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Mud balance Sea Scheldt

SUBREPORT 6 - HISTORICAL EVOLUTION (1930-2011) OF MUD DEPOSITION/EROSION IN THE INTERTIDAL AREAS OF THE SCHELDT ESTUARY

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Abstract

The mud dynamics in an estuary are known to be a key element in estuarine functioning, as increasing suspended sediment concentrations may be both harmful for ecological functions such as biomass production by phytoplankton, as well as deteriorative for human functions such as by siltation of shipping channels. Considering the potential risk of increase in suspended sediment concentration in the Scheldt estuary, it is relevant to know the historical evolution of the mud deposition/erosion in intertidal areas. This subreport aims to quantify the mud deposition/erosion in different time periods since 1930 to present, for different intertidal ecotope types, and for different zones along the Scheldt estuary, including the Western Scheldt and Sea Scheldt. We analyzed the height change, volume change, eroded or deposited mud mass, and the overall mud balance in time steps between 1930 and 2011.

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1. Introduction

1.1. Background

The mud dynamics in an estuary are known to be a key element of estuarine functioning, as increasing suspended sediment concentrations may be both harmful for ecological functions such as biomass production by phytoplankton, as well as deteriorative for human functions such as by siltation of shipping channels.

Within the scope of the project “Slibhuishouding Sea Scheldt”, this report describes the results of the historical evolution (1930-present) of the mud deposition/erosion in intertidal areas in Western Scheldt and Sea Scheldt.

1.2. Objectives

The objective of this subproject is to quantify the mud deposition/erosion that has occurred in intertidal areas along the Scheldt estuary:

1) in different time periods (1930’s till present),
2) in different intertidal ecotope types (vegetated marshes and non-vegetated intertidal flats),
3) in different spatial zones along the Scheldt estuary, including the Western Scheldt and Sea Scheldt.

1.3. Outline

In chapter 2, the material and methods are briefly described, including the data used for elevation, tidal water levels, ecotopes, mud content, spatial zonation, and statistical analyses.

Chapters 3 and 4 show the results of the temporal and spatial change of ecotopes and sediment surface height in the different spatial zones along the Western Scheldt and Sea Scheldt and for the different time periods.

Chapters 5 till 8 present the sediment height change, sediment volume change, mud content and eroded /deposited mud mass in the different ecotopes, different spatial zones along the Western Scheldt and Sea Scheldt, and for the different time periods.

Chapter 9 presents the total mud balance for the intertidal areas in the Western Scheldt and Sea Scheldt, for the different spatial zones and different time periods.

Chapter 10 concludes with the main findings of this study.

2. Material and methods

2.1. General methodological approach

The general methodological approach is schematically shown in figure 1. The green parts are the original input data needed for the calculations, and the blue parts are the intermediate calculation results. Ecotope maps with three classes (i.e., marsh, intertidal flat and subtidal zone) are extracted based on elevation maps, tidal data and vegetation maps. Ecotope maps of different years have been compared to get the difference maps of ecotope changes between the different time steps. Elevation data are compared between different years to get the elevation change between the different time steps. Height change in the different ecotope change classes are extracted based on the combination of elevation change maps and ecotope change maps. Volume change in the different ecotope change classes are calculated by multiplying the height change in the different ecotope change classes with the area of different ecotope change classes. Mud volume change was calculated by multiplying the volume change in the different ecotope change classes with mud content data. In the end, mud mass change is calculated by multiplying mud volume change with dry bulk density data.

In an attempt to quantify the uncertainty on the mud mass estimates, the statistical distribution of height change and mud content is combined with an uncertainty estimate of the dry buld density to give percentile estimates of the mud mass.

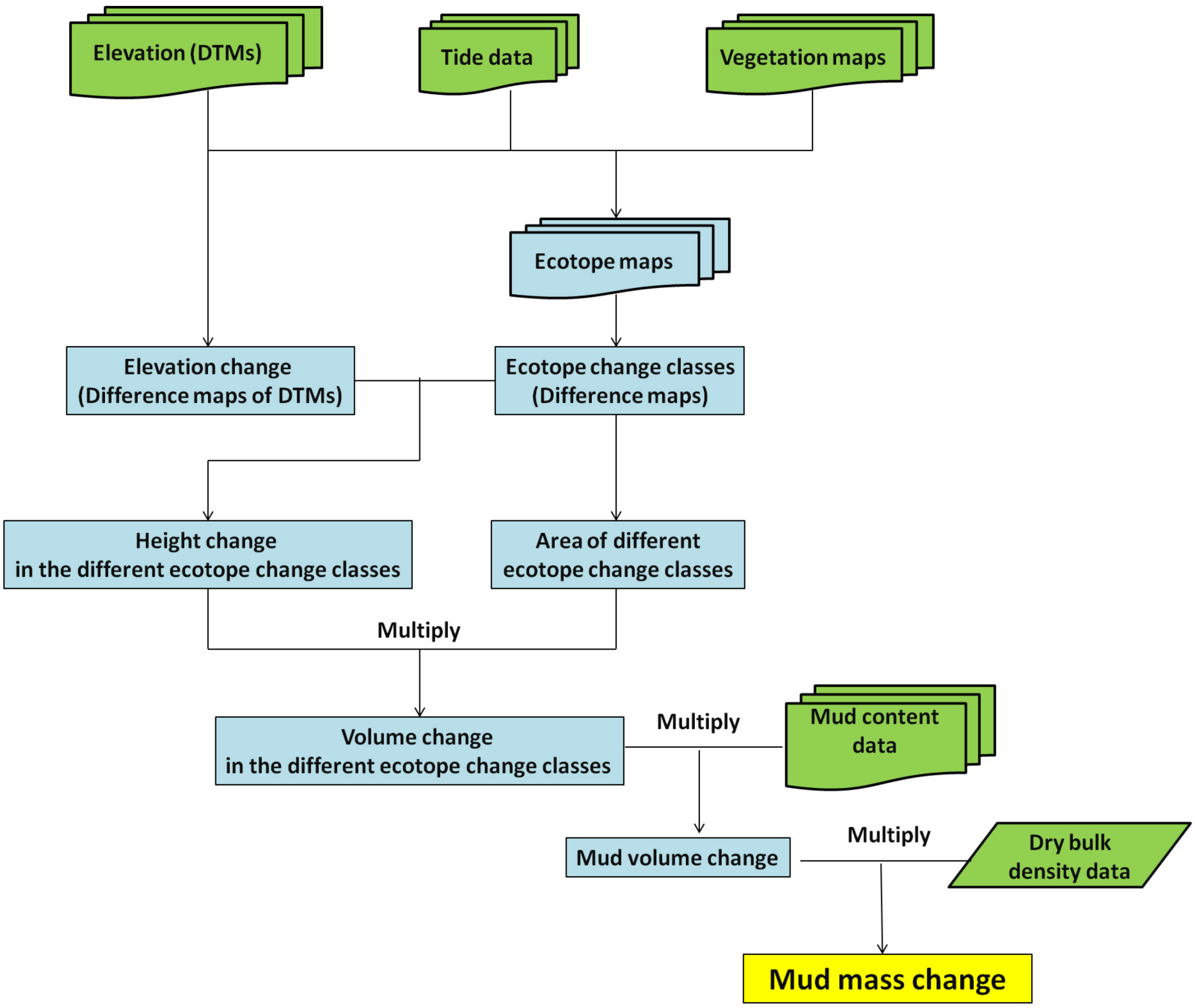

Figure 1 – Flow chart of the general methodological approach

2.2. Elevation

All calculations in this report are based on Digital Terrain Models (DTMs). The DTM is a combined topographic and bathymetric model representing the elevation of the subtidal, intertidal and supratidal areas of the estuary. In general, the DTMs were mosaiced from topographic grids, LIDAR grids and bathymetric grids.

In the Western Scheldt (Table 1), the elevation data are available for the subtidal areas and lower part of the intertidal flats from the bathymetric grids, and for the vegetated marshes and higher parts of the intertidal flats from the topographic grids before 2000 and from the LIDAR grids after 2000. The bathymetric grids were interpolated with a resolution of 20×20 m from bathymetric sounding from boats during high tide. The topographic grids were interpolated with a resolution of 20×20 m from topographic surveys using conventional methods (theodolite) [*Temmerman et al.*, 2004; *Van der Pluijm and De Jong*, 1998]. The LIDAR grids were interpolated with a resolution of 2×2 m from LIDAR surveys during low tide [*Alkemade*, 2004; *Rijkswaterstaat*, 2011; *Temmerman et al.*, 2004; *Van Heerd and Van 't Zand*, 1999]. LIDAR data of 2004 and 2010 were finally selected for a better temporal coverage after testing analyses with the LIDAR data from 2004, 2006, 2007, 2008, 2009 and 2010. Generally consistent yearly height changes were obtained with all the LIDAR data. All the grid data were provided by Rijkswaterstaat in the NAP reference system.

In the Sea Scheldt (Table 2), the elevation data are available for the subtidal areas and lower part of the intertidal flats from the bathymetric grids [*Van Braeckel et al.*, 2012]. For the vegetated marshes and higher parts of the intertidal flats no topographic grids before 2000 were available, but only LIDAR grids after 2000 [*Van Ryckegem et al.*, 2014]. The bathymetric grids were interpolated with a resolution of 5×5 m from bathymetric sounding from boats during high tide. The bathymetric data were digitized from historic maps, on which the depth values are expressed in a vertical reference system, “Nul Krijgsdepot”, that is outdated and not used anymore. During digitalization of the old maps, the depth values were converted to the current TAW reference system. The LIDAR grids were interpolated with a resolution of 5×5 m in 2004 and 1×1 m in 2011 from LIDAR surveys during low tide. The LIDAR grids of 2004 and 2011 were selected after testing analyses of LIDAR grids of 2003, 2004, 2007, 2010, 2011 and 2012. Compared with the other data, the LIDAR grids of 2004 and 2011 have several adavantages, such as better coverage of the whole Sea Scheldt and better timing of the LIDAR surveys during the seasons (data obtained in spring with less influence from vegetation). All the grid data were provided in the current TAW reference system by aMT (afdeling Maritieme Toegang), as well as the LIDAR grid of 2004 provided by INBO (Instituut voor Natuur- en Bosonderzoek).

Table 1 – Elevation data in Western Scheldt (data source: Rijkswaterstaat).

Year	Data	Cell size
1930’s	Topographic 1931 Bathymetric 1931	20 m 20 m
1960	Topographic 1963 Bathymetric 1963-1964	20 m 20 m
1990	Topographic 1992 Bathymetric 1990-1993	20 m 20 m
2000	LIDAR 2004 Bathymetric 2003	2 m 20 m
2010	LIDAR 2010 Bathymetric 2009	2 m 20 m

Table 2 – Elevation data in Sea Scheldt (data source: Maritieme Toegang).

Year	Data	Cell size
1930	Bathymetric 1928-1935	5 m
1960	Bathymetric 1960-1962	5 m
2000	Bathymetric 1995-2004 LIDAR 2004	5 m 5 m
2010	LIDAR 2011	1 m

2.3. Tides

In order to delineate the lower limit of the intertidal areas from the DTMs, the mean low water at spring tide (MLWS) was used from a number of tidal gauge stations, including Vlissingen, Terneuzen, Hansweert and Bath for the Western Scheldt, as well as Prosperpolder, Liefkenshoek, Kallo, Antwerpen, Schelle, Temse, Sint-Amands, Dendermonde, Schoonaarde, Wetteren, Melle for the Sea Scheldt, and Boom, Walem for the Rupel. The MLWS was calculated as the average of 4 years (year of mapping and the 3 years before).

2.4. Ecotope maps

The intertidal zone of the estuary was spatially classified into three ecotope classes: marsh, intertidal flat and subtidal zone (Table 3-4 and Figure 2). In general, the delineation of the boundary between intertidal flat and subtidal zone was based on the MLWS. The boundary between marshes (defined here as vegetated intertidal areas) and intertidal flats (defined here as non-vegetated intertidal areas) was extracted from aerial photographs or hydrographic maps. As a first step, the surface of MLWS was interpolated (by Kriging) from the 4-year average MLWS data calculated for the tidal gauge stations (see 2.3). By subtracting the MLWS surface with the Digital Terrain Model, the subtidal zone and the intertidal zone were separated from each other. All the areas with elevation lower than the MLWS surface were classified as subtidal, while all the areas with elevation higher than the MLWS surface were classified as intertidal. The maps of the borders of vegetated marshes in the Western Scheldt were provided by Rijkswaterstaat, and were extracted from black-white aerial photographs (1935 and 1959) or false-color near-infrared aerial photographs (1988, 2004 and 2010) [*Huijs*, 1995; *Reitsma*, 2006; *Rijkswaterstaat*, 2011; *Van der Pluijm and De Jong*, 1998]. All aerial photographs were processed in a similar way, by scanning them into digital pictures with a resolution of 0.5 m (or better), from which the vegetated area could be clearly distinguished and was digitized manually. For the Sea Scheldt, the three-class classification (i.e., marsh, intertidal flat and subtidal zone) was modified from the detailed ecotope maps of 1930, 1960, 2001 and 2010 provided by INBO [*Van Braeckel*, 2013]. Marsh boundary was extracted from hydrographic maps (1930 and 1960) or false-color near-infrared aerial photographs (2001 and 2010). The boundary between intertidal flat and subtidal zone (2001 and 2010) was based on the low water frequency of 30% which corresponds with the MLWS at the Dutch-Belgian border (Table 5). The reason for using this value is because upstream of Dendermonde the MLWS is higher than the mean low water at neap tide (MLWN), which would result in underestimation of intertidal flat area.

Table 3 – Data to make ecotope maps in Western Scheldt (data source: Rijkswaterstaat).

Time step	DTM	Tidal data	Data to generate vegetation map
1930	1931	Decadal mean MLWS 1931-1940	Black-white aerial photographs in 1935
1960	1963	4-year mean MLWS (1960-1963)	Black-white aerial photographs in 1959
1990	1992	4-year mean MLWS (1989-1992)	False-color near-infrared aerial photographs 1988
2000	2004	4-year mean MLWS (2001-2004)	False-color near-infrared aerial photographs 2004
2010	2010	4-year mean MLWS (2007-2010)	False-color near-infrared aerial photographs 2011

Table 4 – Data to make ecotope maps in Sea Scheldt (made by INBO).

Time step	DTM	Tidal data	Data to generate vegetation map
1930	1930	4-year mean MLWS (1927-1930)	Hydrographic maps 1930
1960	1960	4-year mean MLWS (1957-1960)	Hydrographic maps 1960
2000	2000	4-year mean low water frequency of 30% (1997-2000)	False-color near-infrared aerial photographs 2003
2010	2010	4-year mean low water frequency of 30% (2007-2010)	True-color aerial photographs 2010

Table 5 – Difference in water level between 30% low water frequency and MLWS.

Location	periode 1997 – 2000		periode 1998 – 2001
	MLWS (4jaar)	stdev MLWS	30% LW
DENDERMONDE	1.13	0.12	1.04
SCHOONAARDE	1.89	0.14	1.71
WETTEREN	2.41	0.20	2.19
MELLE	2.60	0.28	2.34

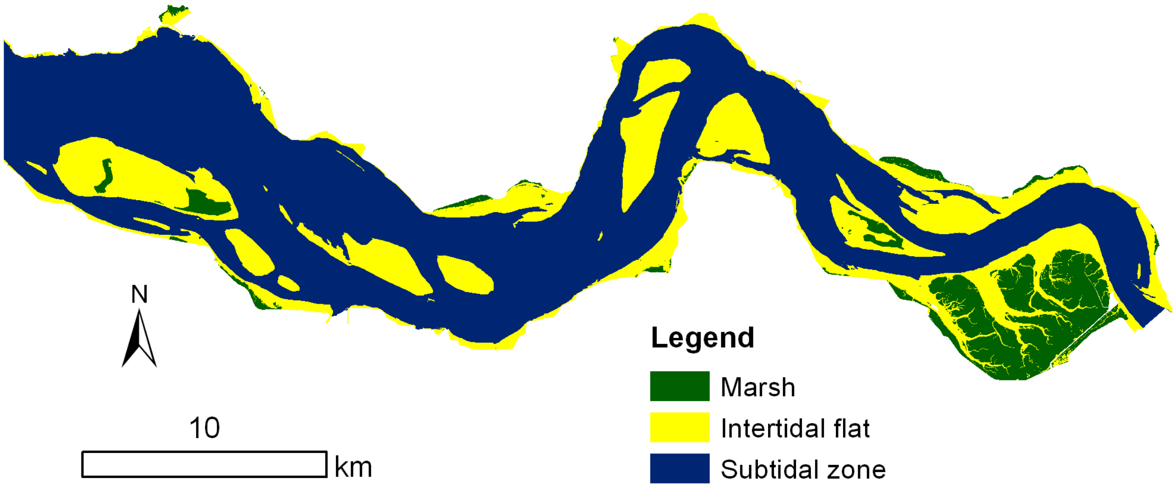

Figure 2 – Example of ecotope map of Western Scheldt in 2004.

2.5. Sediment grain size data

Sediment grain size data were collected from different sources, including the data from MOVE project [*Plancke et al.*, 2011], from INBO [*Speybroeck et al.*, 2014] and UA-ECOBE [*Jongepier et al.*, Submitted; *Temmerman et al.*, 2003, 2004; *Teuchies et al.*, 2013] during several projects (Tables 6-8). For the intertidal flats (Table 6), we used sediment grain size data resulting from the MOVE project (Figures 3-4) for the Western Scheldt (1992-1993 and 2002) and the lower Sea Scheldt (1992-1993), the data provided by INBO (Figure 5) for the entire Sea Scheldt (2008-2009), and the data provided by UA-ECOBE for the intertidal flats close to Lippenbroek (2006-2014). For the marshes (Table 7-8), we used sediment grain size data that were measured for several marshes in both the Western Scheldt and Sea Scheldt by UA-ECOBE (Figures 6-7) during several projects in the period from 2000-2012 (Table 7-8). Only data for inner marshes were used in the analyses. Data of creek bank levees within marshes were not considered because levees have a higher sand content than the average marsh samples but take a very small percentage of the total surface area of marshes. A few samples of the MOVE data and INBO data were also located in marshes, which were extracted by the ecotope maps (Figures 6-7). However, these samples were not used in the analyses, because most of them are located on levees after comparison with the aerial photographs. All the mud content data are used together with the assumption that the mud content stays constant over time and thus over the depth profile as sediments are deposited and accumulated over time (figure 8) [*Temmerman et al.*, 2004].

Table 6 – Sediment grain size data for intertidal flats in the Western Scheldt and Sea Scheldt.

Location	Year	Data source	Sample number	Total sample number
Western Scheldt	1992-1993	MOVE project	312	465
	2002	MOVE project	153	
Sea Scheldt	1992-1993	MOVE project	9	327
	2008-2009	INBO	258	
	2006-2014	UA-ECOBE	60	

Table 7 – Sediment grain size data for marshes in the Western Scheldt.

Location	Data source	Year	Total sample number	Sample number of levee	Sample number of inner marsh
Paulina	UA-ECOBE	2000-2001	5	1	4
Rilland	UA-ECOBE	2012	6	0	6
Saeftinghe	UA-ECOBE	2011	20	10	10
Several marshes	MOVE project	1992	8	-	-
Several marshes	MOVE project	2002	9	-	-
SUM	**-**	**-**	**48**	**11**	**20**

Table 8 – Sediment grain size data for marshes in the Sea Scheldt.

Row Labels	Data source	Year	Total sample number	Sample number of levee	Sample number of inner marsh
Notelaar	UA-ECOBE	2000-2001	4	2	2
Kruibeke	UA-ECOBE	2011	2	0	2
Natural marsh close to Lippenbroek	UA-ECOBE	2006-2014	120	0	120
Groot Buitenschoor	UA-ECOBE	2012	6	0	6
MOVE_ZS_1992	MOVE project	1992-1993	2	-	-
MOVE_ZS_2009	INBO	2008-2009	23	-	-
SUM	**-**	**-**	**792**	**4**	**130**

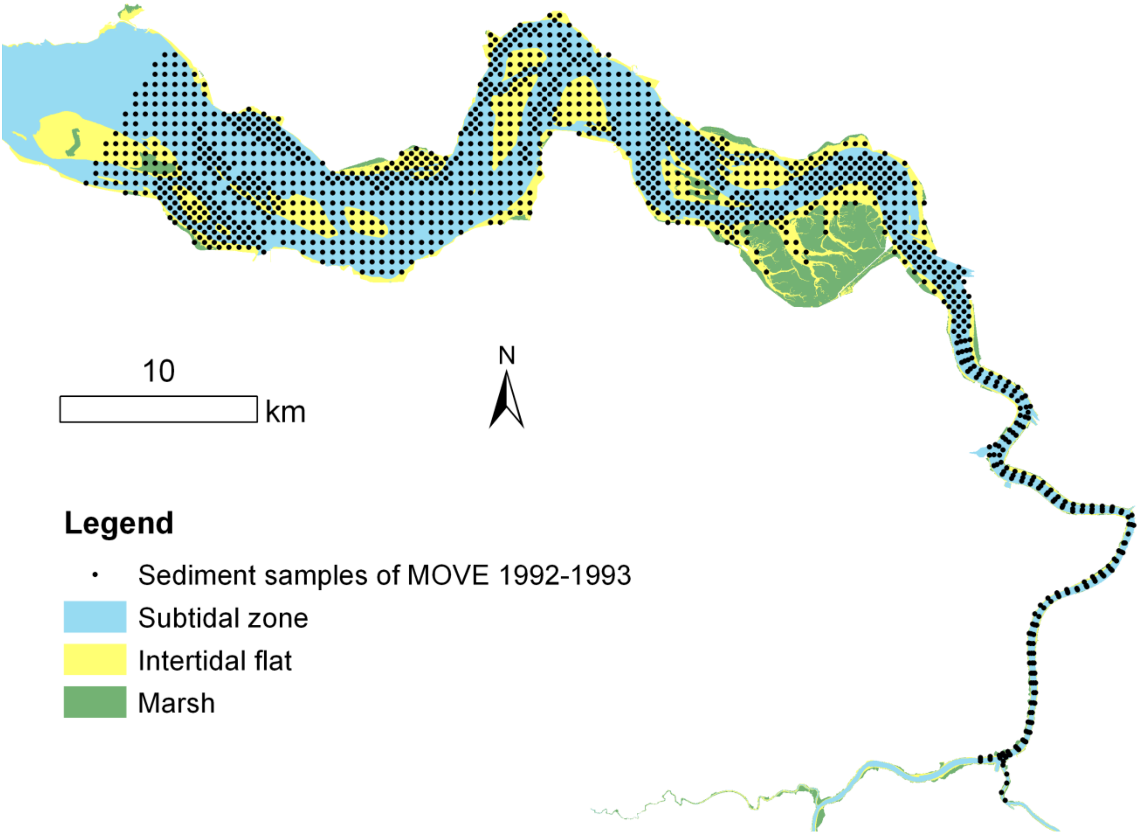

Figure 3 – Sediment grain size survey of MOVE 1992-1993

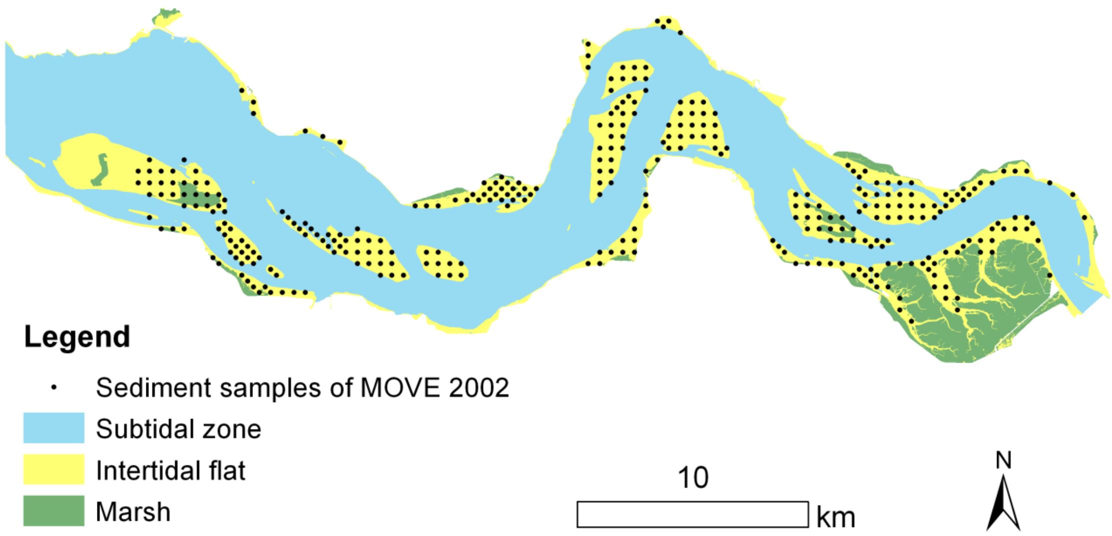

Figure 4 – Sediment grain size survey of MOVE 2002

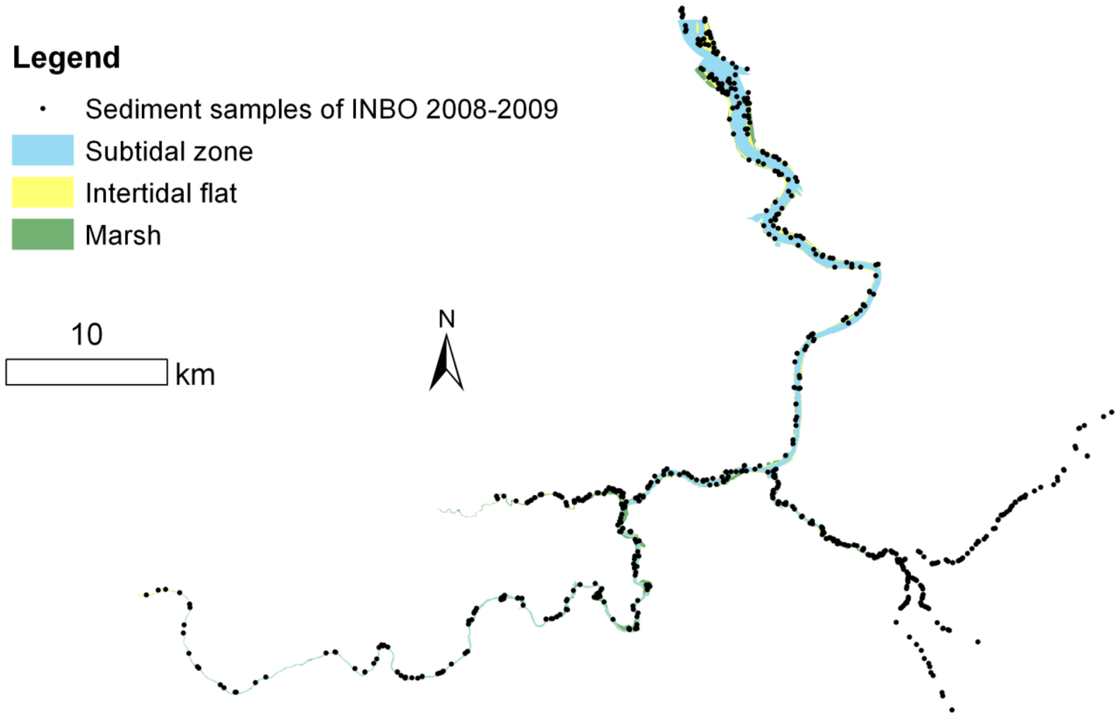

Figure 5 – Sediment grain size survey of INBO 2008-2009

Figure 6 – Sediment grain size data for marshes in the Western Scheldt.

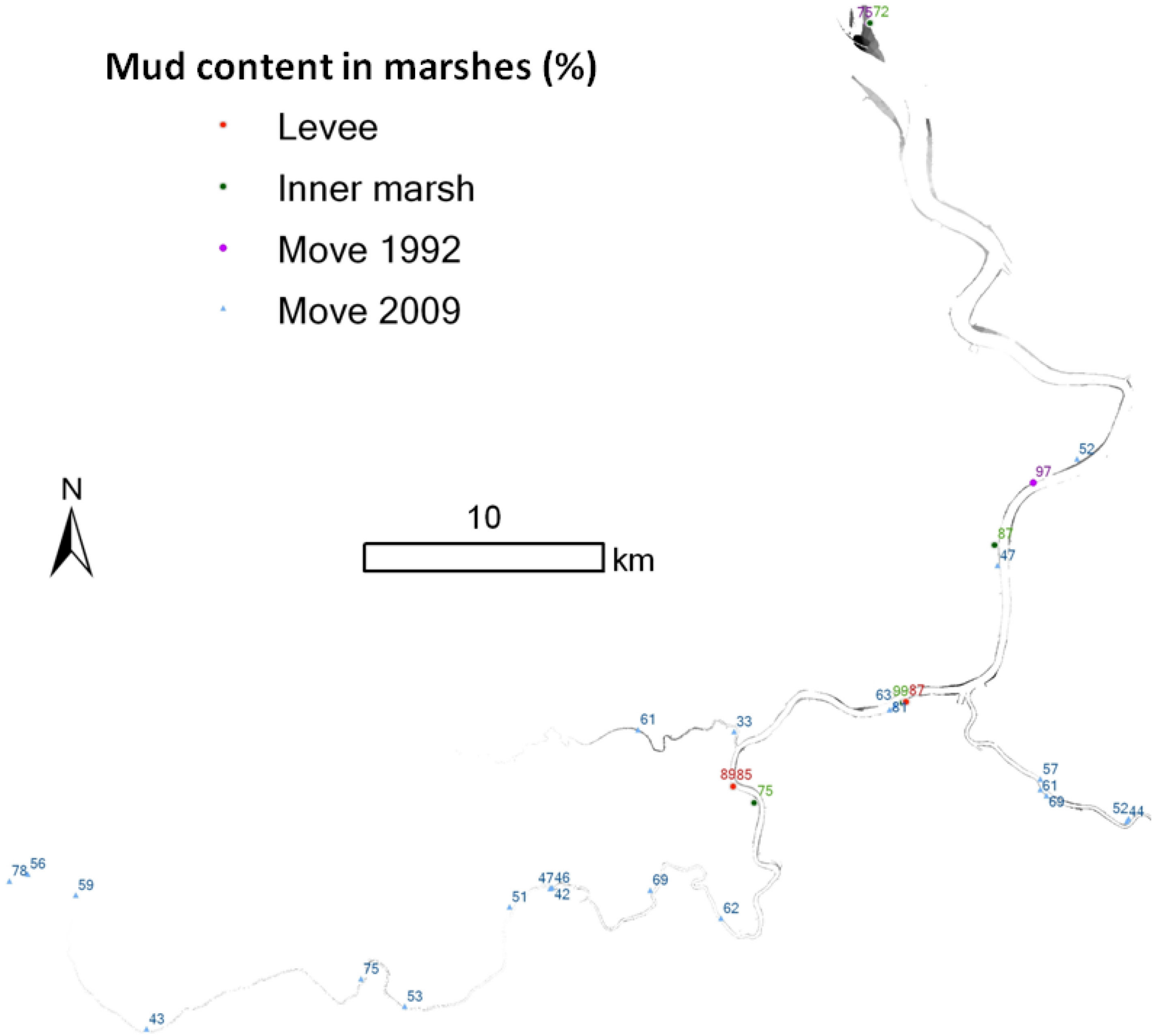

Figure 7 – Sediment grain size data for marshes in the Sea Scheldt.

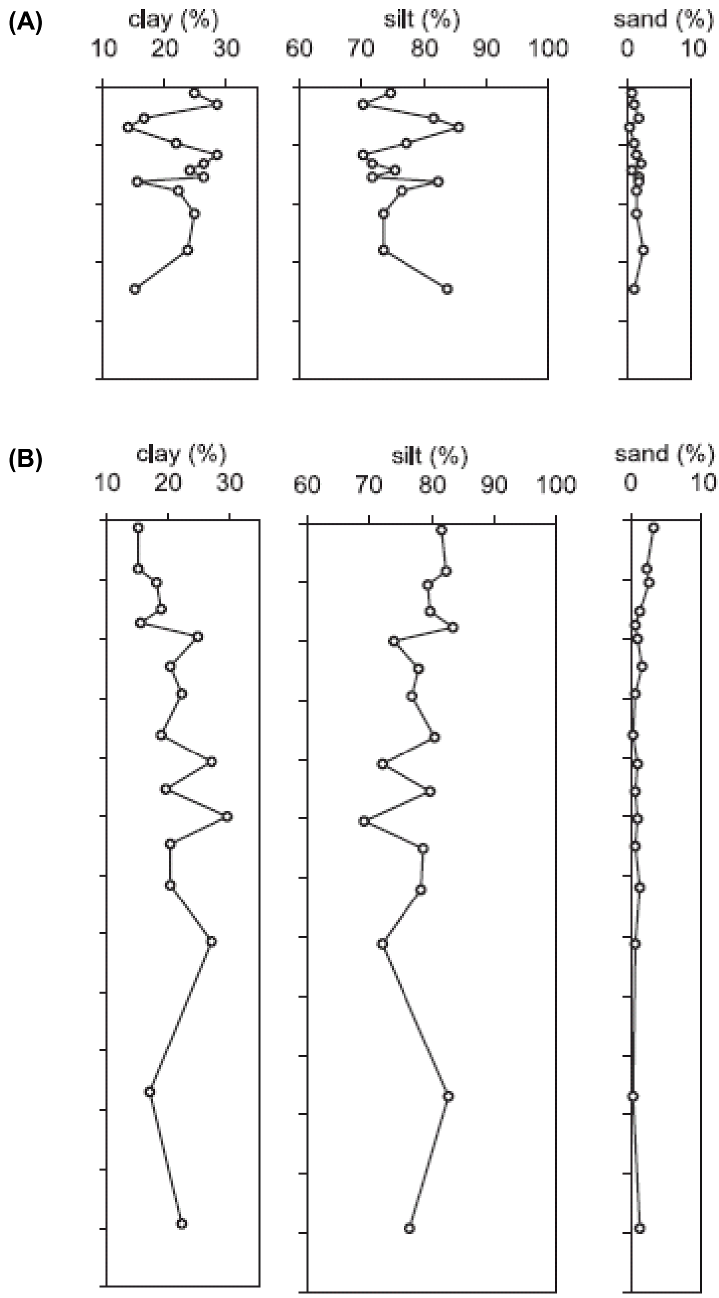

Figure 8 – Two examples of depth profiles of clay (<2 μm), silt (2–63 μm), and sand (>63 μm) content determined from sediment cores [Temmerman et al., 2004]. (A) Paulina marsh; (B) Notelaar marsh.

Several statistical values (i.e., 5, 25, 50, 75 and 95 percentile as well as the mean value) were calculated for the mud content in marshes and intertidal flats in the Western Scheldt and Sea Scheldt (Figure 9) based on a number of sediment samples (Section 2.5). In general, the mud content in marshes is higher than that in the intertidal flats. For the same ecotope types, the mud content in the Sea Scheldt is higher than that in the Western Scheldt. The highest mud content is observed in marshes of the Sea Scheldt, and the lowest in the intertidal flats in the Western Scheldt. The variation of mud content is the largest in the marshes in the Western Scheldt although the sample number is the smallest.

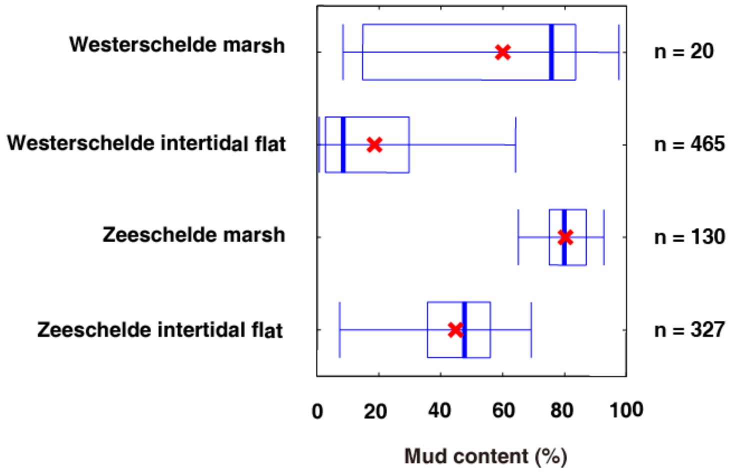

Figure 9 – Mud content in marsh and intertidal flat in the Western Scheldt and Sea Scheldt. The upper bounds and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile (median value), and the cross indicates the mean value.

In the later analyses, the statistical values of mud content in marshes and intertidal flats are used for different ecotopes as follows:

- Stable marsh: Mud content in marshes is used.
- Stable intertidal flat: Mud content in intertidal flats is used.
- Marsh → intertidal flats: Mud content of marshes is used, because we expect the shift from marsh to intertidal flat is associated with erosion of marsh sediments.
- Intertidal flats → marsh: The average of the mud content of intertidal flats and marshes is used, because we expect the shift from intertidal flats to marshes is associated with sedimentation, first sedimentation on the intertidal flat, and then as soon as marsh vegetation establishes, sedimentation on the marsh. Since we do not know when vegetation established exactly during the considered period, we use the average of the mud content of intertidal flats and marshes.
- Intertidal flat → subtidal zone, and subtidal zone → intertidal flat: The mud content of intertidal flats is used, because we expect that these shifts are associated with respectively erosion and sedimentation on intertidal flats.

2.6. Dry bulk density

The dry bulk density is estimated based on measurements on sediment samples from the Scheldt estuary with a high mud content, in particular marsh samples [Temmerman et al., 2003; Teuchies et al., 2013]. These are marsh samples already had had a certain degree of consolidation (no fresh depositions). Some marsh sample cores showed an increase of mud content with depth, some showed a uniform value over depth [Temmerman, pers. comm.]. No spatial trend in bulk density is assumed along the estuary, so an average dry bulk density of 500 ± 100 kg/m^3 is used for all zones. The mass fluxes scale linearly with the assumed dry bulk density, so there is a linear error propagation.

The dry bulk density in marshes is clearly lower compared with the dry bulk density of sand, which is generally between 1200 and 1500 kg/m³. It should be noted that Van Maldegem (1993) assumes a dry bulk density of 1 ton/m³ in his mud balance. Vereeke (1994) uses the data of Van Maldegem (1993) but assumed the dry density on the tidal flats to be 1,5 ton/m³. Those values seem to be quite high, when compared to the data presented by Temmerman et al (2004), who list the dry bulk density at 13 marsh sites along the Scheldt estuary, and who report values ranging between 260 and 685 kg/m³.

2.7. Spatial zonation

All calculations were done for different spatial zones along the estuary. Both the Western Scheldt and Sea Scheldt were subdivided into seven zones (figure 10). For the Western Scheldt, the same subdivision was used as in the report G02A of the V&T research on mud, because this study also calculated the mud balances [*Dam and Cleveringa*, 2013]. The Sea Scheldt was divided into the following zones: Gent-Dendermonde, Dendermonde-Durmemonding, Durmemonding-Schelle, Schelle-Antwerp and Antwerp-border, with Rupel and Durme as separate zones.

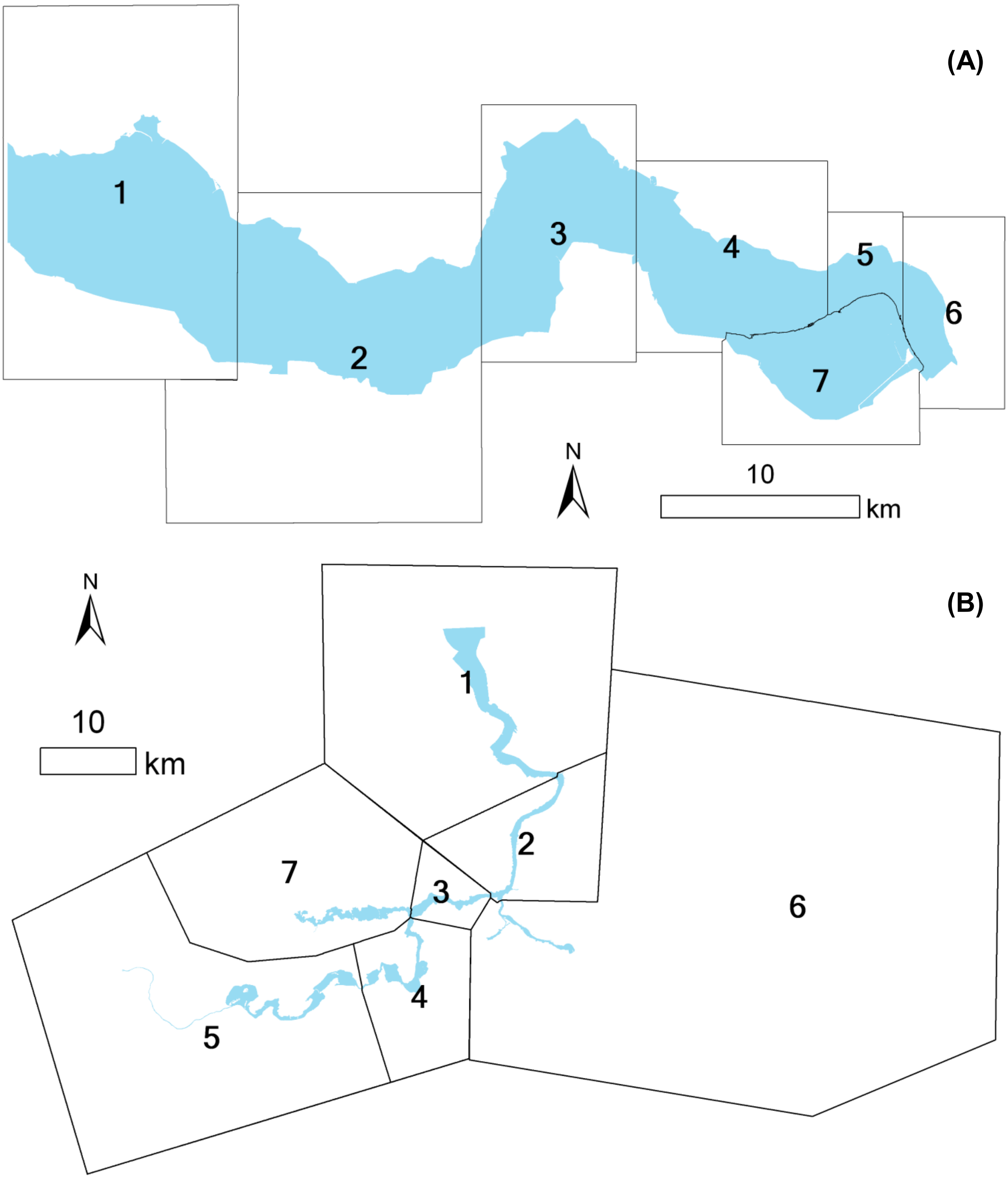

Figure 10 – Zonation of Western Scheldt (A) and Sea Scheldt (B).

2.8. GIS, statistical analyses, and uncertainty estimates

All spatial map analyses described above were performed using GIS (Geographical Information Systems) techniques using the software package ArcGIS 10.1 [*Gorr and Kurland*, 2013]. The ecotope maps were compared (overlaid) between two subsequent time steps in order to get the spatial distribution of ecotope changes. The DTMs were subtracted between two subsequent time steps in order to get the spatial distribution of elevation changes. Height change data from marker horizon measurements (1996-2000, provided by INBO) were also used for marshes in the Sea Scheldt, since LIDAR data were less accurate in freshwater marshes with high vegetation (see results below). Volume change is calculated by multiplying the height change with the area of corresponding ecotope changes. The eroded / deposited mud mass was calculated by multiplying the volume change with the mud content and the dry bulk density. Several statistical values were calculated and plotted to indicate the variation and uncertainty in the data, including the 5 percentile, 25 percentile, 50 percentile, 75 percentile, 95 percentile and mean value. In the end, the statistical values for mud mass is calculated as follows:

5 percentile of mud mass = 5 percentile of height change × area × 5 percentile of mud content × (500-100) kg/m^3

25 percentile of mud mass = 25 percentile of height change × area × 25 percentile of mud content × 500 kg/m^3

50 percentile of mud mass = 50 percentile of height change × area × 50 percentile of mud content × 500 kg/m^3

75 percentile of mud mass = 75 percentile of height change × area × 75 percentile of mud content × 500 kg/m^3

95 percentile of mud mass = 95 percentile of height change × area × 95 percentile of mud content × (500+100) kg/m^3

Mean of Mud mass = mean of height change × area × mean of mud content × 500 kg/m^3

All statistical analyses were done with the software package EXCEL and MATLAB [*Hunt et al.*, 2001].

3. Ecotope change classes

Spatial distribution of ecotope changes are mapped by comparing the ecotope maps between two subsequent time steps.

3.1. Temporal and spatial change of ecotopes in the Western Scheldt

The temporal and spatial changes of ecotopes in the Western Scheldt are shown in Figures 11-14. Most marshes are stable (i.e. with limited changes in surface area of marshes) in the period of 2004-2010 and 1988-2004, with only degradation (i.e. decrease of marsh area) on small scales at the outer edge of marshes. Large scale conversion of intertidal flats into marshes has occurred on the offshore flats in the middle of the estuary during the periods of 2004-2010 and 1988-2004, while such large scale conversions of bare flats to vegetated marshes have occurred on the onshore flats along the borders of the estuary during the periods of 1959-1988 and 1935-1959. Onshore flats (in Dutch: “slikken”) are defined here as fringing intertidal flats along the borders of the estuary that are connected to the mainland, such as Saeftinghe for example. Offshore flats (in Dutch: “platen”) are defined here as intertidal flats that are located in the middle of the estuary and are surrounded by subtidal channels, such as the “Plaat van Walsoorden” and “Hooge Platen” for example (sometimes “platen” are also called “intertidal shoals” but we prefer to use the terms offshore and onshore flats here in this report). Large scale conversion between intertidal flats and subtidal zones was also observed in the periods of 1959-1988 and 1935-1959 (dark and light blue zones in Figures 13 and 14). In the periods of 1959-1988 and 1935-1959, large parts of marshes and intertidal flats disappeared due to embankments (dark and light purple zones in Figures 13 and 14). Some areas were mapped as shift from ‘no data’ to ‘intertidal flat’ or ‘Subtidal zone’ (dark and light red zones in Figures 12 and 13), because elevation data was missing in some years so that the classification of ecotopes was not possible.

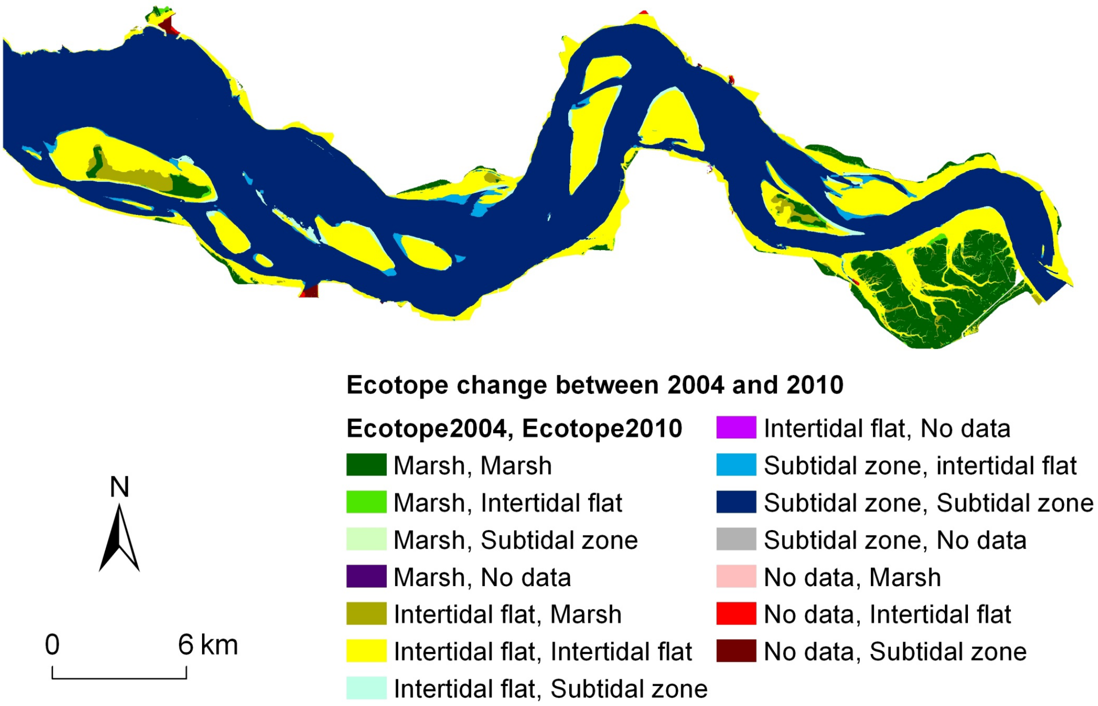

Figure 11 – Ecotope change in Western Scheldt between 2004 and 2010.

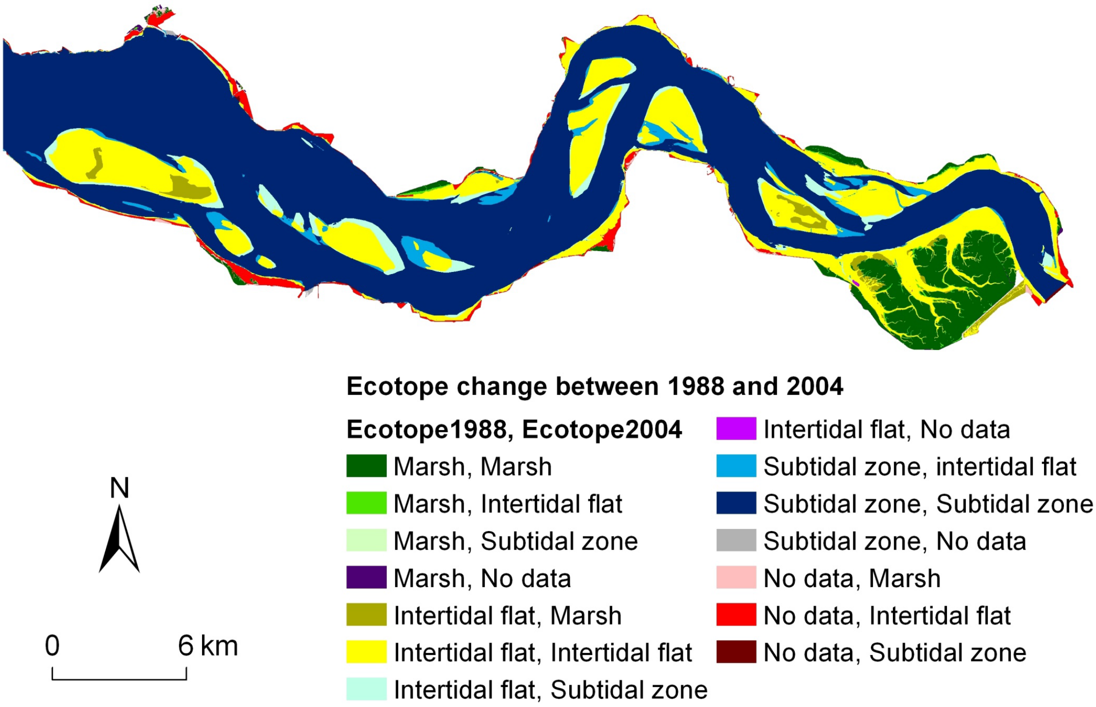

Figure 12 – Ecotope change in Western Scheldt between 1988 and 2004.

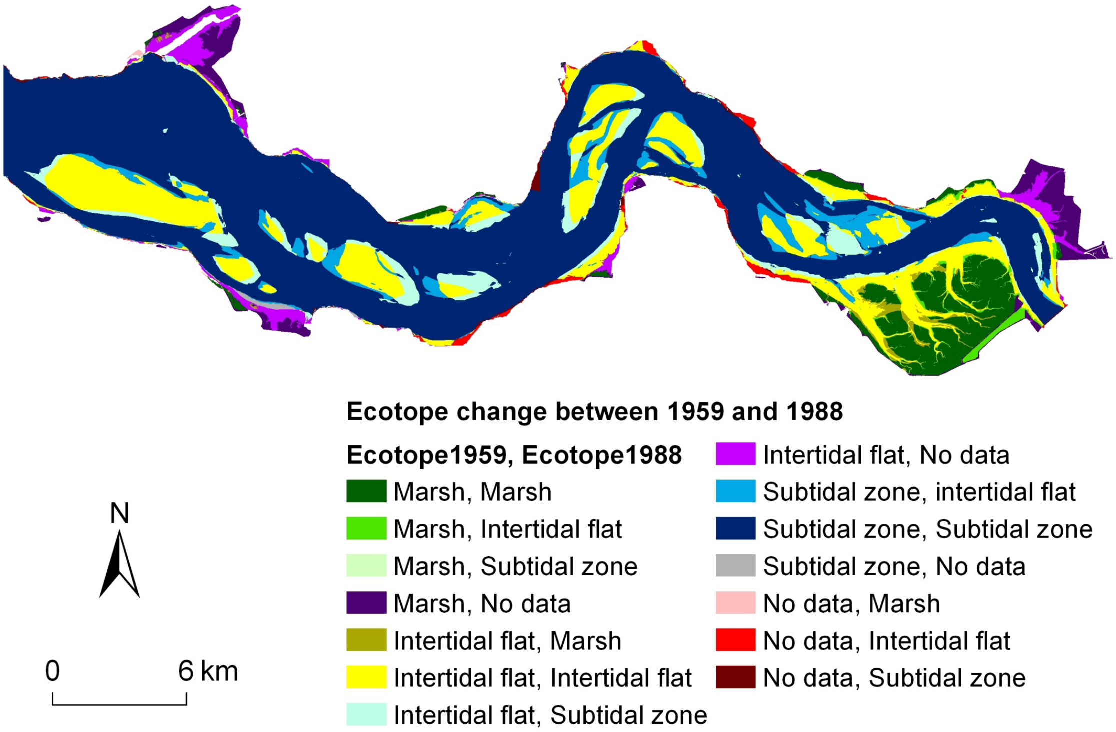

Figure 13 – Ecotope change in Western Scheldt between 1959 and 1988.

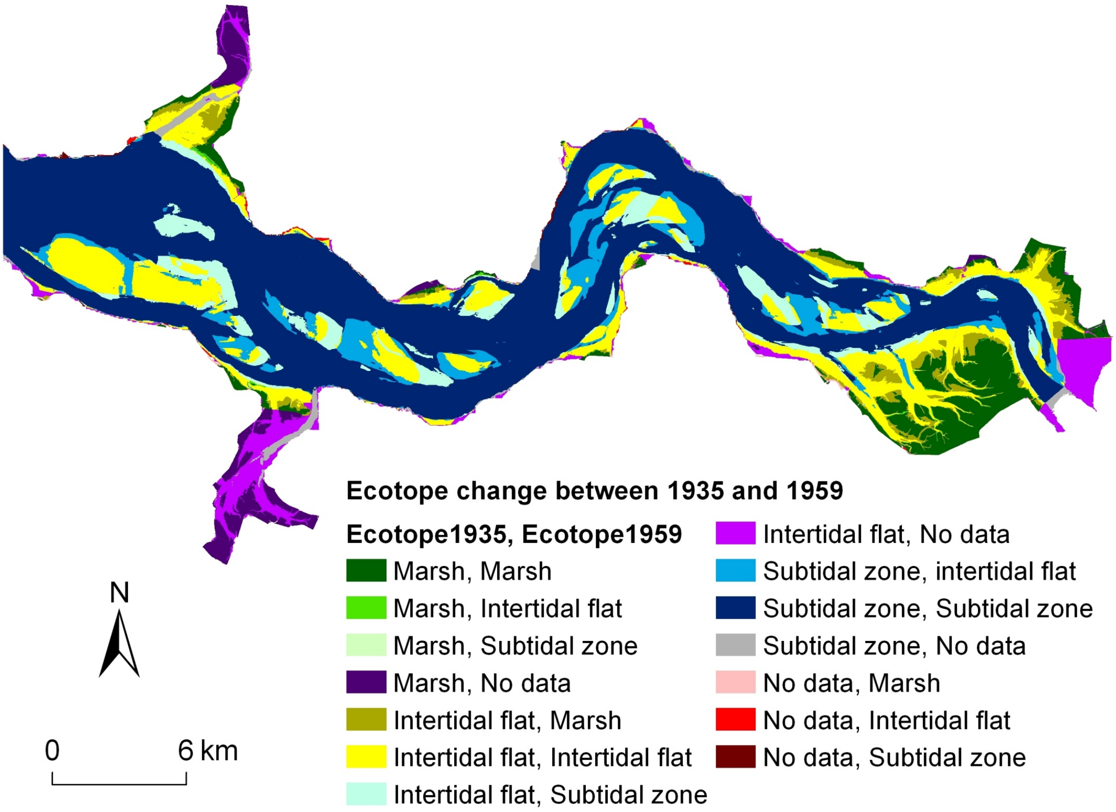

Figure 14 – Ecotope change in Western Scheldt between 1935 and 1959.

3.2. Temporal and spatial change of ecotopes in the Sea Scheldt

The temporal and spatial change of ecotopes in the Sea Scheldt are shown in Figures 15-17. The areas of marshes, intertidal flats and subtidal zones are relatively stable, except for rather large parts of marshes that disappeared due to embankments close to the Dutch-Belgian border during the periods of 1960-2001 and 1930-1960 (dark purple zones in Figures 16 and 17). During the same periods, marsh embankment also occurred on locally smaller scales more upstream along the Sea Scheldt.

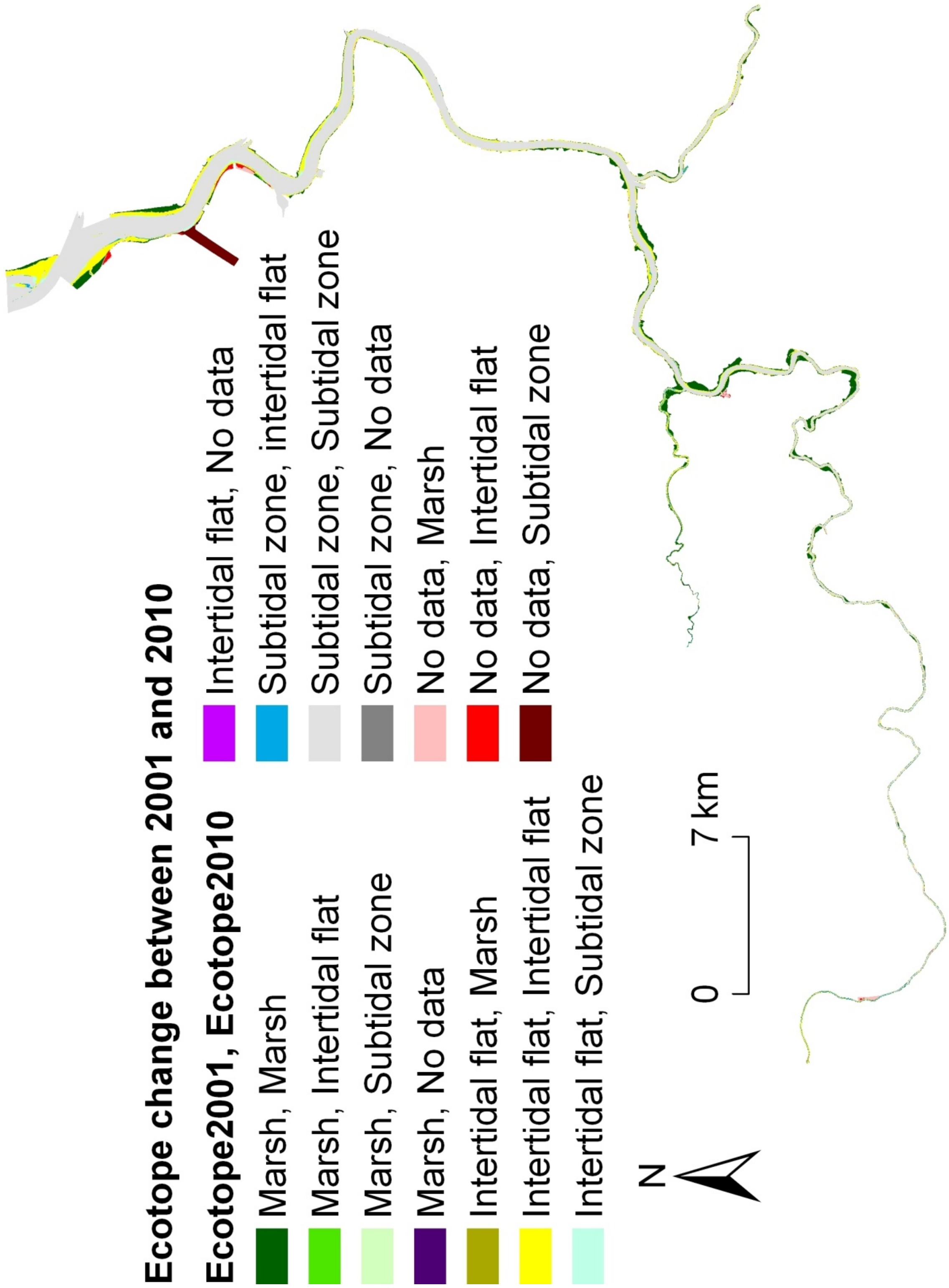

Figure 15 – Ecotope change in Sea Scheldt between 2001 and 2010.

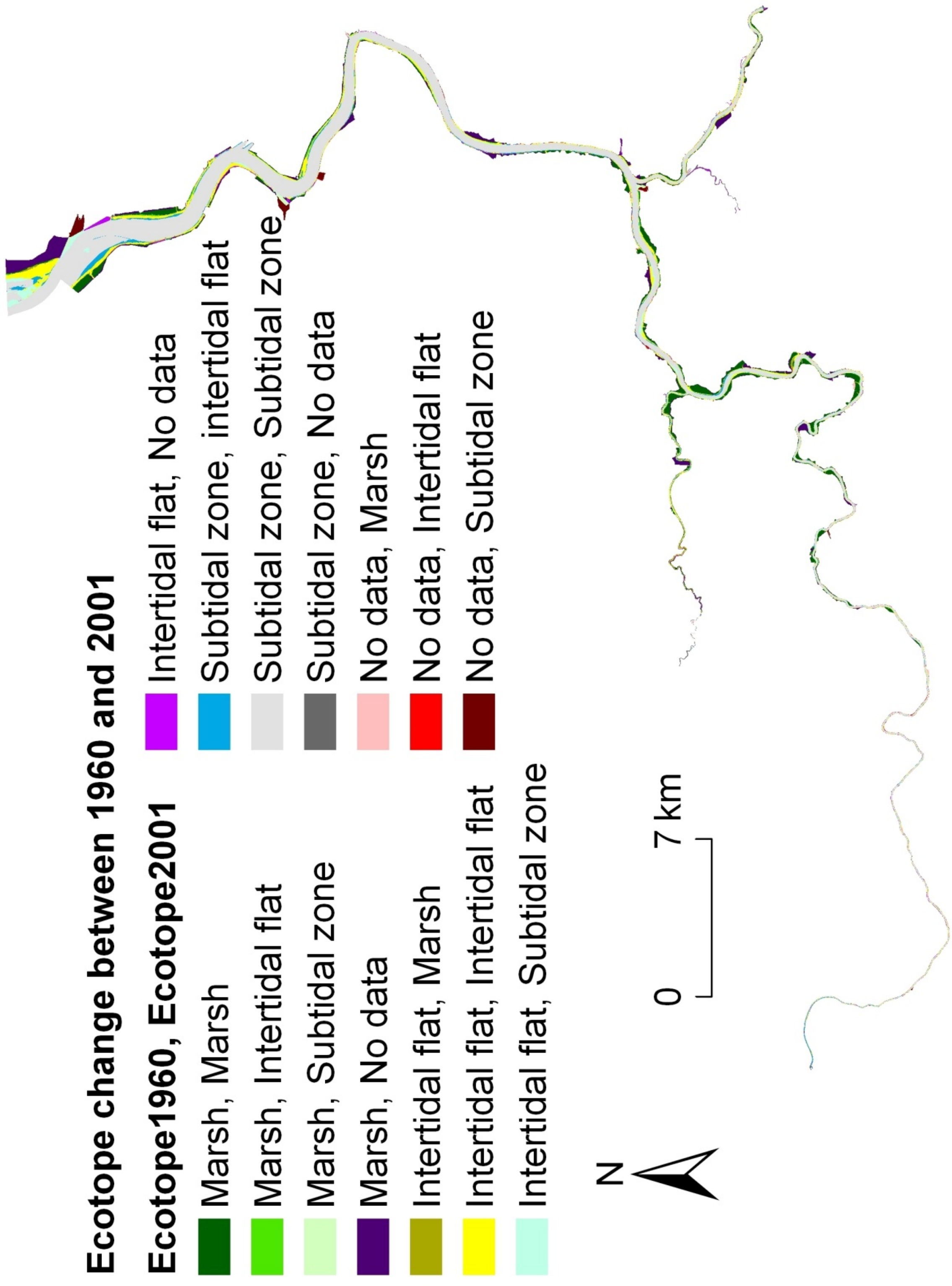

Figure 16 – Ecotope change in Sea Scheldt between 1960 and 2001.

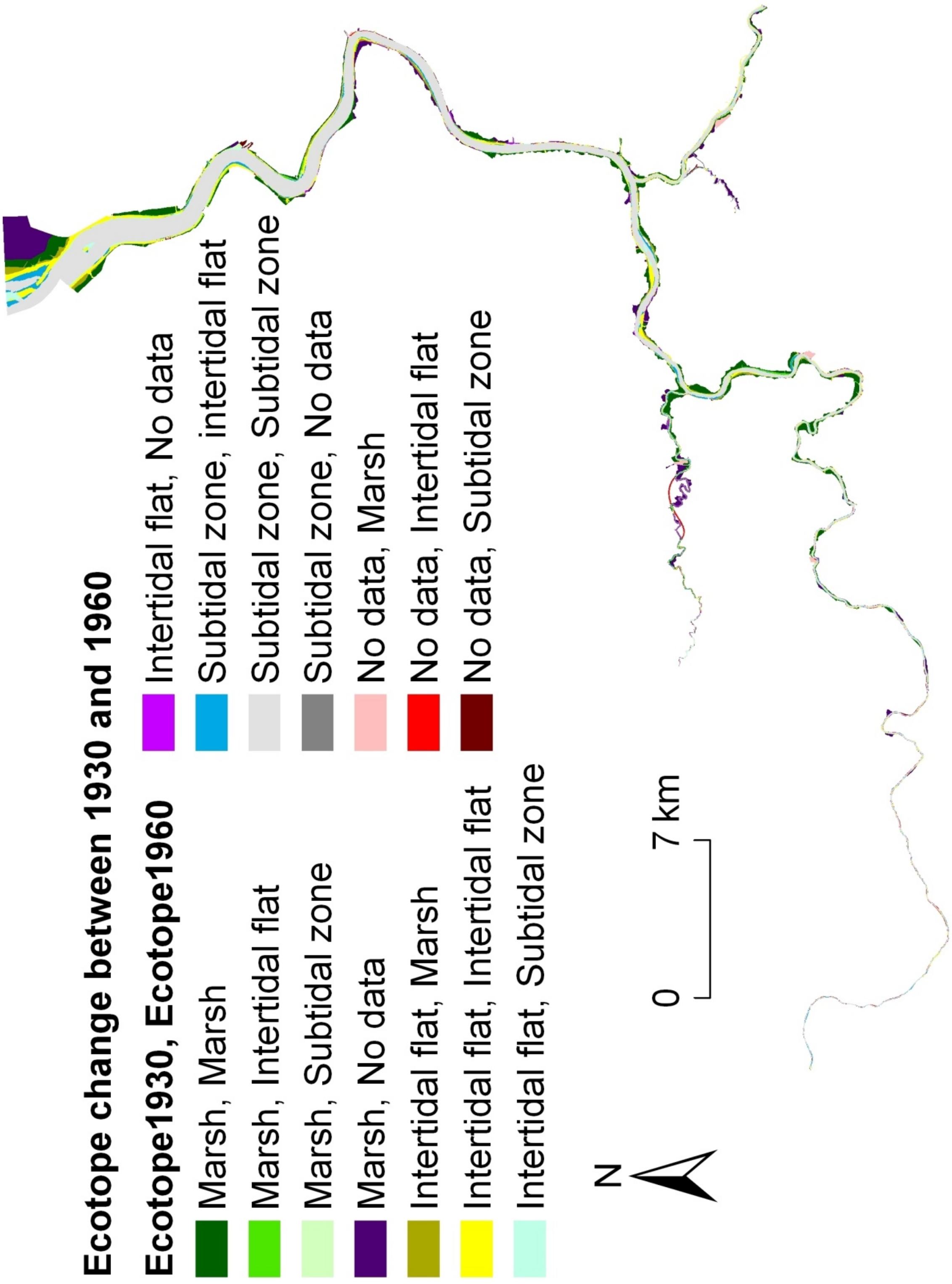

Figure 17 – Ecotope change in Sea Scheldt between 1930 and 1960.

3.3. Conclusion

In the Western Scheldt, large parts of marshes and intertidal flats disappeared due to embankments in the periods before 1988. After 1988, most marshes are stable. Large scale conversion of intertidal flats into marshes has occurred on the onshore flats in the periods before 1988 and on the offshore flats after 1988. Large scale conversion between intertidal flats and subtidal zones was also observed in the periods before 1988. In the Sea Scheldt, the areas of marshes, intertidal flats and subtidal zones are relatively stable, except for rather large parts of marshes that disappeared due to embankments close to the Dutch-Belgian border, and small scales of marsh embankment more upstream along the Sea Scheldt during the historical periods of 1930-2001, especially before 1960.

4. Temporal and spatial change of height

Spatial distribution of height changes were mapped by subtracting the Digital Terrain Models between two subsequent time steps.

4.1. Temporal and spatial change of height in the Western Scheldt

The temporal and spatial changes of height in the Western Scheldt are shown in Figures 18-21. In general, the largest changes in elevation happened on the offshore flats and at the outer edge of onshore flats, where hydrodynamic forces are likely to be highest. For the offshore flats, large scale erosion on one side of flats and sedimentation on the opposite side is observed for certain offshore flats, and in general erosion of offshore flats is strongest at the outer edge of the offshore flats, while the interior parts of the flats are generally increasing in height. The height increase in Saeftinghe in the period of 2004-2010 is smaller than in the earlier years, because large parts of Saeftinghe have developed from low pioneer marshes in 1931 to high marshes above mean high water level by 2004 and 2010 [*Wang and Temmerman*, 2013].

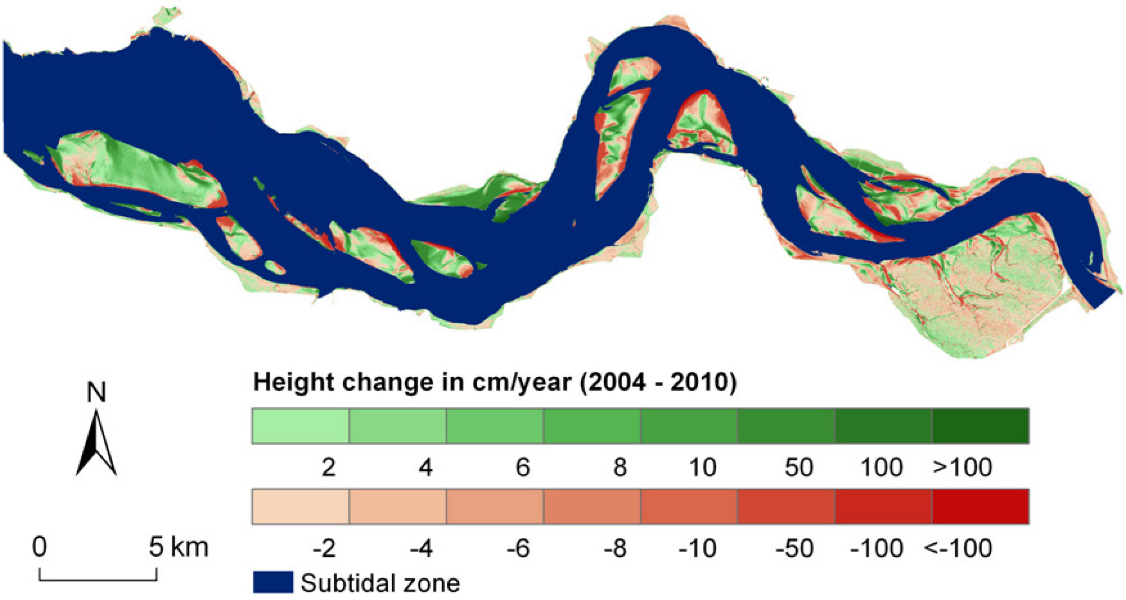

Figure 18 – Yearly height change in the Western Scheldt between 2004 and 2010.

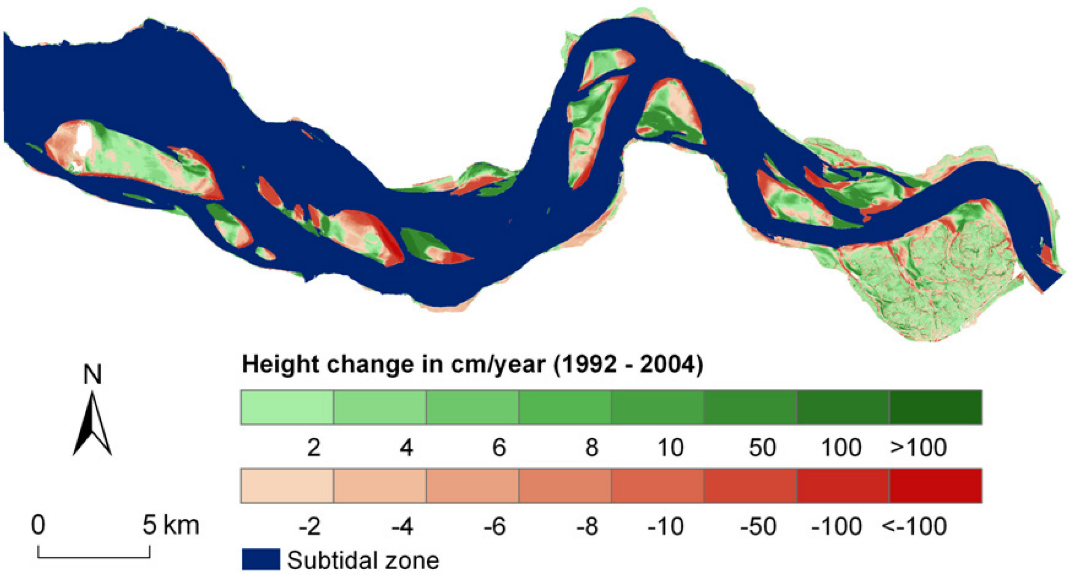

Figure 19 – Yearly height change in the Western Scheldt between 1992 and 2004.

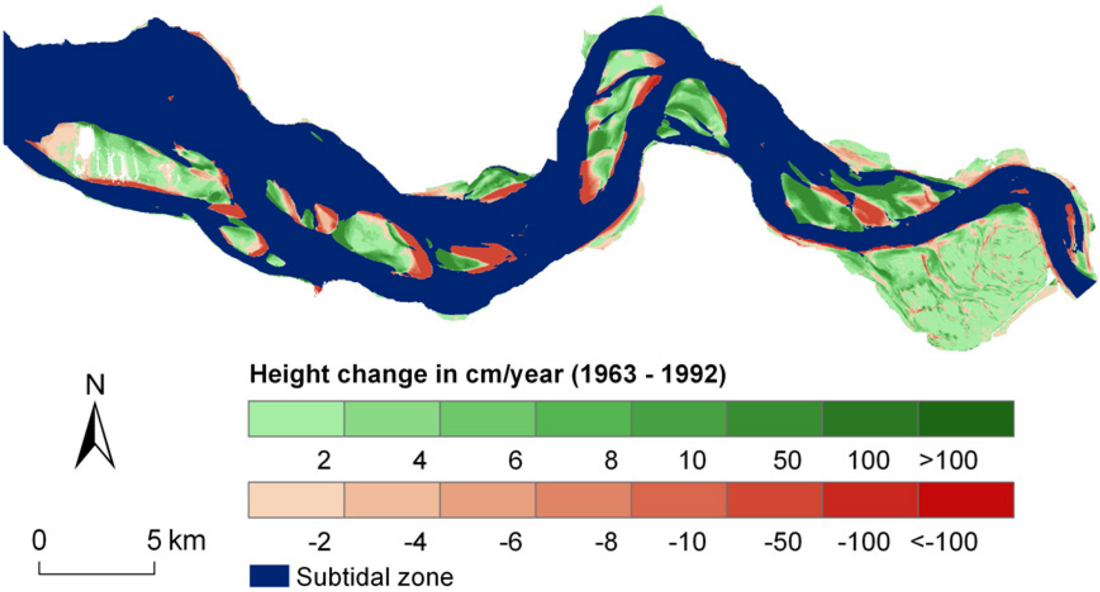

Figure 20 – Yearly height change in the Western Scheldt between 1963 and 1992.

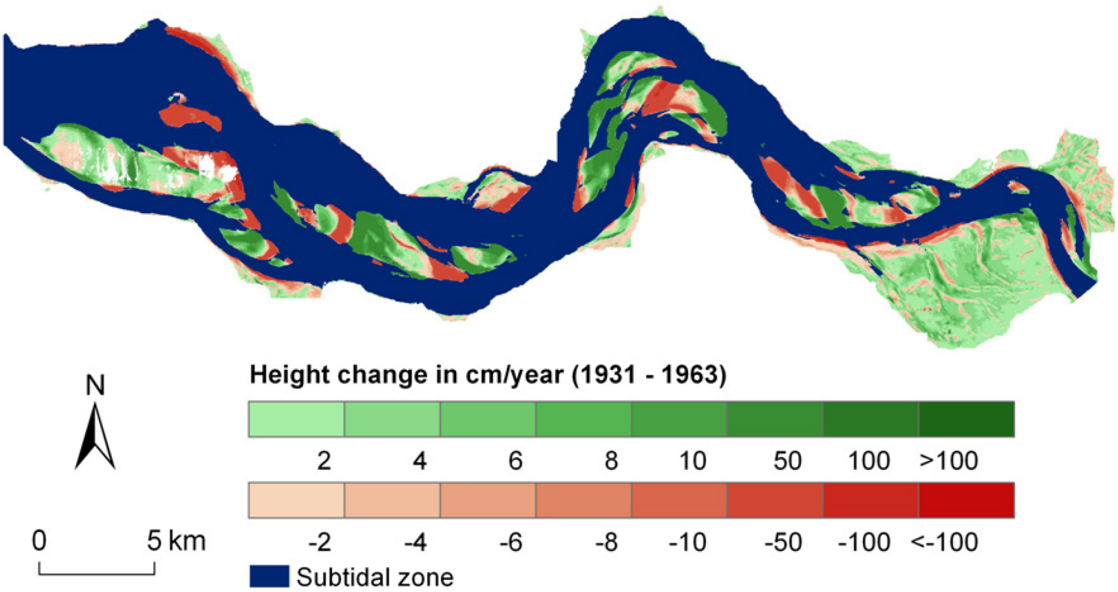

Figure 21 – Yearly height change in the Western Scheldt between 1931 and 1963.

4.2. Temporal and spatial change of height in the Sea Scheldt

The temporal and spatial change of height in the Sea Scheldt is shown in Figures 22-24. For the Sea Scheldt, LIDAR data is only available for the period of 2004-2011. The available data of height change in the intertidal zones are limited for the period of 1960-2000 and 1930-1960, because the elevation data is only available for the lower part of intertidal zones through bathymetric surveys, so that no elevation data are available for most of the intertidal area for the period of 1960-2000 and 1930-1960.

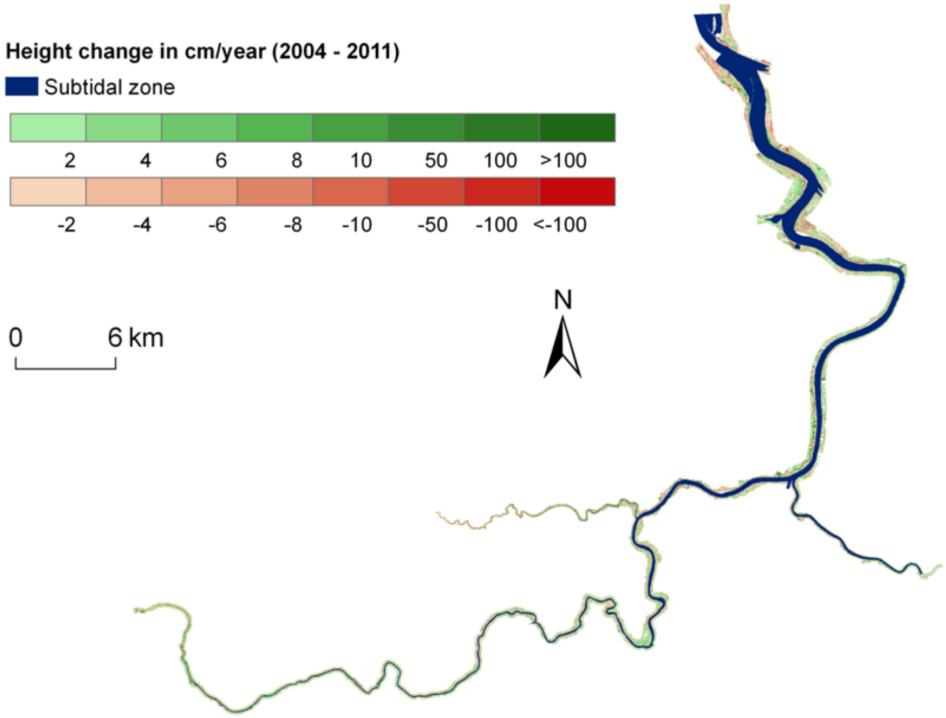

Figure 22 – Yearly height change in the Sea Scheldt between 2004 and 2011.

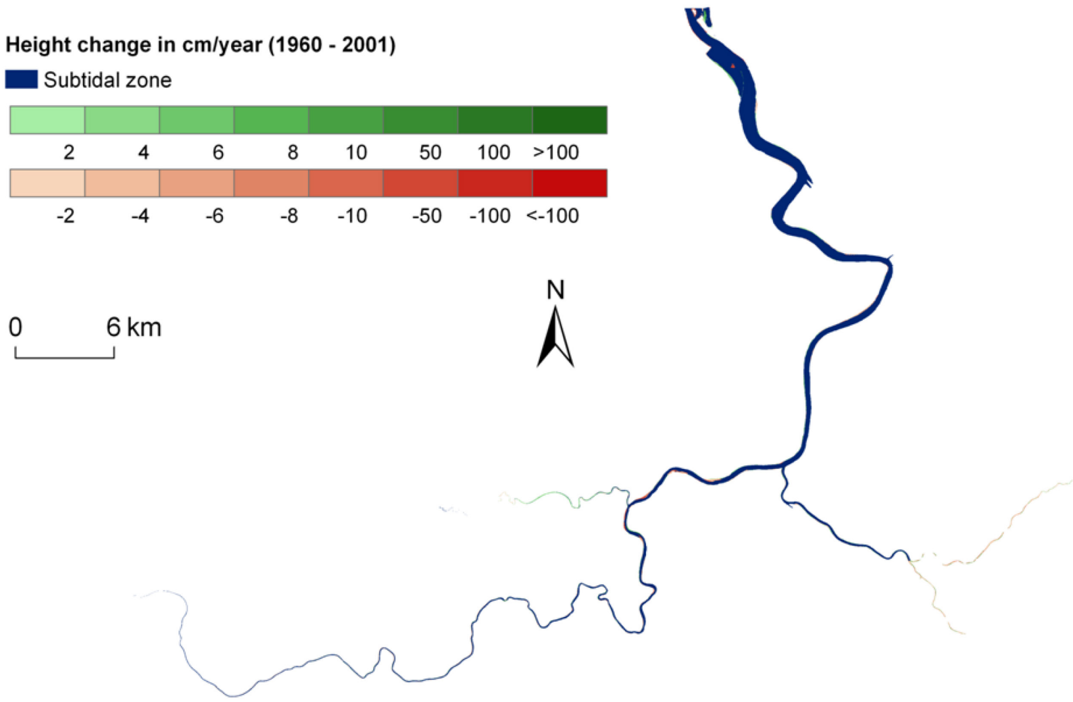

Figure 23 – Yearly height change in the Sea Scheldt between 1960 and 2001.

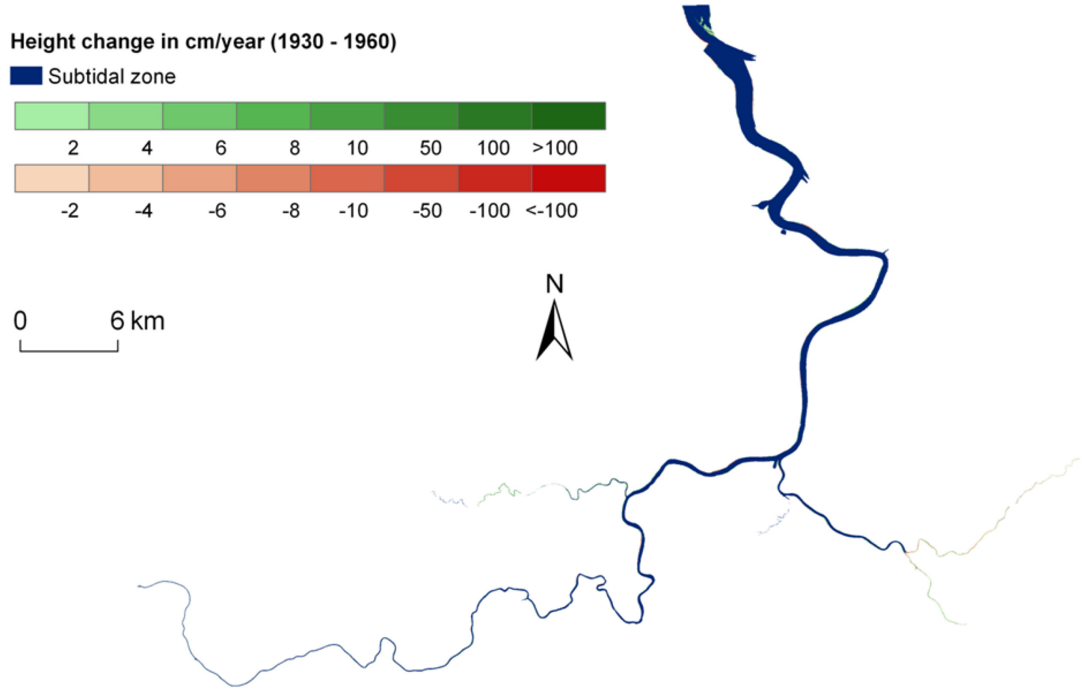

Figure 24 – Yearly height change in the Sea Scheldt between 1930 and 1960.

4.3. Conclusion

Spatial data of elevation in the intertidal areas are more available in the Western Scheldt but limited in the Sea Scheldt. In the Western Scheldt, elevation changes most on the offshore flats and at the outer edge of onshore flats, where hydrodynamic forces are likely to be highest. Large amounts of erosion on one side and sedimentation on the opposite side is observed for certain offshore flats. In general, erosion is strongest at the outer edge of the offshore flats, while deposition dominates on the interior parts of the flats with increasing height. The height increase in Saeftinghe is smaller in the period of 2004-2010 than in the earlier years, because large parts of Saeftinghe have developed from low pioneer marshes in 1931 to high marshes by 2004 and 2010.

5. Ecotope areas in different zones and different periods

For six different ecotope change classes, the area is calculated in different subdivision zones and in different periods. The six ecotope change classes are:

1. Stable marshes: classified as marsh in both years
2. Stable intertidal flat: classified as intertidal flat in both years
3. Marsh → Intertidal flat: classified as marsh in the earlier time step and intertidal flat in the later time step
4. Intertidal flat → Marsh: classified as intertidal flat in the earlier time step and marsh in the later time step
5. Intertidal flat → Subtidal zone: classified as intertidal flat in the earlier time step and subtidal zone in the later time step
6. Subtidal zone → intertidal flat: classified as subtidal zone in the earlier time step and intertidal flat in the later time step

5.1. Ecotope areas in different zones and different periods in the Western Scheldt

In all the periods in the Western Scheldt (Figures 25-28), most of the stable marshes are located in Zone 7, which is the Saeftinghe area. Large areas of stable intertidal flats are found in Zone 1-4 and Zone 7. Large areas of conversion between intertidal flats and subtidal zones are observed in Zone 1-4 in the period of 1963-1992 and 1931-1963.

A lot of subtidal area was converted to intertidal areas in Zone 1-4 in the period 1931-1992. Most of these newly formed intertidal areas remained stable.

Figure 25 – Ecotope areas in different zones between 1931 and 1963 in the Western Scheldt.

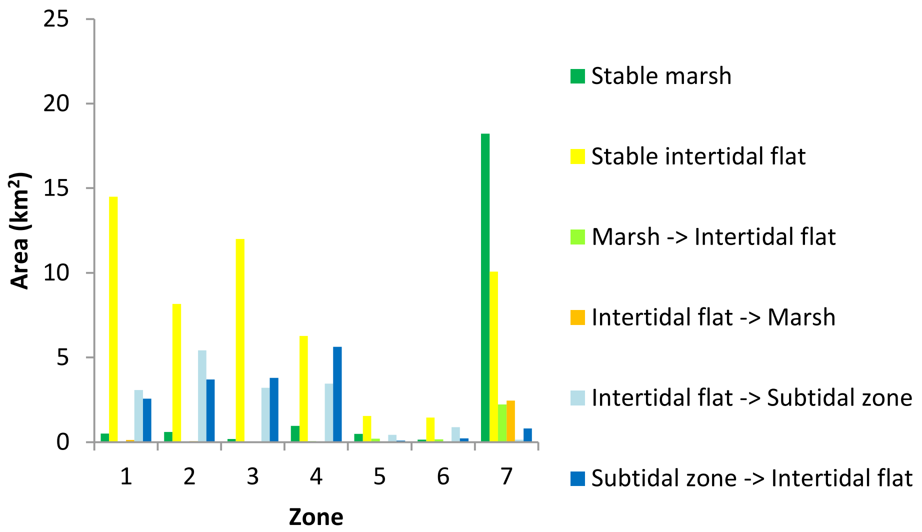

Figure 26 – Ecotope areas in different zones between 1963 and 1992 in the Western Scheldt.

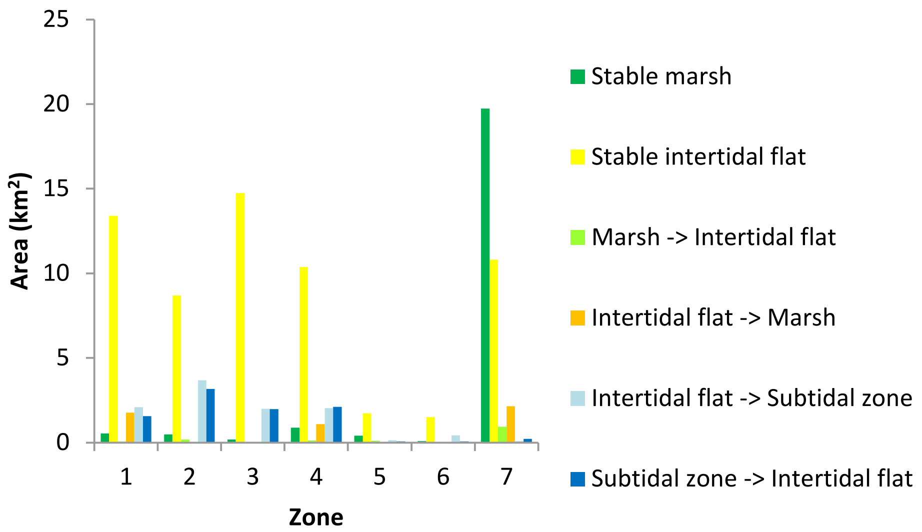

Figure 27 – Ecotope areas in different zones between 1992 and 2004 in the Western Scheldt.

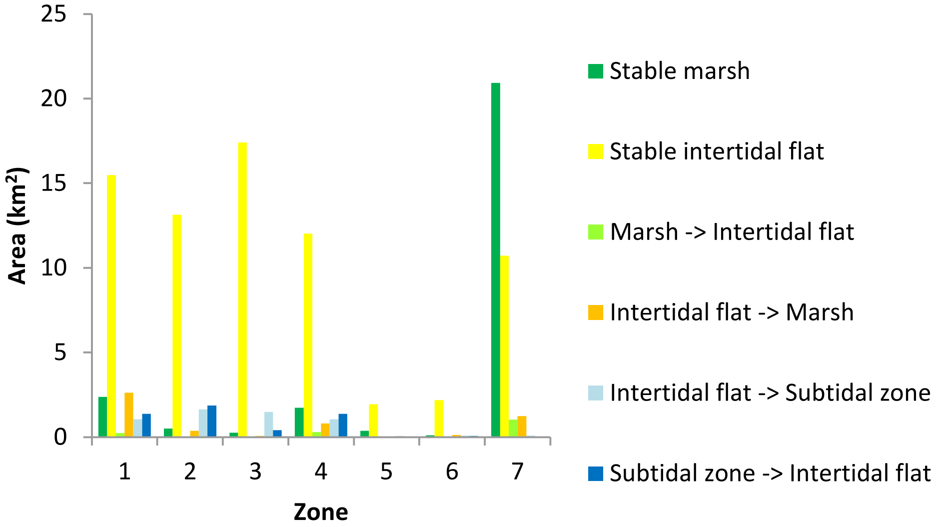

Figure 28 – Ecotope areas in different zones between 2004 and 2011 in the Western Scheldt.

5.2. Ecotope areas in different zones and different periods in the Sea Scheldt

In general, intertidal ecotopes occupy a much smaller area in the Sea Scheldt (Figures 29-31) than in the Western Scheldt. Stable marshes are found in all subdivision zones, with a slightly larger area in Zone 1 and Zone 4. Large areas of marshes disappeared in Zone 1 in 1960-2000 (mainly due to embankments). Stable intertidal flats are mainly found in Zone 1.

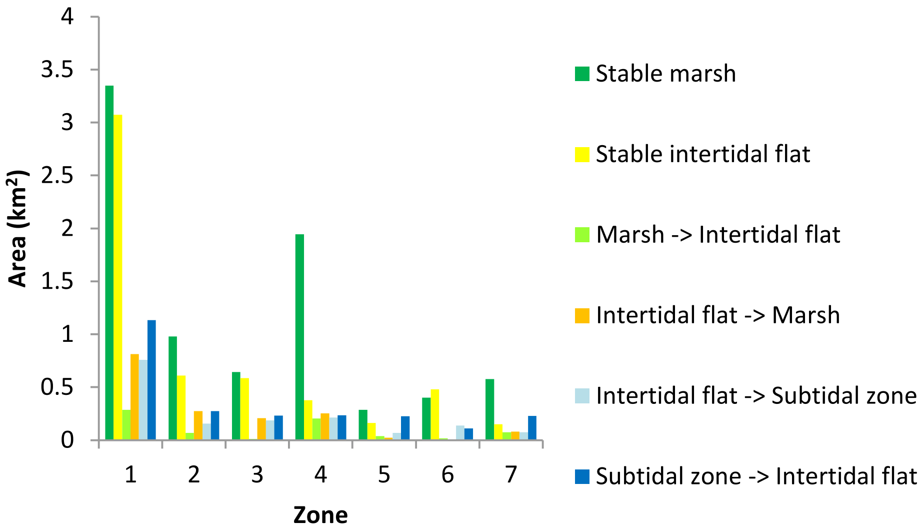

Figure 29 – Ecotope areas in different zones between 1930 and 1960 in the Sea Scheldt.

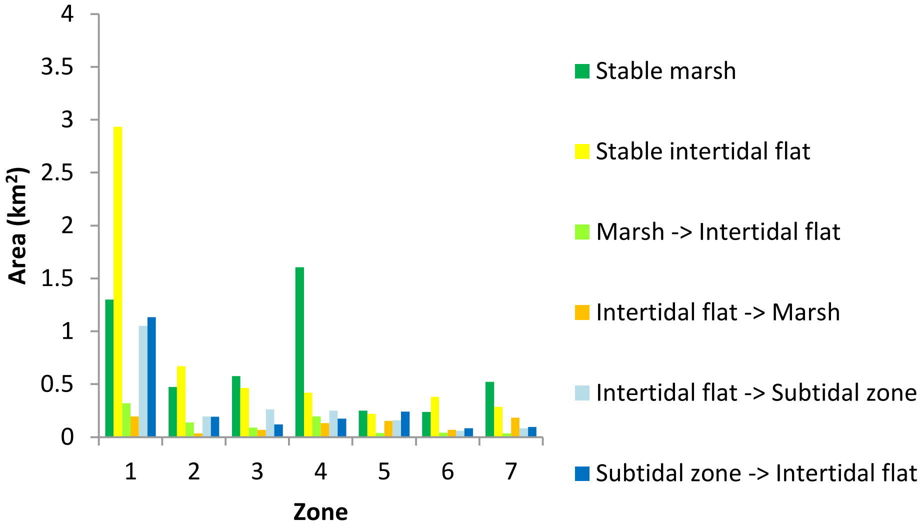

Figure 30 – Ecotope areas in different zones between 1960 and 2000 in the Sea Scheldt.

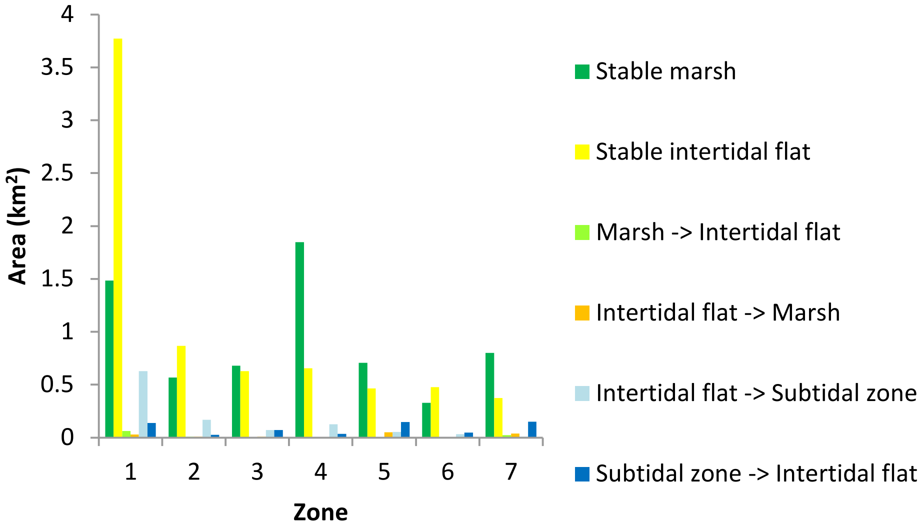

Figure 31 – Ecotope areas in different zones between 2004 and 2011 in the Sea Scheldt.

5.3. Conclusion

The intertidal area is much larger in the Western Scheldt than in the Sea Scheldt. In both the Western Scheldt and Sea Scheldt, large areas of intertidal zones are covered by 'Stable marsh' and 'Stable intertidal flat'. Most of the 'Stable marsh' is located in Saeftinghe (zone 7 in the Western Scheldt) with gradual increase of area in time. A lot of subtidal areas were converted to intertidal flats in the Western Scheldt before 1992, and remained stable in the later periods.

The area of 'Stable marsh' in the Sea Scheldt decreased a lot from 1960-2000 due to embankments, and slightly increased in recent years.

Table 9 gives the overview of the areas of the different ecotope change classes over time.

Table 9 – Areas (ha) of different ecotope areas in the Western Scheldt and the Sea Scheldt in different sub-periods

Location	**Period**	Stable marshes	Stable intertidal flat	Subtidal zone -> Intertidal flat	Intertidal flat -> Marsh	Marsh -> Intertidal flat	Intertidal flat -> Subtidal zone
Western Scheldt	**1931-1963**	2,435	5,529	2,587	1,131	77	2,260
	1963-1992	2,109	5,398	1,680	266	267	1,657
	1992-2004	2,228	6,126	916	505	146	1,044
	2004-2010	2,624	7,287	511	524	165	548
	Mean	2,349	6,085	1,423	606	164	1,377
Sea Scheldt	**1930-1960**	818	544	244	165	70	160
	1960-2000	497	537	204	84	85	206
	2004-2011	642	724	61	14	10	108
	Mean	652	601	170	88	55	158

6. Height change in different zones and different ecotopes

Several statistical values, including 5, 25, 50, 75 and 95 percentiles as well as the mean value, of the height changes in different ecotope change classes (see classes in Figures 32-38) were calculated for each spatial zone in the Western Scheldt and Sea Scheldt (see zones in Figure 10). For zones with limited elevation data, a mean value of the adjacent zones was used as a rough estimation.

6.1. Height change in different zones and different ecotopes in the Western Scheldt

The height change in the Western Scheldt is shown in Figures 32-35. In general, a slight increase in elevation is observed in 'Stable marsh' in all zones and in all periods. The average height changes are close to zero in 'Stable intertidal fat', but the variation is larger than in 'Stable marsh'. Generally negative height change is observed for areas of 'Marsh → Intertidal flat' and 'Intertidal flat → Subtidal zone', suggesting erosion in these areas. Generally positive height change is observed for areas of 'Intertidal flat → Marsh' and 'Subtidal zone → Intertidal flat', suggesting deposition in these areas. Larger values are observed for areas shifting between subtidal zone and intertidal flat, which can also be seen on the maps of spatial distribution of elevation changes (Figures 18-21).

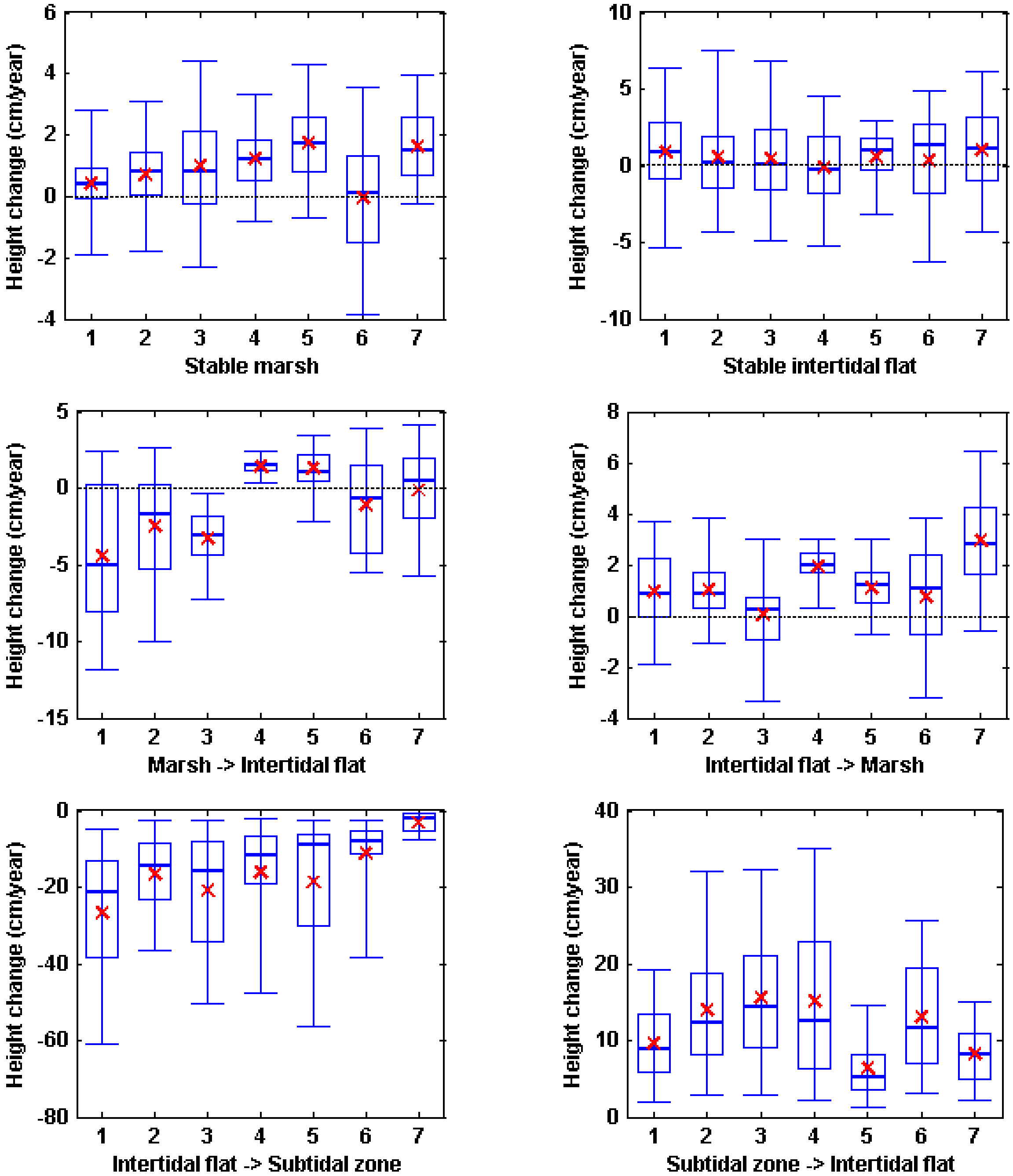

Figure 32 – Boxplots of yearly height change between 1931 and 1963 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

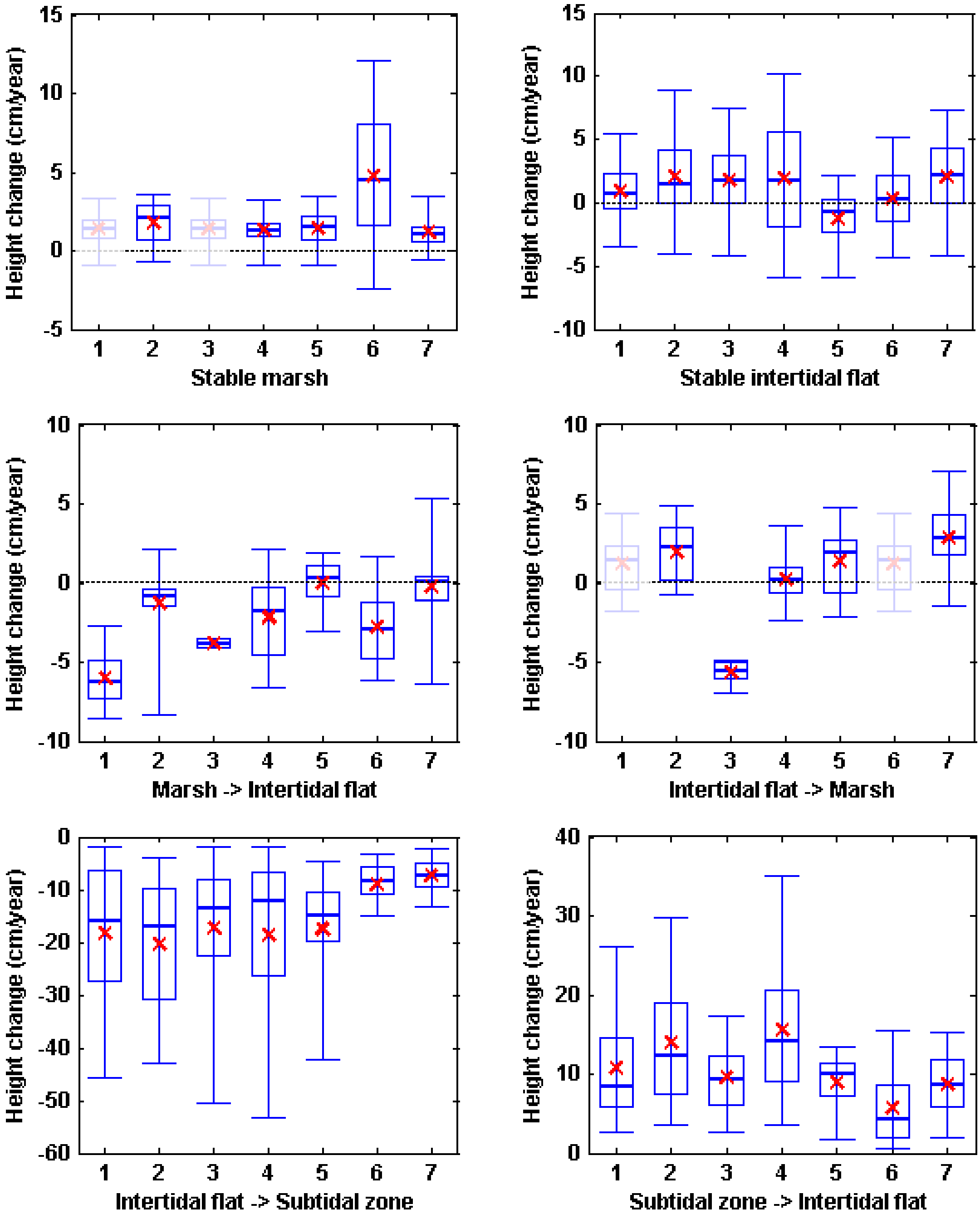

Figure 33 – Boxplots of yearly height change between 1963 and 1992 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. A mean value of the adjacent zones was used as a rough estimation for zones with limited elevation data, shown with lighter colors in the figures.

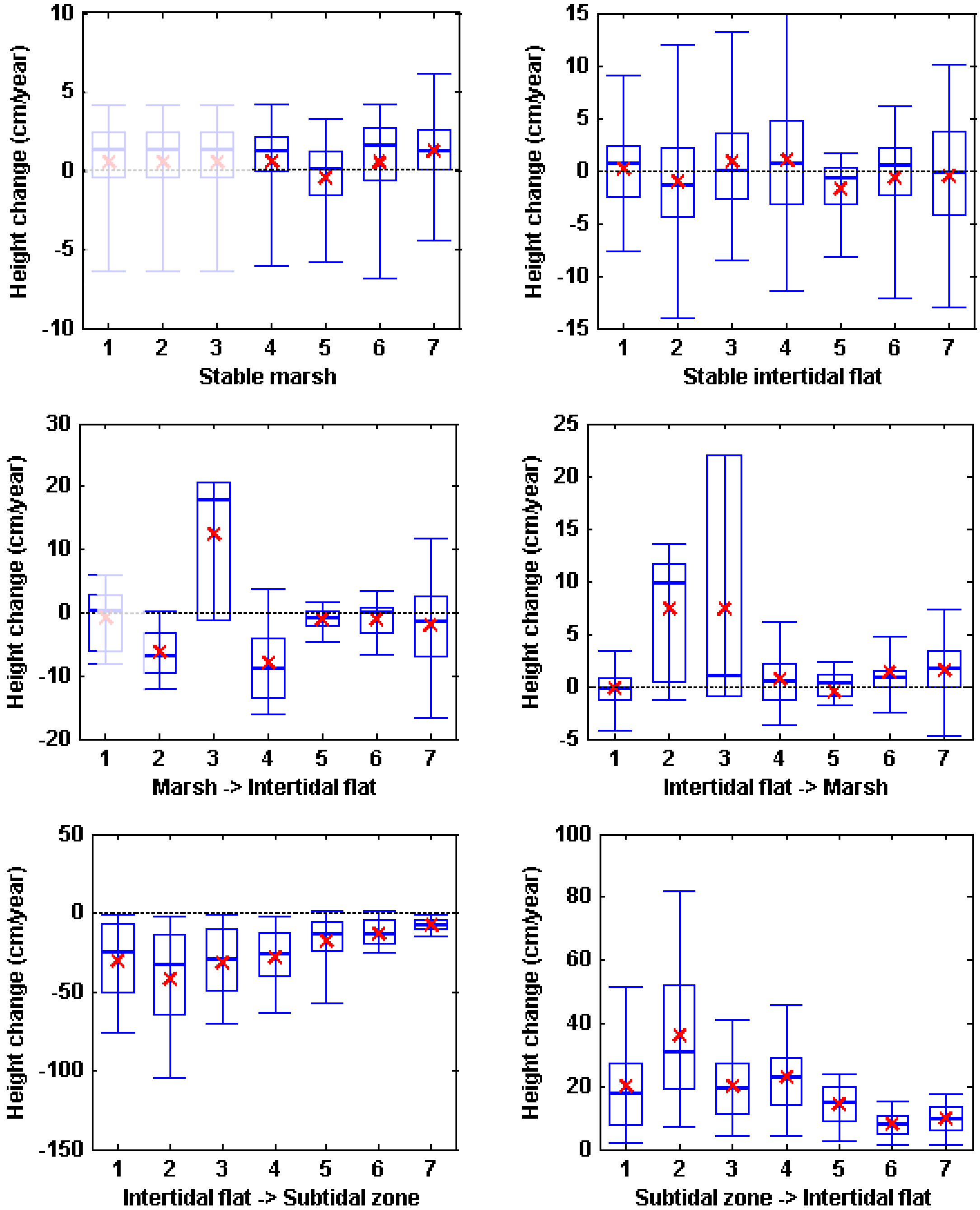

Figure 34 – Boxplots of yearly height change between 1992 and 2004 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. A mean value of the adjacent zones was used as a rough estimation for zones with limited elevation data, shown with lighter colors in the figures.

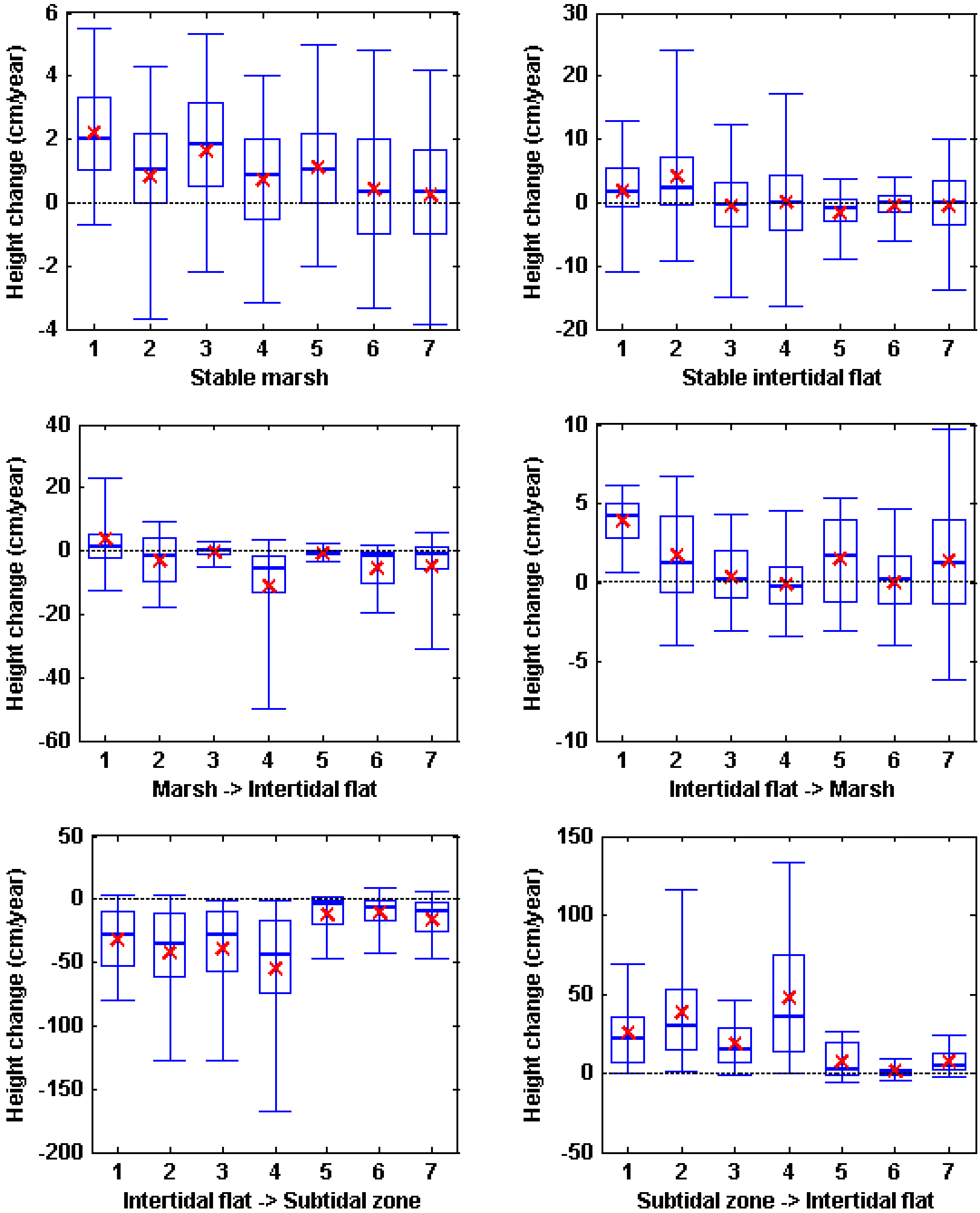

Figure 35 – Boxplots of yearly height change between 2004 and 2011 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

6.2. Height change in different zones and different ecotopes in the Sea Scheldt

For the Sea Scheldt (Figures 36-38), the statistical values of height change data from marker horizon measurements (1996-2000, provided by INBO) were used for stable marshes, because the results from LIDAR data were found to be not accurate in freshwater marshes with high vegetation. In freshwater marshes, LIDAR beams could be reflected by dense reed meadows and willow forests, of which the vegetation canopy height is a few meters or even over 10 meters tall. Hence, the error of the resulting DTM is much larger even after filtering vegetation, especially for the LIDAR data of 2004, which is based on a lower LIDAR point density.

Generally, similar results are obtained as for the Western Scheldt. An important notice is that some results are not as logical as for the Western Scheldt, and this is most likely because the availability of elevation data for the intertidal zone is limited in the Sea Scheldt. For example, a negative height change is observed between 2004 and 2011 in the ecotope ‘subtidal zone → intertidal flat’ (Figure 36). The reason is possibly that the calculation for this period is based on LIDAR data, which is limited in the lower part of the intertidal zone due to water coverage. In addition, a positive height change is observed between 1930 and 1960 in the ecotope ‘marsh → intertidal flat’ (Figure 38), which seems also contradictory. The reason is probably that bathymetric data is used for the calculation for this period, which is limited in the higher part of the intertidal zone. Consequently, the results obtained for the Sea Scheldt need to be interpreted with caution.

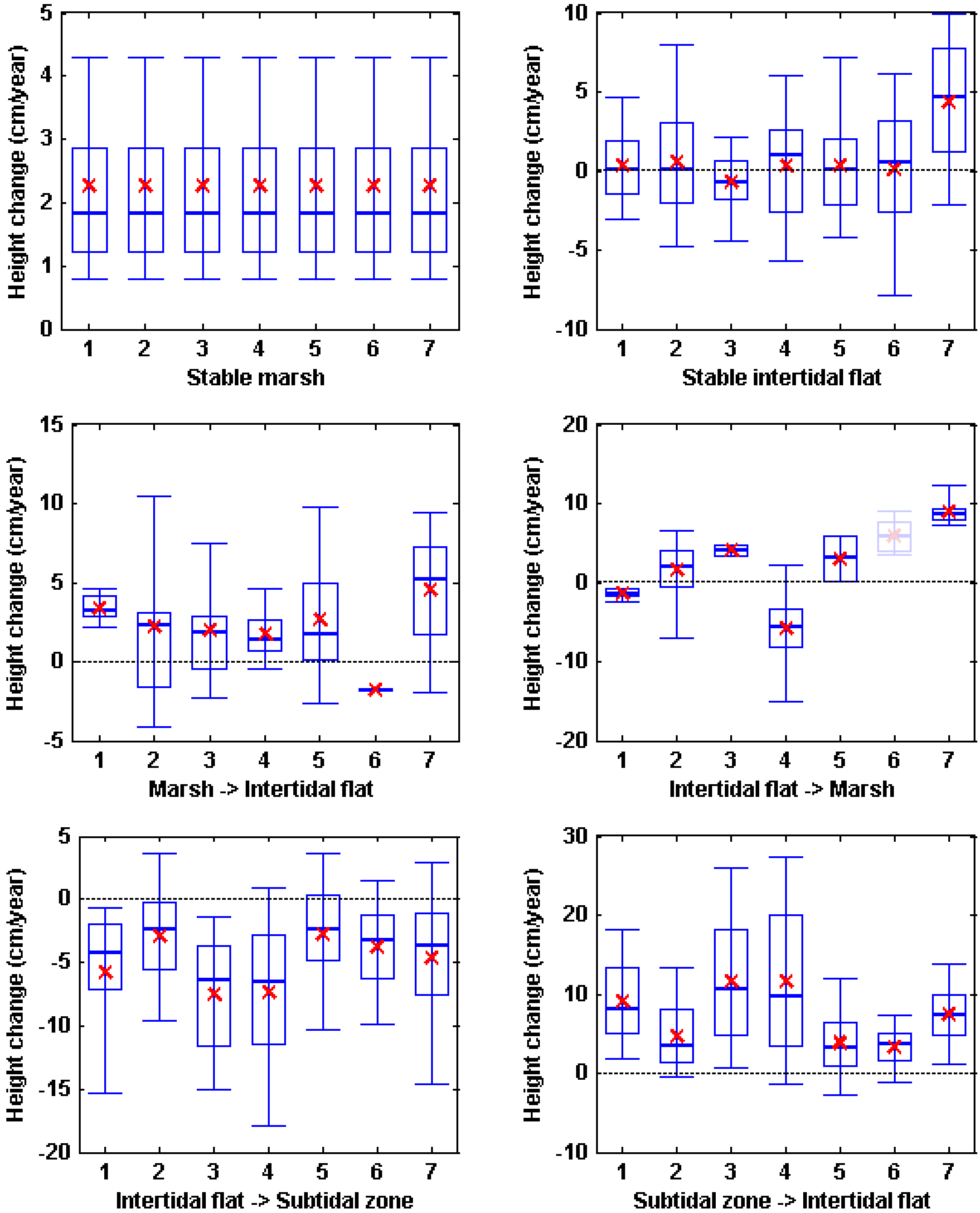

Figure 36 – Boxplots of yearly height change between 1930 and 1960 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. A mean value of the adjacent zones was used as a rough estimation for zones with limited elevation data, shown with lighter colors in the figures.

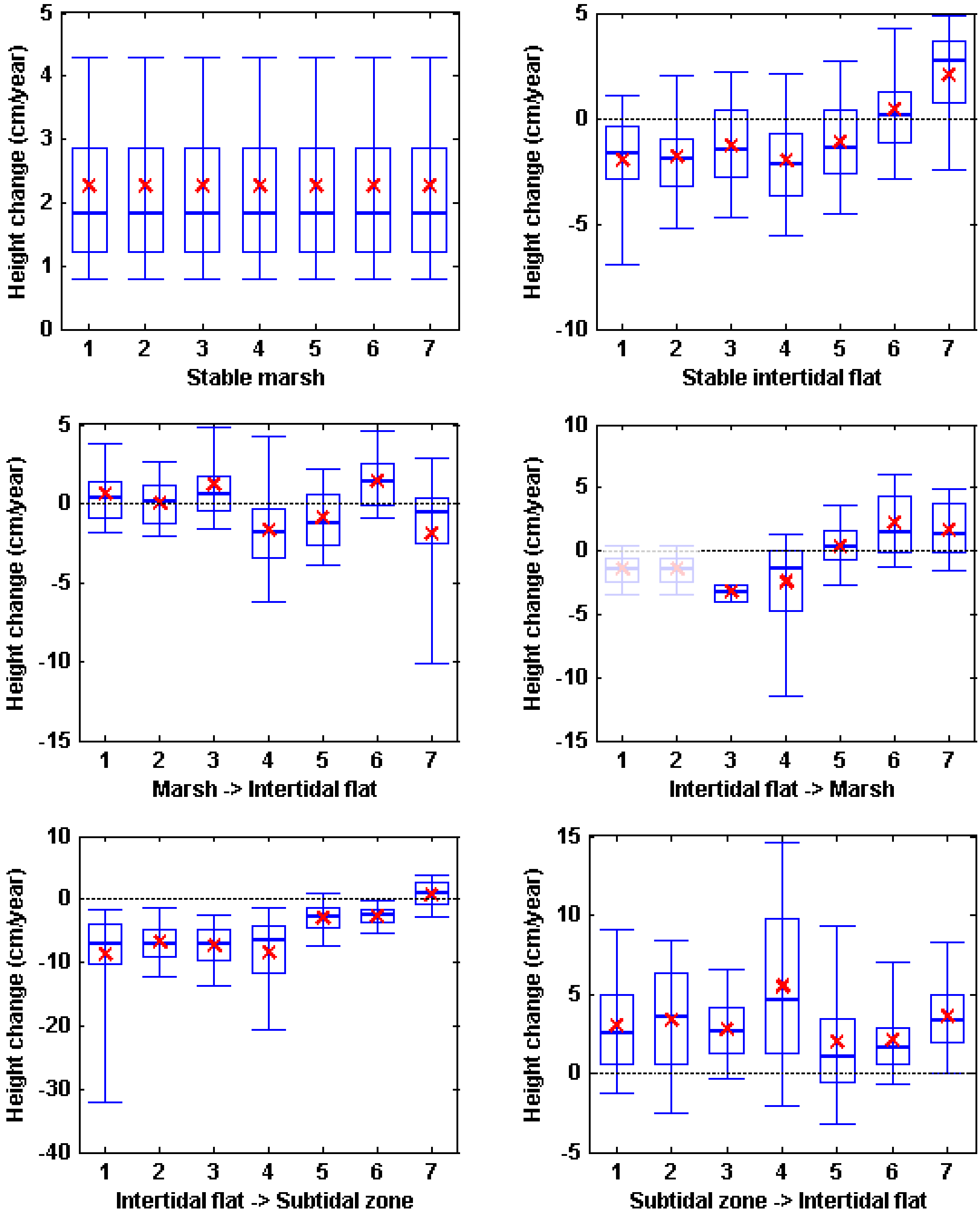

Figure 37 – Boxplots of yearly height change between 1960 and 2000 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. A mean value of the adjacent zones was used as a rough estimation for zones with limited elevation data, shown with lighter colors in the figures.

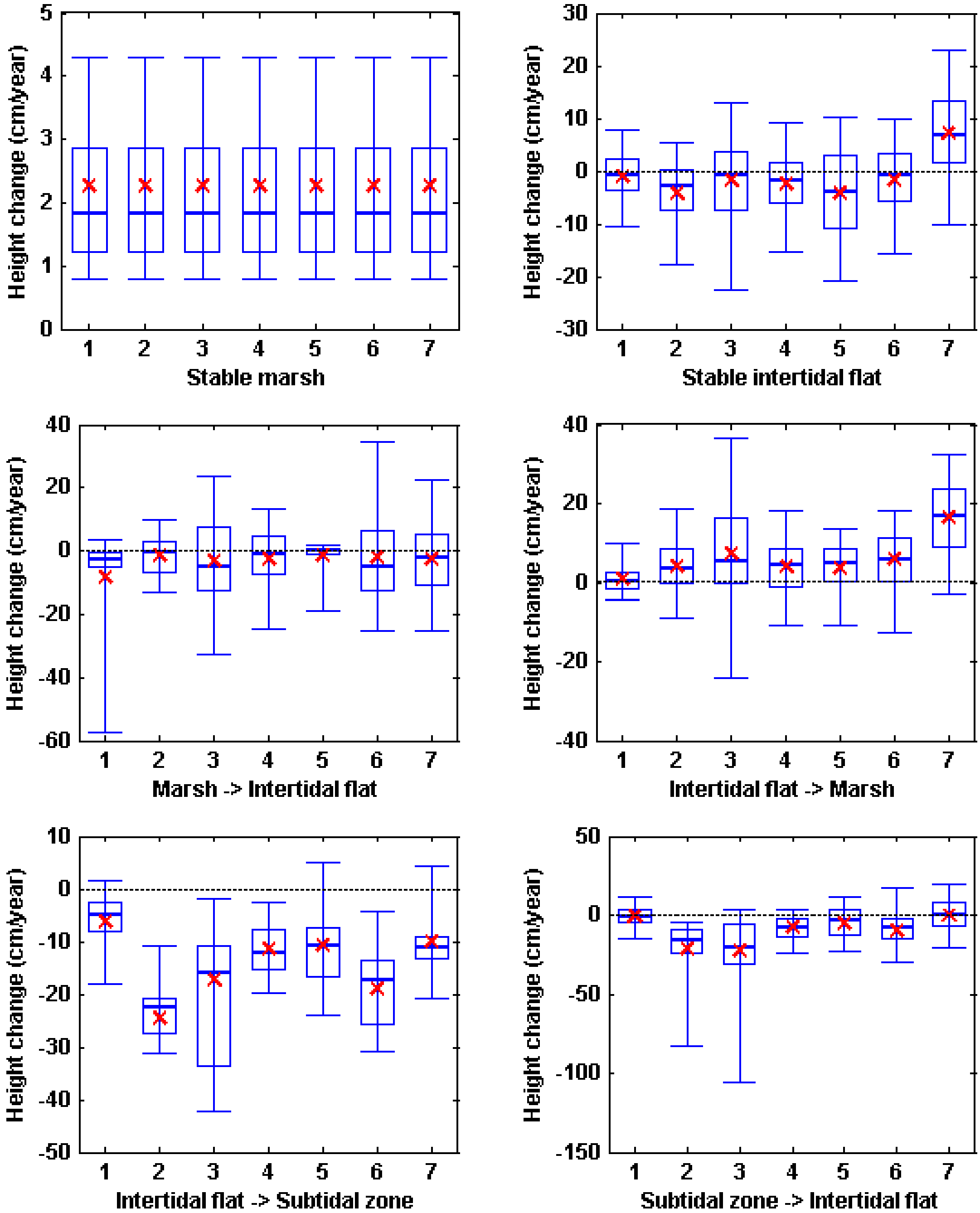

Figure 38 – Boxplots of yearly height change between 2004 and 2011 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

6.3. Conclusion

In both the Western Scheldt and Sea Scheldt, a generally positive change in heights is observed in 'Stable marsh', 'Intertidal flat → Marsh' and 'Subtidal zone → Intertidal flat', suggesting deposition of sediments, while negative changes in height are observed in 'Marsh → Intertidal flat' and 'Intertidal flat → Subtidal zone', suggesting erosion of sediments,. 'Stable intertidal flat' is observed to be more dynamic. Larger values are observed for areas shifting between subtidal zone and intertidal flat. Some results seem contradictory in the Sea Scheldt, probably because of the limited availability of elevation data for the intertidal zone.

7. Volume change in different zones and different ecotopes

Volume change in different zones and different ecotope change classes are calculated by multiplying the height change with the corresponding area. Several statistical values, including 5, 25, 50, 75 and 95 percentiles as well as the mean value, of the volume changes in different ecotopes were calculated for each zone in the Western Scheldt and Sea Scheldt.

7.1. Volume change in different zones and different ecotopes in the Western Scheldt

In the Western Scheldt (Figures 39-42), positive volume changes are observed in 'Stable marsh', 'Intertidal flat → Marsh', and 'Subtidal zone → Intertidal flat'. Negative volume changes are observed in 'Marsh → Intertidal flat', and 'Intertidal flat → Subtidal zone'. 'Stable intertidal flat' is observed to be in dynamic equilibrium with slightly positive volume change in some periods. Most of the volume change in 'Stable marsh' is observed in Zone 7, Saeftinghe. Furthermore, the volume increase in Saeftinghe is larger in the older time periods than in the recent periods, which is in accordance with the sediment filling-up progress of Saeftinghe in the last 80 years [*Wang and Temmerman*, 2013].

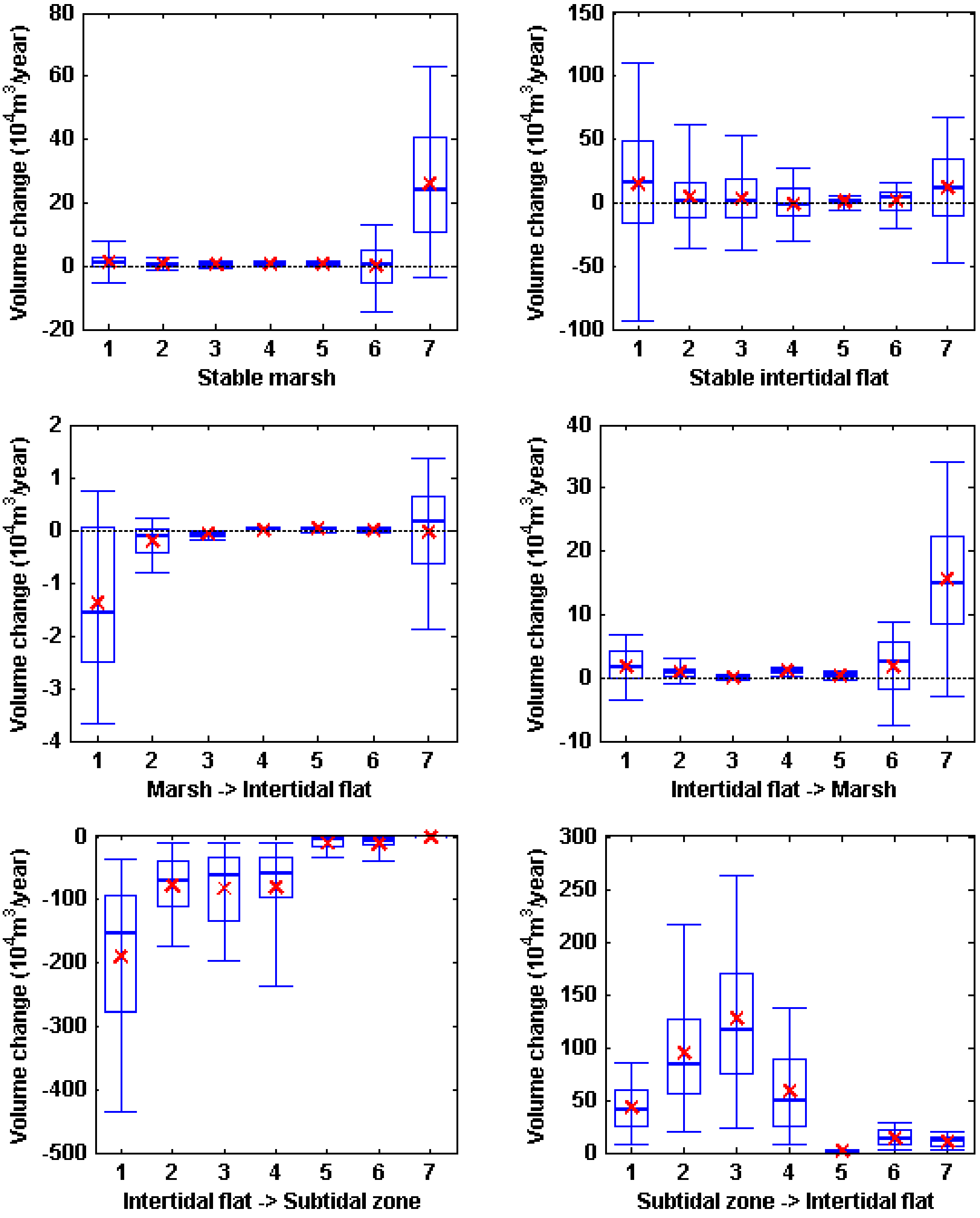

Figure 39 – Boxplots of yearly volume change between 1931 and 1963 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

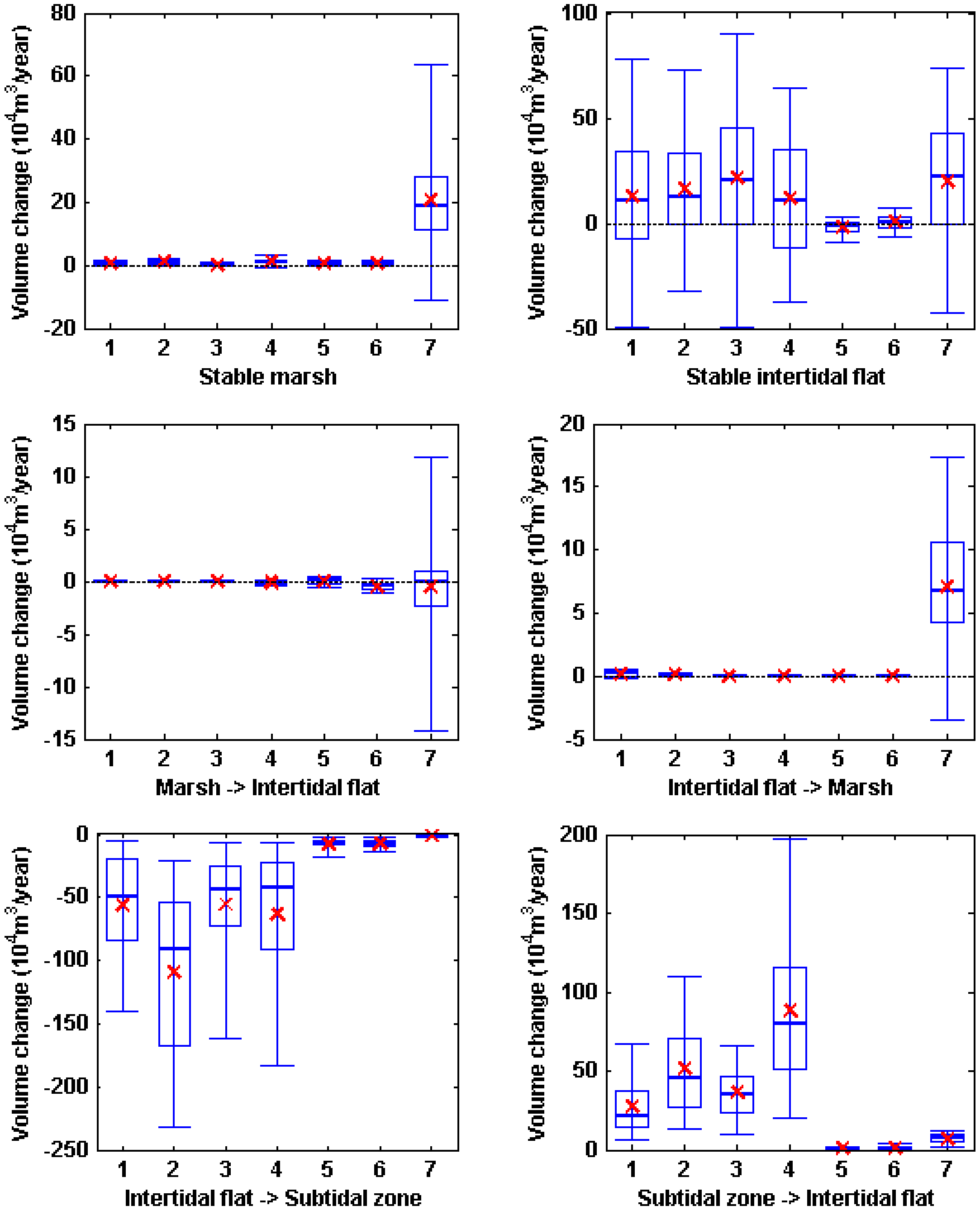

Figure 40 – Boxplots of yearly volume change between 1963 and 1992 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

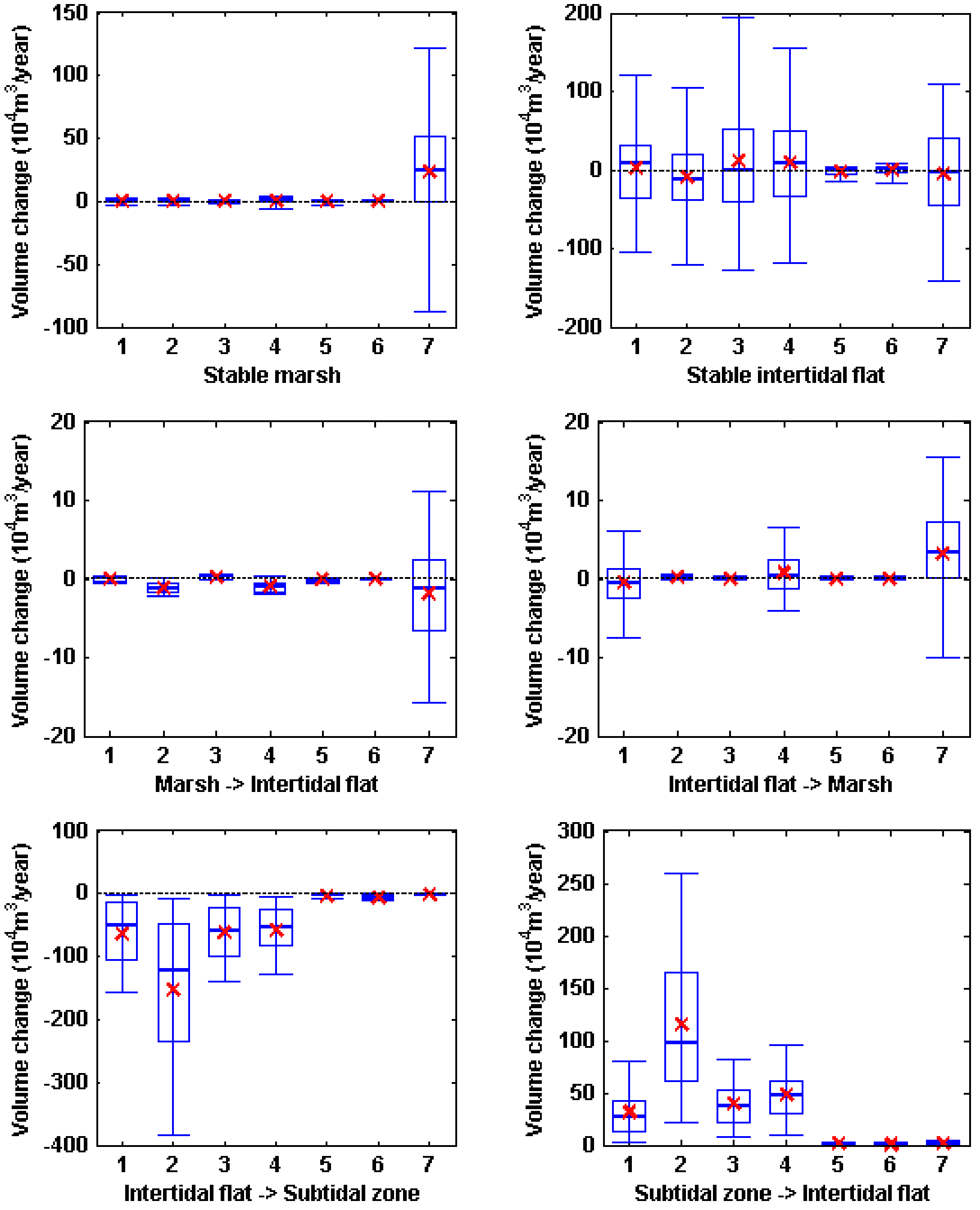

Figure 41 – Boxplots of yearly volume change between 1992 and 2004 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

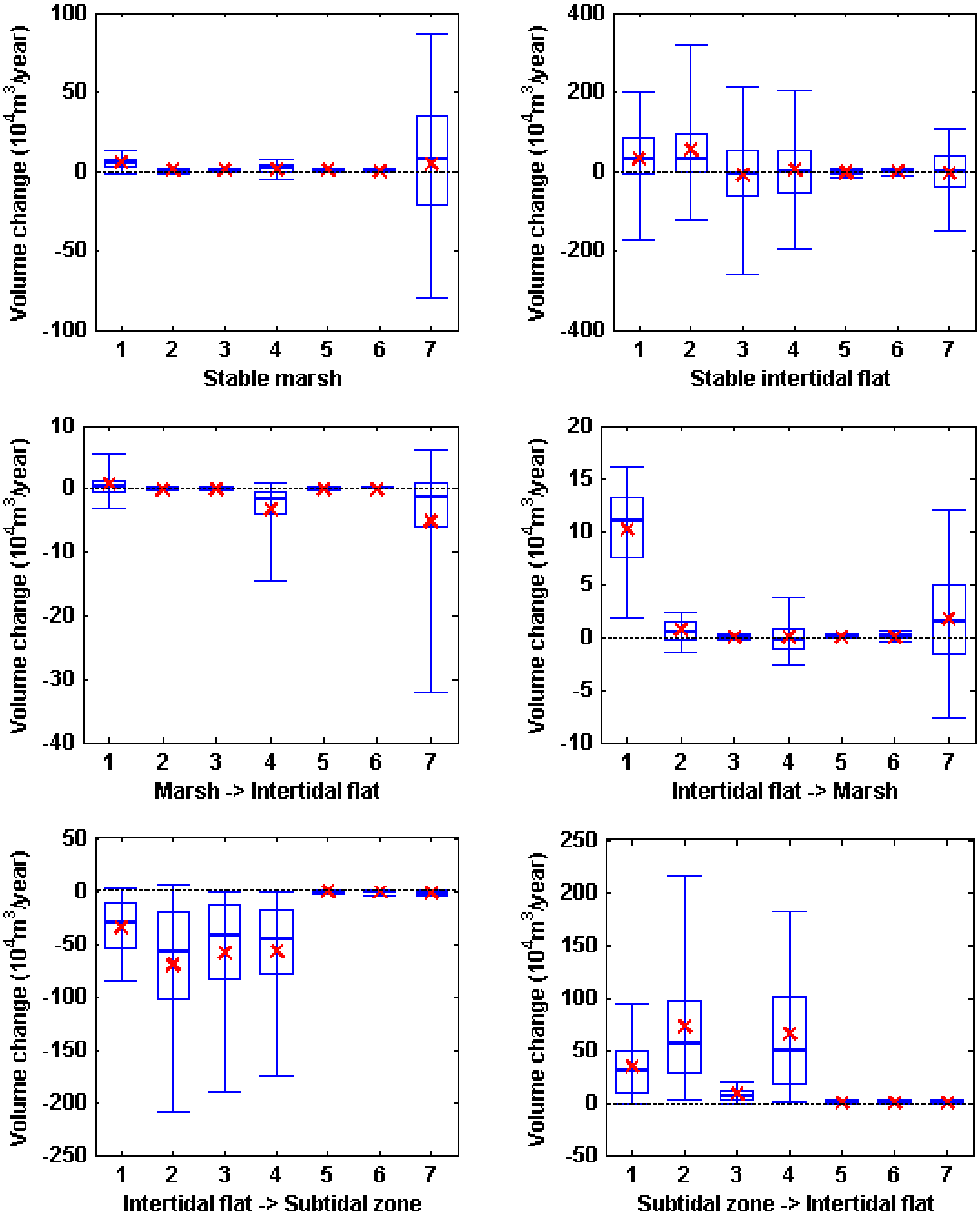

Figure 42 – Boxplots of yearly volume change between 2004 and 2011 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5^{th} percentile and 95^{th} percentile of the values. The box indicates the 25^{th} and 75^{th} percentile. The thick line indicates the 50^{th} percentile, and the cross indicates the mean value.

7.2. Volume change in different zones and different ecotopes in the Sea Scheldt

In the Sea Scheldt (Figures 43-45), less volume change is observed than in Western Scheldt. Similarly as in the Western Scheldt, positive volume changes are observed in 'Stable marsh', 'Intertidal flat → Marsh', and 'Subtidal zone → Intertidal flat'. Negative volume changes are observed in 'Marsh → Intertidal flat', and 'Intertidal flat → Subtidal zone'. 'Stable intertidal flat' is observed to be in dynamic equilibrium. Some of the results are less logic than in the Western Scheldt, because of the limitation in data availability. For example, a negative volume change is observed between 2004 and 2011 in the ecotope 'subtidal zone → intertidal flat' (Figure 43). The reason is possibly that LIDAR data is used for the calculation for this period, which is limited in the lower part of the intertidal zone due to water coverage. Another contradictory example is that a positive volume change is observed between 1930 and 1960 in the ecotope 'marsh → intertidal flat' (Figure 45). The potential reason is that the calculation for this period is based on bathymetric data, which is limited in the higher part of the intertidal zone.

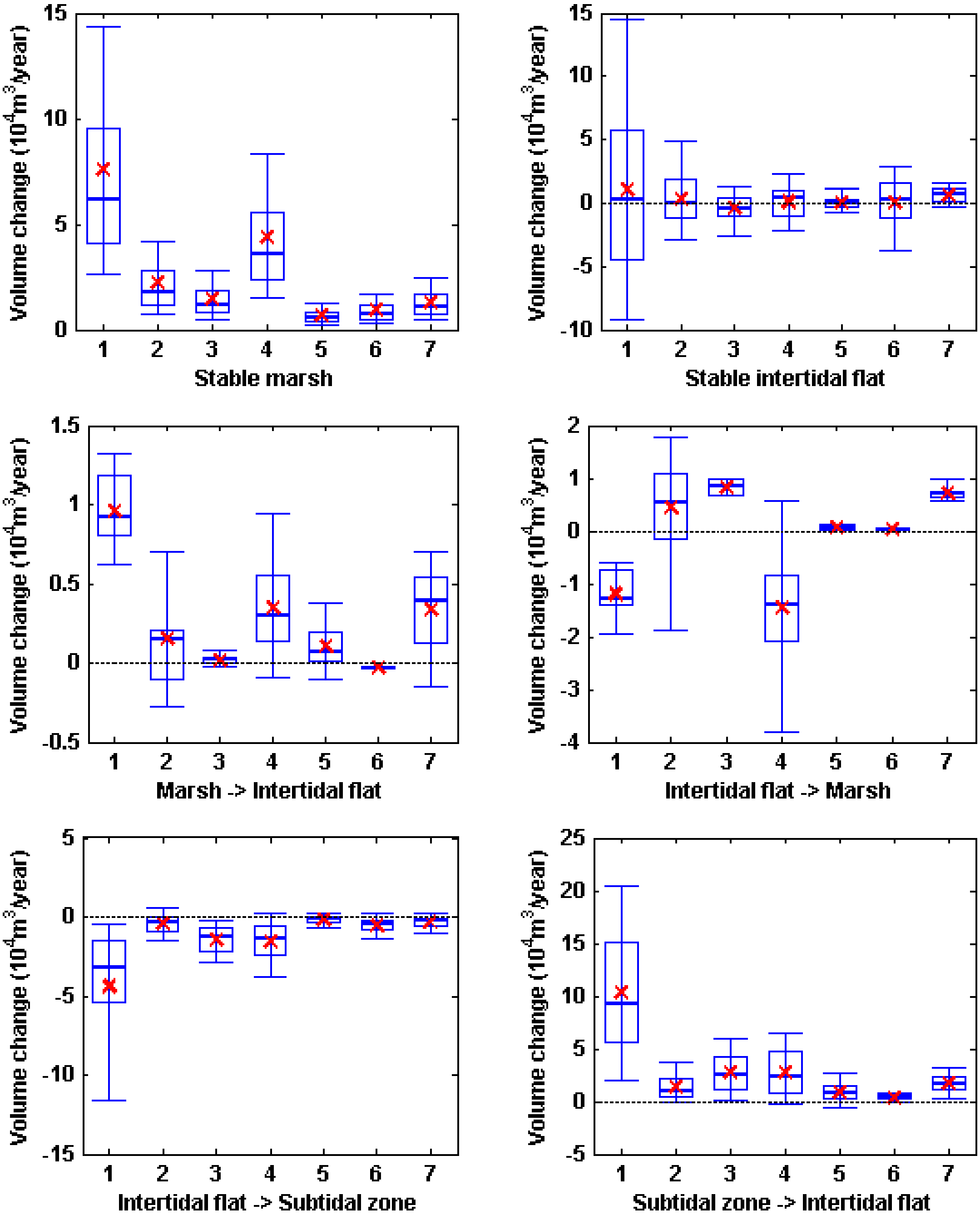

Figure 43 – Boxplots of yearly volume change between 1930 and 1960 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

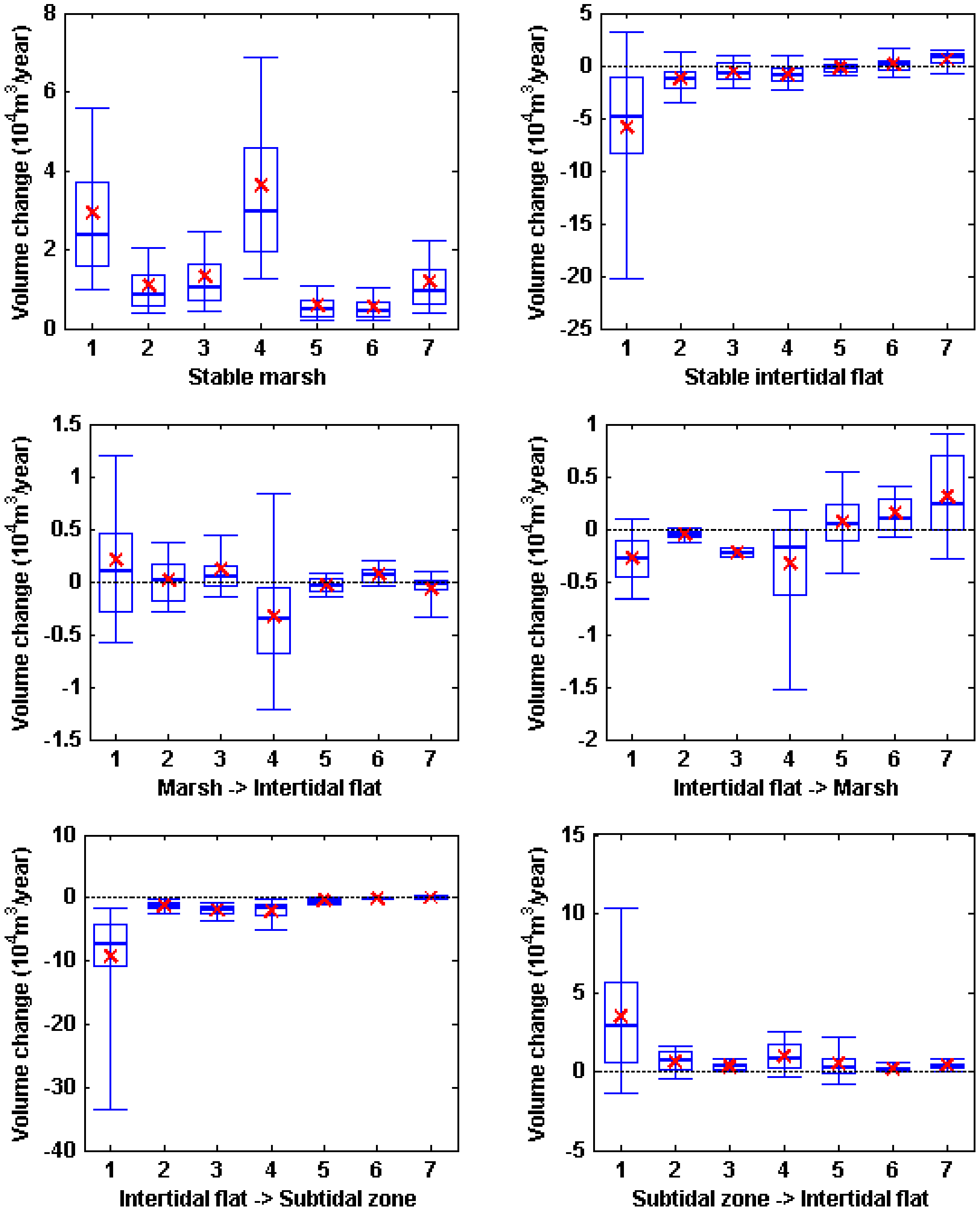

Figure 44 – Boxplots of yearly volume change between 1960 and 2000 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

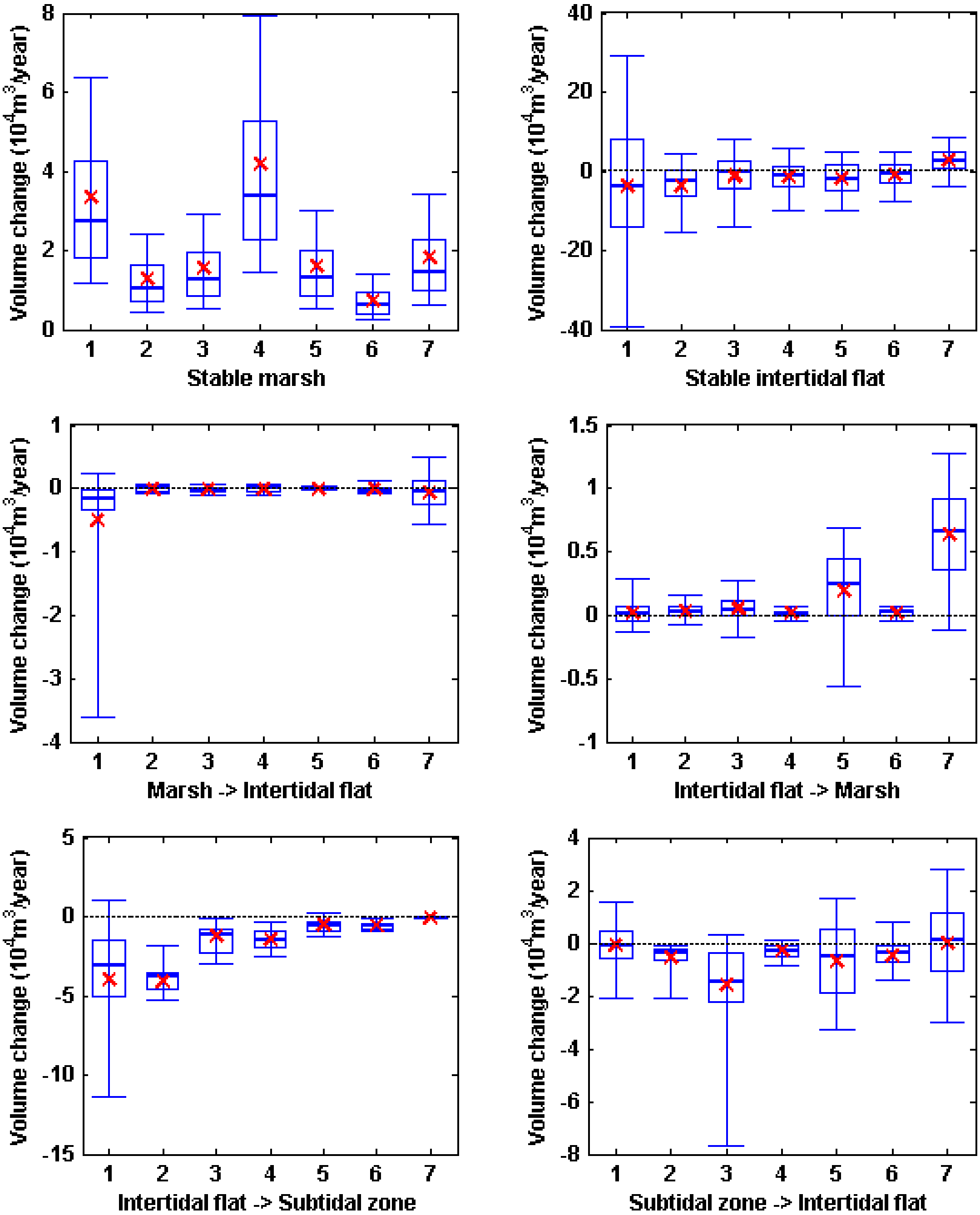

Figure 45 – Boxplots of yearly volume change between 2004 and 2011 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

7.3. Conclusion

In both the Western Scheldt and Sea Scheldt, positive volume changes are observed in 'Stable marsh', 'Intertidal flat → Marsh' and 'Subtidal zone → Intertidal flat', while generally negative volume changes are observed in 'Marsh → Intertidal flat', and 'Intertidal flat → Subtidal zone'. 'Stable intertidal flat' is observed to be dynamic with positive volume changes in some periods. Larger volume changes are observed in the Western Scheldt than in the Sea Scheldt. Most of the volume changes in 'Stable marsh' in the Western Scheldt is observed in Saeftinghe, especially in the historical periods. Some of the results seem contradictory in the Sea Scheldt, because of the limited data availability.

In the western and middle part of the Western Scheldt (zones 1-4), the data shows the large dynamics in between the ecotopes subtidal and intertidal flat, with typical volumes around 500.000 m³ per subzone eroding and depositing.

8. Eroded / deposited mud mass in different zones and different ecotopes

The eroded / deposited mud mass in different zones and different ecotopes were calculated by multiplying the volume change with the mud content and an estimated dry bulk density (500 ± 100 kg/m^3). Several statistical values, including 5, 25, 50, 75 and 95 percentiles as well as the mean value, of the mud mass in different ecotopes were calculated for each subdivision zone in the Western Scheldt and Sea Scheldt.

8.1. Eroded / deposited mud mass in different zones and different ecotopes in the Western Scheldt

In the Western Scheldt (Figures 46-49), mud deposition is observed in ‘Stable marsh’, ‘Stable intertidal flat’, ‘Intertidal flat → Marsh’ and ‘Subtidal zone → Intertidal flat’. Mud erosion is observed in ‘Marsh → Intertidal flat’, and ‘Intertidal flat → Subtidal zone’. Most of the mud deposition in ‘Stable marsh’ is observed in Zone 7, which includes the big marsh area of Saeftinghe. The mud deposition in Saeftinghe was larger in the older time periods than in the recent periods, which is in accordance with the sediment filling-up progress of Saeftinghe in the last 80 years [*Wang and Temmerman*, 2013].

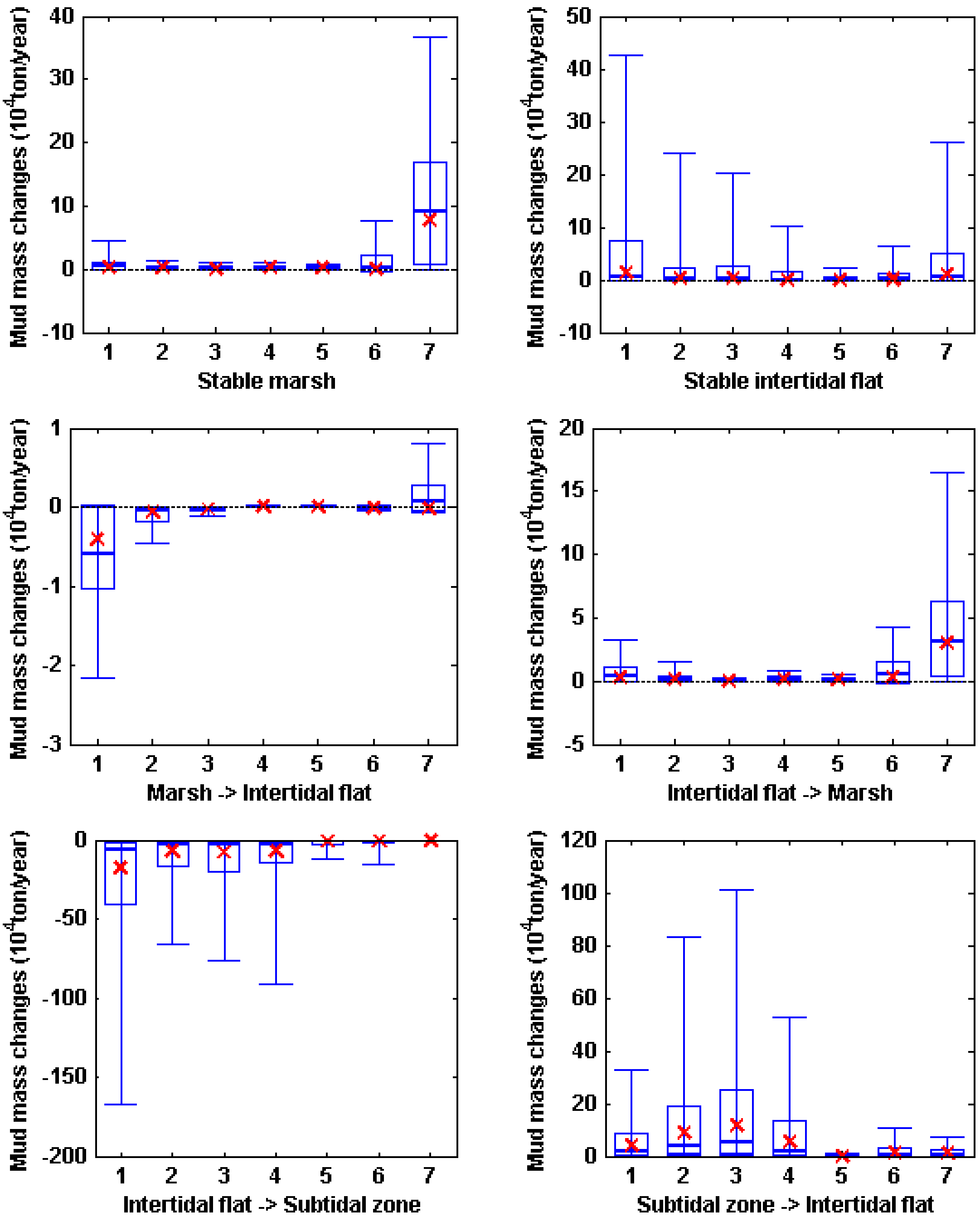

Figure 46 – Boxplots of yearly mud deposition / erosion between 1931 and 1963 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

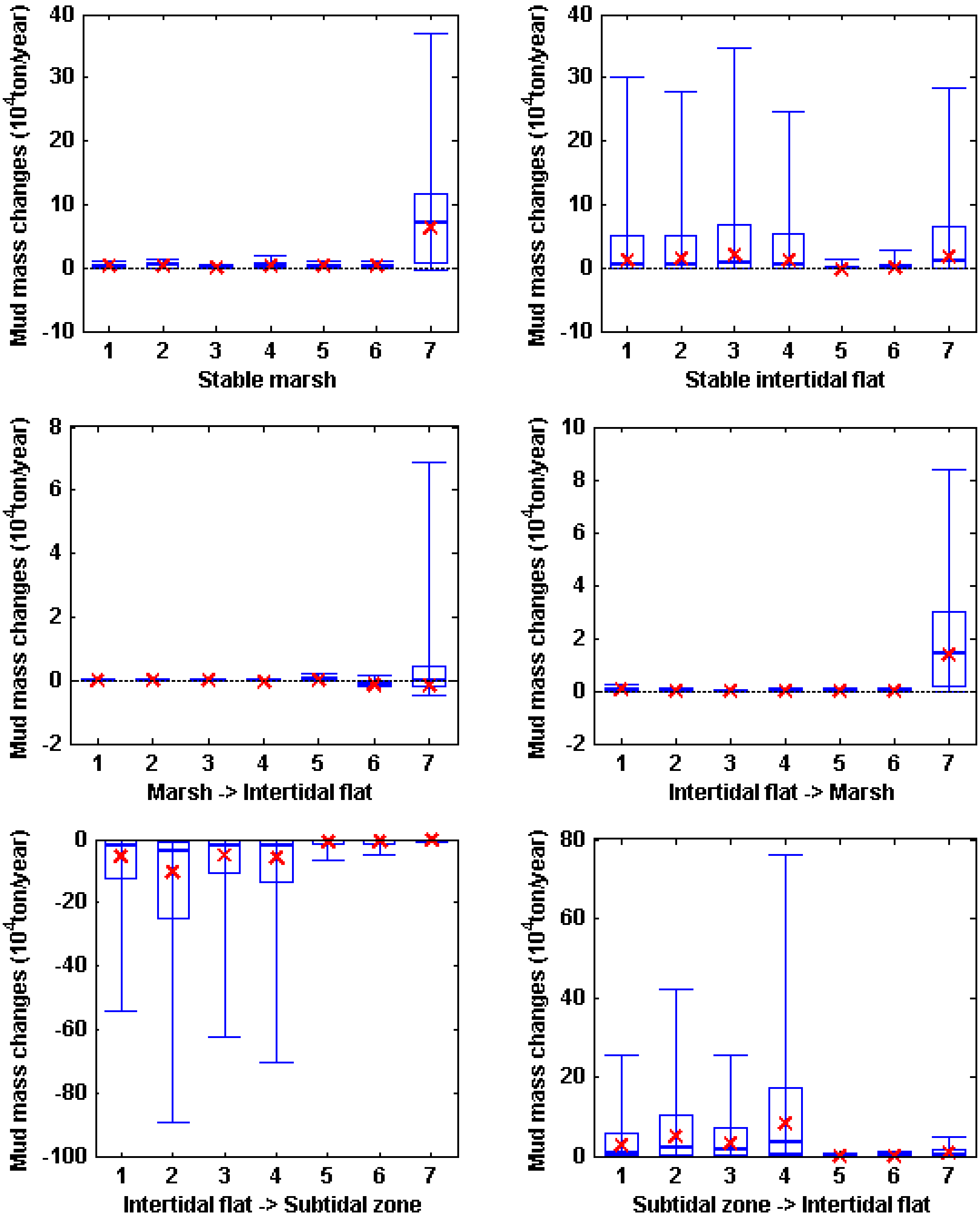

Figure 47 – Boxplots of yearly mud deposition / erosion between 1963 and 1992 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

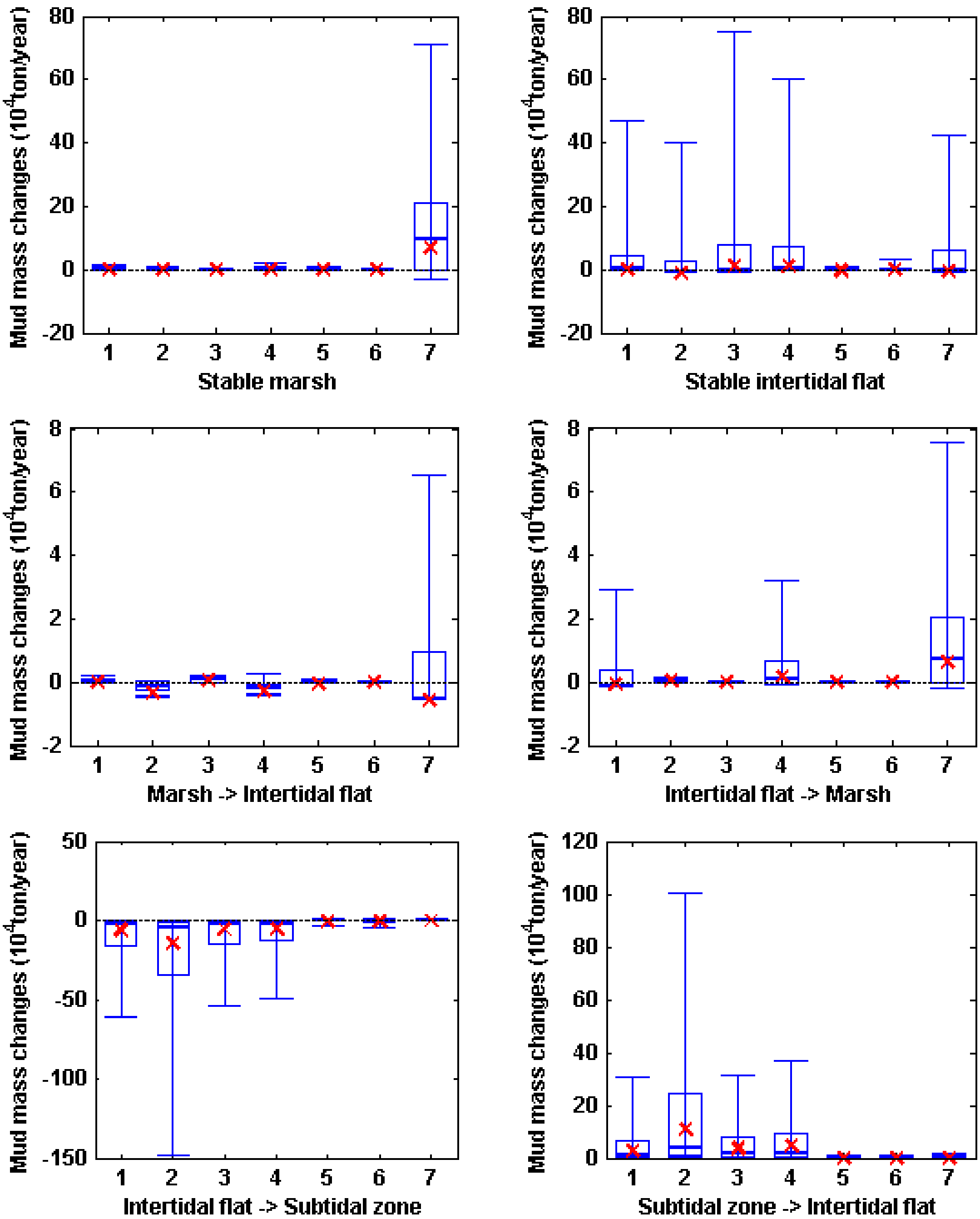

Figure 48 – Boxplots of yearly mud deposition / erosion between 1992 and 2004 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

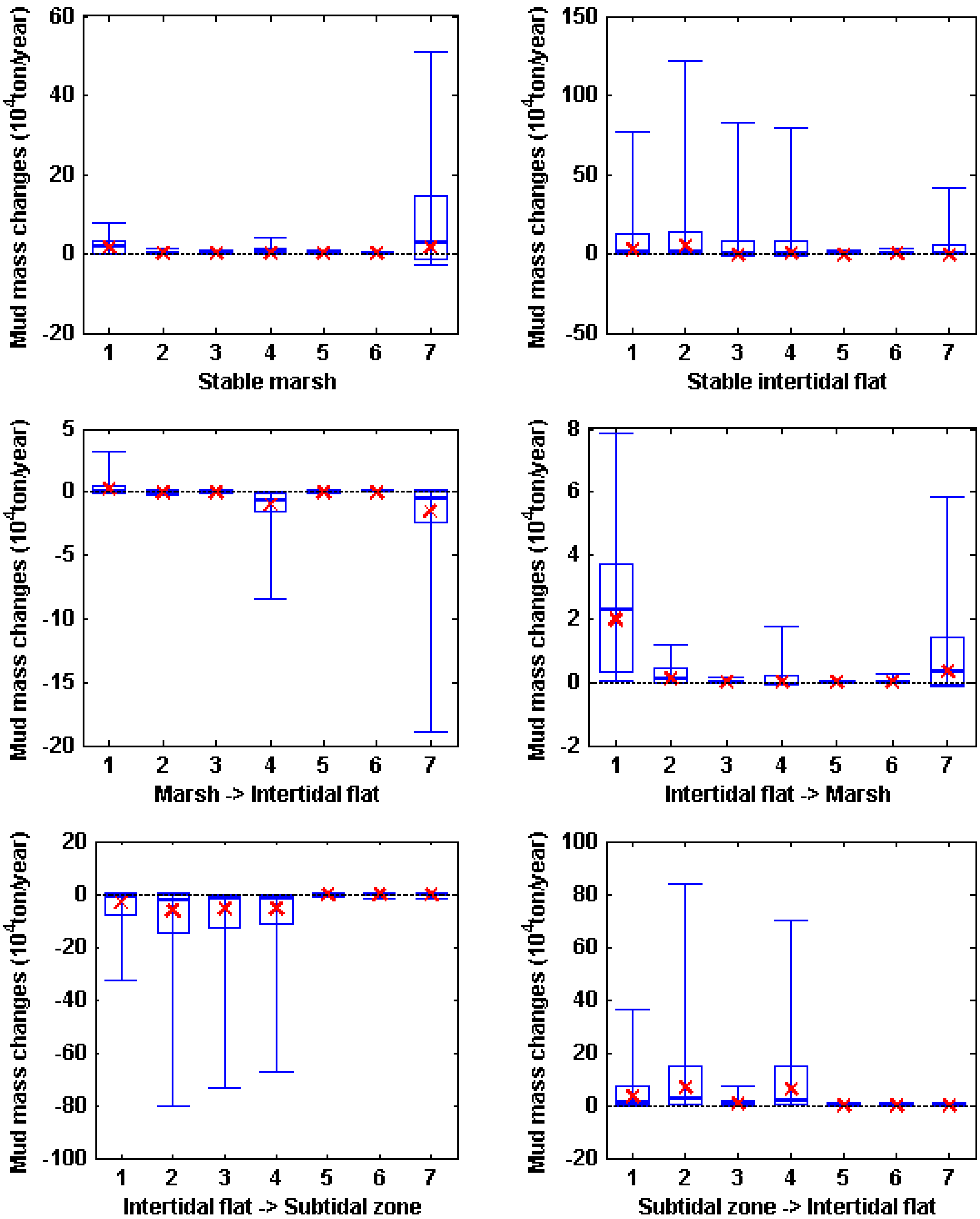

Figure 49 – Boxplots of yearly mud deposition / erosion between 2004 and 2011 in the Western Scheldt. The X axis indicates the zone number shown in Figure 10A. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

8.2. Eroded / deposited mud mass in different zones and different ecotopes in the Sea Scheldt

In the Sea Scheldt (Figures 50-52), smaller values of eroded / deposited mud mass are observed than in the Western Scheldt. The mud deposition in 'Stable marsh' and 'Stable intertidal flat' plays a more important role than in other ecotopes. Similar as in the Western Scheldt, mud deposition is observed in 'Stable marsh', 'Stable intertidal flat', 'Intertidal flat → Marsh' and 'Subtidal zone → Intertidal flat'. Mud erosion is observed in 'Marsh → Intertidal flat', and 'Intertidal flat → Subtidal zone'. Some of the results are less logic than in the Western Scheldt, because of the limitation in data availability. For example, mud erosion is observed between 2004 and 2011 in the ecotope 'subtidal zone → intertidal flat' (Figure 50), potentially because LIDAR data is used for the calculations for this period, which is limited in the lower part of the intertidal zone due to water coverage. In addition, mud deposition is observed between 1930 and 1960 in the ecotope 'marsh → intertidal flat' (Figure 52), which also seems unreasonable. It is probably due to the fact that the calculations for this period are based on bathymetric data, which is limited in the higher part of the intertidal zone.

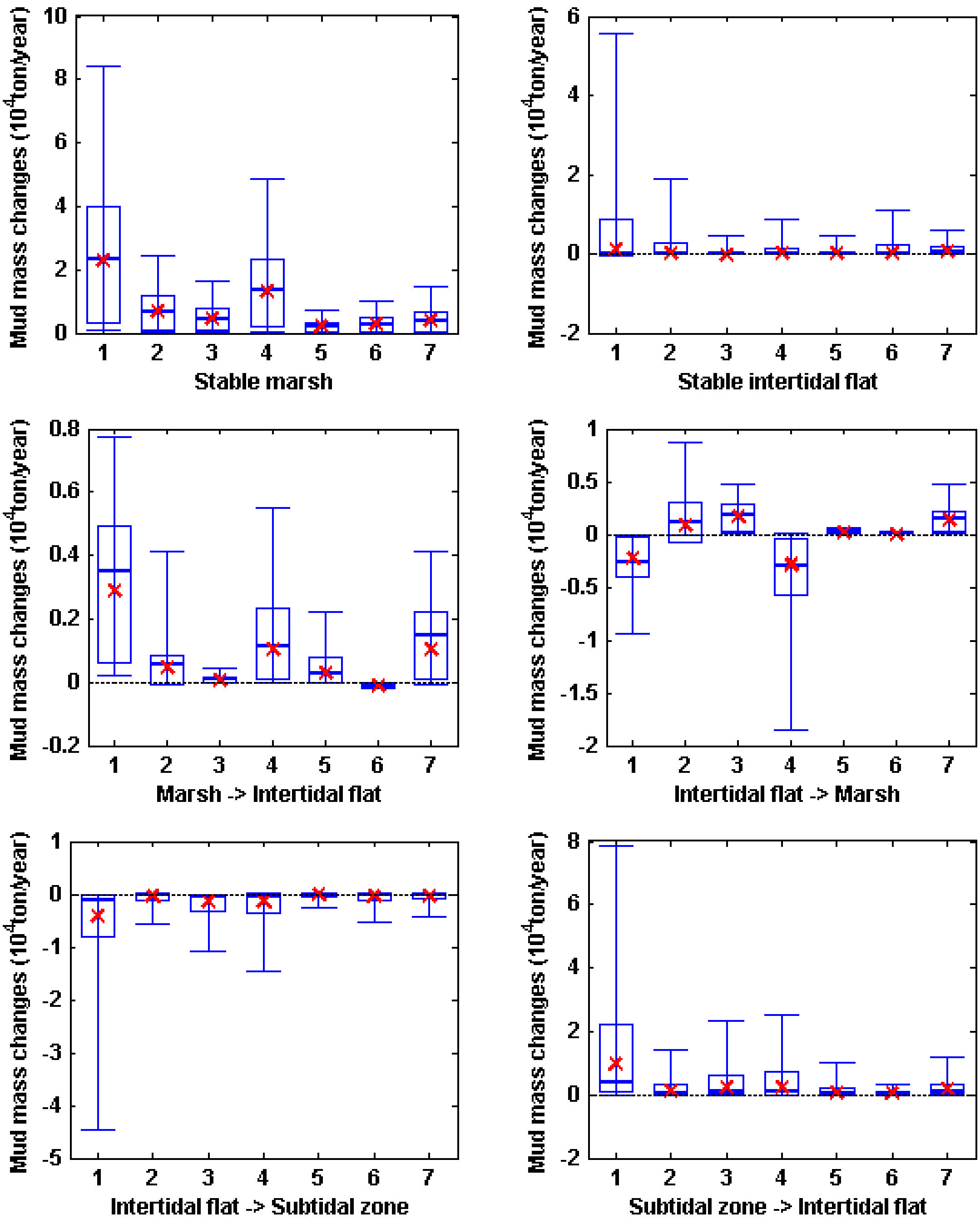

Figure 50 – Boxplots of yearly mud deposition / erosion between 1930 and 1960 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

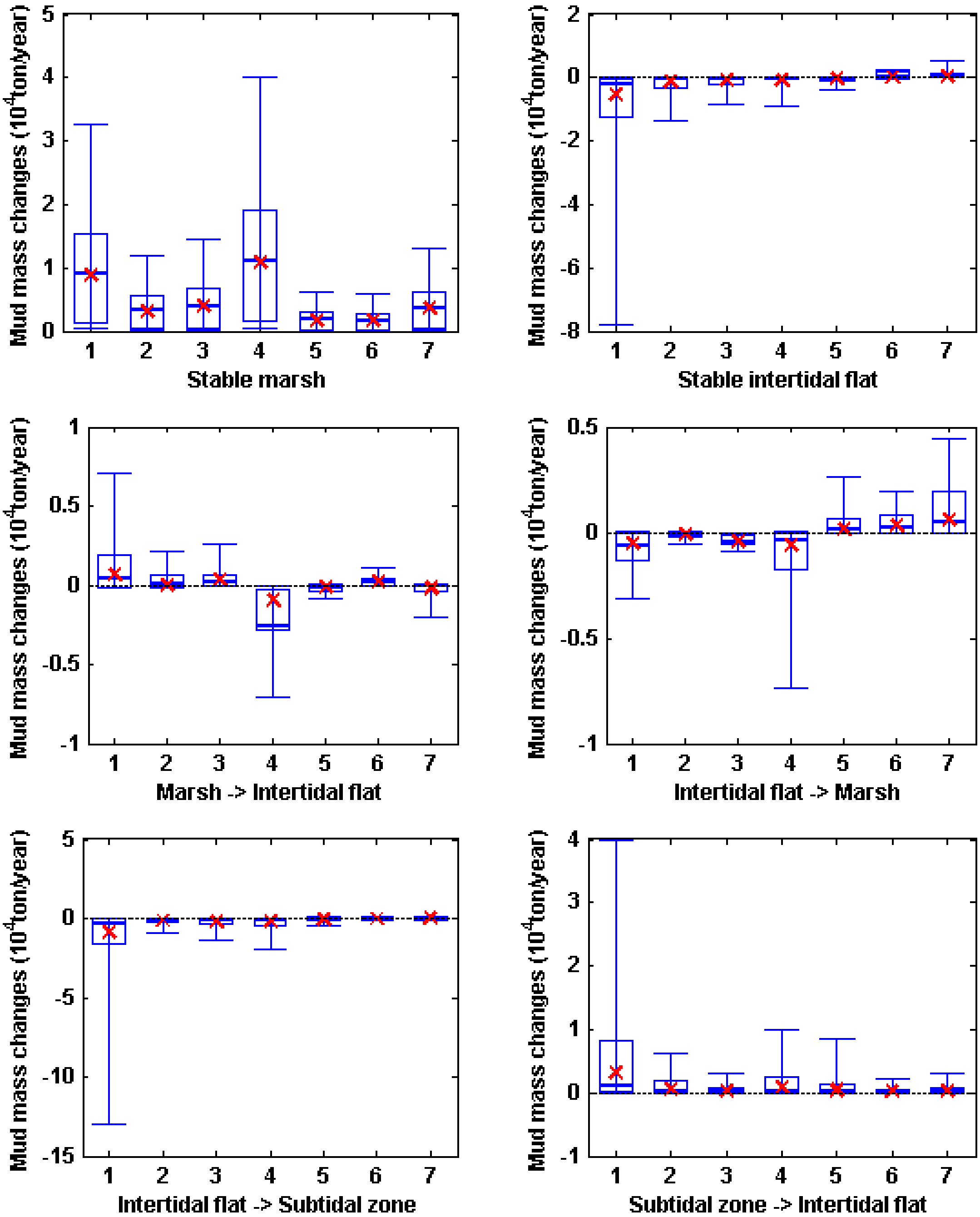

Figure 51 – Boxplots of yearly mud deposition / erosion between 1960 and 2000 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

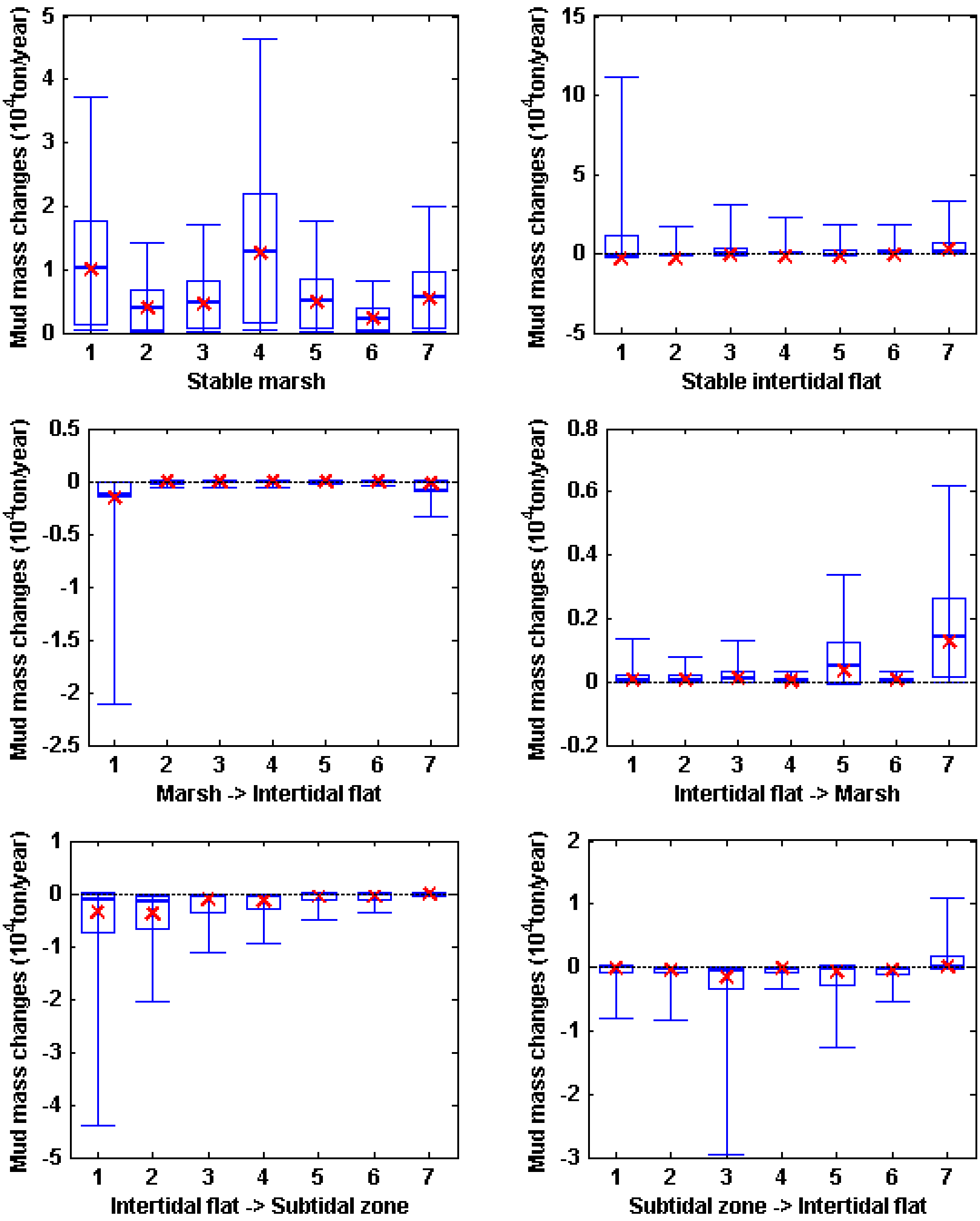

Figure 52 – Boxplots of yearly mud deposition / erosion between 2004 and 2011 in the Sea Scheldt. The X axis indicates the zone number shown in Figure 10B. The upper bound and lower bounds indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value.

8.3. Conclusion

In both the Western Scheldt and Sea Scheldt, we observed mud deposition in ‘Stable marsh’, ‘Stable intertidal flat’, ‘Intertidal flat → Marsh’ and ‘Subtidal zone → Intertidal flat’, while mud erosion dominates in ‘Marsh → Intertidal flat’, and ‘Intertidal flat → Subtidal zone’.

The mud erosion / deposition in the Western Scheldt is larger than in the Sea Scheldt. The mud deposition in ‘Stable marsh’ and ‘Stable intertidal flat’ plays a more important role than in other ecotopes in both the Western Scheldt and Sea Scheldt. In the Western Scheldt, most of the mud deposition in ‘Stable marsh’ is observed in Saeftinghe. The mud deposition in Saeftinghe was larger in the past than recently, following the sediment filling-up progress in the last 80 years.

Some of the results seem contradictory in the Sea Scheldt, because of the limitation in data availability.

9. Mud balance in the Western Scheldt and Sea Scheldt

9.1. Average eroded / deposited rates in different ecotopes and in the whole intertidal areas in the Western Scheldt and Sea Scheldt in different time periods

The average eroded / deposited mud mass are summed up for different ecotopes in all subdivision zones of the Western Scheldt and Sea Scheldt, and further summed up to get the total mud balance in the whole intertidal areas in the Western Scheldt and Sea Scheldt. In general, the intertidal areas are a net sink of mud in both the Western Scheldt and Sea Scheldt in almost all the different periods. Intertidal mud deposition in the Western Scheldt (on average 42.6 × 10^3 ton/year averaged over all time periods, see table 10) plays a more important role compared with the Sea Scheldt (on average 36.2 × 10^3 ton/year).

The differences in mud deposition between the different time periods are mainly due to differences in changes in elevation in stable intertidal flats, which cover the largest area (see also table 9).

It has to be emphasized that the availability of data for the intertidal areas along the Sea Scheldt was very limited, and therefore the results for the Sea Scheldt must be interpreted with caution. The data availability for the Western Scheldt was good and hence our results for the Western Scheldt may be interpreted as more reliable.

The mud deposition in stable marshes plays an important role in both the Western Scheldt (on average 68.7 × 10^3 ton/year) and Sea Scheldt (on average 44.3 × 10^3 ton/year) and in all time periods. A large amount of mud deposition is also observed in stable intertidal flats (on average 43.0 ×10^3 ton/year in the Western Scheldt). Sedimentation on stable marches is more important however than sedimentation on stable intertidal flats in the Western Scheldt, even though there's 2.5 times more surface area of intertidal flats on average. This is investigated in more detail in the following paragraph.

The largest dynamics in mud fluxes are observed in areas that shift from subtidal to intertidal or vice-versa.

Table 10 – Average mud erosion/deposition rates (ton/year) in different ecotope types of all sub-division zones in the Western Scheldt and Sea Scheldt, and total mud balance in intertidal areas in the Western Scheldt and Sea Scheldt.

Location	Period	Stable marsh	Stable intertidal flat	Subtidal zone -> Intertidal flat	Intertidal flat -> Marsh	Marsh -> Intertidal flat	Intertidal flat -> Subtidal zone	Total in intertidal areas
Western Scheldt	1931-1963	37,030	59,882	166,318	24,260	-22,898	-208,212	56,380
	1963-1992	74,419	3,961	220,310	7,489	-11,984	-320,907	-26,712
	1992-2004	76,132	75,200	197,189	14,190	-3,723	-279,502	79,486
	2004-2010	87,387	33,283	325,563	41,918	-5,061	-421,727	61,364
	Mean	68,742	43,081	227,345	21,964	-10,916	-307,587	42,629
Sea Scheldt	1930-1960	43,627	-9,869	-3,448	1,914	-1,836	-11,121	19,268
	1960-2000	33,773	-7,482	5,925	-728	-124	-14,021	17,342
	2004-2011	55,596	1,667	18,486	-1,125	5,684	-8,262	72,045
	Mean	44,332	-5,228	6,988	20	1,241	-11,135	36,219

9.2. Role of mud deposition in the intertidal marshes

In order to evaluate the relative role of mud deposition in the intertidal marshes as compared to net mud deposition in the intertidal zone as a whole, we compared the statistical values of mud deposition in the intertidal marshes (the orange boxes in Figure 53) with those in all the intertidal areas (the blue boxes in Figure 53) in the Western Scheldt and Sea Scheldt in the different periods. The mud mass change in marshes was calculated by summing up the deposition in the ecotope of stable marsh in all subdivision zones for the Western Scheldt and Sea Scheldt. Several statistical values, including 5, 25, 50, 75 and 95 percentiles as well as the mean value, were calculated for the comparison. Apparently, the mud mass deposition in stable marshes plays an important role in the total mud mass deposition in both the Western Scheldt and Sea Scheldt and in all time periods.

The mud deposition in Saeftinghe (the green boxes in Figure 53) is also included in the comparison, so as to evaluate the importance of Saeftinghe. Apparently, the mud deposition in Saeftinghe determines the largest part of the mud deposition in marshes in the Western Scheldt, especially in the earlier periods. In Saeftinghe, the vegetated marshes extended in area and increased steadily in elevation from 1931 to 2004 (Figure 54) [*Wang and Temmerman*, 2013]. The intertidal flats evolved into marshes, which are associated with an increase in elevation, and therefore large amounts of mud deposition in the area. After 2004, most of the marshes in Saeftinghe are above MHWL and close to the upper limit in elevation, resulting in a slower increase in elevation and less mud deposition.

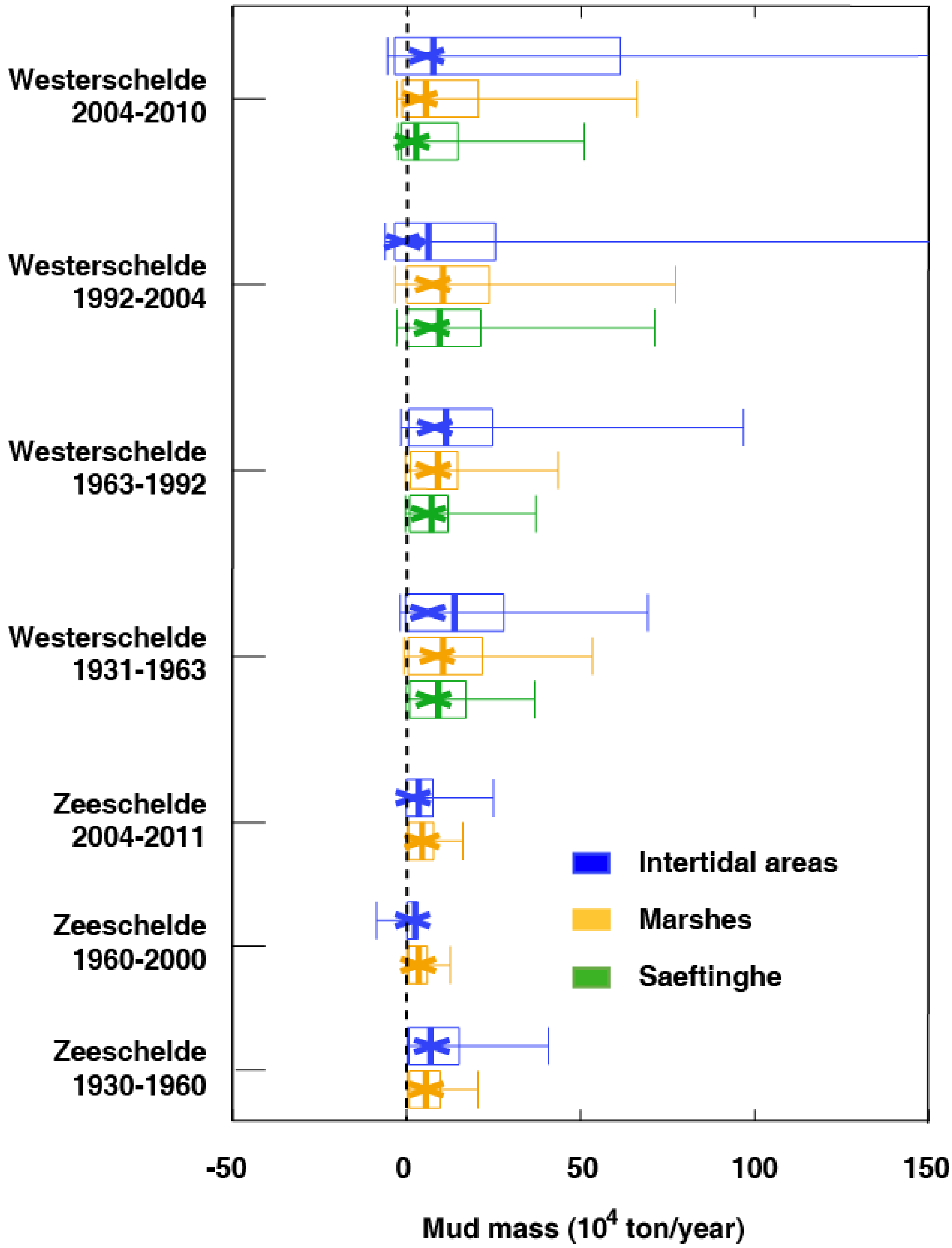

Figure 53 – Boxplots of mud balance in the intertidal areas, marshes and Saeftinghe in the Western Scheldt and Sea Scheldt in different periods. Intertidal areas = onshore tidal flats + offshore tidal flats + tidal marshes. The upper bound and lower bound indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. The 95th percentile of the values in the Western Scheldt in 2004-2010 and 1992-2004 are 407 × 10^4 ton/year and 249 × 10^4 ton/year, respectively, which are outside of the range of the x-axis.

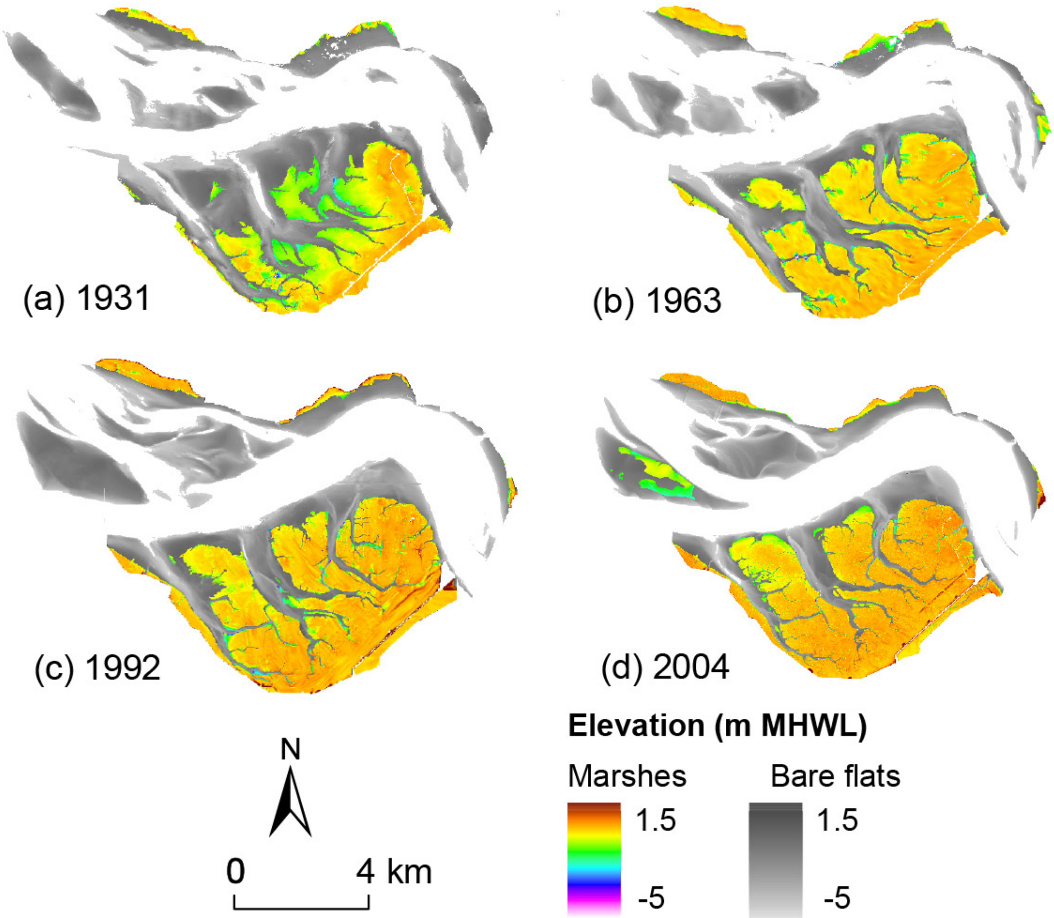

Figure 54 – DTM of vegetated marshes (colors) and bare flats (grey scale) in Saeftinghe and surrounding areas (zones 5, 6, 7 and part of zone 4 in Fig. 9) in 1931 (a), 1963 (b), 1992 (c) and 2004 (d).
The elevations are expressed relative to mean high water level (MHWL) at that time. Maps are based on Wang & Temmerman (2013).

9.3. Conclusion

In general, the intertidal areas are a net sink of mud in both the Western Scheldt and Sea Scheldt in almost all the different periods. Intertidal mud deposition in the Western Scheldt plays a more important role compared with the Sea Scheldt.

The results for the Sea Scheldt must be interpreted with caution, because the availability of data for the intertidal areas along the Sea Scheldt was very limited. The results for the Western Scheldt may be interpreted as more reliable, because the calculation is based on a more reliable database.

The mud deposition in stable marshes plays an important role in both the Western Scheldt and Sea Scheldt and in all time periods. The mud deposition in Saeftinghe determines the largest part of the mud deposition in marshes in the Western Scheldt, especially in the earlier periods. A large amount of mud deposition is also observed in stable intertidal flats and areas that shifted from intertidal flat to marshes or from subtidal zone to intertidal flat in the Western Scheldt.

The largest dynamics in mud fluxes are observed in areas that shift from subtidal to intertidal or vice-versa.

10. Conclusions and Recommendations

Based on the analyses of available topographic and bathymetric data, vegetation maps (ecotope maps), tidal data, sediment mud contents and sediment dry bulk densities, we may conclude that there was a net mud deposition in intertidal areas in both the Western Scheldt and Sea Scheldt from 1930 to 2011. The total estimated deposition flux is about 80.000 ton/year.

Mud deposition in the intertidal areas of the Western Scheldt (on average 42.6 $\times 10^3$ ton/year averaged over all time periods) plays a more important role compared with the Sea Scheldt (on average 36.2$\times 10^3$ ton/year). Large amounts of mud deposition are observed in stable marshes in both the Western Scheldt (on average 68.7 $\times 10^3$ ton/year) and Sea Scheldt (on average 44.3 $\times 10^3$ ton/year), as well as transitions from subtidal zone to intertidal flat (on average 227.3 $\times 10^3$ ton/year), stable intertidal flats (on average 43.0 $\times 10^3$ ton/year) and transitions from intertidal flat to marsh (on average 22.0 $\times 10^3$ ton/year) in the Western Scheldt. The mud mass deposition in stable marshes plays an important role in the total mud mass change in both the Western Scheldt and Sea Scheldt and in all time periods.

The calculated mud mass exchange flux is complemented in this report with an uncertainty estimate. This is only meant as a first, rather crude approximation. A better approach would be to calculate the distribution of the mud mass exchange flux by combining the statistical distributions of the different input parameters in a Monte Carlo approach. There was insufficient time however within the current project to perform this analysis.

In the last 80 years, large parts of intertidal flats have evolved into marshes in the Western Scheldt on both onshore flats and offshore flats. Most of the deposition in stable marshes is observed in Saeftinghe. A decreasing amount of deposition is observed over time in Saeftinghe. This is in accordance with the expected filling up of marshes.

Over 90% of mud erosion happens in the highly dynamic transition between intertidal flat and subtidal zone in the Western Scheldt.

In general, good data are available for the intertidal areas along the Western Scheldt, and therefore the result for the Western Scheldt may be interpreted as more reliable. However, limited data is available on the intertidal areas in the Sea Scheldt, and hence the results for the Sea Scheldt should be interpreted with caution.

Additional study based on radiometric dating of sediment cores sampled from intertidal areas would give a more reliable mud balance for the intertidal areas in the Sea Scheldt.

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