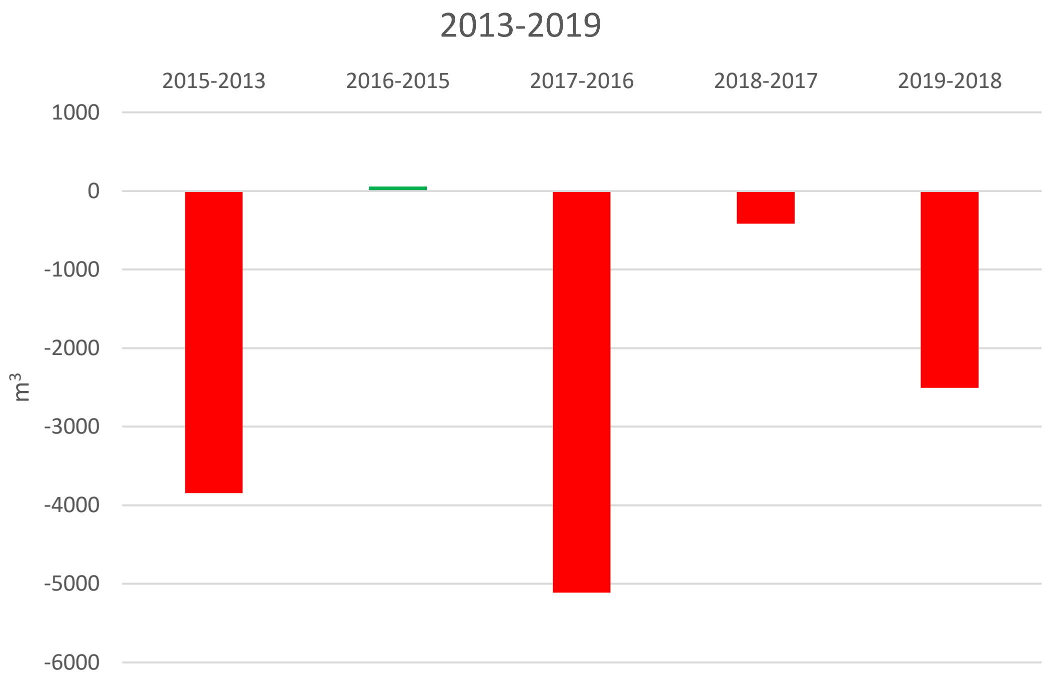
✓ **-1,00 m³/m²; -0,17 m³/m²/yr**

Results – Sediment budget

Section I

- Mostly clay cliff – relatively resistant sediments,
- Low height – 19-27 m,
- **Total erosion (2013-2019) – -11228.6 m^3,**
- Lowest erosion - +27.9 m^3 (period II 2015-2016)
    - max sea level 586 cm, storm duration – only 2 h.
- Max erosion - -4892,83 m^3 (period III 2016-2017) – extensive abrasion undercut
    - max sea level – 640 cm, storm duration 75 h.
- **Cliff efficiency – - 4,90 m^3/m/yr**
- **Cliff dynamics - -0,24 m^3/m^2/yr**



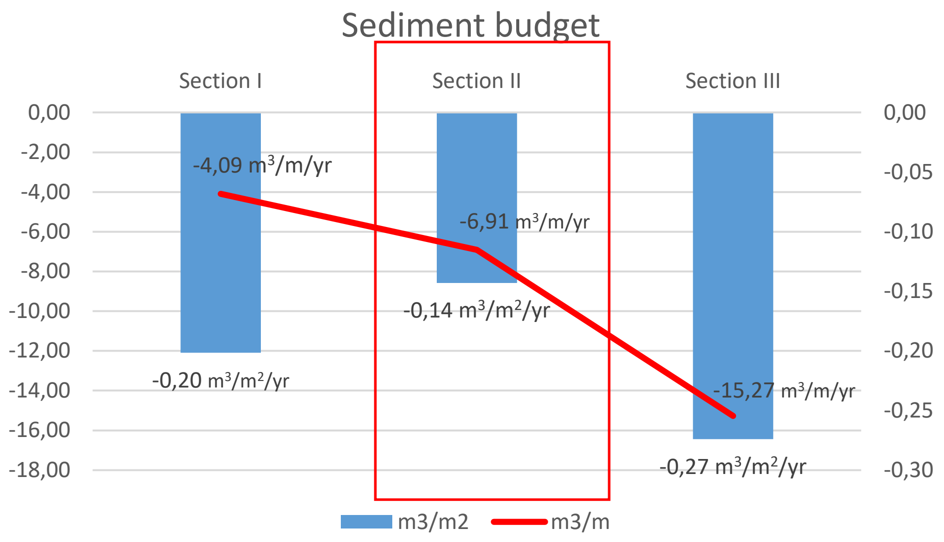


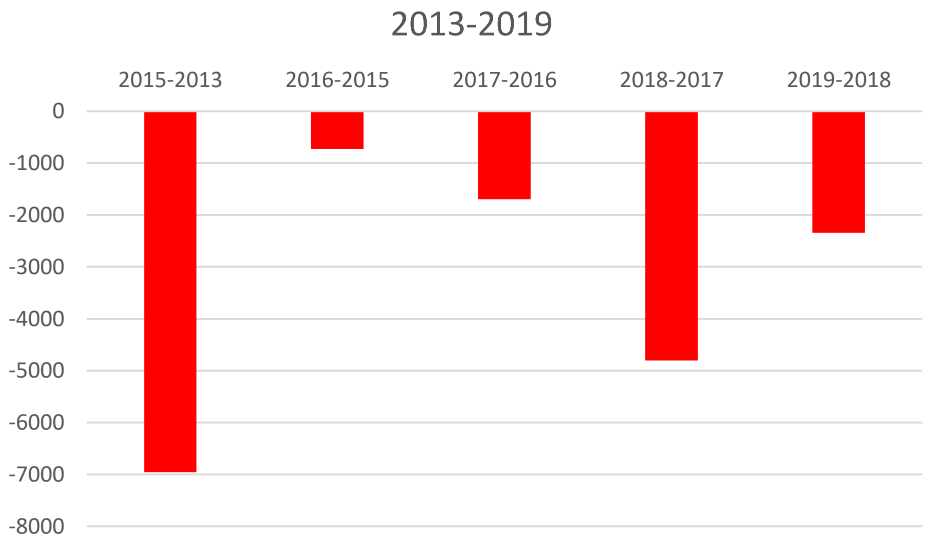
Section I – after heavy storm surge (Axel Storm), January 2017 (max erosion)

Results – Sediment budget

Section II

- Various geology structure (west and east – clay, middle – sand),
- Increased height – 35-60 m,
- **Total erosion (2013-2019) – -16542,6 m^3,**
- Lowest erosion - -726,84 m^3 (period II 2015-2016)
  - max sea level 586 cm, storm duration – only 2 h.
- Max erosion - -6472,1 m^3 (period I 2013-2015) – extensive scatter niche
  - max sea level – 600 cm, storm duration 31 h.
- **Cliff efficiency – - 8,06 m^3/m/yr**
- **Cliff dynamics - -0,17 m^3/m^2/yr**





Section II – extensive scatter niche in the middle part of section , June 2015

Conclusions

- In the years 2013-2019 geomorphological monitoring of sea cliffs was carried out using TLS.
- It is an accurate and fast method for estimating the denudation balance on cliff coasts.
- Two denudation indicators were used to estimate the balance:
    - m^3/m – giving information about the amount of submerged underwater sediment supply (performance),
    - ✓ m^3/m^2 – giving information about the dynamics of the cliff.
- The conducted tests showed that in the analyzed period the examined sections were characterized by varied performance and dynamics.
- Within 6 years, the most material to the submerged areas was delivered by section II (-16542,6 m^3).
- The high dynamics of section I was conditioned by the northern exposure of the shore and the largest exhibition towards the sea of all sections. Waves in the biggest storm (Axel Storm - January 2017) were flowing perpendicular to the shoreline. At that time, the greatest damage was recorded on the northern exposure shores.
- The low efficiency and dynamics of section II depends mainly on clay bedrock. These deposits are very resistant to denudative processes. Mainly colluvial forms with reduced resistance are abraded. The highest dynamics in this section occurred in its western part. An extensive landslide was created there, which was then quickly abraded.
- The conducted research showed that the denudation balance of the Wolin island cliffs is mostly influenced by the number of storm surges and their duration and, above all, the degree of development of the colluvial forms.
    - In the case of good forming of colluvial forms, it does not need high storm surges to remove a lot of material from the base of cliff.
    - Even high storms does not guarantee a large cliff loss if no colluvial deposits are deposited at the base of cliff.

The established space-time regularities of the dynamics of the Wolin island cliff coast can be approximately transposed to other fragments of the Southern Baltic cliff coast.


Thank you for your attention