Supplementary information to Asymmetric morphodynamics of the Wadden Sea

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Bathymetry distributions aid in understanding morphodynamics

Elevation probability density functions (PDF) from 1996 to 2022 give an indication of the morphologic evolution (Supplementary Fig. 1). Since the underlying data is structured on a regular 10 m grid, our PDFs are proportional to the amount of sediment within the regional units. Therefore, any changes to the PDFs can be interpreted as morphodynamics and as erosion-accretion change.

The majority of elevation samples were located in the intertidal zone, i.e., between the tidal high and low water. All elevation PDFs shifted to the right with time, demonstrating that the shallower elevations became more frequent or that the deep elevations diminished. This aligns with reported increases in mean intertidal elevation and the increases in tidal high and low water in the Wadden Sea (Milbradt et al., 2015) (Benninghoff & Winter, 2019).

Changes in the distribution's shape vary from unit to unit. While few changes occurred in the Western and Eastern Dutch Wadden Sea, the distribution's peaks increased and the quantile range decreased in other units. There, an increasing number of samples was noted in the proximity of the intertidal zone which hints at a spatial expansion of the intertidal zone. An example for this is the Weser-Jade (Supplementary Fig. 1e) where the 75% quantile moved to shallower depths and thus further away from the tidal low water. This indicates that more values were located in shallower depths than the low water line in 2022 than in 1996; the intertidal flat's surface area increased. A similar but distinct pattern was observed in the East Frisia unit, where the 75% quantile shifted toward shallower depths while simultaneously acquiring more depth samples. This indicates that bathymetric changes were nonlinear and, more importantly, varied across different elevation levels, as shown by the changing range between quantiles. In other words, distinct elevation levels may evolve in opposite directions. The development is asymmetric: Different parts of the intertidal zone experienced simultaneous accretion and erosion depending on the respective elevation bin.

Supplementary Figures

Figure 1. Probability density functions (PDF) illustrate the evolution of the elevation distributions of regional bathymetries in the morphological units of Fig. 1 (a - h) for the period from 1996 (yellow solid lines) to 2022 (brown solid lines). Markers indicate key quantiles (Q(n)) at the beginning and at the end of the evaluated period. Light blue shades represent the tidal low water range and dark blue shades the tidal high water range at tide gauges in the morphological units during the period.

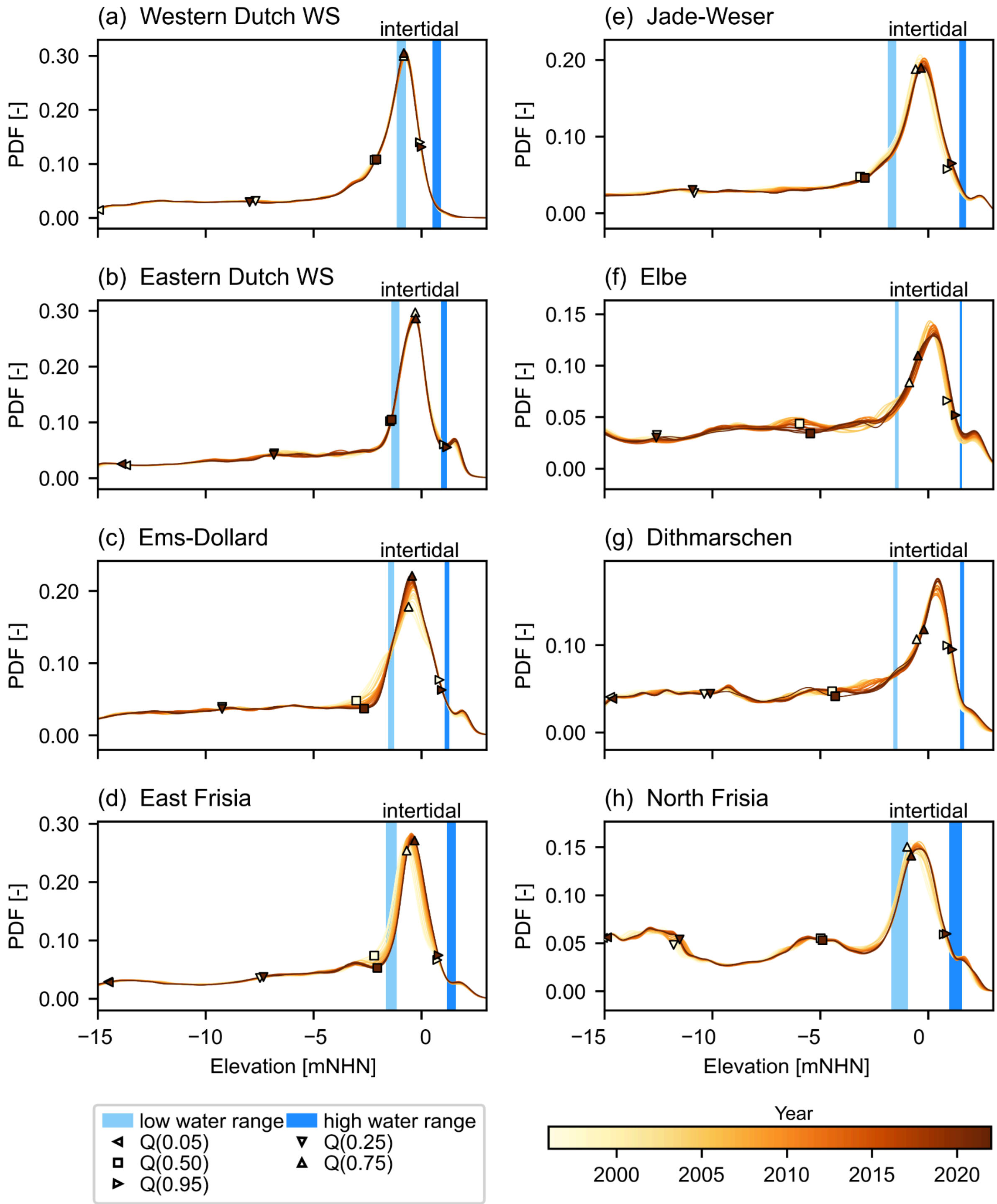


Figure 2. High-resolution, local elevation change rates from the period of 1996 to 2009 (difference of the 2009 and 1996 topographies).

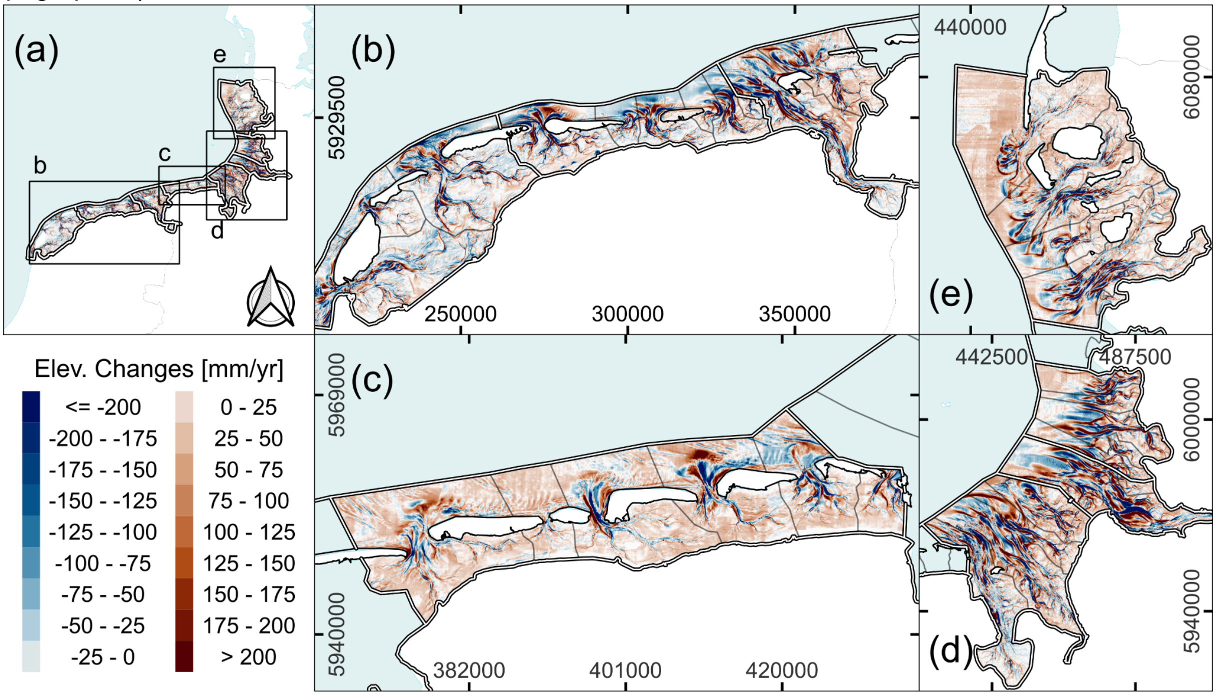


Figure 3. High-resolution, local elevation change rates from the period of 2009 to 2022 (difference of the 2022 and 2009 topographies).

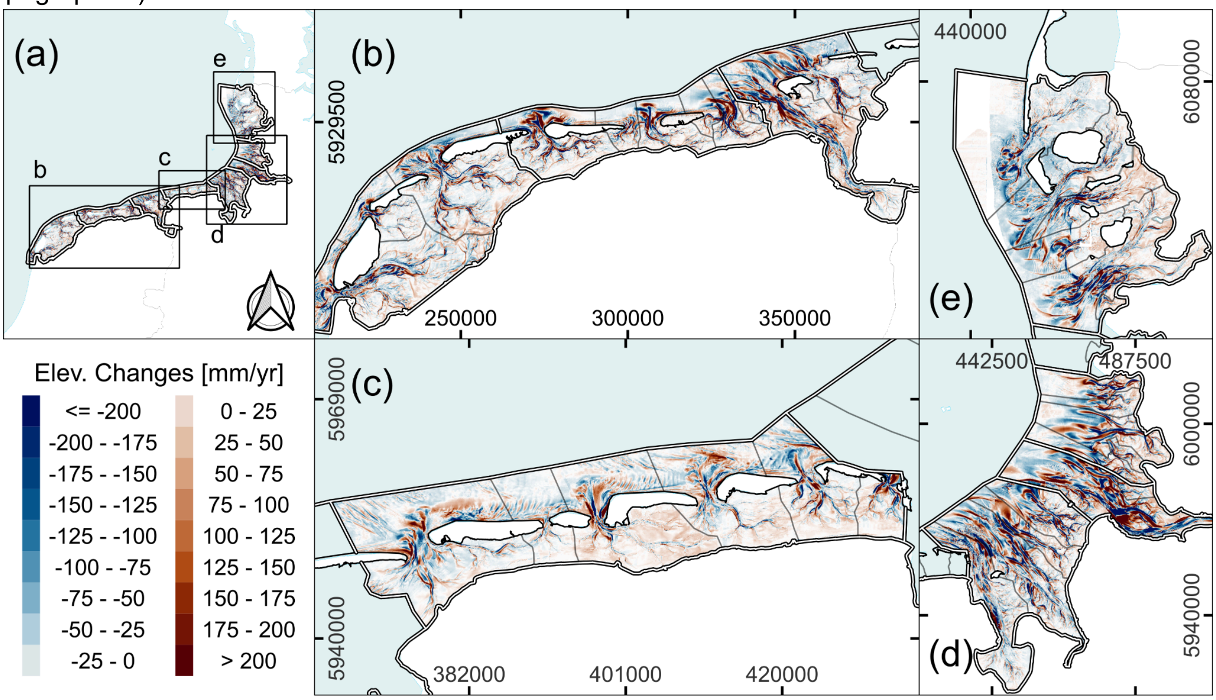


Figure 4. Local accretion-erosion patterns in the period of 1996 to 2022 as a discrete difference of the 2022 and 1996 topographies with blue shades indicating accretion and red shades erosion, respectively. Additional topography differences were provided in the supplement. Figure provides a zoomed perspective of Figure 2 in the main document. Projection UTM 32N (EPSG: 25832).

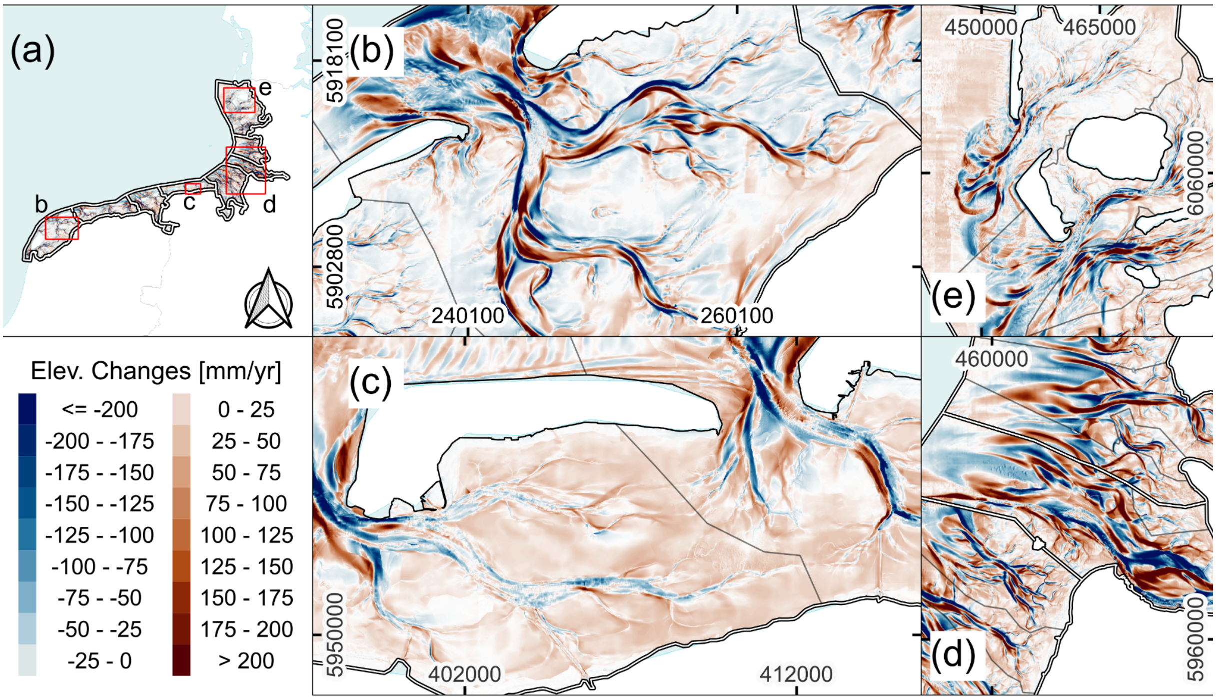
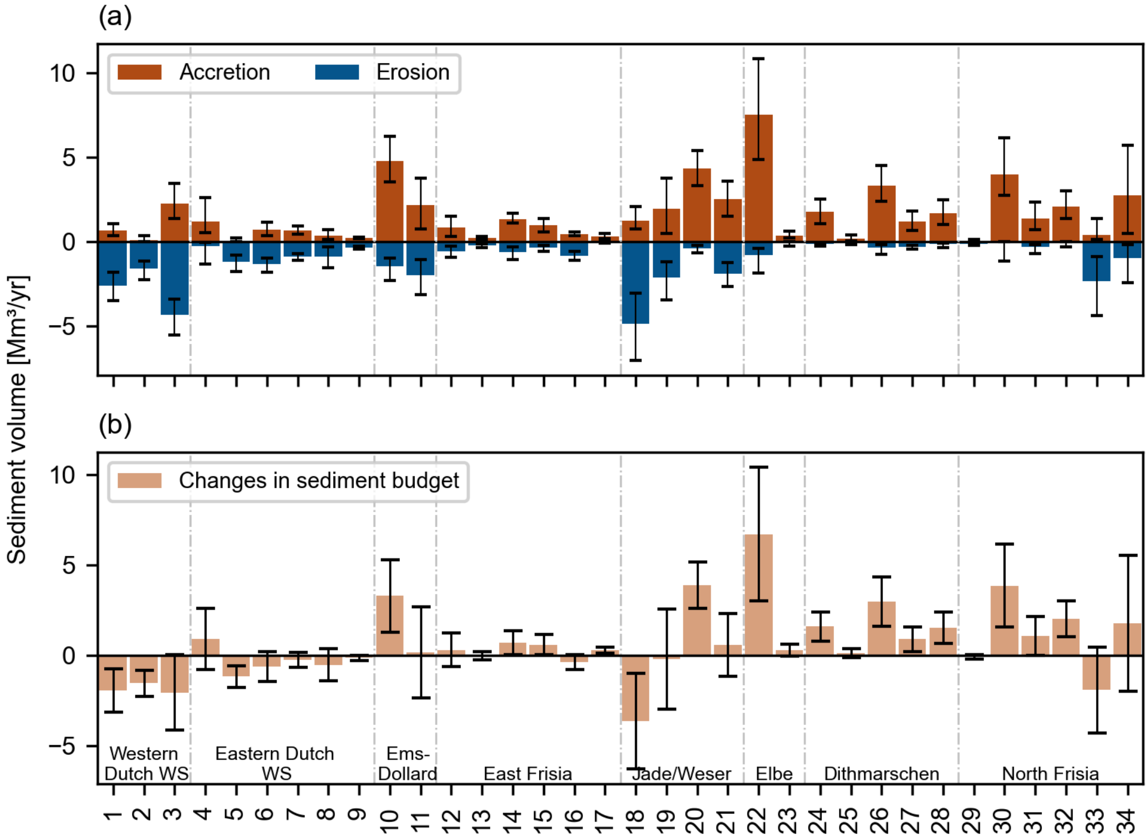


Figure 5. Overview about the eroded and accreted sediment volume (a) in the morphological units with the 95% confidence bounds of the quantile regression indicating uncertainty. The cumulated changes in the sediment budgets from trend analyses are given in (b). Values in Supplementary Table 4.

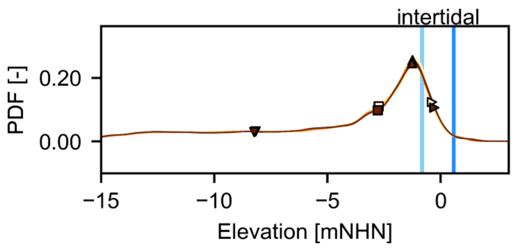
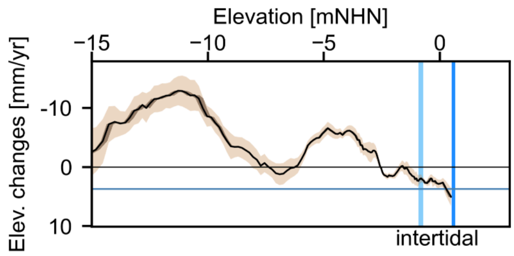
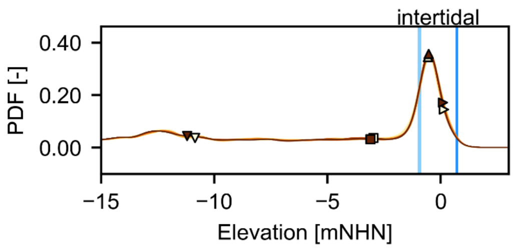
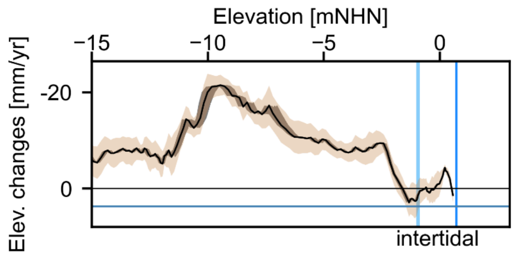
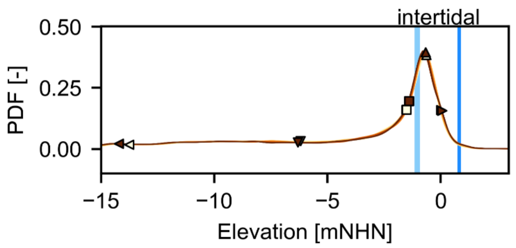
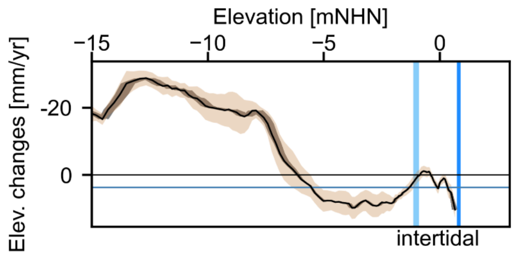
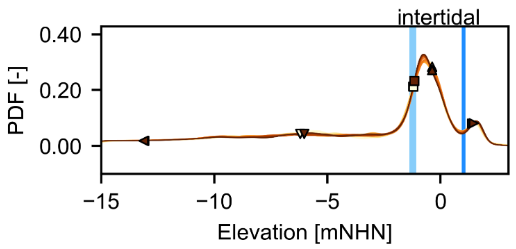
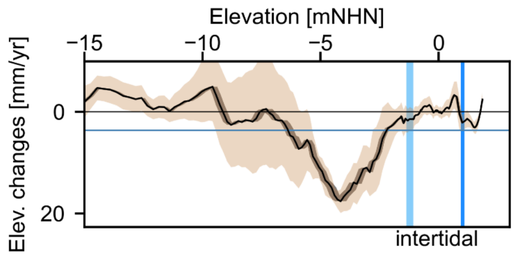
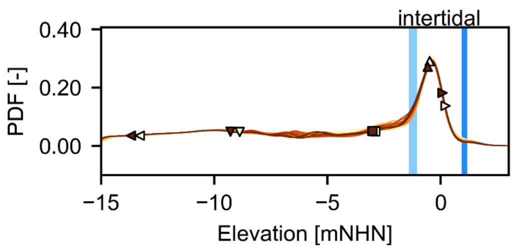
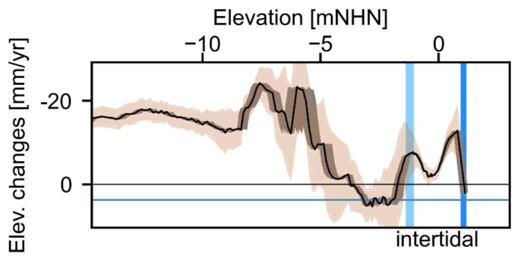


Supplementary Tables

Table 1: Overview of the parameters used for equation (2) for the different scenarios.

Scenario	D_0 in mNHN	α	μ in m	x_0 in km	σ in km	Tlw in mNHN	Thw in mNHN
reference	$-\ 9.0$	$2\ /\ L$	6.0	10.0	2.0	$-\ 2.0$	2.0
i) coastal squeezing	$-\ 9.0$	$2\ /\ L$	6.0	10.5	2.0	$-\ 2.0$	2.0
ii) coastal expansion	$-\ 9.0$	$2\ /\ L$	6.0	9.5	2.0	$-\ 2.0$	2.0
iii) growth with SLR (1m)	$-\ 8.0$	$2\ /\ L$	6.0	10.0	2.0	$-\ 1.0$	3.0
iv) flattening	$-\ 8.0$	0.0	6.0	10.0	2.0	$-\ 2.0$	2.0
v) steepening	$-\ 10.0$	$4\ /\ L$	6.0	10.0	2.0	$-\ 2.0$	2.0

Table 2. On the left, probability density functions (PDF) illustrate the evolution of the elevation distributions of bathymetries in the morphological units of Fig. 6 for the period from 1996 (blue solid lines) to 2022 (red solid lines). Markers indicate key quantiles (Q(n)) at the beginning and at the end of the evaluated period. Light blue shades represent the tidal low water range and dark blue shades the tidal high water range at tide gauges in the morphological units during the period. On the right, high-resolution, depth related elevation change rates from 1996 to 2022 in the morphological units. The solid black line represents the mean elevation changes for each quantile, mapped back to elevation over the entire time period. The shaded dark gray area indicates the confidence intervals of the remapping to depth, while the light orange area depicts the confidence intervals of the quantile regression analysis. Same legends as in Supplementary Figure 1 and Figure 4. The y-axis is the Quantile regression based elevation changes, plots are inverted to assimilate the orientation of plots in Fig. 4 when viewing the page in horizontal format.

Morphological unit	Probability density functions of elevation raster points	Quantile regression based elevation changes
(01) Marsdiep		
(02) EijerlandseGat		
(03) Vlie		
(04) Borndiep		
(05) Pinkegat		

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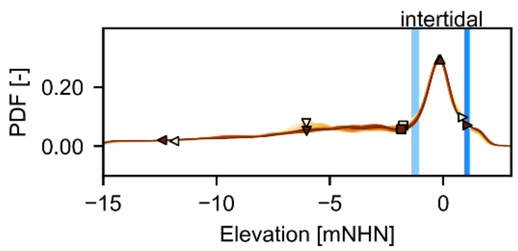
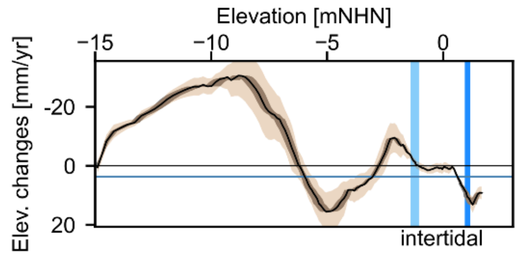
<tr><td>(06) Zoutkamperlaag</td><td>
</td><td>
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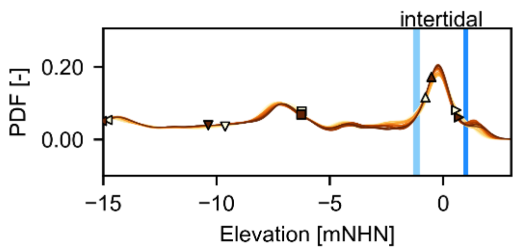
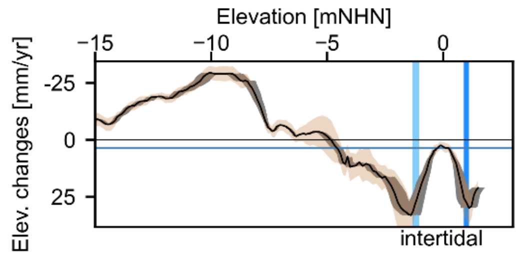
<tr><td>(07) Eilanderbalg</td><td>
</td><td>
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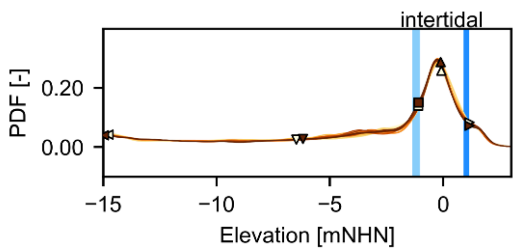
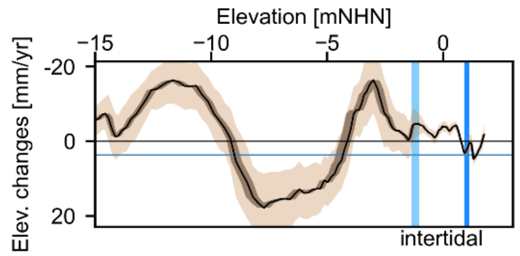
<tr><td>(08) Lauwers</td><td>
</td><td>
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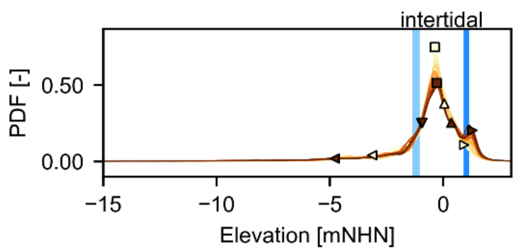
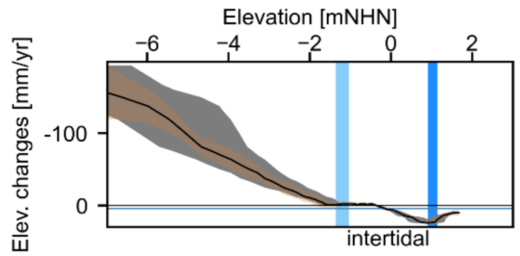
<tr><td>(09) Schild</td><td>
</td><td>
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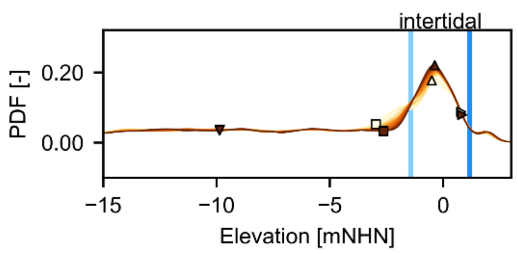
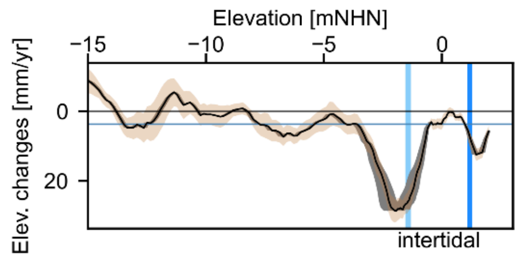
<tr><td>(10) Eems-Dollard</td><td>
</td><td>
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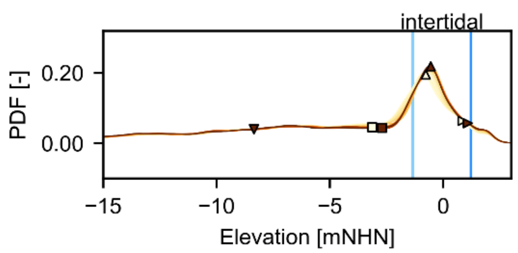
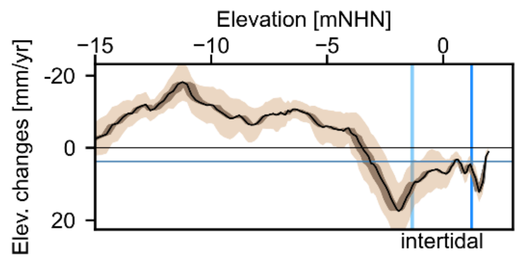
<tr><td>(11) Osterems</td><td>
</td><td>
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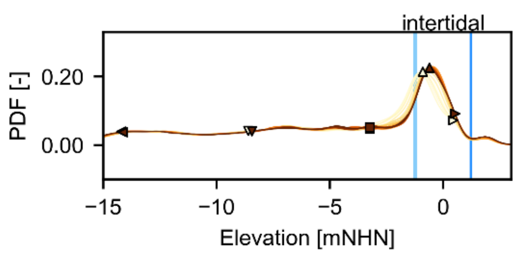
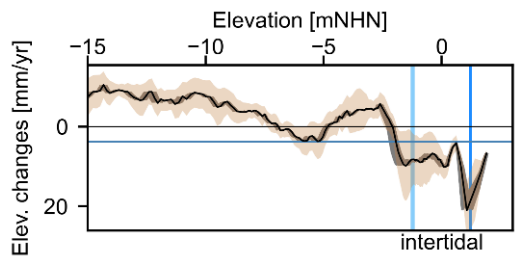
<tr><td>(12) NorderneyerSeegat</td><td>
</td><td>
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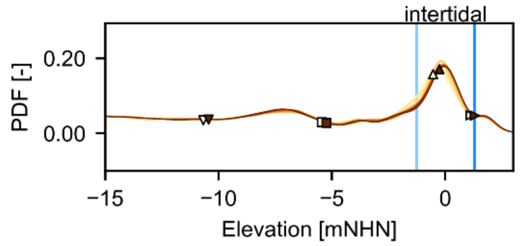
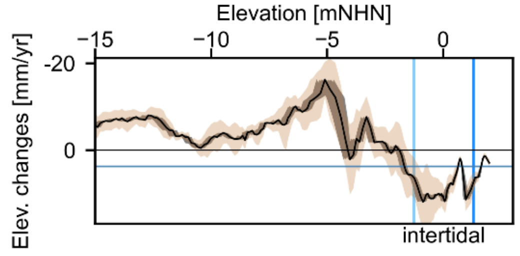
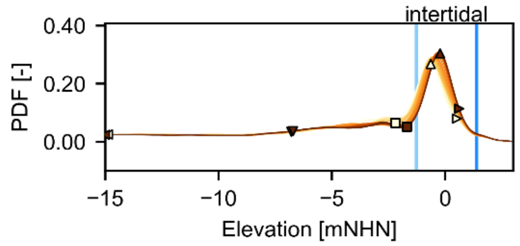
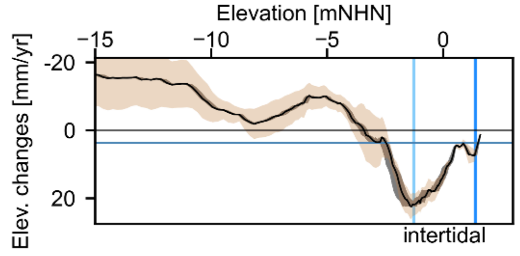
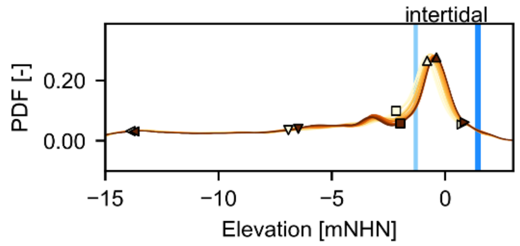
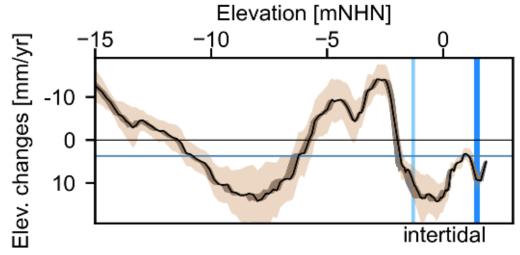
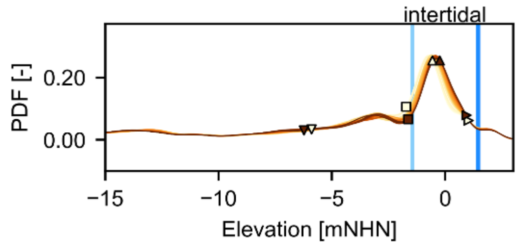
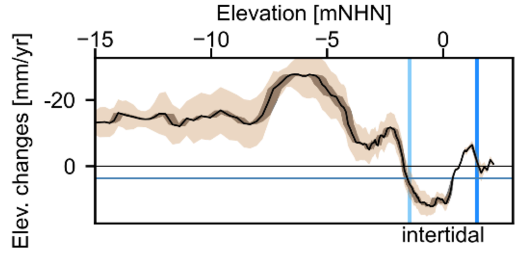
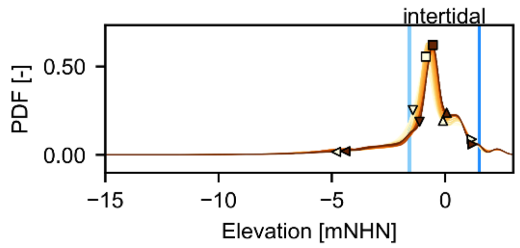
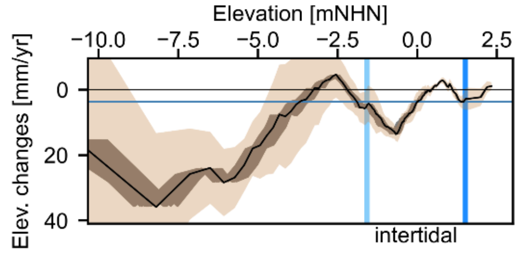
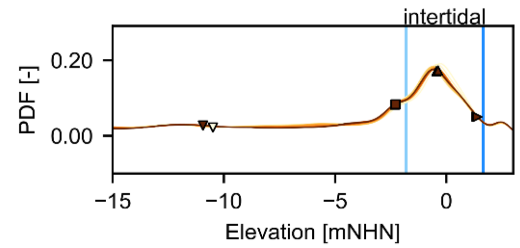
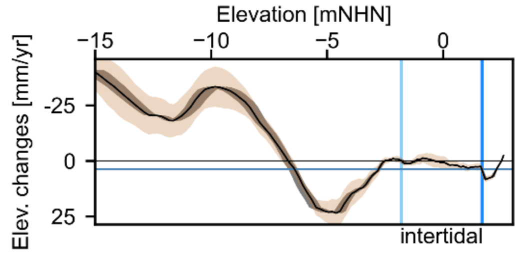
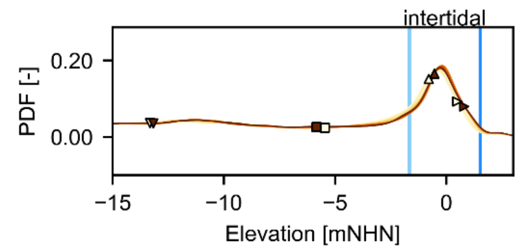
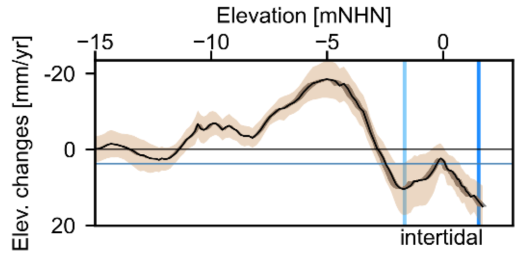
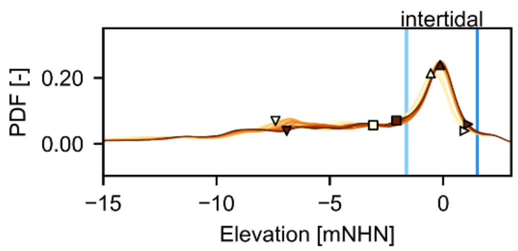
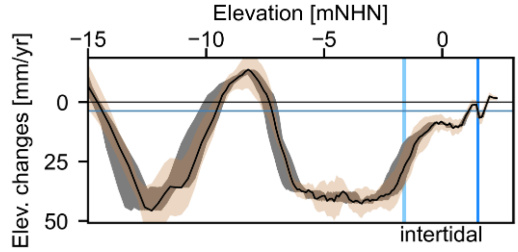
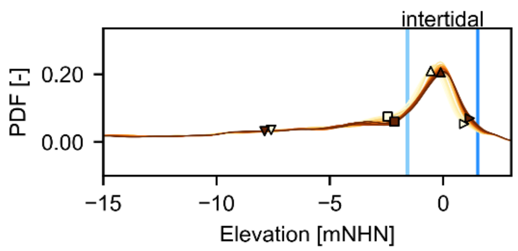
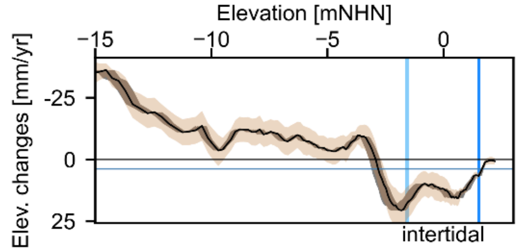
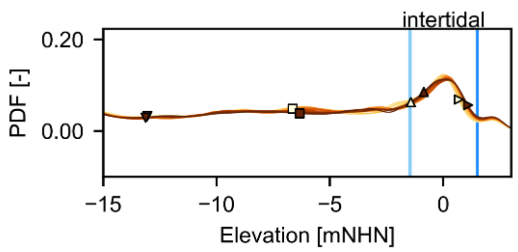
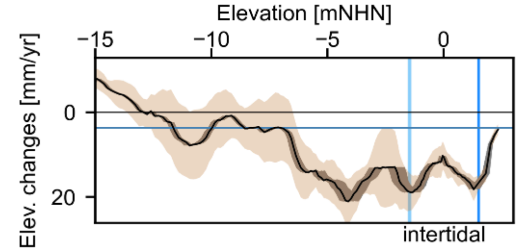
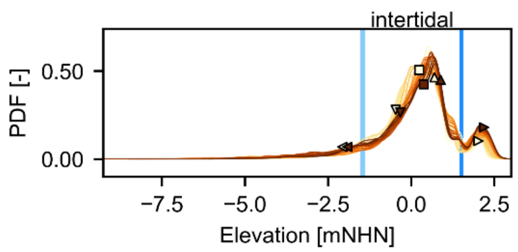
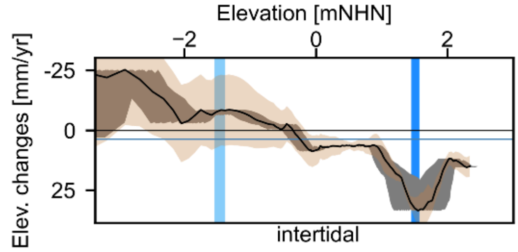
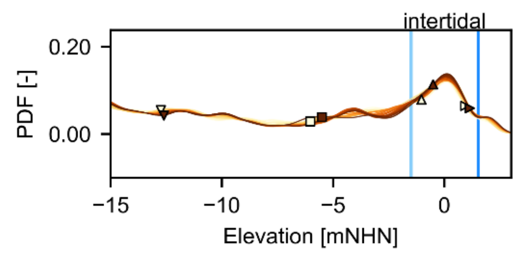
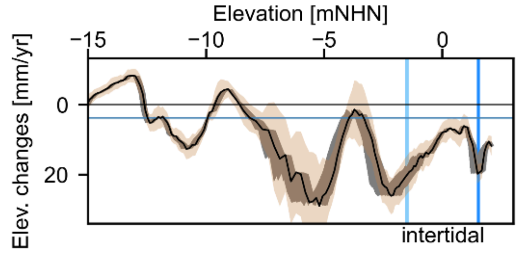
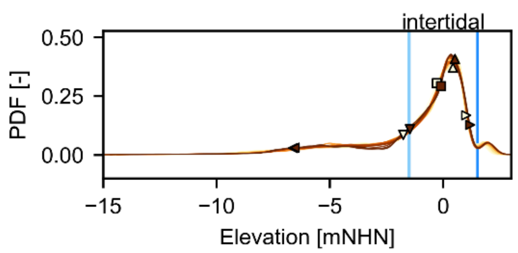
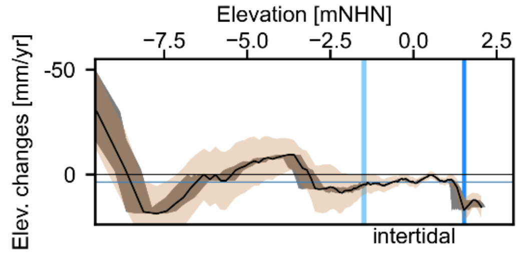
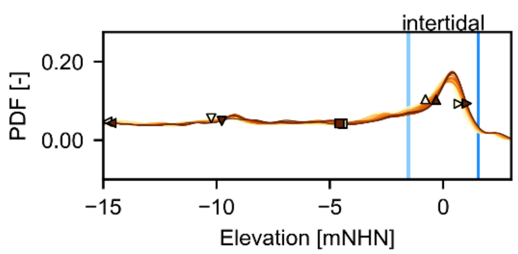
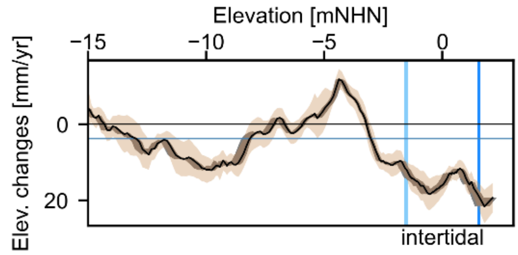
Morphological unit	Probability density functions of elevation raster points	Quantile regression based elevation changes
(13) WichterEe		
(14) AccumerEe		
(15) OtzumerBalje		
(16) Harle		
(17) BlaueBalje		
(18) Jade		
(19) Weser		

Morphological unit	Probability density functions of elevation raster points	Quantile regression based elevation changes
(20) Robinbalje		
(21) Westertill-Nordertill		
(22) Elbe		
(23) Schatzkammer		
(24) Neufahrwasser		
(25) Flackstrom		
(26) Piep-MeldorferBucht		

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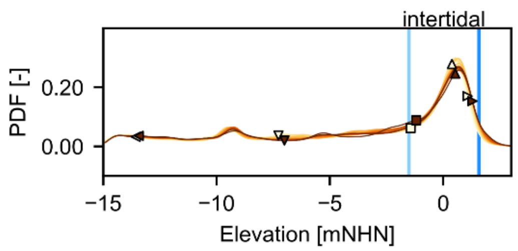
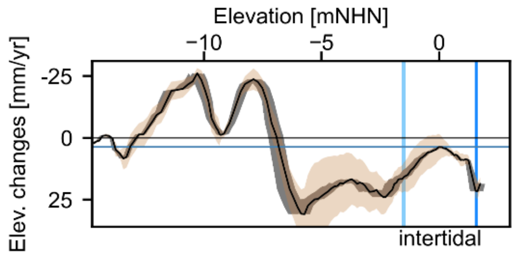
<tr><td>(27) WesselburenerLoch</td><td>
</td><td>
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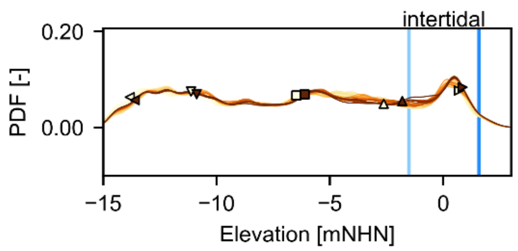
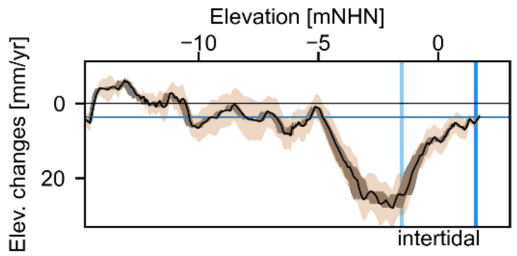
<tr><td>(28) Eidermuendung</td><td>
</td><td>
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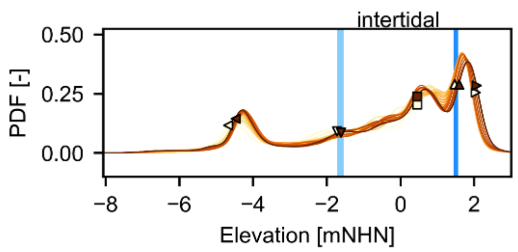
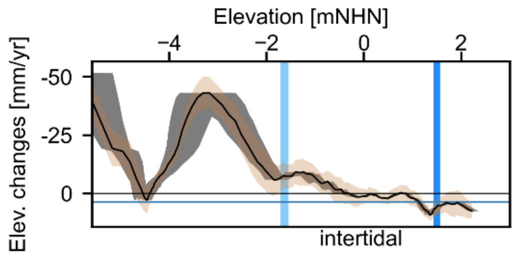
<tr><td>(29) TümlauerBucht</td><td>
</td><td>
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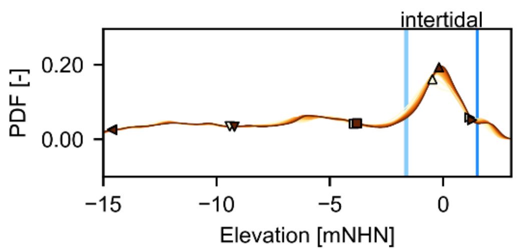
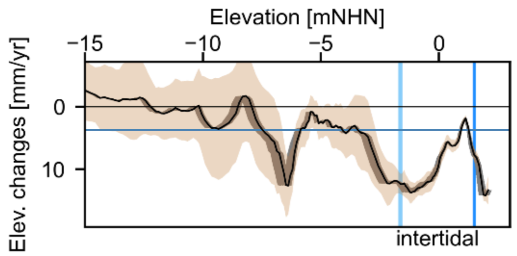
<tr><td>(30) Norderhever-Heverstrom</td><td>
</td><td>
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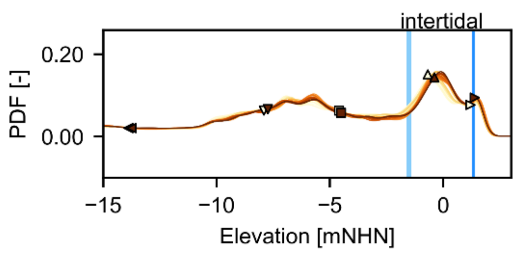
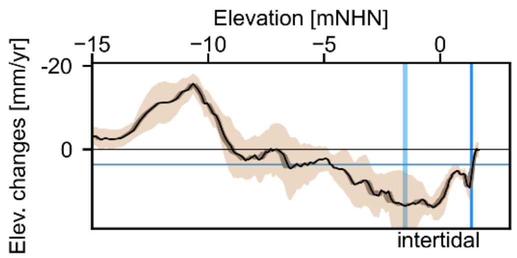
<tr><td>(31) RummerlochWest</td><td>
</td><td>
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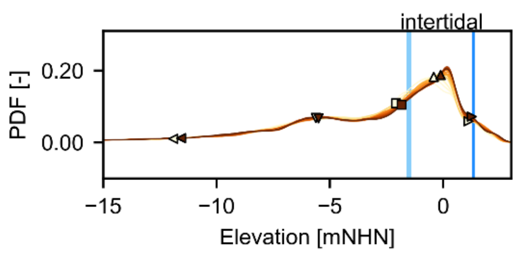
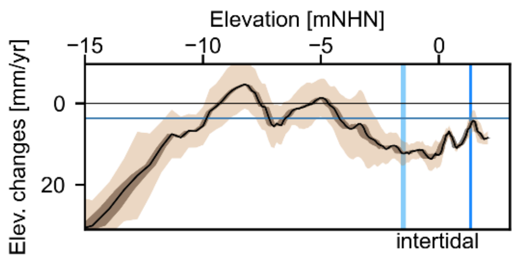
<tr><td>(32) Suederaue</td><td>
</td><td>
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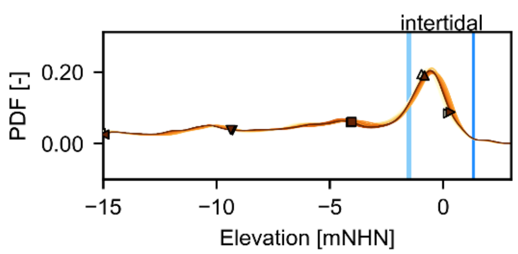
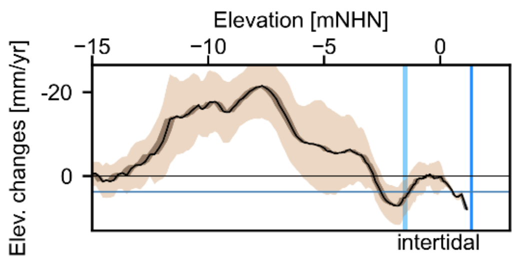
<tr><td>(33) Norderaue</td><td>
</td><td>
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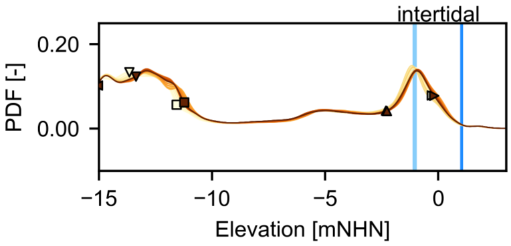
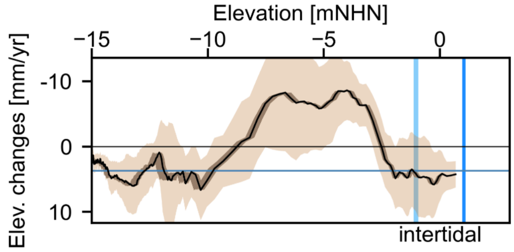
Morphological unit	Probability density functions of elevation raster points	Quantile regression based elevation changes
(34) HoernumTief		

Table 3: Sediment accretion / erosion trends in terms of volume per year for each region. Values represent the calculations based on the lower confidence interval, the trend, and the upper confidence interval respectively.

Region	Sediment Accreted [M m³/yr]	Sediment Eroded [M m³/yr]	Sediment Profit / Deficit [M m³/yr]	OLS Change in Sediment Volume [m³/yr]
Western Dutch WS	1.04 / 2.00 / 3.37	-8.59 / -6.83 / -5.48	-7.55 / -4.83 / -2.11	-4.85 / -3.70 / -2.55
Eastern Dutch WS	1.19 / 2.26 / 4.11	-5.11 / -3.16 / -1.99	-3.92 / -0.90 / 2.12	-2.16 / -1.04 / 0.09
Ems-Dollard	4.13 / 5.63 / 7.32	-4.66 / -2.93 / -1.38	-0.53 / 2.70 / 5.94	1.72 / 3.84 / 5.96
East Frisia	2.65 / 3.78 / 4.95	-3.11 / -2.11 / -1.15	-0.46 / 1.67 / 3.80	-0.08 / 0.76 / 1.60
Jade-Weser	4.20 / 7.53 / 10.95	-9.14 / -6.77 / -4.48	-4.95 / 0.76 / 6.48	-2.05 / 0.76 / 3.57
Elbe	4.88 / 7.70 / 11.21	-1.86 / -0.79 / -0.40	3.02 / 6.92 / 10.81	5.97 / 6.96 / 7.95
Dithmarschen	4.91 / 7.01 / 9.49	-0.72 / -0.18 / -0.03	4.19 / 6.82 / 9.46	5.20 / 6.51 / 7.81
North Frisia	4.62 / 8.91 / 15.85	-7.35 / -2.35 / -0.01	-2.73 / 6.55 / 15.83	0.85 / 6.75 / 12.65
Total	**27.62 / 44.82 / 67.26**	**-40.55 / -25.11 / -14.92**	**-12.93 / 19.70 / 52.34**	**4.61 / 20.84 / 37.07**

Table 4: Sediment accretion / erosion trends in terms of volume per year for each morphological unit. Values represent the calculations based on the lower confidence interval, the trend, and the upper confidence interval respectively.

Tidal Basin	Sediment Accreted [M m³/yr]	Sediment Eroded [M m³/yr]	Sediment Profit / Deficit [M m³/yr]	OLS Change in Sediment Volume [m³/yr]
Marsdiep	0.37 / 0.66 / 1.09	-3.50 / -2.59 / -1.81	-3.13 / -1.93 / -0.73	-1.91 / -1.46 / -1.02
EijerlandseGat	0.00 / 0.07 / 0.36	-2.25 / -1.60 / -1.16	-2.25 / -1.53 / -0.80	-1.57 / -1.39 / -1.22
Vlie	1.37 / 2.28 / 3.47	-5.50 / -4.31 / -3.42	-4.13 / -2.04 / 0.06	-1.64 / -0.83 / -0.02
Borndiep	0.55 / 1.20 / 2.63	-1.32 / -0.28 / -0.03	-0.77 / 0.92 / 2.61	0.13 / 0.67 / 1.22
Pinkegat	0.00 / 0.06 / 0.24	-1.75 / -1.21 / -0.79	-1.75 / -1.15 / -0.55	-1.28 / -0.99 / -0.71
Zoutkamperlaag	0.37 / 0.72 / 1.17	-1.81 / -1.34 / -0.97	-1.44 / -0.62 / 0.20	-0.50 / -0.25 / 0.00
Eilanderbalg	0.44 / 0.66 / 0.92	-1.09 / -0.89 / -0.72	-0.65 / -0.23 / 0.20	-0.40 / -0.21 / -0.01
Lauwers	0.15 / 0.36 / 0.70	-1.53 / -0.86 / -0.32	-1.38 / -0.50 / 0.38	-0.51 / -0.33 / -0.14
Schild	0.18 / 0.21 / 0.27	-0.45 / -0.33 / -0.24	-0.27 / -0.12 / 0.03	-0.14 / -0.11 / -0.07
EemsDollard	3.56 / 4.77 / 6.26	-2.27 / -1.46 / -0.95	1.29 / 3.30 / 5.31	2.51 / 3.09 / 3.68
Osterems	0.76 / 2.17 / 3.76	-3.11 / -2.00 / -1.06	-2.35 / 0.17 / 2.70	-1.06 / 0.53 / 2.13
Norderneyer Seegat	0.31 / 0.87 / 1.49	-0.92 / -0.55 / -0.25	-0.61 / 0.32 / 1.25	-0.32 / 0.16 / 0.63
WichterEe	0.13 / 0.22 / 0.34	-0.35 / -0.23 / -0.13	-0.22 / -0.01 / 0.21	-0.15 / 0.01 / 0.16
AccumerEe	1.10 / 1.35 / 1.67	-1.04 / -0.63 / -0.29	0.06 / 0.72 / 1.38	0.34 / 0.52 / 0.69
OtzumerBalje	0.60 / 0.96 / 1.36	-0.56 / -0.36 / -0.20	0.04 / 0.60 / 1.16	0.20 / 0.39 / 0.57
Harle	0.34 / 0.47 / 0.60	-1.12 / -0.83 / -0.55	-0.77 / -0.36 / 0.05	-0.51 / -0.40 / -0.28
BlaueBalje	0.20 / 0.32 / 0.49	-0.06 / -0.01 / 0.00	0.13 / 0.31 / 0.48	0.31 / 0.34 / 0.37
Jade	0.77 / 1.23 / 2.07	-7.02 / -4.84 / -3.04	-6.25 / -3.61 / -0.97	-4.34 / -3.32 / -2.30
Weser	0.48 / 1.94 / 3.74	-3.42 / -2.12 / -1.17	-2.94 / -0.19 / 2.57	-1.00 / 0.20 / 1.41
Robinbalje	3.31 / 4.32 / 5.38	-0.67 / -0.41 / -0.20	2.63 / 3.91 / 5.18	3.50 / 4.17 / 4.83
WestertillNordertill	1.51 / 2.51 / 3.58	-2.63 / -1.90 / -1.23	-1.13 / 0.61 / 2.35	-0.80 / 0.03 / 0.86
Elbe	4.88 / 7.50 / 10.83	-1.85 / -0.78 / -0.40	3.03 / 6.73 / 10.43	5.76 / 6.68 / 7.59
Schatzkammer	0.22 / 0.37 / 0.63	-0.26 / -0.08 / 0.00	-0.04 / 0.29 / 0.63	0.16 / 0.26 / 0.36

Tidal Basin	Sediment Accreted [M m³/yr]	Sediment Eroded [M m³/yr]	Sediment Profit / Deficit [M m³/yr]	OLS Change in Sediment Volume [m³/yr]
Neufahrwasser	1.07 / 1.75 / 2.51	-0.27 / -0.14 / -0.08	0.80 / 1.61 / 2.43	1.06 / 1.42 / 1.78
Flackstrom	0.05 / 0.20 / 0.41	-0.16 / -0.05 / -0.01	-0.11 / 0.15 / 0.40	0.04 / 0.14 / 0.25
PiepMeldorferBucht	2.39 / 3.34 / 4.50	-0.75 / -0.35 / -0.16	1.64 / 2.99 / 4.33	2.17 / 2.71 / 3.24
WesselburenerLoch	0.67 / 1.22 / 1.80	-0.43 / -0.31 / -0.22	0.24 / 0.91 / 1.58	0.41 / 0.68 / 0.96
Eidermuendung	1.04 / 1.69 / 2.48	-0.35 / -0.14 / -0.07	0.69 / 1.55 / 2.42	1.13 / 1.58 / 2.04
TuemlauerBucht	0.01 / 0.06 / 0.13	-0.20 / -0.13 / -0.08	-0.19 / -0.07 / 0.05	-0.09 / -0.06 / -0.02
Norderhever Heverstrom	2.73 / 3.97 / 6.16	-1.15 / -0.10 / 0.00	1.58 / 3.87 / 6.16	2.52 / 3.71 / 4.89
Rummelloch West	0.70 / 1.38 / 2.34	-0.71 / -0.30 / -0.18	0.00 / 1.08 / 2.16	0.21 / 0.70 / 1.18
Suederaue	1.38 / 2.09 / 3.03	-0.32 / -0.05 / 0.00	1.06 / 2.05 / 3.03	1.53 / 1.99 / 2.45
Norderaue	0.12 / 0.43 / 1.36	-4.39 / -2.32 / -0.89	-4.27 / -1.90 / 0.47	-2.34 / -0.67 / 1.00
HoernumTief	0.49 / 2.77 / 5.73	-2.44 / -0.96 / -0.17	-1.95 / 1.80 / 5.56	-0.32 / 2.29 / 4.89
Total	**32.24 / 54.09 / 83.48**	**-55.64 / -34.44 / -20.78**	**-23.40 / 19.65 / 62.70**	**3.12 / 22.24 / 41.36**