Challenges and perspectives of the North Frisian Halligen Hooge, Langeness and Nordstrandischmoor

Marshland accretion and adaptation capacity to sea-level-rise

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CONTENTS

ABBREVIATIONS

English

AD	Anno Domini
BDD	Bulk Dry Density
BP	Before Present
CIC	Constant Initial Concentration
CRS	Constant Rate of Supply
Cs	Caesium
d-GPS	differential Global Positioning System
GOL	German Ordnance Level
GPS	Global Positioning System
HHW	Highest High Water
IUSS	International Union of Soil Sciences
LDPE	Low-Density Polyethylene
LIDAR	Light Detection And Ranging
LOI	Loss On Ignition
MHW	Mean High Water
NPP	Net Primary Production
Pb	Lead
PE	Polyethylene
RMSL	Relative Mean Sea-level
RSD	Relative Standard Deviation
SEB	Sedimentation Erosion Bar
SET	Sedimentation Erosion Table
SLR	Sea-Level-Rise
SSC	Suspended Sediment Concentration
UNESCO	United Nations Educational Scientific and Cultural Organization

German

ALK	Automatisierte Liegenschaftskarte
ATKIS	Amtliches Topographisch-Kartographisches Informationssystem
DGM	Digitales Geländemodell
DOP	Digitales Orthophoto
fwu	Forschungsinstitut Wasser und Umwelt (Siegen)
GOF	Geländeoberfläche
GZG	Geowissenschaftliches Zentrum Göttingen
HThw	Höchstes Tidehochwasser
IfS	Institut für Soziologie (Aachen)
IWW	Institut für Wasserbau und Wasserwirtschaft (Aachen)
LKN-SH	Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (Kiel)
LU	Land-Unter
LVermA-SH	Landesamt für Vermessung und Geoinformation (Kiel)
MHThw	Mittelwert der Höchsten Tidehochwässer
MThw	Mittleres Tidehochwasser
NN	Normalnull
NLWKN	Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz
PNP	Pegelnullpunkt
vLU	vollständiges Land-Unter
WW	Wasserwirtschaftsjahr

SUMMARY

Low coastlands, marshlands and islands all over the world are challenged by rising water levels due to climatic changes. Especially tidal marshlands can compensate for a certain degree of hydrological changes. Their rate of vertical accretion depends on sufficient sediment depositions due to a frequent flooding. The 10 insular North Frisian Halligen (Northern Germany) (**chapter 1**) are inhabited marshlands, which have to be distinguished from tidal marshlands in general by reason of manifold anthropogenic modifications (e.g. the construction of shallow dykes and tidal gates). To date, a lack of knowledge about the interdependency between those modifications and sediment dynamics prevent a sound discussion about the adaptation capacity of the Halligen to recent and future sea-level changes. This Ph.D.-thesis is meant to fill this gap of knowledge. Marshland accretion and the adaptation capacity of the Halligen Hooge, Langeness and Nordstrandischmoor to sea-level-rise (SLR) is investigated and future perspectives are discussed.

To determine factors and processes which affect sediment dynamics on the Hallig marshlands, a variety of different methods has been developed and employed. To gain knowledge about the inundation frequency, gauge level thresholds for inundation events were defined, based on digital elevation models (DGMs) and d-GPS (differential global positioning system) measurements (**chapter 2**). A combined field and laboratory method was developed to calculate marshland accretion based on annual rates of sediment deposition (**chapter 3**). One litre low density polyethylene (LDPE) bottles and small synthetic turf mats were used as simple but coast, time and quantity efficient sediment trap devices during a field study which lasted from November 2010 to March 2013. For the transformation of sediment deposition into rates of vertical accretion, the bulk dry density (BDD) as well as the organic matter concentration of the correspondent marsh soil was considered using data from 12 shallow percussion cores (depth ≤ 100 cm). The combination of this short-term sedimentological data with results of a ^{137}Cs and ^{210}Pb dating campaign (**chapter 4**) allows to compare marshland accretion rates (since 1915) with recent gauge level data and regional projections of SLR.

Analyses of the available gauge level data of the study sites (chapter 2) revealed different inundation frequencies for the investigated Halligen. The annual inundation frequency between 2001 and 2010 amounts to 2 events for Hooge, 9 to 10 events for Langeness, and 15 events for Nordstrandischmoor. By reason of a heightened marshland edge (i.e. shallow summer dykes) at Hooge (+ 1.54 m above mean high water, MHW) and Langeness (+ 0.98 m above MHW), these Halligen are flooded only during extreme storm surge events. In contrast the impermeable revetment height of the more frequent flooded Hallig Nordstrandischmoor is only + 0.7 m above MHW.

The methodological research on the application of the sediment traps (chapter 3) revealed that both devices gain comparable results up to a deposition rate, of ~ 2.0 kg/m^2. Above this threshold the retention efficiency of the turf mats decreases compared to the LDPD bottles. The combined use of bottles and mats, especially when deposition rates do not exceed the threshold, allows (1) to check the internal consistency of the data, (2) to detect outliers with respect to cattle- or man-made damage, and (3) to estimate possible effects of post-storm sediment remobilization. To transfer sediment depositions into rates of vertical accretion, the BDD as well as the organic matter concentration of the correspondent marsh soil has to be considered. Results of the soil coring campaign show that these parameters are different among all Halligen. Higher inundation frequencies cause lower soil organic matter concentrations, resulting in higher BDD of the soil (Hooge 0.64 g/cm^3, Langeness 0.67 g/cm^3, Nordstrandischmoor 0.83 g/cm^3). Furthermore, autochthonous organic material (by source of the marshland vegetation) contributes by 9.0 ± 1.4 % (Hooge) to 21.4 ± 6.6 % (Nordstrandischmoor) to marshland accretion, for a correspondent time scale of 1915 to 2011.

The combination of short-term accretion data with results of the ^{137}Cs and ^{210}Pb dating campaign (chapter 4) shows clearly that marshland accretion is in disequilibrium with sea-level-rise since the beginning of the 20th century. Long-term accretion rates (1915 – 2011) based on ^{210}Pb data (1.0 ± 0.3 mm/a at Hooge, 1.2 ± 0.3 mm/a at Langeness and 2.6 ± 0.9 mm/a at Nordstrandischmoor) cannot compensate the fast increasing MHW level (5.0 ± 0.3 mm/a, Wyk on Föhr) at the study site. Future sea-level projections until 2100 (conducted by the fwu, Siegen) revealed that the extreme values (highest high waters, HHW, 6.6 ± 3.8 mm/a) tend to rise much faster than the MHW or relative mean sea-level (RMSL, 2.6 ± 0.4 mm/a). Therefore an increasing hazard potential for the Halligen has to be expected if vertical marshland accretion does not accelerate in the future. An increase in wave height and period due to higher water levels on the Hallig and a declining wave transmission at the summer dyke will result in higher hydrodynamic forces on the marshland and the Warften. The lack in marshland accretion (especially at Hooge and Langeness) is clearly a matter of an inappropriate hydrological management. Beside the low inundation frequency due to water impermeable revetments (i.e. dykes), tidal gates in front of the channel system prevent a sufficient sediment transport from the marsh edge to the hinterland. This transport limitation decreases marshland accretion distant to the marshland edge.

New strategies to change the disequilibrium between marshland accretion and rising water levels (discussed in **chapter 6**) have to focus on well adapted, long-term management strategies, consistent with the special needs of the local habitants. This contains to minimize economic damage like restrictions to farming and tourism by reason of an increased inundation frequency. Beside an adjustment of the marshland edge (lowering of dykes and water impermeable revetments) or replacement by water and sediment permeable gravel revetments (e.g. Elastocoast®, BASF), the reactivation of the tidal channel system could be feasible. First field tests on Hallig Langeness (**chapter 5**) revealed an enhanced sediment input to the inner marsh by open tidal gates during appropriate weather conditions (high tides exceeding spring tide level). To accelerate the development of constructive solutions for the Halligen, those must be forced by local decision makers and the inhabitants themselves. To do so, it is necessary to realize that inundations and storm surges are not solely a hazard for the Halligen and their inhabitants but also a natural hydrological phenomenon that is essential to keep sediment accretion in balance to SLR.

ZUSAMMENFASSUNG

Die Anpassung von Küstenniederungen, Seemarschen und Inseln an klimatische Veränderungen und einen steigenden Meeresspiegel ist eine der großen Herausforderungen des 21. Jahrhunderts. Im Gegensatz zu eingedeichten Küstenmarschen und Inseln besitzen tidebeeinflusste Seemarschen ein natürliches Anpassungspotential an sich verändernde hydrologische Rahmenbedingungen. Überflutungsabhängige Sedimenteinträge führen zu einem Anwachsen der Marschoberfläche und kompensieren somit einen Anstieg des Meeresspiegels. Die 10 verbliebenen nordfriesischen Halligen (Schleswig-Holstein, Deutschland) (**Kapitel 1**) sind bewohnte Inselmarschen, welche aufgrund ihrer anthropogenen Überprägung von naturbelassenen Seemarschen unterschieden werden müssen. Diese umfasst z.B. den Bau von flachen Sommerdeichen und Sielanlagen. Inwiefern sich diese Veränderungen auf die Sedimentdynamik der Marschen auswirken, ist bislang unzureichend belegt, was eine fundierte Diskussion bezüglich zukünftiger Entwicklungsperspektiven der Halligmarschen verhindert. Die vorliegende Arbeit ist dazu angelegt, diese Wissenslücke zu schließen. Sie untersucht das vertikale Marschwachstum exemplarisch auf den Halligen Hooge, Langeneß und Nordstrandischmoor und beurteilt deren Anpassungsvermögen an einen steigenden Meeresspiegel. Darüber hinaus werden zukünftige Entwicklungsperspektiven diskutiert.

Um Faktoren und Prozesse, welche maßgeblich die Sedimentdynamik der Halligen beeinflussen, messbar zu machen, mussten geeignete Methoden entwickelt und angewendet werden. Zur Berechnung jährlicher Überflutungshäufigkeiten wurden Pegelschwellenwerte für Überflutungsereignisse auf Basis von digitalen Geländemodellen (DGMs) und d-GPS (differential global positioning system) Messungen errechnet und auf die verfügbaren, regionalen Pegeldaten angewendet (**Kapitel 2**). Sedimentfallen, bestehend aus LDPE (low density polyethylene) Flaschen (1 Liter) und Kunstrasenmatten (20 x 30 cm), bilden die Grundlage einer dreijährigen (November 2010 – März 2013) Feld- und Laborstudie zur zeitlichen und räumlichen Erfassung der sturmflutabhängigen Sedimentdeposition (**Kapitel 3**). Durch die Verwendung regionaler bodenphysikalischer Parameter (Lagerungsdichte und Gehalt an organischer Bodensubstanz) können Depositionsraten in eine vertikale Wachstumskomponente transformiert werden. Dazu werden Ergebnisse einer Rammkernsondierung genutzt, welche 12 Sedimentkerne mit einer Länge von maximal 100 cm umfasst. Die Sedimentbohrkerne sind weiterhin die Grundlage für eine ^{137}Cs- und ^{210}Pb-Datierung. Die Kombination beider Datensätze (**Kapitel 4**) ermöglicht einen schlüssigen Vergleich der Marschentwicklung seit dem Jahr 1915 mit regionalen Pegeldaten und Projektionen des zukünftigen Meeresspiegelanstiegs.

Die Analyse der verfügbaren Pegeldaten (Kapitel 2) zeigt eine hohe Variabilität der jährlichen Überflutungshäufigkeiten. Das zehnjährige Mittel eintretender Ereignisse beträgt 2 Überflutungen auf Hooge, 9 – 10 Überflutungen auf Langeneß und 15 Überflutungen auf Nordstrandischmoor. Aufgrund der künstlichen Überhöhung der Marschkante durch Sommerdeiche mit + 1.54 m ü. mittlerem Tidehochwasser (MThw) auf Hooge und + 0.98 m ü. MThw auf Langeneß werden die betreffenden Halligen lediglich bei selten eintretenden Sturmflutereignissen überflutet. Die Höhe des wasser- und sedimentundurchlässigen Steinpflasters auf Nordstrandischmoor beträgt lediglich + 0.7 m ü. MThw.

Die methodischen Untersuchungen bezüglich der Nutzung von Sedimentfallen (Kapitel 3) zeigen, dass beide Typen von Sedimentfallen vergleichbare Ergebnisse liefern. Oberhalb einer Depositionsrate von ~ 2.0 kg/m^2 sinkt das Rückhaltevermögen der Kunstrasenmatte im Vergleich zur LDPE Flasche deutlich ab. Die parallele Nutzung beider Fallentypen, insbesondere wenn die Depositionsraten den Schwellenwert (~ 2.0 kg/m^2) nicht überschreiten, erlaubt: (1) Die Überprüfung, ob beide Datensätze konsistent sind. (2) Die Identifizierung von Ausreißern. (3) Eine Abschätzung, ob Sediment auf oder in der Sedimentfalle nach der Überflutung remobilisiert wird. Um die Sedimentdeposition in eine vertikale Wachstumsrate zu übersetzen, muss die mittlere Bodendichte als auch der Gehalt an organischer Bodensubstanz des Marschbodens berücksichtigt werden. Die Bohrkernuntersuchungen zeigen, dass diese bodenphysikalischen Parameter auf den unterschiedlichen Halligen stark variieren. Marschen, die häufig überflutet werden lagern weniger organisches Material im Oberboden ein als selten überflutete Marschen. Niedrige Gehalte an leichten organischen Materialien geringer Dichte resultieren wiederum in einer höheren Lagerungsdichte des Marschbodens (Hooge 0.64 g/cm^3, Langeneß 0.67 g/cm^3, Nordstrandischmoor 0.83 g/cm^3). Autochthones organisches Material (welches primär von der Halligvegetation stammt) trägt mit einem Anteil von 9.0 ± 1.4 % (Hooge) bis 21.4 ± 6.6 % (Nordstrandischmoor) zum Marschwachstum bei.

Die Ergebnisse der Sedimentfallenuntersuchungen als auch der Datierungen zeigen deutlich ein Ungleichgewicht zwischen Marschwachstum und Meeresspiegelanstieg seit Beginn des 20. Jahrhunderts. Die langjährigen Wachstumsraten, basierend auf der ^{210}Pb-Datierung, liegen mit 1.0 ± 0.3 mm/a auf Hooge, 1.2 ± 0.3 mm/a auf Langeneß und 2.6 ± 0.9 mm/a auf Nordstrandischmoor deutlich unterhalb des MThw-Anstiegs von 5.0 ± 0.3 mm/a (1951 – 2011, Wyk auf Föhr). Projektionen des Meeresspiegelanstiegs bis zum Jahr 2100 (Berechnet durch das fwu, Siegen) weisen darauf hin, dass extreme Wasserstände (höchste, jährliche Tidehochwasserstände, HThw, 6.6 ± 3.8 mm/a) deutlich schneller ansteigen werden als das MThw oder der mittlere Meeresspiegel (2.6 ± 0.4 mm/a). Aufgrund dieser Beobachtungen ist von einem zukünftigen Anstieg des Gefährdungspotentials für die Halligen auszugehen, wenn es nicht gelingt, ein sedimentologisches Gelichgewicht zwischen Meeresspiegel und Marschwachstum herzu stellen. Der Anstieg der Wellenhöhe und Periode, aufgrund von steigender Wassertiefe und einer geringeren Wellentransmissionsrate an den Sommerdeichen, resultiert in einer steigenden hydrodynamischen Belastung der Warften und der Marschoberfläche. Das sedimentäre Ungleichgewicht, besonders auf Hooge und Langeneß, kann eindeutig auf das hydrologische Management der Halligen zurückgeführt werden. Aus sedimentologischer Sicht sind die beiden Hauptkritikpunkte (1) die geringe Anzahl an Überflutungen aufgrund der Deichanlagen und (2) der eingeschränkte Transport suspendierter Feststoffe über die Binnenpriele. Letzteres resultiert aus der Blockade der Binnenpriele durch Sielanlagen und führt zu einer Abnahme der Sedimentdeposition mit zunehmender Entfernung zur Uferlinie.

Um dem Ungleichgewicht zwischen Marschwachstum und Meeresspiegelanstieg entgegenzuwirken, ist es dringend erforderlich, neue Managementstrategien für die Halligen zu entwickeln (**Kapitel 6**), welche sedimentologische/geomorphologische Aspekte sowie die speziellen Bedürfnisse der Halligbevölkerung gleichermaßen berücksichtigen. Letztere beinhalten die Minimierung ökonomischer Schäden wie etwa Einschränkungen der landwirtschaftlichen Nutzung oder des Tourismus. Mögliche Szenarien können ein Abflachen der bestehenden Deiche oder deren Rückbau und Erneuerung durch wasser- und sedimentdurchlässige Rauhstreifen (z.B. Elastocoast®, BASF) beinhalten. Weiterhin erscheint die Reaktivierung der blockierten Binnenpriele eine plausible Maßnahme zu sein. Erste Freilandexperimente auf Hallig Langeneß (**Kapitel 5**) belegen einen erhöhten Sedimenttransport in die Binnenmarsch aufgrund geöffneter Sielanlagen in Verbindung mit Windstau (Thw-Ereignisse über Springtideniveau). Ob die generelle Umsetzung derartiger Maßnahmen möglich ist, ist in erster Linie davon abhängig, ob die Halligbevölkerung derartigen Veränderungen ihrer Umwelt aufgeschlossen gegenübersteht und diese lokalpolitisch getragen werden. Auf jeden Fall ist ein Umdenken dahingehend erforderlich, die halligtypischen Überflutungen (Land-Unter) nicht ausschließlich als Bedrohung zu verstehen. Sie sind ein natürliches Phänomen, welches notwendig ist, um das Gleichgewicht zwischen Meeresspiegelanstieg und Sedimentdeposition aufrechtzuerhalten.

CHAPTER 1 INTRODUCTION TO THE THESIS

1.1 MOTIVATION

There is no doubt that adaptation to coastal flooding around the world will be a major challenge during the 21st century (Seneviratne et al. 2012). A variety of studies predict increasing water levels on global as well as regional scale (e.g. Rahmstorf 2007, Katsman et al. 2008, Church et al. 2013, Slangen 2014). Especially tidal lowlands like the marshes of the German Wadden Sea region will need to adapt to fast changing hydrological conditions. During the last decades multiple studies have been conducted about the adaptation process, persistence as well as on future perspectives of tidal marshlands (chapter 1.3, State of research). All these studies have in common that they focus on natural or semi-natural tidal habitats rather than on inhabited marshlands. Among the inhabited marshlands worldwide, the insular North Frisian Halligen are a unique phenomenon. During a long history of settlement, which is well documented since the 17th century (Müller and Fischer 1917), the inhabitants transformed the marshland into a cultural landscape (see chapter 1.2 for a summary). Man-made modifications have already been suggested to have negative influences on the development of marshlands (e.g. Flemming and Bartholomä 1997, Flemming 2002, Reise 2005), but to date there is almost no data available which focuses in detail on the interdependency between human activities and the adaptation capacity of the Halligen to SLR. This deficit of knowledge also prevents for a well-funded discussion about their recent situation and further perspectives. Furthermore, reliable data is the indispensable scientific base for the development of management strategies to strengthen the Halligen against SLR, as well as inhabited tidal marshland in general. This Ph.D.-thesis is meant to fill this gap of knowledge. It researches marshland accretion and the adaptation capacity of the Halligen Hooge, Langeness and Nordstrandischmoor to SLR and discusses perspectives for their future persistence.

1.2 REGIONAL SETTING AND HISTORY

The etymological origin of the word "Hallig" is not exactly known. Müller and Fischer (1917) interpret "Hallig" as an analogy for the medieval word "Halg" or "Halgen" which means shallow marshlands or islands which are located in front of the dyked mainland and not protected for water levels exceeding MHW. Furthermore the Old to Middle High German meaning of "hal(l)" points to medieval places of salt production (Stifter 2005). Therefore the word "Hallig" could also be related to the mining of salty peat that was a preindustrial economy mainly during the

12th century in North Frisia (Behre 2008). Nowadays, the term “Hallig” is used to name the 10 small marshlands in front of the North Sea coastline of the German federal state of Schleswig-Holstein (fig. 1-1). About 300 residents are living on a total area of 21.1 km^2. To protect themselves and their goods against storm surges, houses are built on top of 37 inhabited or farmed artificial dwelling mounts. Those dwelling mounts; called “Warften” (fig. 1-2); are a criterion which separates Halligen from dyked marsh islands like Pellworm or Nordstrand. Instead of a main dyke, the marshlands edge is protected by block pavements and stone revetments against further erosion. As a result, the Halligen seem to be in a durable condition without any storm surge related losses of land area since nearly 100 years.

To enhance draining, the tidal channel system was straightened and equipped with tidal gates. In some cases (Hooge and Langeness), shallow summer dykes also prevent inundations during moderate high tide events, i.e. during the summer month (cf. chapter 2, Schindler and Willim 2014). The number of inundations is directly related to the occurrence of depression systems, moving with WNW to ESE direction towards the German Bight (Petersen and Rohde 1991, Gönnert 2001). Their magnitude depends on the regional bathymetry, tidal conditions as well as wind duration and speed (Woth et al. 2005). Due to those rough environmental conditions, a unique lifestyle has developed. Furthermore, the Halligen are of ecological importance. They are a refugee for salt marsh plants as well as migratory birds, which use the marshland for resting and breeding. In addition, they are surrounded by the national park and UNESCO World Heritage

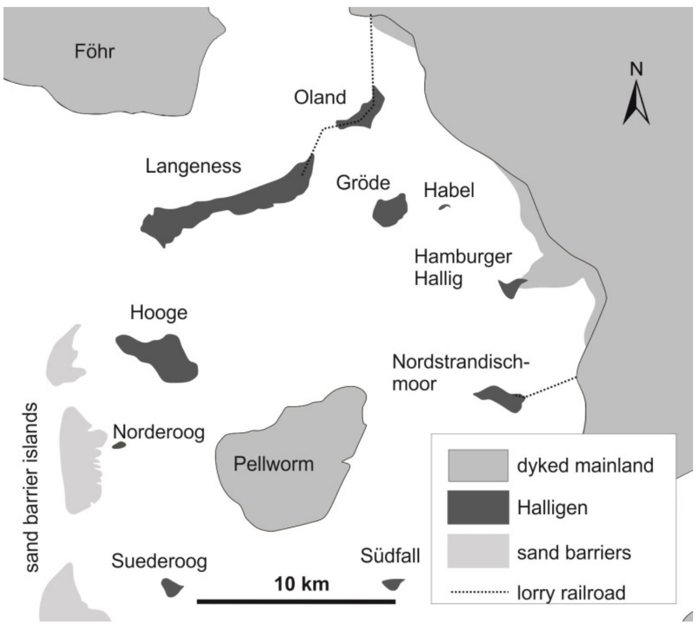

Figure 1-1: Location map of the Halligen and islands at the North Frisian North Sea Coast (Schleswig-Holstein).

Figure 1-2: Morning after a storm surge at Nordstrandischmoor in November 2012. The image is taken from “Westerwarft” towards the dwelling mount of “Halberweg”.

“Schleswig-Holsteinisches Wattenmeer“ (since 2009) and belong to the biosphere reserve “Schleswig-Holsteinisches Wattenmeer und Halligen“ (since 1990). By reason of this advantageous combination of cultural and environmental features, the Halligen are as well an attraction for supra-regional tourism.

The origin of the Halligen is related to the latest period of landscape evolution of the North Frisian Wadden Sea. It started at the end of the Weichselian glacial period 16.000 BP with a eustatic triggered SLR (Reise 2005). The latest reconstruction of the Holocene sea-level curve for the North Sea coast, based on sea-level index points, was published by (Behre 2007) and supplemented by (Bungenstock and Weerts 2009, 2011). The overall SLR was approximately 110 to 120 m (Streif 1989, Behre 2002). It could be divided in a highly transgressive period until 7000 BP and a sea-level high stand period (Bungenstock 2005) with short intercalated regression periods until 5000 BP (Behre 2007). During the regression periods brackish sediments and peat bogs accumulated (which could be age dated and used as sea-level index points, as they develop around MHW level), forming reclaimable marshlands, which were protected by large sandy barrier spits westward of the islands Sylt, Amrum and Eiderstedt against the sea (Reise 2005, Ahrendt 2007). Around the beginning of the last millennium, land reclamation as well as draining was increased. First dykes were built to keep the hinterland dry and to protect settlers and their goods against the tides (Riecken 1982). Preindustrial peat digging activities lowered the elevation within the new polder landscape. A new sea-level transgression between 1000 to 1500 AD (Behre 2007) raised the water level in front of the dykes until a number of catastrophic storm surges during the Late Middle Age, formed the contemporary appearance of the North Frisian Wadden Sea. Especially two surge events, the so called 1st and 2nd "Grote Mandränke" (*drowning of many people 'man'*), had a major impact to the landscape and happened in 1362 and 1634. During both events, large arable marshlands were reclaimed by the sea and cut through by tidal channels. The Halligen (fig. 1-1) are most probably the last insular remnants of the former continuous marshland (Behre 2008). But to date, there is no clear evidence for the theory of their appearance.

1.3 STATE OF RESEARCH

The topic of salt marsh adaptation in general has been discussed by various studies (Allen 2000, D'Alpaos et al. 2007, Kirwan and Guntenspergen 2010). Just as much data exists about regional observations in the context of SLR and marshland accretion (Craft et al. 1993, Andersen et al. 2011, Schuerch et al. 2012, Spencer et al. 2012, Suchrow et al. 2012) as well as on local predictions of future marshland development (van Wijnen and Bakker 2001, French and Burningham 2003, Bartholdy et al. 2004). It can be summarized that intact tidal marshlands are highly dynamic systems, which can compensate for a certain degree of SLR, if the hydrological, geomorphological and sedimentological conditions are appropriate. In detail, a variety of physical factors are affecting sediment dynamics (fig 1-3). In order to quantify if a tidal marshland is still in equilibrium with changing hydrological conditions, knowledge about the different parameters (1) suspended sediment concentration, (2) sediment deposition, (3) vertical marshland accretion and (4) surface elevation change (Cahoon et al. 1995, Wijnen and Bakker 2001, Nolte et al. 2013), related to the marshlands adaptation capacity, is essential to allow for a reliable estimation. At least, the elevation gain due to a sufficient sediment input by frequent flooding has to compensate SLR. In case of anthropogenic marshlands like the Halligen, an additional factor which influences sediment dynamics are human activities (e.g. dyking and hydrological management strategies) (Deicke et al. 2007, Stock 2011). As mentioned before, those were already suggested to have influence on marshland development (e.g. Flemming and Bartholomä 1997, Flemming 2002, Reise 2005).

To date, detailed research data about sediment dynamics on anthropogenic marshlands, especially for the North Frisian Halligen, is rare. Stock (2011) provides data about surface elevation change at the Hamburger Hallig. The present Ph.D.-thesis is based on first studies conducted by the Department of Sedimentology and Environmental Geology (Geoscience Centre Göttingen) on the Halligen Hooge, Langeness and Nordstrandischmoor (Deicke et al. 2007, Karius and Machunze 2011, Sander et al. 2011, Vogt et al. 2011). Those studies revealed first hints about the negative interdependency of man-made coastline constructions (e.g. dykes) to sediment dynamics and provided the basis for the current research approach applied for this thesis.

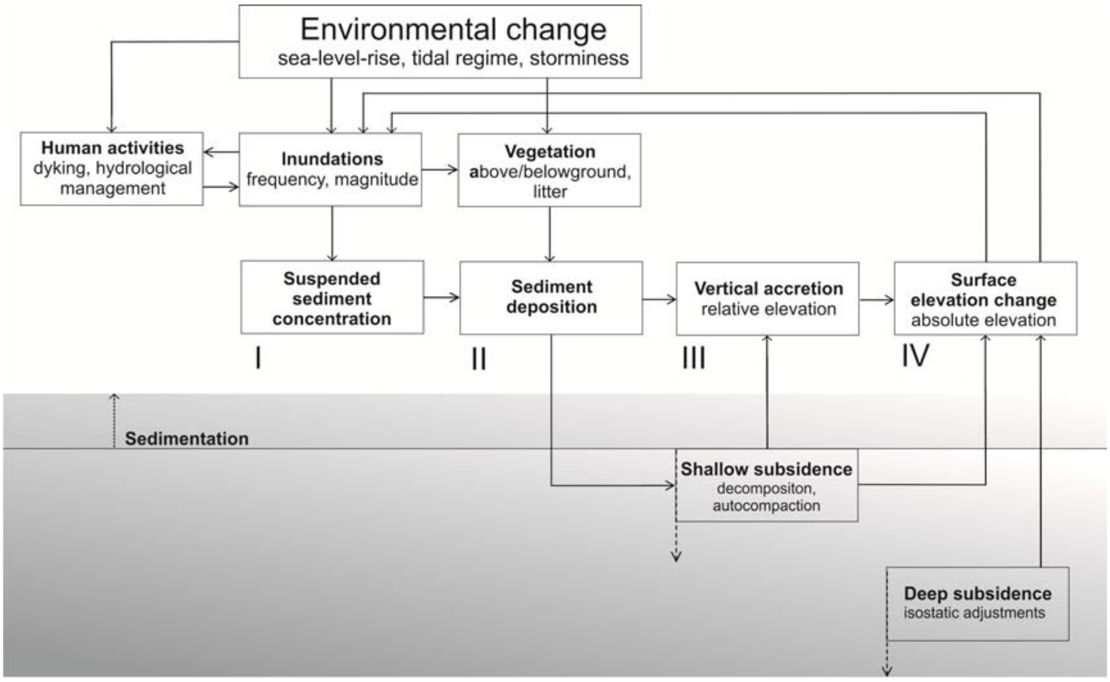

Figure 1-3: Several physical, biological and anthropogenic factors influence the surface elevation of the marshlands at the North Frisian Halligen. Four different processes (I-IV) leading to marshland growth can be distinguished (modified after Allen 2000, Nolte et al. 2013).

1.4 THESIS OUTLINE

Chapter 1 clearly revealed that there is a lack of knowledge about sediment dynamics on anthropogenic marshland like the Halligen. To understand this issue in detail, knowledge about the controlling physical and anthropogenic factors; in detail the interdependency between human activities and inundation frequency (cf. fig. 1-3); is essential. **Chapter 2** deals with the calculation of the inundation frequency at the three investigated Halligen Hooge, Langeness and Nordstrandischmoor as well as with its temporal variation. To highlight the anthropogenic aspect, topographical survey data, including spatial information about the elevation of artificial coastline constructions (e.g. dykes and revetments), is used to process hydrographical data. To gain knowledge about short to long-term sediment dynamics on the Hallig marshlands, a three year lasting (November 2010 to March 2013) measurement campaign has been conducted. The campaign focusses on the calculation of short- to long-term marshland accretion rates.

A second focus is the spatial distribution of flood sediments at the marsh surface to gain information about sediment transport processes. By reason of a general time limitation (a project period of three years) and seasonal limitations enacted by farmers and the national park administration, which reduces field work to a period of October to March, an adapted measurement methodology was developed (**chapter 3**). Beside the evaluation of simple measurement devices (one litre LDPE bottles and small mats of synthetic turf) to calculate short-term deposition rates, the transformation of annual deposition rates into rates of vertical accretion is discussed. Furthermore, chapter 3 highlights the contribution of organic matter to marshland accretion and its relation to soil bulk dry density (BDD) and sediment age that is an essential parameter for the transformation process. In **chapter 4,** short-term accretion data (2010 to 2013) is supplemented by results of a sediment dating campaign based on radiometric measurements (^{137}Cs and ^{210}Pb). Combining both data (short- and long-term) with regional hydrographic data (chapter 2) and projections for the future sea-level (IPCC 2013) allows for a well-founded discussion about the adaptation capacity of the Hallig marshlands to SLR. Spatial distribution patterns of sediment depositions enable a discussion about the influence of human activities on marshland accretion. **Chapter 5** analyses the recent topography of the Hallig marshlands as a result of spatial highly variable sediment deposition patterns and presents the outcome of a further field study on Hallig Langeness to enhance marshland accretion by a re-establishment of sufficient sediment transport mechanisms. Finally, conclusions on the entire research conducted within this Ph.D.-project are summarised and discussed in **chapter 6** as well as future perspectives and recommendations for management strategies at the Halligen.

Chapter 2 to 4 are identical with the following accepted publications:

<u>Chapter 2</u>

"Calculating the long-term inundation frequencies for the Halligen Hooge, Langeness and Nordstrandischmoor based on local gauge level data"

"Berechnung langjähriger Überflutungshäufigkeiten für die Halligen Hooge, Langeneß und Nordstrandischmoor auf Basis regionaler Pegeldaten"

by Malte Schindler and Katharina Willim

Accepted for publication in Coastline Reports

Chapter 3

"Measuring sediment deposition and accretion on anthropogenic marshland - Part I: Methodical evaluation and development"

by Malte Schindler, Volker Karius, Matthias Deicke, Hilmar von Eynatten

Accepted for publication in Estuarine, Coastal and Shelf Science

Chapter 4

"Measuring sediment deposition and accretion on anthropogenic marshland - Part II: The adaptation capacity of the North Frisian Halligen to sea-level-rise"

by Malte Schindler, Volker Karius, Arne Arns, Matthias Deicke, Hilmar von Eynatten

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CHAPTER 2 CALCULATING THE LONG-TERM INUNDATION FREQUENCIES FOR THE HALLIGEN HOOGE, LANGENESS AND NORDSTRANDISCHMOOR BASED ON LOCAL GAUGE LEVEL DATA

BERECHNUNG LANGJÄHRIGER ÜBERFLUTUNGSHÄUFIGKEITEN FÜR DIE HALLIGEN HOOGE, LANGENEß UND NORDSTRANDISCHMOOR AUF BASIS REGIONALER PEGELDATEN

Malte Schindler, Katharina Willim

ACCEPTED FOR PUBLICATION IN COASTLINE REPORTS

ABSTRACT

The 10 North Friesian Halligen (small marsh islands) have to cope with changing environmental and climatic conditions such as sea-level-rise (SLR). The adaptive capacity of those marshlands is based on an adequate inundation frequency and sediment input. To develop sustainable management strategies for the preservation of the Halligen, detailed knowledge about the inundation frequency is essential. By use of digital elevation models and d-GPS measurements, gauge level thresholds for inundation events were developed for the Halligen Hooge, Langeneß, and Nordstrandischmoor. Analyses of the available gauge level data of the study sites reveal variable inundation frequencies between different Halligen. The annual inundation frequency between 2001 and 2010 was calculated with 2 events for Hooge, 9 to 10 events for Langeneß, and 15 events for Nordstrandischmoor. By reason of higher revetments at Hooge and Langeness compared to Nordstrandischmoor, these Halligen are only flooded during extreme storm surge events. The average marshland elevation of Nordstrandischmoor is about 20 cm higher above the recent mean high water level than the elevation of Hooge and Langeneß, indicating a better adaptation capacity to SLR. Construction of water permeable revetments at Hooge and Langeneß resulting in an increase of the inundation frequency and therefore increasing sediment deposition could contribute to the protection of the Halligen.

Schlagwörter: Nordsee**;** Halligen; Sturmflut; Küstenschutz; Meeresspiegelanstieg

2.1 MOTIVATION UND ZIELE

Die Landoberfläche der zehn nordfriesischen Halligen liegt größtenteils nur knapp über dem mittleren Tidehochwasser (MThw). Sie sind nicht nur von großer soziokultureller und ökologischer Bedeutung, sondern nehmen auch eine Schlüsselstellung beim Schutz der schleswig-holsteinischen Festlandküste vor Sturmfluten ein. Gemeinsam mit den drei großen Außensänden wirken sie als Wellenbrecher und verringern somit die hydrodynamischen Kräfte und den Wellenauflauf an den Deichlinien. Bereits Müller und Fischer (1917) verweisen auf die Bedeutung der Halligen als „natürliche Schutzwerke" vor der Küste im Sinne eines ganzheitlichen Küstenschutzes, welcher den gesamten Naturraum bei der Konzeption von Hochwasserschutzmaßnahmen berücksichtigt. Die Halligen selbst wurden erst Anfang des 20. Jahrhunderts mittels steinerner Deckwerke gegen fortschreitende Landverluste gesichert. Langeneß und Hooge erhielten zudem in den 1910er Jahren einen umschließenden Sommerdeich (Müller und Fischer 1917). Die Sommerdeiche verringern die Anzahl der jährlichen Überflutungen, Entwässerungsgräben und Sielanlagen garantieren eine effektive Entwässerung nach einem Land-Unter. Gleichfalls bedeutet diese Entwicklung die Transformation einer bis dato in ihren Grundzügen natürlichen Küstenmarsch hin zu einer nutzungsintensivierten Kulturlandschaft, welche nur noch selten während der stürmischen Wintermonate überflutet wird.

In der gegenwärtigen Diskussion bezüglich notwendiger Anpassungsstrategien an sich ändernde klimatische und hydrologische Rahmenbedingungen nehmen die Halligen auch aufgrund ihrer exponierten Lage eine besondere Stellung ein. In jüngerer Vergangenheit stieg der relative mittlere Meeresspiegel (RMSL) im Bereich der Halligen um 3,6 ± 0,9 mm/a (Pegel Husum 1971 – 2008) bis 4,6 ± 0,8 mm/a (Pegel Wyk, 1971 – 2008) (Jensen et al. 2011). Alle verfügbaren globalen und regionalen Projektionen für die zukünftige Entwicklung des mittleren Meeresspiegels weisen darauf hin, dass sich dieser Trend fortsetzen wird. Je nach Szenario wird für den Zeitraum von 2090 – 2099 verglichen mit 1980 – 1999 ein Anstieg von 18 bis 59 cm (1.8 – 5.9 mm/a) projiziert (IPCC 2007). Im Allgemeinen besitzen Seemarschen an Gezeitenküsten ein bemerkenswert hohes Anpassungsvermögen gegenüber einem steigenden Meeresspiegel (D'Alpaos et al. 2011). Ist die Überflutungshäufigkeit sowie der Gehalt an Feststoffen, welche mit dem Überflutungswasser auf die Marschen transportiert werden, ausreichend hoch, kann nach Kirwan et al. (2010) auch ein Meeresspiegelanstieg von > 10 mm/a durch Höhenzuwachs kompensiert werden. Eine Reduzierung der Überflutungshäufigkeit hätte somit eine Verringerung des natürlichen Anpassungspotentials gegenüber dem steigenden Meeresspiegel zur Folge, weshalb der Themenkomplex der Überflutungshäufigkeiten ein zentrales Element bei der Diskussion um die Erhaltung der Halligen selbst und ihrer Schutzfunktion für die Festlandküste ist.

Die vorliegende Arbeit quantifiziert die mittleren Überflutungshäufigkeiten der Halligen Langeneß, Hooge und Nordstrandischmoor auf der Grundlage vorhandener Pegeldaten des Landesbetriebs für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKN-SH). Sie bewertet den Einfluss unterschiedlicher wasserbaulicher Schutzkonzepte und stellt damit eine Diskussionsgrundlage bezüglich des anthropogenen Einflusses auf das natürliche Anpassungsvermögen der Halligmarschen gegenüber Meeresspiegeländerungen dar.

2.2 MATERIAL UND METHODEN

2.2.1 DATENGRUNDLAGE

Die verwendeten Wasserstandsdaten in Form von Scheitelwerten der Tidenhochwässer (Thw) wurden vom LKN-SH aufbereitet und zur Verfügung gestellt. Die Standorte aller für die vorliegende Arbeit genutzten Pegel sind Abbildung 2-1 zu entnehmen. Unterschieden werden Binnenpegel, welche wenig bis keine Tidebeeinflussung zeigen, und die zugehörigen Außenpegel, welche tidebeeinflusst sind. Digitale Binnenpegel wurden auf Halligen erst im Jahr 2009 installiert. Somit wurde auch auf benachbarte Außenpegel zurückgegriffen, deren Daten teilweise bis in die 50er Jahre des 20. Jahrhunderts zurückreichen (Pegel Wyk auf Föhr). Tabelle 2-1 gibt eine Übersicht über die genutzten Binnen- und Außenpegel sowie deren Datenverfügbarkeit. Die Daten der Außenpegel Langeneß/Hilligenley und Nordstrandischmoor sind aufgrund der

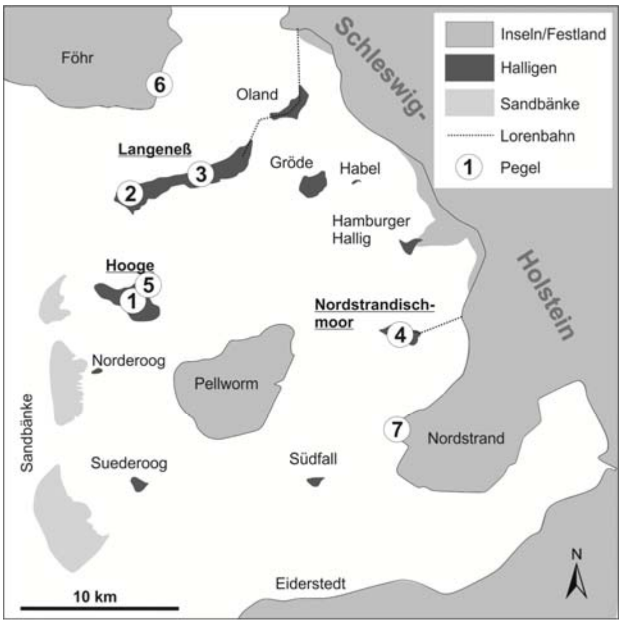

Abbildung 2-1: Lageskizze des Nordfriesischen Wattenmeeres zwischen der Halbinsel Eiderstedt (Süden) und Insel Föhr (Norden). Die drei in der vorliegenden Studie behandelten Halligen sind hervorgehoben. Die Nummerierungen der Pegelstandorte entsprechen der Auflistung in Tabelle 2-1.

Tabelle 2-1: Aufstellung der Binnenpegel sowie der zugeordneten Außenpegelstandorte nebst den Zeiträumen verfügbarer digitaler Wasserstandsdaten. Die Standorte sind entsprechend der Nummerierung in der Lageskizze (Abb. 2-1) verzeichnet.

Hallig	**Binnenpegel**	**Außenpegel**
Hooge	1 Schulwarft:	5 Anleger:
	Thw: 11.2009 – 04.2012	Thw: 12.1976 – 04.2012
Langeneß	2 Kirchhofwarf:	6 Wyk/Föhr:
(Nordmarsch)	Thw: 12.2009 – 05.2012	Thw: 11.1951 – 04.2012
Langeneß	3 Kirchwarf:	6 Wyk/Föhr:
(Alt-Langeneß)	Thw: 12.2009 – 05.2012	Thw: 11.1951 – 04.2012
Nordstrandischmoor	4 N. Moor Hallig:	7 Strucklahnungshörn:
	Thw: 11.2009 – 04.2012	Thw: 11.1994 – 03.2012

schlechten Qualität nicht nutzbar. Zum einen weisen die Daten bei dem Pegel Langeneß Hilligenley Lücken auf. Zum anderen stellt der Pegel Strucklahnungshörn, welcher als nächster verfügbarer Außenpegel der Hallig Nordstrandischmoor zugeordnet ist, lediglich für die Wasserwirtschaftsjahre (WW) 1995 – 2011 Wasserstandsdaten bereit. Die Berechnung eines 10-jährigen MThw kann mit diesen Daten somit nicht durchgeführt werden. Stattdessen wurden die Binnenpegel Langeneß/Kirchhofwarf und Langeneß/Kirchwarf dem Außenpegel Wyk/Föhr sowie der Binnenpegel Nordstrandischmoor dem Außenpegel Strucklahnungshörn/Nordstrand gegenüber gestellt.

Digitale Geoinformationsdaten des Landesamtes für Vermessung und Geoinformation Schleswig-Holstein (LVermA-SH) wurden ebenfalls über das LKN-SH bezogen. Hierzu zählen Ausschnitte des digitalen Geländemodells (DGM1, 2005) und digitale Orthophotos (DOP) des Amtlichen Topographisch-Kartographischen Informationssystems (ATKIS) sowie Daten der Automatisierten Liegenschaftskarte (ALK). Differentielle GPS-Vermessungen (d-GPS) der Küstenschutzbauwerke und Warften wurden seitens des LKN-SH vorgenommen. Die genutzten Vermessungsdaten der Sommerdeichlinien stammen aus den Jahren 1999 (Hooge) und 2010 (Langeneß). Alle digitalen kartographischen Arbeiten wurden mittels der Software ArcGIS 9.3 und 10.1 (ESRI, Inc.) ausgeführt.

2.2.2 SCHWELLENWERTE DER ÜBERFLUTUNGSEREIGNISSE

Die bisherige Dokumentation von Überflutungshäufigkeiten auf den einzelnen Standorten sowie die Definition von Referenzhöhen beruht vor allem auf Beobachtungen und mündlich überlieferten Richt- und Schätzwerten. Dibbern und Müller-Navarra (2009) legten erstmals für die

Halligen Hooge, Gröde und Nordstrandischmoor Richtwerte in Form von Pegelständen für beginnende sowie vollständige Überflutungen fest. Diese beruhen sowohl auf Mitteilungen der Halligbewohner und des LKN-SH als auch auf der Topographie der Halligen und deren Deckwerken. Die hier vorgestellte Arbeit zur Berechnung langjähriger Überflutungshäufigkeiten übernimmt den Ansatz von Dibbern und Müller-Navarra (2009) und definiert Schwellenwerte sowohl für „beginnende Land-Unter Ereignisse“ (im Folgenden als LU bezeichnet) sowie für „vollständige Land-Unter Ereignisse“ (im Folgenden als vLU bezeichnet).

2.2.3 BEGINNENDES LAND-UNTER EREIGNIS

Als Schwellenwert eines LU Ereignisses wurde die mittlere Höhe der Geländeoberfläche (GOF) der betreffenden Hallig gewählt. Erreicht der Binnenwasserstand das mittlere Niveau der GOF, sind weite Bereiche der Marsch bereits überflutet. Als Datengrundlage dient das DGM1, basierend auf der landesweiten, luftgestützten LIDAR-Vermessung (light detection and ranging) mit einer Gitterweite von 1 x 1 m und einer Höhengenauigkeit von ± 15 cm (Mitteilung des LKN-SH) aus dem Jahr 2005. Vorbereitend erfolgte die Identifizierung und Eliminierung von fehlerhaften Datenpunkten mittels des ArcGIS-eigenen Tools „Locate outliers“ (3D Analyst). Da anthropogen geformte Geländeerhöhungen und artifizielle Strukturen wie Deckwerke, Deiche und Warften bei der Berechnung mittlerer Geländehöhen unberücksichtigt bleiben sollten, wurden diese Strukturen mittels der ALK identifiziert und aus dem DGM1 entfernt. Abbildung 2-2 zeigt die resultierende Karte.

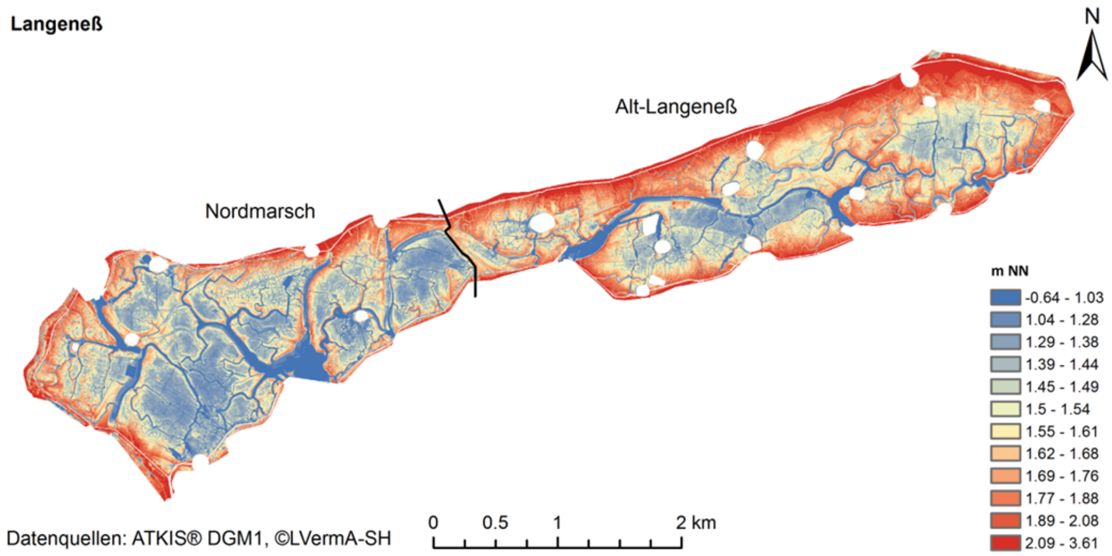

Abbildung 2-2: Digitales Höhenmodell (DGM1) der Hallig Langeneß nach der Extraktion aller künstlichen Geländestrukturen (Deiche, Deckwerke, Warften). Die schwarze Linie unterteilt das heutige Langeneß in die Bereiche der ursprünglichen Halligen Nordmarsch (Westen) und Alt-Langeneß (Osten).

2.2.4 VOLLSTÄNDIGES LAND-UNTER EREIGNIS

Ein vLU Ereignis tritt ein, wenn der Wasserstand am Binnenpegel das Niveau der nicht Wasser permeablen Deckwerke der Hallig erreicht und somit eine vollständige Füllung der Hallig vorliegt. Als nicht permeable Deckwerke werden Sommerdeiche und Steinpflaster angesehen. Halligrauhstreifen (Hallig-Igel) schließen sich binnenseitig dem Steinpflaster an. Sie sind als permeable Deckwerke konzipiert und werden somit bei der Berechnung der Höhe der nicht durchströmbaren Deckwerke nicht berücksichtigt. Sie bestehen zumeist aus verkanteten Blöcken welche mit Bitumen oder Beton verklammert sind (Abb. 2-3a), bzw. in jüngerer Zeit aus verklebtem Granitschotter (Elastocoast®, BASF, Abb. 2-3b), und dienen lediglich der Wellendämpfung. Die Berechnung der mittleren Kronenhöhe der Sommerdeiche auf Hooge und Langeneß basiert auf den d-GPS Vermessungen des LKN-SH. Nordstrandischmoor verfügt weder über einen Sommerdeich noch ist es vollständig von einem Deckwerk umschlossen. Das nordöstliche Ufer in Richtung des Lorendamms geht in ein offenes Lahnungsfeld über. Zudem ist an den Stellen, an denen Deckwerke und Halligrauhstreifen das Ufer befestigen, die

Abbildung 2-3: (a) Konservativer wasserdurchlässiger Rauhstreifen (Hallig-Igel) auf Nordstrandischmoor. Foto: Schindler 2011. (b) Moderner wasserdurchlässiger Rauhstreifen (Hallig-Igel) auf Langeneß. Schotter wird mittels eines Zwei-Komponenten-Klebers (Elastocoast®, BASF) zu einem Rauhstreifen modelliert. Dem Streifen vorgelagert ist ein wasserundurchlässiges Pflaster aus Basaltblöcken. Foto: Deicke 2014. (c) Alter Rauhstreifen auf Nordstrandischmoor. Das Niveau der binnenseitigen Salzmarsch wächst über die Höhe des Rauhstreifens hinaus. Foto: Schindler 2012.

Marschoberfläche oftmals über das Niveau des Deckwerks oder sogar der älteren Rauhstreifen hinaus gewachsen (Abb. 2-3c). Somit muss die mittlere Höhe der Marschoberfläche binnenseitig der Rauhstreifen als maßgebendes Überflutungshindernis angesehen werden. Die entsprechende Höhe wurde näherungsweise aus dem DGM1 abgeleitet. Den räumlichen Bezug gibt eine manuell editierte Linie vor, welche direkt binnenseitig der Rauhstreifen die Marschfläche der Hallig umfasst. Zu beachten ist der Höhenfehler der LIDAR basierten DGM Daten von ± 15 cm im Gegensatz zu d-GPS Vermessungen mit einer Genauigkeit im Millimeterbereich.

2.2.5 BERECHNUNG DER ÜBERFLUTUNGSHÄUFIGKEITEN

Alle Berechnungen sowie die vom LKN-SH bereitgestellten Pegeldaten basieren auf Wasserwirtschaftsjahren (WW, 1.11. – 31.10). Die Berechnung der langjährigen Überflutungshäufigkeiten, sowohl für LU als auch für vLU, erfolgt anhand der Außenpegeldaten, da diese eine wesentlich längere Zeitspanne abdecken als die 2009 installierten Binnenpegel. Eine direkte Anwendung der Binnenpegelschwellenwerte auf die assoziierten Außenpegel ist jedoch nicht möglich, da aufgrund der nicht permeablen Deckwerke die Reaktion des Binnenpegels auf einen erhöhten Außenwasserstand erst dann erfolgt, wenn Pegel und Seegang vor der Hallig eine kritische Größe erreichen, ab welcher ausreichend Überflutungswasser, zunächst durch Wellenschlag, auf die Hallig gelangt. Die Überschreitung der definierten Schwellenwerte für ein Überflutungsereignis erfolgt daher je nach Außenwasserstand verzögert oder bleibt vollständig aus, wenn der kritische Außenwasserstand nicht überschritten wird. Die Berechnung des Außenpegelschwellenwertes (H_A) kann näherungsweise anhand von Wasserstandsdaten des Zeitraums 2009 – 2012 vorgenommen werden, welche sowohl für Binnen- als auch Außenpegel vorliegen. Die gesuchte Größe (H_A) entspricht der Summe von Binnenpegelschwellenwert (H_B) und der mittleren Höhendifferenz ($\overline{\Delta_h}$) zwischen Außenwasserstand h_A und Binnenwasserstand h_B zum Zeitpunkt t (H_B). Es gilt:

(1)

$$H_{A\,(LU/vLU)} = H_{B\,(LU/vLU)} + \overline{\Delta_h}$$

(2)

$$\overline{\Delta_h} = \frac{\sum(h_A - h_B)}{n}$$

$H_{A\,(LU/vLU)}$: Schwellenwert des Außenpegels für ein Überflutungsereignis (LU/vLU)

h_A : Außenwasserstand

$H_{B\,(LU/vLU)}$: Schwellenwert des Binnenpegels für ein Überflutungsereignis (LU/vLU)

h_B : Binnenwasserstand

$\overline{\Delta_h}$: mittlere Pegeldifferenz

Bei der Berechnung von $H_{A\,(LU)}$ wurde lediglich die erste Tide einer Überflutung als Ereignis gewertet. Oftmals erfolgte während der Folgetiden eine erneute Pegelüberschreitung des Schwellenwertes $H_{B\,(LU)}$ um wenige Zentimeter, welche aufgrund eines niedrigen Außenwasserstandes h_A nicht auf Wellenschlag zurück zu führen ist. Um sicher zu stellen, dass h_A während der Folgetiden signifikant niedriger ausfallen, wurden diese in zwei Datenkollektive unterteilt: (1) Wasserstände h_A zum Zeitpunkt der Schwellenwertüberschreitung $H_{B\,(LU)}$ während der ersten Tide eines Ereignisses und (2) Wasserstände h_A zum Zeitpunkt der Schwellenwertüberschreitung $H_{B\,(LU)}$ während einer Folgetide eines Ereignisses. Mittels Zweistichproben-T-Test bei normal verteilten Datenkollektiven bzw. Mann-Whitney-U-Test bei nicht normal verteilten Datenkollektiven konnte nachvollzogen werden, dass Wasserstände in Abhängigkeit von Folgetiden signifikant niedriger ausfallen. Bei der Berechnung der Außenpegelschwellenwerte $H_{A\,(vLU)}$ wurden alle Außenpegelwasserstände h_A sowohl der Ersten als auch der Folgetiden in einem Datenkollektiv zusammen gefasst, da diese im Gegensatz zu den Pegelständen der LU Ereignisse nicht signifikant unterschiedlich waren.

Abschließend erfolgte eine Berechnung der jährlichen Überschreitungshäufigkeiten der berechneten Außenpegelschwellenwerte $H_{A\,(LU)}$ und $H_{A\,(vLU)}$ und der assoziierten Außenpegeldaten (vgl. Tab 2-1). Da Pegelzeitreihen oftmals zu kurz sind, um Trendanalysen der jährlichen Häufigkeit mittels 19-jährigem gleitendem Mittel und damit unter Berücksichtigung eines möglichen Einflusses der Nodaltide anzufertigen (Houston & Dean 2011, Woodworth 2012), wurde ein 9-jähriges gleitendes Mittel angewandt.

2.3 ERGEBNISSE

2.3.1 BINNENPEGELSCHWELLENWERTE

Abbildung 2-2 veranschaulicht das angewandte Verfahren zur Berechnung mittlerer Geländehöhen am Beispiel der Hallig Langeneß. Der Bereich der Warften und Küstenschutzbauwerke sowie weiterer artifizieller Geländestrukturen wurde aus dem DGM1 extrahiert bevor die verbleibenden Höhenpunkte gemittelt wurden. In Abbildung 2-4 sind die mittleren Gelände- und Deich/Deckwerkshöhen über Normalnull (NN) sowie das regionale MThw als Mittel der letzten Dekade (2001 – 2010) dargestellt. Die absolute Geländehöhe ist auf Hooge (151 cm NN) im Vergleich zu Langeneß (153 cm NN) nur geringfügig niedriger. Für beide Halligen wird ein MThw von 136 cm NN angenommen, was dem mittleren 10-jährigen Hochwasser (2001 – 2010) des Pegels „Hooger Anleger" entspricht. Die GOF sowie das MThw auf Nordstrandischmoor (Pegel Strucklahnungshörn 2001 – 2010) liegen mit 192 cm NN (GOF) und 155 cm (MThw) deutlich höher. Nordstrandischmoor verfügt zudem über die niedrigste Deich/Deckwerkshöhe (225 cm NN) was lediglich 70 cm über MThw entspricht. Die mittleren Deich/Deckwerkshöhen von Langeneß (234 cm NN) und Hooge (290 cm NN) entsprechen einem Niveau von 98 cm (Langeneß) bzw. 154 cm (Hooge) über MThw.

Um die Referenzhöhen der Binnenpegelschwellenwerte objektiv nach hydrologischen Gesichtspunkten bewerten zu können, ist deren Konvertierung in relative Höhen mit Bezug auf

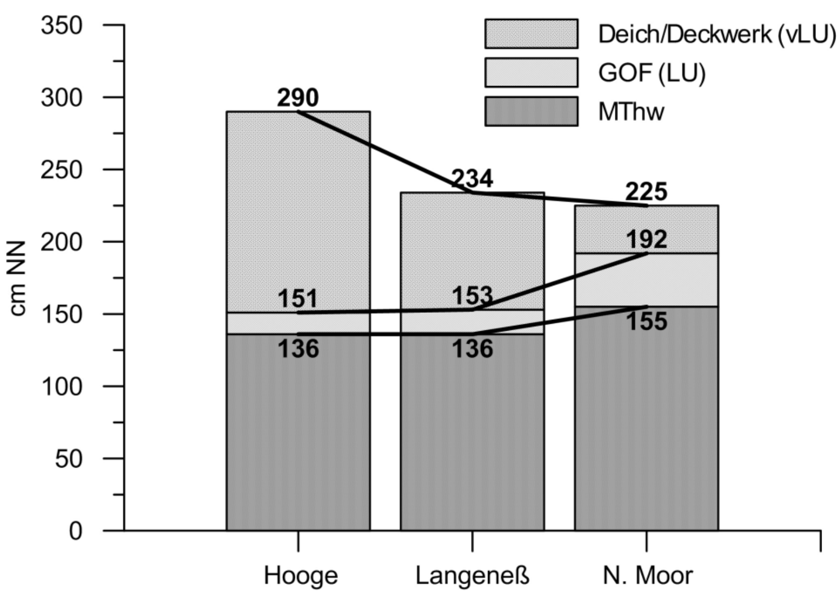

Abbildung 2-4: Mittlere Bezugshöhen der Halligen Hooge, Langeneß und Nordstrandischmoor über Normalnull (NN). Dargestellt sind das mittlere Tidehochwasser (MThw), die mittlere Geländeoberfläche (GOF) und die mittlere Höhe der Sommerdeiche (Hooge und Langeneß) bzw. nicht Wasser permeablen Deckwerke (Nordstrandischmoor).

Tabelle 2-2: Referenzhöhen der Binnenpegelschwellenwerte für Land-Unter (LU) sowie vollständige Land-Unter Ereignisse (vLU) bezogen auf Normalnull (NN) sowie das mittlere Tidehochwasser (MThw).

	Geländehöhe		**Deich/Deckwerk**	
	cm ü. NN	cm ü. MThw	cm ü. NN	cm ü. MThw
Hooge	151 ± 24	15	290 ± 21	154
Langeneß	153 ± 40	17	234 ± 19	98
(Alt-Langeneß)	143 ± 38	7	227 ± 20	91
(Nordmarsch)	162 ± 38	26	240 ± 16	104
Nordstrandischmoor	192 ± 28	37	225 ± 19	70

das regionale MThw notwendig (Tab. 2-2). Da auf Langeneß die berechnete mittlere Geländehöhe eine große Standardabweichung besitzt, wurde die Fläche der Hallig in die Areale der ehemaligen Halligen Nordmarsch (westlicher Teil) und Alt-Langeneß (östlicher Teil, vgl. Müller und Fischer 1917) unterteilt. Das DGM1 in Abbildung 2-2 veranschaulicht den Gradienten steigender GOF von West nach Ost durch den Farbwechsel von blau (tief) zu rot (hoch). Die schwarze Trennlinie unterteilt Langeneß in Nordmarsch und Alt-Langeneß. Auch wenn Langeneß einheitlich betrachtet mit 17 cm ü. MThw geringfügig höher liegt als Hooge (Abb. 2-4), ist das westlich gelegenen Nordmarsch mit lediglich 7 cm ü. MThw die am tiefsten gelegene aller betrachteten Halligmarschen.

2.3.2 AUßENPEGELSCHWELLENWERTE

Für die Berechnung der Außenpegelschwellenwerte $H_{A\,(LU)}$ und $H_{A\,(vLU)}$ anhand parallel vorhandener Zeitreihen von Außen- und zugehörigen Binnenpegeln standen jeweils Zeitreihen von 30 Monaten zur Verfügung (vgl. Tab. 2-1). Die Anzahl der im Zeitraum beobachteten Überschreitungen der Binnenpegelschwellenwerte für LU und vLU sowie die nach Gleichung (1) und (2) berechneten Außenpegelschwellenwerte bezogen auf den Pegelnullpunkt (PNP) sind Tabelle 2-3 zu entnehmen. Eine größere Zahl an vLU im Vergleich zu LU (Alt-Langeneß und Nordstrandischmoor) ist auf die Eliminierung der Folgetiden bei der Berechnung der LU Außenpegelschwellenwerte zurück zu führen (vgl. Kap. 2.2.5). Auffällig ist die geringe Varianz von $H_{A\,(LU/vLU)}$, welche oftmals unter 1 % liegt. Die maximale Varianz beträgt 4,6 % für den Außenpegelschwellenwert $H_{A\,(LU)}$ auf Alt-Langeneß (n = 17).

Tabelle 2-3: Außenpegelschwellenwerte $H_{A\ (LU/vLU)}$ bezogen auf den Pegelnullpunkt (PNP) zur Berechnung langjähriger Überflutungshäufigkeiten für Land-Unter (LU) und vollständige Land-Unter (vLU) Ereignisse anhand der den Halligen zugeordneten Außenpegel. (RSD) Variationskoeffizient der angepassten Schwellenwerte. (n) Anzahl der zur Berechnung genutzten Wasserstände am Außenpegel.

	H_A LU	RSD	n	H_A vLU	RSD	n
	cm ü. PNP	%		cm ü. PNP	%	
Hooge	772,7	2,1	13	806,0	0,3	3
Alt-Langeness	740,4	4,6	17	772,7	0,9	15
Nordmarsch	737,0	0,7	14	758,5	0,8	17
Nordstrandischmoor	744,6	0,9	32	761,4	2,1	35

2.3.3 ÜBERFLUTUNGSHÄUFIGKEITEN

Die jährlichen Überflutungsanzahlen der einzelnen Halligen (Abb. 2-5a,b,c,d) sind innerhalb der betrachteten Zeiträume sehr variabel. Sowohl auf Hooge (1979, 1987, 1996, 2003, 2006, Abb. 2-5a) als auch auf Nordmarsch und Alt-Langeneß (1960, Abb. 2-5b,c) gibt es Wasserwirtschaftsjahre ohne Überflutungsereignis. Die bisher sturmflutaktivste Periode mit 14 (Hooge) bzw. 26 (Langeneß) LU pro Jahr ist das WW 1990. Prozentual erreichen auf Langeneß 58 % (Alt-Langeneß) bis 65 % (Nordmarsch) aller LU Ereignisse das Niveau eines vLU mit einer kompletten Füllung der Hallig bis zur mittleren Deichhöhe. Auf Hooge entwickeln sich lediglich 50 % aller Ereignisse zu einem vLU. Das überflutungsreichste Jahr im Beobachtungszeitraum ist das WW 2007 mit 28 berechneten LU auf Hallig Nordstrandischmoor (Abb. 2-5d). Weiterhin erreichen auf Nordstrandischmoor 67 % aller Ereignisse das Niveau einer vollständigen Überflutung (vLU).

Trendanalysen der jährlichen Überflutungshäufigkeiten (9-jähriges gleitendes Mittel) zeigen auf Hallig Langeneß (Abb. 2-5b,c) eine Verdopplung der LU Häufigkeiten von 6 auf max. 12 Ereignisse in dem Zeitraum von Beginn der Pegelaufzeichnungen 1951 bis Mitte der 1980er Jahre. Mit Ende der 1990er Jahre kehrt sich dieser Trend um. Hallig Hooge zeigt eine vergleichbare Trendentwicklung der LU Ereignisse (Abb. 2-5a). Sowohl Zunahme als auch erneutes Sinken der LU Häufigkeiten um den Zeitraum häufiger Überflutungen (1985 – 2000) fallen wesentlich sprunghafter aus als auf Langeneß. Innerhalb einer Zeitspanne von lediglich 5 Jahren (1994 – 1999) fällt das 9-jährige Mittel der Überflutungsanzahlen (LU) von 5 auf 3 Ereignisse pro Jahr. Die mittlere Anzahl der vLU folgt dem Trend der LU im Rahmen der allgemeinen Differenz zwischen

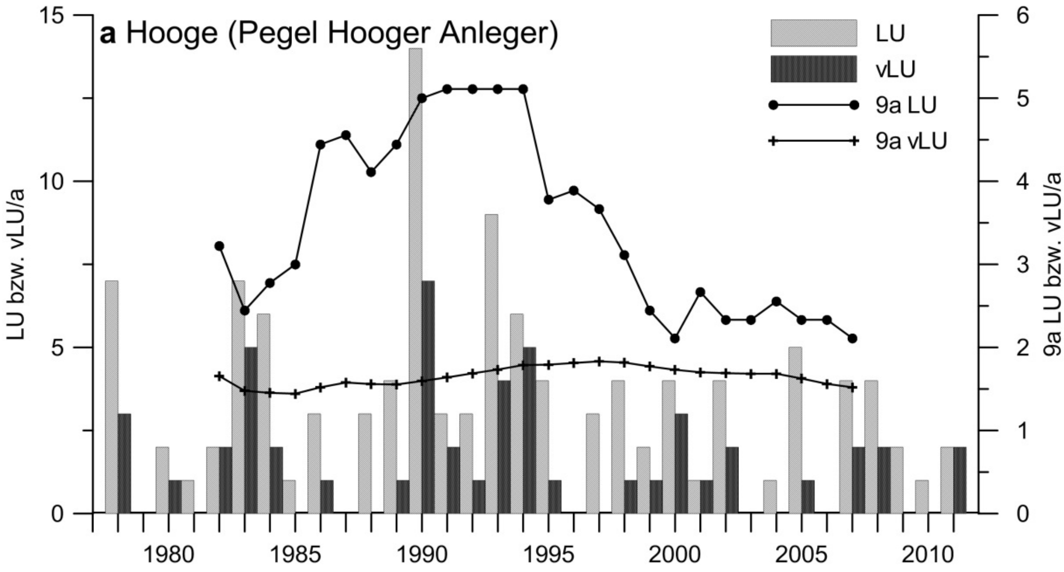

Abbildung 2-5a: Langjährige Überflutungshäufigkeiten der Hallig Hooge. Dargestellt sind sowohl die absoluten jährlichen Anzahlen der Land-Unter (LU) als auch vollständigen Land-Unter (vLU) Ereignisse sowie der Trend anhand des 9-jährigen gleitenden Mittels der jährlichen Anzahlen (9a).

LU und vLU Häufigkeiten. Aufgrund der kurzen Zeitreihe des Pegels Strucklahnungshörn von lediglich 16 Jahren (1995 – 2011) konnte für Nordstrandischmoor keine Trendanalyse der Überflutungshäufigkeiten erstellt werden.

Die Darstellung mittlerer Überflutungshäufigkeiten als 10-jähriges Mittel in dekadischer Form (Tab. 2-4) ermöglicht sowohl einen einfachen visuellen Vergleich der Halligen untereinander als auch den Vergleich mit Referenzwasserständen der Pegelhaupttabellen betreffender Außenpegel. Der Vergleich der Halligen untereinander zeigt eine deutliche Zunahme der Überflutungsanzahlen von Hooge über Langeneß zu Nordstrandischmoor. Während sich die jährlichen Überflutungsanzahlen zwischen Nordstrandischmoor und Alt-Langeneß/Nordmarsch im Zeitraum 2001 – 2010 lediglich um den Faktor 1,5 (LU) bis 2 (vLU) unterscheiden, wurde Nordstrandischmoor im gleichen Zeitraum sieben bis zehnmal häufiger überflutet als Hooge. Auch die dekadische Darstellung der Überflutungshäufigkeiten von Hooge und Langeneß verweist auf eine erhöhte Überflutungsfrequenz während der 1980er und 1990er Jahre. Das dekadische Mittel der höchsten jährlichen Tidehochwasserstände (MHThw) am Pegel Wyk auf Föhr zeigt im selben Zeitraum einen deutlichen Anstieg der Extremwasserstände.

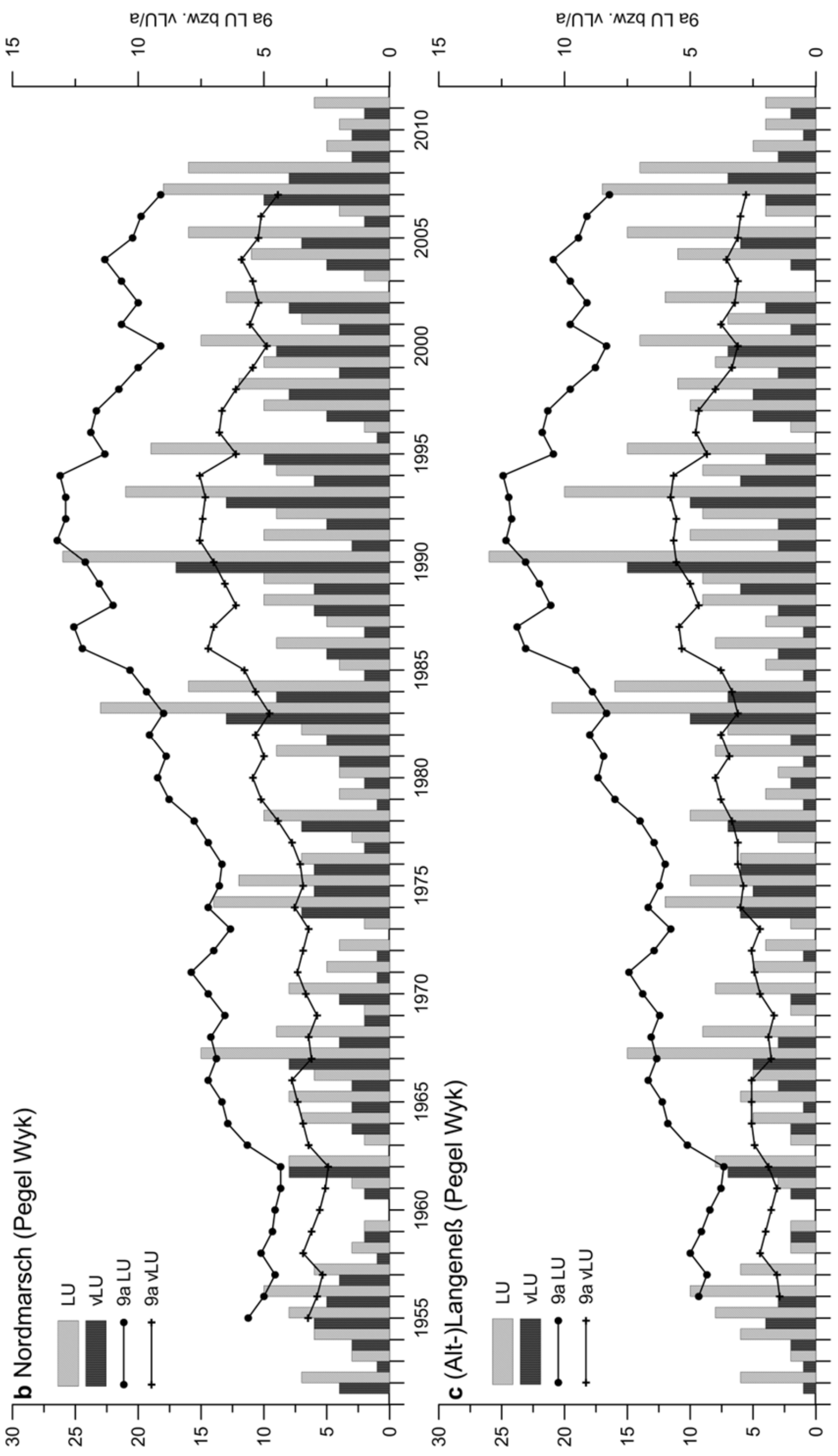

Abbildung 2-5b,c: Langjährige Überflutungshäufigkeiten der Halligen (b) Nordmarsch und (c) Alt-Langeneß. Dargestellt sind sowohl die absoluten jährlichen Anzahlen der Land-Unter (LU) als auch vollständigen Land-Unter (vLU) Ereignisse sowie der Trend anhand des 9-jährigen gleitenden Mittels der jährlichen Anzahlen (9a).

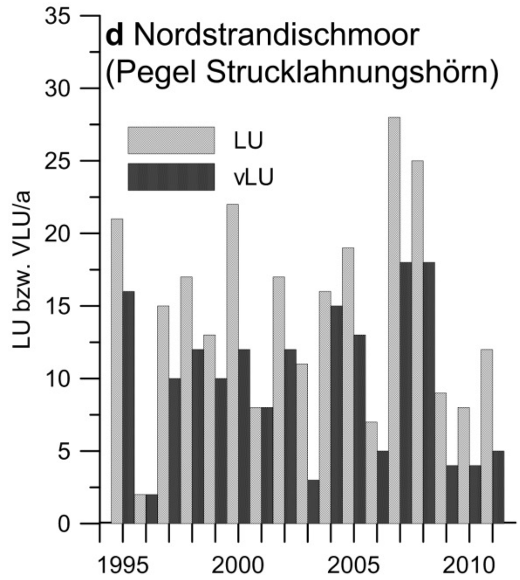

Abbildung 2-5d: Langjährige Überflutungshäufigkeiten der Hallig Nordstrandischmoor. Dargestellt sind sowohl die absoluten jährlichen Anzahlen der Land-Unter (LU) als auch vollständigen Land-Unter (vLU) Ereignisse.

Tabelle 2-4: Dekadische Aufstellung der mittleren jährlichen Häufigkeit von Land-Unter (LU) und vollständigen Land-Unter (vLU) Ereignissen auf den Halligen, sowie des MThw nach der Pegelhaupttabelle (Wyk/Föhr).

	1961 – 1970	**1971 – 1980**	**1981 – 1990**	**1991 – 2000**	**2001 – 2010**
	L.u. (v.L.u.)	L.u. (v.L.u.)	L.u. (v.L.u.)	L.u. (v.L.u.)	L.u. (v.L.u.)
Hooge			4 (2)	4 (2)	2 (1)
Alt-Langeness	6 (3)	6 (5)	11 (5)	11 (3)	9 (3)
Nordmarsch	7 (4)	7 (3)	12 (7)	12 (6)	10 (5)
Nordstrandischmoor					15 (10)
MHThw Wyk (cm NN)	315	308	343	346	312

2.4 DISKUSSION UND SCHLUSSFOLGERUNG

2.4.1 REFERENZHÖHEN UND SCHWELLENWERTE

Das angewandte Verfahren zur Übertragung halligspezifischer Binnenpegelschwellenwerte auf Basis von Referenzhöhen für das Eintreten von LU und vLU Ereignissen auf Außenpegelzeitreihen, welche räumlich entfernt sind, jedoch eine ausreichend lange Zeitreihe zwecks Berechnung mittlerer Eintrittshäufigkeiten besitzen, generiert plausible Ergebnisse. Die beiden Referenzhöhen der mittleren Geländeoberfläche sowie der mittleren Deich- bzw. nicht permeablen

Deckwerkshöhe sind reproduzierbar und auf weitere Standorte übertragbar. Die berechneten Höhen für Hooge und Nordstrandischmoor sind um 2 bis 4 Dezimeter höher als die von Dibbern und Müller-Navarra (2009) publizierten. Somit treten LU und vLU Ereignisse nach dem hier vorgestellten Berechnungsansatz seltener ein.

Bei der Interpretation der Ergebnisse muss weiterhin berücksichtigt werden, dass die Bezugshöhen der Binnenpegelschwellenwerte in der vorliegenden Arbeit als stationär betrachtet wurden. Da der überflutungsabhängige Sedimenteintrag ein stetiges vertikales Wachstum der Marschoberfläche zur Folge hat, müssen die mittleren Geländehöhen zu Beginn der verfügbaren Pegelzeitreihen niedriger als heutzutage gewesen sein. Folge ist eine zunehmende Unterschätzung der Überflutungshäufigkeiten bei Anwendung eines stationären Schwellenwertes mit zunehmendem Alter der Pegeldaten. Suchrow et al. (2012) berechnen das mittlere Höhenwachstum für Salzmarschen entlang der Küste Schleswig-Holsteins für einen 20-jährigen Beobachtungszeitraum mit 0,6 mm/a. Eigene Untersuchungen für die Halligmarschen zeigen höhere Wachstumsraten von 1,0 bis 2,6 mm/a und damit gute Übereinstimmung mit Arbeiten von Schuerch et al. (2012) auf der Insel Sylt (1,0 – 2,8 mm/a). Ebenso liegen keine historischen Informationen bezüglich baulicher Veränderungen an Deichen und Deckwerken sowie möglicher Höhenänderungen selbiger durch Setzung bzw. Kompaktion vor (vgl. Cahoon et al. 1995). Bei künftiger Verwendung lokaler Referenzhöhen wird daher eine regelmäßige Aktualisierung empfohlen, wobei zukünftig ein direkter Bezug zu den seit 2009 auf den Halligen flächendeckend vorhandenen Binnenpegeldaten hergestellt werden kann.

2.4.2 ÜBERFLUTUNGSHÄUFIGKEITEN

Der Zusammenhang zwischen anthropogenen baulichen Maßnahmen (Deich/Deckwerkshöhe) und der jährlichen Anzahl an Überflutungen ist offensichtlich. Mit zunehmender Höhe der äußeren Marschbefestigung (Abb. 2-4) sinkt die jährliche Überflutungsanzahl, da lediglich extreme Witterungsbedingungen mit entsprechendem Windstau und Wellenhöhe ausreichend hohe Tiden generieren, um das Niveau der Deiche/Deckwerke erreichen. Der Außenpegelschwellenwert $H_{A\,(LU)}$ von Hallig Hooge mit einer Höhe von 773 cm ü. PNP am Pegel Wyk entspricht einem Wasserstand von 134 cm ü. MThw am Pegel Hooger Anleger. Er verfehlt damit nur knapp die Marke von 150 cm ü. MThw und damit die offizielle Definition eines Sturmflutereignisses. Der Vergleich der mittleren dekadischen Überflutungshäufigkeiten (Alt-Langeneß und Nordmarsch) mit den MHThw Wasserständen am Pegel Wyk (Tab. 2-4) bestätigt den Zusammenhang zwischen Extremwasserständen und Überflutungshäufigkeit

($R^2 \geq 0,78$; $p < 0,05$; $n = 5$). Ursächlich für Dekaden hoher Überflutungsfrequenz (1981 – 2010) sind vor allem einzelne Jahre (1983, 1990, 1993, 1995; Abb. 2-5b,c) mit überdurchschnittlich vielen Überflutungen aufgrund lang anhaltender Sturmwetterlagen (vgl. Bissolli et al. 2002). Schuerch et al. (2012) beobachten für die Insel Sylt während der 1980er und 1990er Jahre ebenfalls eine Häufung signifikant hoher Wasserstände.

Erste Annahmen bezüglich des Anpassungspotentials der drei Halligmarschen gegenüber einem steigenden Meeresspiegel sind durch die Information zum Niveau der mittleren GOF im Vergleich zum gegenwärtigen MThw möglich (Abb. 2-4). Nordstrandischmoor als Hallig mit den meisten jährlichen Überflutungen liegt im Mittel (37 cm ü. MThw) deutlich höher als Langeneß (Ø 17 cm ü. MThw) und Hooge (Ø 15 cm ü. MThw). Die anthropogen bedingte Reduzierung der jährlichen Überflutungen bedeutet daher zwangsläufig auch eine Reduzierung der Sedimenteinträge und damit ein eingeschränktes Oberflächenwachstum. Andersen und Pejrup (2001) verweisen darauf, dass Sturmfluten mit überdurchschnittlich hohen Wasserständen für das vertikale Wachstum von Tidenmarschen von besonderer Bedeutung seien, da ein beträchtlicher Anteil der jährlichen Sedimentdeposition auf diese unregelmäßigen Ereignisse zurück zu führen ist. Eigene Untersuchungen bezüglich der Höhenentwicklung der drei betreffenden Halligen zeigen jedoch, dass bereits seit Mitte des 20. Jahrhunderts eine Diskrepanz zwischen vertikalem Marschwachstum und Meeresspiegelanstieg besteht (Schindler et al. 2014b). Auch kleinere Überflutungsereignisse scheinen somit von Bedeutung für ein ausreichendes vertikales Wachstum zu sein. Wird der Rückhalt des Überflutungswassers durch Deiche und Sieltore bei der Berechnung der realen Überflutungshäufigkeiten übergangen und die mittlere GOF direkt als Schwellenwert für ein LU verwendet, so steigt deren Häufigkeit für Hallig Hooge auf mehr als 100 Ereignisse pro Jahr. Diese „potentiell natürliche“ Häufigkeit eines LU Ereignisses wäre somit für den Zeitraum 2001 – 2010 um den Faktor 50 höher als in dieser Studie berechnet. Es scheint daher angebracht, das bestehende hydrologische Management sowie die vorhandenen Deiche und Deckwerke neu zu überdenken und zu prüfen, ob eine moderate Erhöhung der jährlichen Überflutungsanzahlen zur langfristigen Sicherung der Halligen beitragen kann. Permeablen Rauhstreifen (Hallig-Igel) wäre bei der Konzeption neuer Schutz- und Bewirtschaftungsstrategien aus sedimentologischer Sicht der Vorzug zu geben.

DANK

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CHAPTER 3 MEASURING SEDIMENT DEPOSITION AND ACCRETION ON ANTHROPOGENIC MARSHLAND – PART I: METHODICAL EVALUATION AND DEVELOPMENT

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ACCEPTED FOR PUBLICATION IN ESTUARINE, COASTAL AND SHELF SCIENCE

ABSTRACT

The North Frisian Halligen (Northern Germany) are inhabited and highly anthropogenic modified coastal marshlands. Today a lack of knowledge about sedimentological parameters prevent for a predicated discussion on their adaptation capacity to recent and future sea-level changes. A combined field and laboratory method to calculate marshland accretion rates based on short-term (2010 – 2013) measurements of sediment depositions was developed. All studies were carried out at the marshlands of the Halligen Hooge, Langeness and Nordstrandischmoor. One litre LDPE bottles and small synthetic turf mats were used as simple but coast, time and quantity efficient sediment trap devices. Up to a deposition rate, of ~ 2.0 kg/m^2, both devices gained comparable results. Above this threshold the retention efficiency of the turf mats is decreasing compared to the LDPD bottles. The combined use of bottles and mats, especially when deposition rates are not exceeding the threshold, allows to (1) checking internal consistency of the data, (2) detecting outliers with respect to cattle- or man-made damage, and (3) estimating possible effects of post-storm sediment remobilization. To transfer sediment depositions into rates of vertical accretion, the bulk dry density as well as the organic matter concentration of the correspondent marsh soil was considered using data from shallow percussion cores. These parameters are different among all Halligen. Higher inundation frequencies cause lower soil organic matter concentrations, resulting in higher bulk dry densities (BDD) of the soil (Hooge 0.64 g/cm^3, Langeness 0.67 g/cm^3, Nordstrandischmoor 0.83 g/cm^3). Autochthonous organic material (by source of the marshland vegetation) contributes by 9.0 ± 1.4 % (Hooge) to 21.4 ± 6.6 % (Nordstrandischmoor) to marshland accretion, for a correspondent time scale of 1915 to 2011. Average accretion rates (2010 – 2013) were calculated with 1.2 ± 0.8 mm/a for Langeness, 1.5 ± 0.9 mm/a for Hooge and 2.6 ± 0.9 mm/a for Nordstrandischmoor.

Keywords: Halligen; salt marsh; sedimentation; surface elevation change; vertical accretion; sediment trap

3.1 INTRODUCTION

The adaptation of tidal environments, especially of salt marshes due to a changing hydrographical environment has been recently discussed by various studies (Craft et al. 1993, Allen 2000, D'Alpaos et al. 2007, Kirwan and Guntenspergen 2010, Andersen et al. 2011, Schuerch et al. 2012, Spencer et al. 2012, Suchrow et al. 2012). Just as much data exists about salt marsh accretion in relation to recent and future sea-level changes (van Wijnen and Bakker 2001, Morris et al. 2002, French and Burningham 2003, Bartholdy et al. 2004, Kolker et al. 2009, Kirwan et al. 2010, D'Alpaos et al. 2011, Schuerch et al. 2013). Nevertheless, most of these studies were examining natural or semi natural tidal marshlands, which have to be distinguished from the marshlands of the North Frisian Halligen. At the beginning of the 20th century, massive coastline protection constructions like revetments and shallow dykes turned the Halligen into an "anthropogenic" marshland. The consequence of these measures was a decrease of the inundation frequency and changes in the sediment availability and distribution.

The present study, presents the first part of two coupled papers about short- to long-term sediment deposition and marshland accretion on the Halligen, dealing with the development and evaluation of field methods to measure the annual sediment deposition and vertical accretion on those anthropogenic marshlands. In detail two reasons forced us to conduct additional methodological research on this topic. (1) The infrastructural conditions of the Hallig marshland as well as the temporal limitation of a three year lasting research project revealed the need for a transportable and easy to handle sediment trap, which could be used in high quantity. Long-term measurement devices for a direct measurement of accretion rates like sedimentation-erosion tables (SET) or bars (SEB) (Cahoon et al. 2000, 2002a, 2002b, van Wijnen and Bakker 2001) as well as sedimentation plates (French and Burningham 2003), which provide reliably results only after decades could not be used during the present study. (2) Previous studies have shown that the organic content of flood related sediment depositions on coastal marshlands is highly variable (Craft et al. 1993, Neubauer 2008) as well as the content of soil organic material with regard to increasing soil depth and time (Bartholdy et al. 2010b). Hence, it is essential for the calculation of long-term vertical accretion rates based on annual, short-term sediment depositions (see chapter 3.2, definition of terms), to know the proportion of organic to clastic sediment contents both of flood sediments and the correspondent soil. For the calculation of vertical accretion from deposition rates we developed a new approach which has not discusses so far.

With regard to those presettings, the main objective of the current study is to (1) test if one litre LDPE bottles in combination with synthetic turf mats could be used as simple but suitable sediment traps to measure short-term sediment deposition rates and (2) to evaluate if the deposition data could be used to calculate long-term accretion rates instead of using direct methods like SEBs/SETs and plates.

The second paper "Measuring sediment deposition and elevation change on anthropogenic marshland - Part II: The case of the North Frisian Halligen" deepens a discussion about marshland accretion, its spatial distribution patterns and the adaptation capacity of the Halligen Hooge, Langeness and Nordstrandischmoor to recent sea-level change based on the dataset conducted by methods introduced in the first paper. The measurement of annual short term sediment deposition (2010 to 2013) is complemented by a ^{210}Pb and ^{237}Cs dating campaign on 12 percussion cores of these Halligen.

3.2 DEFINITION OF TERMS

Commonly the term "sedimentation" is widely used when referring to different processes leading to surface adjustment in tidal environments. In this study we adapted the terminology of Cahoon et al. (1995) and van Wijnen and Bakker (2001), which lately was supplemented by Nolte et al. (2013). Terms are (1) suspended sediment concentration (SSC) in mg/l, (2) sediment deposition in g/m^2 or kg/m^2, (3) vertical accretion and (4) surface-elevation change calculated in mm/a. Concerning the adaptation of a tidal salt marsh to a rising sea-level the term sediment deposition refers to the amount of accumulated material whereas vertical accretion and surface elevation change refers to differences in elevation, based on a reference height. "Accretion" considers changes related to a local fix point or reference layer. "Elevation change" always provides absolute values in reference to a local ordnance datum (Nolte et al. 2013).

3.3 STUDY AREA

The Halligen are located onto the tidal flats of the North Frisian Wadden Sea in front of the federal state Schleswig-Holstein, Germany (fig. 3-1). Hallig Langeness and Hallig Hooge are the biggest Halligen with an area of 9.2 km^2 and 5.5 km^2 respectively. At the beginning of the 20th century, Hooge and Langeness were encompassed with a shallow "summer" dyke (Müller and Fischer 1917) with an average height of 1.0 m (Langeness) to 1.5 m (Hooge) above the present 10 year average mean high water (MHW) of 2001 to 2010. The channel systems were straightened and equipped with gates/sluices closing automatically by rising tides. Therefore inundation of the marshland occurs only during heavy, westerly storm conditions, mostly at the winter season from October to March. The 10 year averages (2001 – 2010) were 2 events per year (Hooge) and 10 events per year (Langeness) (Schindler and Willim 2014).

Today the marsh platforms are elevated ~ 0.15 m (Hooge) and ~ 0.17 m (Langeness) above MHW. The about 300 residents live on 26 artificial dwelling mounts, so called “Warften”, to protect themselves and their goods against storm surges. The small Hallig Nordstrandischmoor (1.6 km^2) is located eastward of the island Pellworm, close to the dyked mainland coast. In contrast to Hooge and Langeness, the marshland was not encompassed by a dyke. Only revetments and water permeable rubble breakwater prevent the marsh against further erosion and migration, resulting in a high inundation frequency, with 15 events per year (2001 – 2010) (Schindler and Willim 2014). The marsh platform is located 0.37 m above MHW. A bulk of livestock is only accommodated for the summer season and shipped back to mainland in autumn.

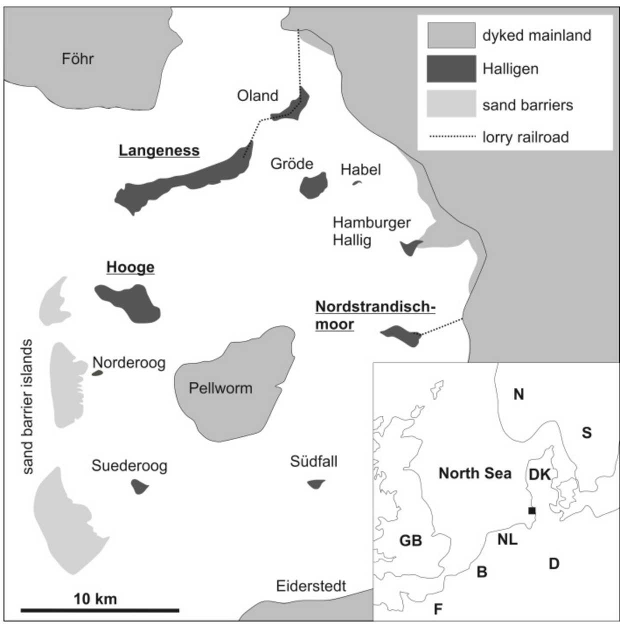

Figure 3-1: Location map showing the most northern region of the German Wadden Sea between the islands of Eiderstedt (south) and Föhr (north). The three Hallig marshlands, correspondent to this paper are labelled in bold. Outline map of the North Sea Region: N=Norway, S=Sweden, DK= Denmark, NL= Netherlands, D=Germany, B=Belgium, F=France, GB=Great Britain, black rectangle= study area.

3.4 METHODS

3.4.1 SEDIMENT TRAPS

Active field work at the anthropogenic marshland of the Halligen is limited to the stormy winter season from October to March. Further specific frame conditions are harsh weather which has the ability to damage or influence permanent installations by ground frost, wave action with ice drift as well as driftwood. For that purpose two different types of sediment traps seemed to be feasible: (1) Containers buried into the ground or pending above the surface or (2) flat boards or mats that are evenly fixed to the marsh surface. For the practical field test, we decided for a combination of one litre LDPE bottles, further named trap type A and PE-synthetic turf mats (20 x 30 cm), further named trap type B (fig. 3-2). Trap type A (bottle) is 9.5 cm in diameter, 20 cm high and has a narrow opening of 5.0 cm in diameter. Trap type B (mat) consists of straight and curled PE-blades with a length of 21 mm, stitched irregular onto a gauze which is rubber coated at the bottom side. Both types of blades together are building a rather dense surface. The structure of the mat seems to be similar to those of Steiger et al. (2003) who reviewed a variety of flat sediment trap devices and finally recommended synthetic turf mats for use at riparian zones and flood plains.

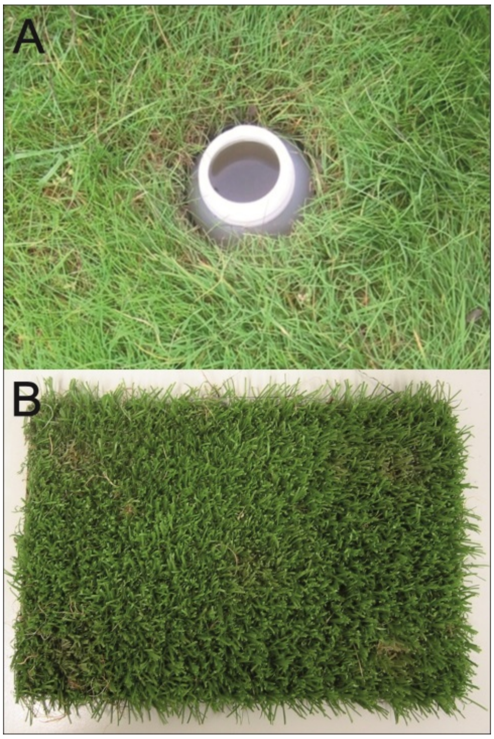

Figure 3-2: Field devices used to sample inundation sediments. (A) One litre LDPE-bottle buried in the marsh soil. (B) Mat of synthetic turf, fixed with steel nails onto the ground.

3.4.2 SEDIMENT SAMPLING CONFIGURATION

Traps type A were filled with brackish water from adjacent ditches before being inserted into the ground to avoid a lifting of the bottle when seawater is flooding the marsh plain. Holes were made with a soil sampler of the same diameter as the bottle and the depth was adjusted in a way that the bottleneck protruded approximately 3 cm above the surface. Traps type B were fixed with five steel nails onto the surface. Both traps were arranged side by side in a regular grid of approximately 400 x 400 m over the whole area of each of the investigated Halligen (fig. 3-3). Due to the individual size and shape of the Halligen, 61, 36 and 12 locations (Langeness, Hooge, Nordstrandischmoor) were equipped with the described combination of trap type A and B. For each trap location the GPS position was recorded. All sampling devices were installed in the field at the beginning of the stormy season in October. Their removal had to be completed before the bird breeding season that started in early April. In between the sampling devices remained untouched for the sampling of all storm surge events, i.e. they record the cumulative sediment

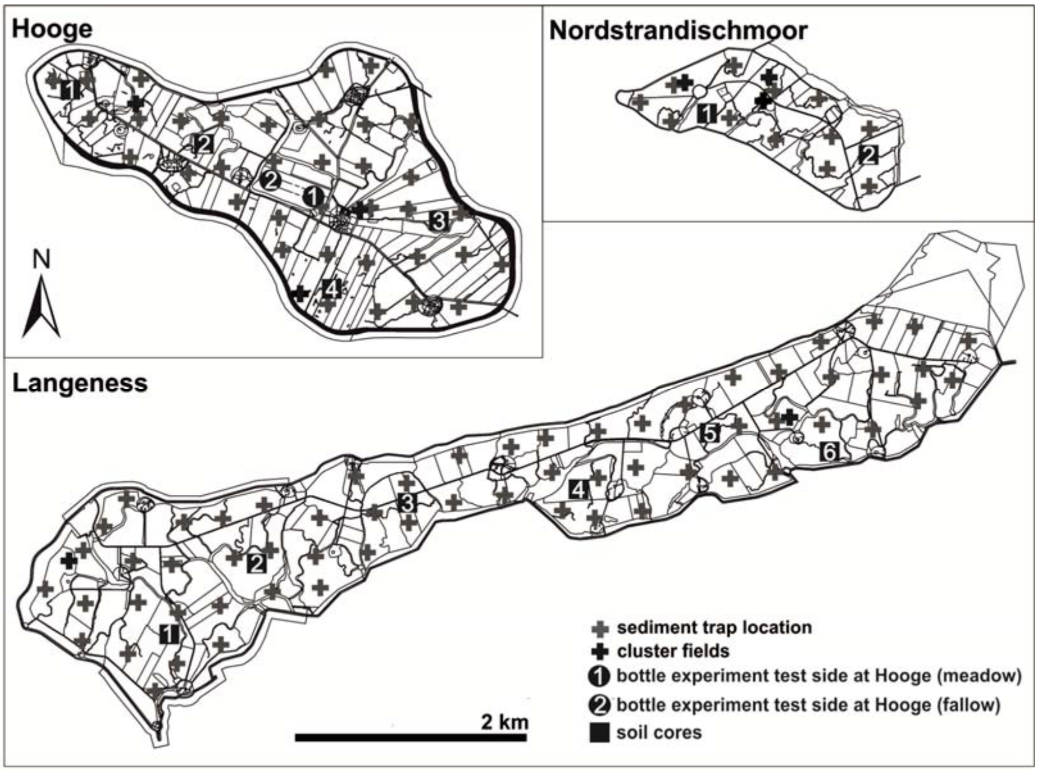

Figure 3-3: Location map showing the positions of regular sediment traps (dark grey crosses), different test sites to validate bottles and mats as sediment traps (numbered black dots) and coring positions (numbered black rectangles). In total 61 (Langeness), 36 (Hooge) and 12 (Nordstrandischmoor) grid positions of a sediment trap combinations A and B, three experimental test sites (Hooge) and 12 coring locations (2 Nordstrandischmoor, 4 Hooge, 6 Langeness) were established.

deposition of the complete winter season which we consider as representative for one calendar year (There are almost no inundations during spring and summer). During the following years, the same positions based on GPS accuracy were used.

3.4.3 METHODOLOGICAL INVESTIGATION ON SEDIMENT TRAPS

To validate the measurement devices for the purpose of calculating areal sediment depositions at the Hallig marshland, we performed methodological investigations on their general sediment sampling efficiency and how that efficiency might be affected by external factors. In detail the following investigations were performed within the project period.

Installation protrusion depth of trap type A

For trap type A the effect of different installation protrusion depths (1, 3, 5, 7, and 9 cm difference between top of the bottle and Hallig surface level) on sediment trap efficiency was tested to evaluate a possible error resulting from an improper installation. Each depth was tested with three replicates. Bottles were placed with a lateral distance of 50 cm to each other. This experiment was performed during a single storm surge event in winter 2011/12 at two different locations at Hallig Hooge. Location 1 was a short grazed meadow and location 2 a young fallow.

Efficiency of trap type A versus B

A variety of different sediment trap devices; containers, funnels as well as mats and flat boards; have been tested under field and/or laboratory conditions (Mansikkaniemi 1985, Bloesch and Burns 1980, Gardner 1980a, 1980b, Steiger 2003). Well knowing that it would be impossible to evaluate the exact sediment trapping efficiency of a sediment trap under the rough and inhomogeneous field conditions of the Halligen, we decided not to rely on only one trap type. The simultaneous use of two trap types; bottles and mats; offers the opportunity to rate their relative sediment sampling and retain capacity in comparison to each other.

Small scale variability of sediment deposition rates

Additional six cluster (two per Hallig and year, fig.3-3) each composed of five sediment traps type A and B were established to gain knowledge about the small scale variability of sediment deposition rates in contrast to the 400 x 400 m grid. The traps were arranged crosswise with a distance of 10 m to each other.

3.4.4 THE ROLE OF ORGANIC MATTER AND BULK DRY DENSITY

To translate sediment deposition into vertical accretion on a longer time perspective, information about alteration of inundation sediments towards soil material are inevitable. Variations of bulk dry density (BDD) and the content of organic matter are important soil parameters in this respect. A total of 12 percussion cores (6 at Langeness, 4 at Hooge, 2 at Nordstrandischmoor) with depth of 74 to 100 cm are available for the Hallig marshlands (fig.3-3). Cores were taken by driving plastic tubes (10 cm diameter, 120 cm length) into the soil.

3.4.5 PROCESSING THE TRAPPED SEDIMENT

Trap type A (bottles)

The samples inside trap type A (bottles) are a mixture of water, sea-salt, clastic material, small organic particles and huge organic compounds like blades of grass. To remove water and salt and to quantify the amount of clastic material and organic particles, all samples were treated either by filtration or dialyses method. After decantation, the sample is transferred by use of a funnel into the filtration device (vacuum or high pressure, ashless cellulose paper of 100 mm in diameter, 12 to 15 µm porosity) or dialyses tubes (molecular mass of 10000 to 20000 Dalton). Grass and flotsam is removed by a sieve (e.g. mesh size of 2.0 mm). The removal of salt was achieved by leaching the filter residual with deionized water or purging the dialyses bath until conductivity reached values < 300 µS/cm. The remaining moisture was removed by drying at 105 °C.

To determine the organic matter content the loss on ignition (LOI) method was used (German Norm 19684-3 2000, Kuntze et al. 1994). The heating time was low as 425 °C for 2 hours to minimize crystallization water losses, which could result in an overestimation of organic matter (Leong and Tanner 1999, Barillé-Boyer et al. 2003).

Trap type B (mats)

To quantify the total mass of solids (Ms) on trap type B, these were dried at temperatures which do not exceed 80 °C. Above theses temperatures the PE material of the mat is losing strength. Afterwards the dry mats are weighted, thoroughly cleaned using a high-pressure cleaner and weighted again. Due to the cleaning process, sediments are not kept but washed away. Therefore the organic matter could only be analyzed for trap type A sediments. Organic matter values for trap type B are calculated using the value of the adjacent trap type A. Further on, the data of each sample location were checked for outliers by comparing sediment deposition values of trap type

A and B. Extreme ratios indicate that sediment mass of either bottle or mat must have been influenced by external factors like grazing livestock or human intervention. Outliers were detected statistically via Grubbs and IQR test.

Soil sediment samples

The upper 25 cm of the core was cut in increments of 1 cm. For depth > 25 cm, the increment size was increased to 5 cm. BDD was analyzed gravimetrically by drying the soil material at 105 °C until no further change in weight was recognized. Afterwards the samples were pulverized by a motor grinder (Fritsch pulverisette, type 02.102). The determination of the organic matter content was also done by the LOI method. BDD and LOI values with respect to soil depth (fig. 3-6) were calculated as average values on the available sediment cores (Langeness n = 6, Hooge n = 4, Nordstrandischmoor n = 2). Depths were corrected by the compaction factor, resulting from percussion coring. This was calculated as the ratio between the length of the core liner (driven into the soil) and the length of the soil column within the liner.

Statistical evaluation

To test the different data collectives, the t-test for independent samples ($\alpha = 0.05$) was used as well as linear regression analyses. All statistical evaluations were performed by the software packages SPSS Statistics 17.0 (SPSS, Inc.) and Grapher 8.8 (Golden Software, Inc.).

3.5 RESULTS AND DISCUSSION

3.5.1 SEDIMENT TRAPPING AND CALCULATION OF SEDIMENT DEPOSITION RATES

A first advantage, which showed up clearly during practical use, is the durability of both trap types under harsh environmental conditions. They are easy to handle and light what is advantageous especially on wide marshlands where transportation by backpack is the only choice to reach remote places on a pathless terrain.

Installation protrusion depth of trap type A

Sediment trapping efficiency of trap type A (bottle) is not sensitive for different installation depth. At the meadow, the apparent trend for lower sediment accumulation rates due to an increase of the bottle neck protrusion could statistically not been proven ($p > 0.05$) (fig. 3-4). For the young fallow, the inclination of the regression line is almost zero ($y = 0.0003$). The highest relative standard deviation (RSD) for 3 data points of equal height is 9.4 % at the meadow and 21.8 % at the fallow. These deviations are not related to different organic matter concentrations which have nearly constant values of 10.7 ± 0.8 % at the meadow and 11.5 ± 2.5 % at the fallow but could be related to an inhomogeneous surface due to the higher fallow vegetation effecting the spatial sediment deposition. The overall sediment accumulation (fig. 3-4) is three times higher at the meadow, compared to the fallow. These variations could also be related to differences in elevation and therefore inundation height. The average elevation of the fallow is about 0.5 m higher than the meadow.

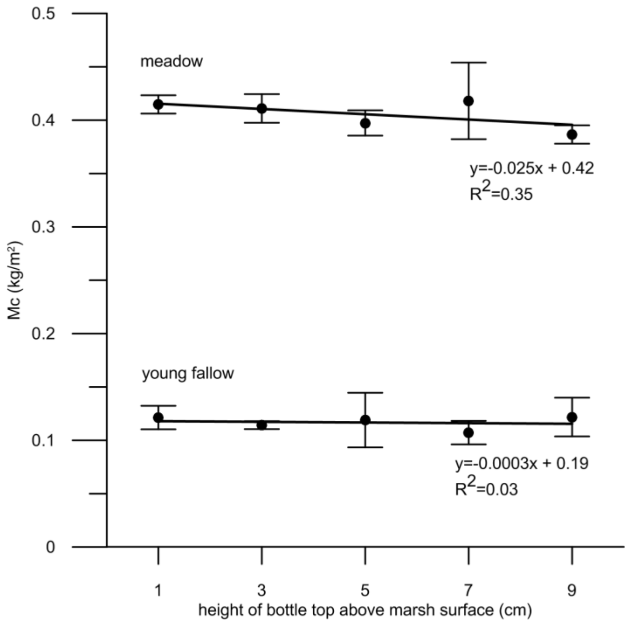

Figure 3-4: Results of the field experiment on different installation depth (1, 3, 5, 7, 9 cm) of trap type A (bottle) are shown. Each installation depth was replicated three times per location (meadow and young fallow). Error bars are presenting the standard deviation of average deposition values. All values are calculated on clastic/mineral contents (Mc) of the sample.

Sampling efficiency of trap type A versus B

A general advantage of trap type A is that sediment, collected by the bottle, can easily be removed from the trap and is available for further compositional analysis. The aspect ratio of the bottle (4.0) should be adequate for stream currents which are expected to be moderate during flood events on the Hallig marshland. Recommendations for the aspect ratio are ranging from 2 to 3 (Gardner 1980a, 1980b) to > 5 (Bloesch and Burns 1980). Trap type B does not offer the ability to maintain the complete mass of sediments for further analyses, but the structure imitates the vegetation of the Hallig quiet well, being mostly a short grazed meadow. Figure 3-5 illustrates sediment deposition rates calculated by trap type A in comparison to rates calculated on trap type B. For trap type B we simply used the extend of the mat (600 cm^2).

For trap type A the base diameter (70.88 cm^2) instead of the opening width (19.63 cm^2) was used to calculate sediment deposition rates.

According to Bloesch and Burns (1980), this makes data, collected by use of container shaped trap devices with narrow openings well comparable to cylindrical trap devices of the same diameter, which are recommended to have the best accuracy under turbulent conditions (Bloesch and Burns 1980, Gardner 1980a). The 2nd degree polynomial fit to the data collective (R^2 = 0.86) of trap type A versus B values (fig. 3-5) reveals that both data seem to follow the 1:1 line until the calculated deposition rates exceed ~ 2.0 $kg/m^2/a$. Above this threshold, the amount of sediment on trap type B (mat) seems to fade, whereas the capacity of tap type A is unaffected by sedimentation rates exceeding the threshold. A linear regression of the data below 2.0 $kg/m^2/a$ ($y = 0.96x + 0.02$, $R^2 = 0.75$, $p \leq 0.01$) is very close to the 1:1 line suggesting, that both devices result in equal rates. Nevertheless, no significant statistical differences of trap type A and B mean values > 2.0 $kg/m^2/a$, could be proven. The annual sediment deposition values for the three correspondent Halligen are summarized in table 3-1. The highest variation between trap type A and B values is calculated for the season of 2011 to 2012 on Nordstrandischmoor where deposition rates with 3.2 ± 0.7 (type B) to 4.3 ± 1.5 $kg/m^2/a$ (type A) are clearly exceeding the 2.0 kg/m^2 threshold.

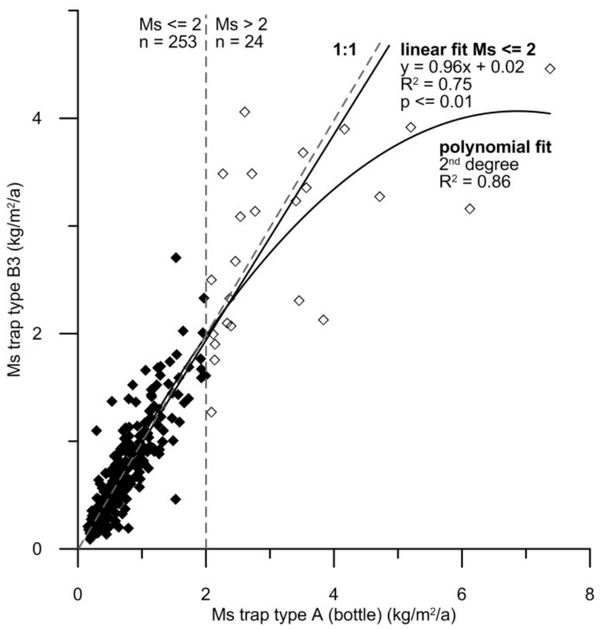

Figure 3-5: Comparison of yearly sediment deposition rates (Ms, $kg/m^2/a$) calculated by trap type A (bottle) and B (mat) on the individual extend of the trap device, being 70.88 cm^2 for the bottle base and 600 cm^2 for the mat. The 2nd degree polynomial fit describes the data collective best. The dashed horizontal line divides the data collective by a trap type A > 2.0 kg/m^2 threshold. The linear regression for bottle and mat data below 2.0 kg/m^2 is close to the 1:1 line.

Table 3-1: Total mass (Ms_{trap}) of inundation sediments of the three winter seasons of 2010 to 2013, collected by trap type A and B (bottle and mat) as well as LOI as a proxy for soil organic matter. LOI is available only for trap type A. The number of samples of trap type A/B differs from the total number of observation points (Hooge 36, Langeness 61, Nordstrandischmoor 12). This is due to losses of trap devices in the field or outliers that were left out.

Hallig	**season**	**trap type**	**n**	**Ms_{trap}** (kg/m^2)	**LOI_{trap}** (% Ms_{trap})
Hooge	2010 – 2011	A	34	0.5 ± 0.3	8.0 ± 9.0
		B	35	0.4 ± 0.4	
	2011 – 2012	A	33	1.2 ± 0.7	13.7 ± 3.5
		B	34	1.2 ± 0.8	
	2012 – 2013	A	33	0.8 ± 0.3	11.8 ± 2.6
		B	30	0.8 ± 0.4	
Langeness	2010 – 2011	A	53	0.6 ± 0.4	7.0 ± 2.3
		B	58	0.5 ± 0.4	
	2011 – 2012	A	57	1.1 ± 0.6	11.9 ± 3.6
		B	57	1.2 ± 0.7	
	2012 – 2013	A	54	0.6 ± 0.3	10.9 ± 3.4
		B	56	0.7 ± 0.5	
N. Moor	2010 – 2011	A	12	1.4 ± 0.8	5.7 ± 2.0
		B	–	–	–
	2011 – 2012	A	11	4.3 ± 1.5	10.5 ± 2.0
		B	12	3.2 ± 0.7	
	2012 – 2013	A	10	1.5 ± 0.5	9.3 ± 3.4
		B	10	1.4 ± 0.5	

Previous surveys, which only focused on a single category of sediment traps (flat devices) and finally recommend synthetic turf mats as suitable (Mansikkaniemi et al. 1985, Steiger 2001) were not able to address the topic of sediment trap efficiency compared to sediment load and flood duration, which showed up by using different devices in a comparative field study. Two reasons for a fading efficiency of type B by higher deposition rates seem to be feasible: (1) The overall sediment load capacity is much lower than for trap type A, decreasing the trapping efficiency at deposition rates exceeding ~ 2.0 kg/m^2. (2) Sediment is lost by remobilization effects due to a high storm surge frequency (like in 2011 – 2012). Mansikkaniemi et al. (1985) tested different structured plywood boards with and without bristles to capture sediments in river flood plains. They observed no significant difference in the trapping efficiency between the different trap types. Therefore we argue that the mat structure does not primarily control the sediment trapping efficiency but is important to retain accumulated sediments for longer time periods after an inundation event.

Employing those results of the comparative study, it is still not possible to quantify if trap type A and B data is overestimating or underestimating the natural sediment deposition rates. But it shows that it could be advantageous to apply more than one single method to reveal where consistent results could be achieved and where further uncertainties have to be considered. Therefore it further seems appropriate to calculate deposition rates on trap type A and B mean values. Furthermore the combined use of two devices allows to detect outliers with are not resulting from a fading sediment retention capacity of a trap device, but from cattle- or man-made damage.

Small scale variability of sediment deposition rates

Results of the methodological tests to determine the small scale sediment deposition variability by use of sediment traps type A and B are shown exemplarily for cluster field no. 1 at Hallig Langeness (tab. 3-2). The average deposition rates of the 10 x 10 m cluster are comparable to the Hallig in total. The RSD values for the cluster vary from 4.2 to 5.4 %. Compared to the Hallig in total, RSD values with 56.8 to 81.9 % clearly exceed those of the small scale cluster area. Those results are comparable with all cluster fields on different Halligen. Therefore we argue that the sediment traps type A and B are appropriate to display also small spatial differences in sediment deposition values.

Table 3-2: Average clastic sediment deposition on the 5 trap A and B cluster fields (10 x 10 m) no. 1 at Hallig Langeness (2010 – 2013) in comparison to deposition values of the Hallig in total. RSD as well as min- and max-values provide information about the small to large-scale spatial variability of sediment depositions.

Langeness cluster 1	**2010 – 2011**		**2011 – 2012**		**2012 – 2013**	
	Mc_{trap} A+B (kg/m^2) cluster	Mc_{trap} A+B (kg/m^2) Hallig	Mc_{trap} A+B (kg/m^2) cluster	Mc_{trap} A+B (kg/m^2) Hallig	Mc_{trap} A+B (kg/m^2) cluster	Mc_{trap} A+B (kg/m^2) Hallig
average	0.3	0.4	0.9	1.0	0.7	0.6
RSD	5.4	81.9	5.4	56.8	4.2	61.8
min	0.3	0.1	0.8	0.4	0.7	0.2
max	0.3	2.0	1.0	3.3	0.7	2.0

3.5.2 SOIL ORGANIC MATTER AND BULK DRY DENSITY

Soils of the Hallig marshlands are young ground water affected Gleysols (IUSS Working Group, WRB 2006) with a strong brackish character. BDD and LOI contents of the soils are highly variable by depth (fig. 3-6). Within the upper 20 to 30 cm, BDD values are lowest at the surface and increase with depth from < 0.5 g/cm^3 to > 1.0 g/cm^3. The organic matter content; represented by the LOI; decreases inversely to BDD from top to bottom. LOI values at the surface are higher on Hooge and Langeness (> 30 %) than on Nordstrandischmoor (> 15 %). Because of the highly significant relationship between LOI and BDD data (fig. 3-6) (regression analysis, R^2 = 0.93, $p < 0.001$), we suppose decomposition of organic matter to be the main driving factor for soil consolidation in the upper most marsh soil (< 100 cm). Bartholdy et al. (2010b) reported similar observations for comparable silty marsh clays of barriers at the Danish Wadden Sea. In detail they were able to describe the curve progressions of BDD and LOI for the upper most 0.5 m by logarithmic functions. Because of the similarities of those findings to our data, we consider those results to be typical for tidal salt marsh soil of the Wadden Sea region. Below 30 cm BDD and LOI values of the Hallig marsh soils show only slight variations. LOI values are more or less constant with ~ 4 to 5 %. Now considering the crystallization water error of the LOI method, the organic matter content of the deeper soil column (> 30 cm) is approximating zero.

To prove a relationship between soil organic matter accumulation, BDD and hydrographical parameters at different Halligen, a marker horizon which enables to compare sediment sections of the same age has to be defined. Due to Müller and Fischer (1917) it could be ensured that at the latest in 1915 the broad installation of coastline protection constructions (block revetments, tidal gates and in some cases summer dykes) was started at the correspondent Halligen. Anticipating results of the ^{137}CS and ^{210}Pb dating campaign, which is discussed in the second paper (Schindler et al. 2014b), the year 1915 corresponds to soil depth of 10.8 ± 1.6 cm (Hooge), 12.0 ± 2.6 cm (Langeness) and 24.9 ± 0.7 cm (Nordstrandischmoor) (tab. 3-3). The decrease of BDD as well as the increase of LOI for sediments deposited after 1915 could be an indication for a rapid change in inundation frequency. The comparison of the average LOI (LOI_{soil}) and BDD values of the “anthropogenic” marsh soil layers younger than 1915 with the average 10 year inundation frequency (tab. 3-3), shows higher organic carbon accumulation and lower BDD than more regular flooded marshlands. Higher rates of organic matter accumulation within the upper soil seem to be related to less organic litter which is removed of the marsh surface due to an irregular flooding. As shown in table 3-3, there is a striking inverse order regarding the inundation frequency and corresponding LOI values at the Halligen.

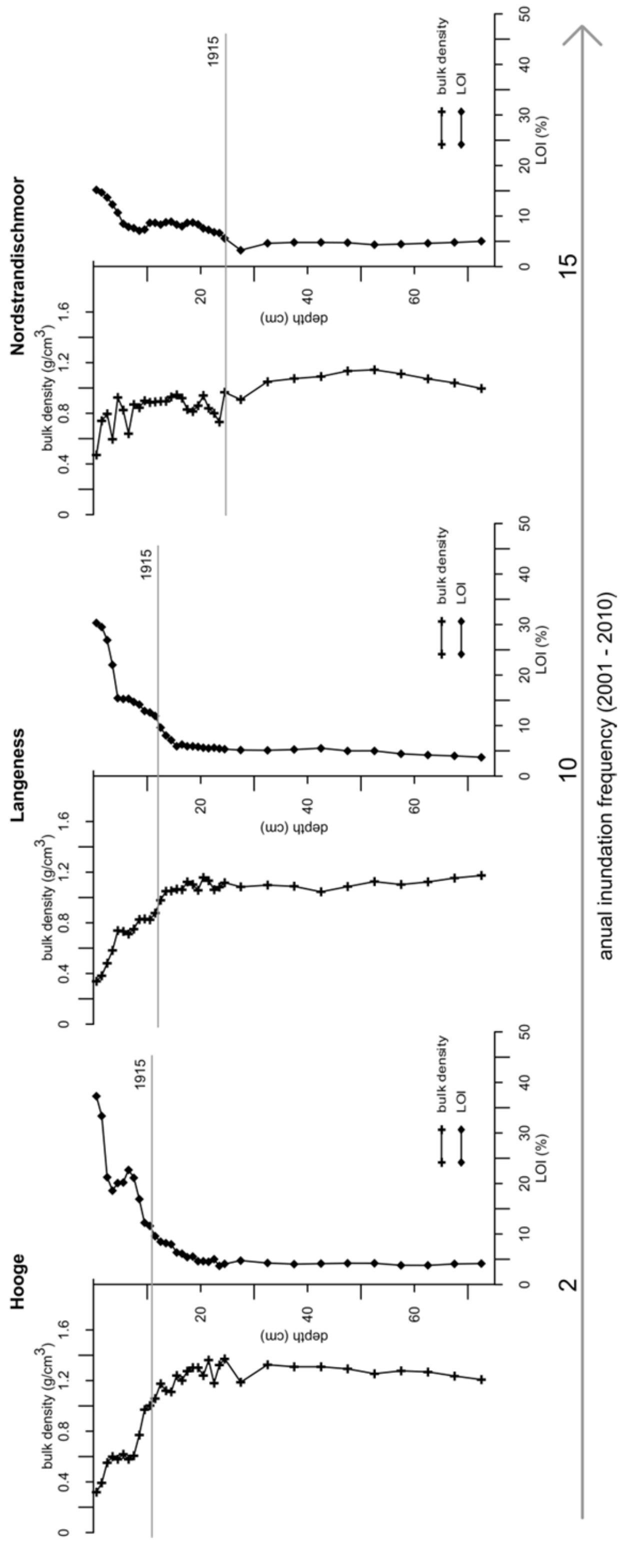

Figure 3-6: Average BDD and LOI as proxies for soil organic matter are shown for marsh soils of Hooge (n = 4 sediment cores), Langeness (n = 6 sediment cores) and Nordstrandischmoor (n = 2 sediment cores). Cores were taken in 2011. The vertical resolution is 1 cm for the upper most 25 cm and then increased to 5 cm. Note that LOI values tend to slightly overestimate organic matter contents. The age of 1915 labels the change over from a semi natural to an anthropogenic salt marsh.

Those observations are in accordance with Craft et al. (1988, 1993) who first mentioned the interdependency between inundation frequency and organic matter accumulation. Even though all three Halligen are flooded only a few times per year due to storm events, a higher inundation frequency results in an increase of the BDD and a decrease in soil organic matter accumulation. Whereas slight variations of "post coastline construction" BDD and LOI of Hooge and Langeness do not have statistical significance (t-test for independent samples), variations between Nordstrandischmoor and Hooge as well as Nordstrandischmoor and Langeness are significant ($p \leq 0.05$). The Soil parameters of sediments older than 1915 ("pre coastline construction") indicate for high BDD values > 1.0 g/cm^3 and invert organic matter concentrations that approach zero.

3.5.3 TRANSFORMATION OF DEPOSITION RATES INTO RATES OF VERTICAL ACCRETION

To transfer sediment deposition values, given in mass per surface area (tab. 3-1), into annual rates of vertical accretion, the variations of BDD and LOI values of the correspondent marsh soils have to be taken into account. Table 3 shows average BDD and LOI values for the time after the construction of dykes (1915 to 2011). Regarding the organic matter, we observed for Hooge and Langeness that LOI values of the upper marsh soil younger than 1915, clearly exceed the average LOI of trapped inundation sediments (tab. 3-1 + 3-3). Thus, calculating accretion on the amount of solids (clastic and organic), based on trapped inundation sediment samples, would results in an underestimation of vertical accretion rates. Variations in LOI for single trap locations, are remarkably highest on Hallig Hooge (1.4 to 41.7 %) during 2010 to 2011, suggesting different allochthonous sources of organic material (organic litter from the Hallig surface), that accumulate into the adjacent traps type A due to redistribution processes during a flooding. An allochthonous input of organic matter by the sea would result in more homogeneous distribution patterns. Referring to those observations the marsh vegetation (litter + root biomass) has to be the major source for soil organic matter. Those results are in accordance to Craft et al. (1988, 1993) who observed 14 to 20 % of yearly NPP on irregular flooded marshlands to be accumulated as autochthonous soil organic matter. Considering the general findings regarding BDD values and organic matter content in inundation sediment samples as well as the corresponding marsh soil, we suggest transferring sediment deposition into vertical marshland accretion on anthropogenic marshlands of the Halligen (beyond 1915) as follows:

First, the mass of clastic solids in the sediment trap (Mc_{trap}) is increased by the average LOI content of the corresponding marsh soil younger than 1915 (LOI_{soil}) (tab. 3-3).

(1)

$$Mc_{trap} = Ms_{trap} \cdot \frac{100 - LOI_{trap}}{100}$$

(2)

$$M_{accretion} = \frac{Mc_{trap} \cdot 100}{100 - Loi_{soil}}$$

($M_{accretion}$) mass of accretion effective solids in/on trap type A or B [kg]

(Ms_{trap}) total mass of solids in/on sediment trap type A or B [kg]

(Mc_{trap}) mass of clastic contents in/on sediment trap type A or B [kg]

(LOI_{trap}) LOI of sediments in soil trap type A (bottle) [%]

(LOI_{soil}) average LOI of correspondent soil depth [%]

Second, the vertical accretion rate ΔH in mm/a is calculated, with regard to the extent of the trap device (A) and the average BDD of the correspondent soil depth (tab.3-3).

(3)

$$\Delta H = \frac{M_{accretion}}{A} \cdot BDD^{-1} \cdot 10$$

(ΔH) vertical marshland accretion [mm/a]

(A) extent of trap device (type A or B) [mm/a]

(BDD) bulk dry density [g/cm^3]

Table 3-3: Depth of the marker horizon correspondent to the year 1915 with related BDD, LOI (LOI_{soil}) calculated as average values on sediment depositions of 1915 to 2011 (age of the upper most sediment layer). As additional information the ten year average inundation frequency (2001 – 2010) is given. BDD and LOI values were used to calculate annual vertical accretion rates.

	Inundations 2001 – 2010	**soil depth 1915** (cm)	**BDD > 1915** (g/cm^3)	**LOI_{soil} > 1915** (%)
Hooge	2	10.8 ± 1.6	0.64 ± 0.17	21.4 ± 6.6
Langeness	10	12.0 ± 2.6	0.67 ± 0.16	18.4 ± 5.9
N. Moor	15	24.9 ± 0.7	0.83 ± 0.09	9.0 ± 1.4

Table 3-4 summarizes the mass of accretion effective solids ($M_{accretion}$), calculated as three year averages on mean values of trap type A and B as well as the vertical accretion rate (ΔH). At Hooge and Langeness the mass of solids is similar (0.7 kg/m^2), but accretion rates are higher at Hooge (1.5 ± 0.9 mm/a) than at Langeness (1.2 ± 0.8 mm/a) due to variations in soil BDD and LOI values (tab. 3-3). At Nordstrandischmoor $M_{accretion}$ as well as ΔH is highest compared to the other Halligen. The RSD values point to a high spatial variability of sediment deposition rates. If a time scale of > 96 years ("pre coastline construction") would be considered, soil organic matter concentrations are significantly lower and approaching zero below a specific soil depth. Hence, in that case it seems to be more appropriate to calculate vertical accretion rates considering only the clastic content of inundation sediments. At the Hallig marshlands, the characteristics of the sediment layer which has to be accumulated before 1915 would fit to a more frequent flooded marsh. But currently it cannot be ensured that low soil organic matter concentrations are related to less primary production which accumulated in the soil due to a frequent flooding or to a complete decomposition based on the sediment age. Nevertheless, regarding the organic matter to be beneficial to vertical accretion on a frequent flooded marsh would result in an overestimation of long term accretion rates. Accordingly, considering a long time scale vertical accretion rates have to be calculated by formula 4.

(4)

$$\Delta H = \frac{Mc_{trap}}{A} \cdot BDD^{-1} \cdot 10$$

While calculating accretion rates based on average soil BDD and LOI values of a time span of 96 years, a certain degree of shallow sediment compaction resulting from decomposition of organic material is considered. But, deeper compaction of the Holocene sediment layer as well as the crustal movement due to glacial fore bulge subsidence or peat compaction may result in a surface elevation change which is less than the vertical accretion rate.

Table 3-4: Accretion effective sediment deposition ($M_{accretion}$) calculated as a three year average (2010-2013), vertical marshland accretion rates (Δh) with RSD as well as the minimum and maximum extreme values. Rates are calculated on formula (1) to (3).

2010 - 2013	$\mathbf{M_{accretion}}$ (kg/m^2)	**ΔH** (mm/a)	**RSD** (%)	**Δh min/max** (mm/a)
Hooge	0.7 ± 0.5	1.5 ± 0.9	58.5	0.3 / 5.4
Langeness	0.7 ± 0.4	1.2 ± 0.8	66.8	0.2 / 6.0
N. Moor	2.0 ± 0.7	2.6 ± 0.9	40.6	0.6 / 7.0

3.6 CONCLUSION

We have designed chosen and tested simple trap devices and laboratory techniques to measure storm-surge related sediment depositions and to quantify the annual vertical marshland accretion rates for the anthropogenic marshland of the North Frisian Hallig Hooge, Langeness and Nordstrandischmoor. The main results can be summarized as follows:

1. One litre LDPE Bottles are cost efficient, durable and their sediment trapping efficiency is not sensitive for an improper handling like variations in installation depth. Their shape varies from cylinders which are meant to be the ideal sediment trap geometry. If the basal area instead of the opening width is used for areal calculations, they gain comparable results to those derived by synthetic turf mats.

2. The use of synthetic turf mats with a highly dense surface as a second sediment trap device gains results which are statistically comparable to those of the bottle devices. If the seasonal sediment deposition rate exceeds a threshold of ~ 2.0 kg/m^2/a, the sediment retention capacity of the mats seems to decrease due to remobilization effects. Disadvantageous is that sediment material is hardly to maintain for further analysis.

3. The combined use of two different categories of sediment traps (container shaped devices like bottles and flat devices like mats) allow for (1) checking internal consistency of the data,

(2) detecting outliers with respect to cattle- or man-made damage, and (3) estimating possible effects of post-storm sediment remobilization.

4. To transfer annual sediment deposition into rates of vertical accretion is an appropriate approach, when direct measurement methods could not be applied due to a limited timeframe, budget or spatial resolution. Additional parameters e.g. LOI and BDD of the soil as well as the proportion of organic to clastic/inorganic solids of the inundation sediment have to be measured. Assuming that the mineral fraction of inundation sediments is solely of allochthonous origin, whereas the organic matter content is related to the marsh vegetation primary production, the mass of inundation sediments has to be corrected for soil organic matter contents. In case of the Halligen, we suggest using soil BDD and LOI-values of sediments which are younger than 1915. Accretion rates for a three year measurement campaign (2010 – 2013) were calculated with 1.5 ± 0.9 for Hooge, 1.2 ± 0.8 for Langeness and 2.6 ± 0.9 for Nordstrandischmoor. Variations of BDD as well as LOI-values of sediments deposited before and after 1915 point to an increasing anthropogenic influence on inundation frequency and sediment deposition rates.

3.7 PERSPECTIVES

Further data, presented in Schindler et al. (2014b) is aligned to investigate the relationship between human interventions such as dykes and other coastal protection activities, inundation frequency, inundation height, and annual sediment accretion. An additional work package comprises the spatial distribution patterns and transport mechanisms of inundation sediments. This knowledge is essential in view of ongoing discussions about new management strategies to enhance natural adaptation processes of the anthropogenic Hallig marshlands to changing environmental conditions like rising sea-level and increasing MHW values. A sediment dating campaign by radioisotopes (^{137}Cs and ^{210}Pb) will provide knowledge about long term sediment deposition and vertical accretion rates of the North Frisian Halligen.

ACKNOWLEDGEMENTS

We thank the communities of Hallig Langeness and Hooge as well as the residents of Hallig Nordstrandischmoor for their hospitality. Stefanie Jähnig, Anna Arsenijevic and David Schomberg we thank for field- and laboratory work. All investigations contribute to the German Coastal Engineering Research Council (KFKI) project "Developing Sustainable Coastal Protection- and Management Strategies for Schleswig-Holstein's Halligen Considering Climate Changes (ZukunftHallig)" funded by the German Federal Ministry of Education and Research (BMBF, 03KIS096).

CHAPTER 4 MEASURING SEDIMENT DEPOSITION AND ACCRETION ON ANTHROPOGENIC MARSHLAND – PART II: THE ADAPTATION CAPACITY OF THE NORTH FRISIAN HALLIGEN TO SEA-LEVEL-RISE

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ABSTRACT

Low coastlands, marshlands and islands all over the world are challenged by rising water levels due to climatic changes. The adaptation capacity of such lowlands is based on frequent inundations and according sedimentation processes. Exemplarily, a system of small islands west of Northern Germany was investigated over three years. At three out of ten so-called Halligen located in the Wadden Sea, the adaptation capacity of the anthropogenic marshland was determined. The Halligen Hooge, Langeness and Nordstrandischmoor have surface elevations only a few decimetres above mean high water and have to cope with an inundation frequency of nowadays up to 22 times per year. By use of methods introduced in Schindler et al. (2014a) in combination with a ^{137}Cs and ^{210}Pb dating campaign on 12 sediment cores, vertical accretion rates were measured and detailed sediment accretion patterns presented. A good agreement was found between the used methods to calculate long term and short term marshland accretion rates. Sediment deposition and vertical marshland accretion is mainly controlled by the high tide events (single storm surges). Coastal protection structures, established in the early 20th century, decrease the inundation frequency and hinder the efficiency of the sediment transport by the tidal channel system on the Halligen. Vertical marshland accretion based on ^{210}Pb dating for the time span 1915 – 2011 (1.0 ± 0.3 mm/a, Hooge, 1.2 ± 0.3 mm/a, Langeness and 2.6 ± 0.9 mm/a, Nordstrandischmoor) is in disequilibrium with the fast increasing mean high water level (MHW, 5.0 ± 0.3 mm/a). Projections until 2100 revealed that the extreme values (highest high waters, HHW) tend to rise much faster than the MHW or relative mean sea-level (RMSL). Therefore an increasing hazard potential for the Halligen has to be expected if vertical marshland accretion does not accelerate in the future.

Keywords: Halligen; salt marsh; sea-level-rise; sedimentation; ^{210}Pb; ^{137}Cs

4.1. INTRODUCTION

The tidal flats and marshes of the North Frisian Wadden Sea, located in the northern part of the German Bight, are a highly dynamic environment, including 10 small islands, the so-called Halligen (fig. 4-1). Like tidal marshlands worldwide, the Halligen have to cope with fast changing environmental conditions due to rising sea-level, but they must be distinguished from typical marshlands by some reason. About 100 years ago, block revetments and in some cases shallow summer dykes were established (Müller and Fischer 1917) to strengthen the marshland against storm surges and to protect the 300 inhabitants and their goods. Beside subsistence issues, the Halligen are an important refugium for salt marsh plants as well as migratory birds. Furthermore they belong to the World Heritage and being part of the ”Biosphärenreservat Schleswig-Holsteinisches Wattenmeer”. Moreover, in times of increasing relative mean sea-level (RMSL) (cf. chapter 4-3), the Halligen play an important role in coastline protection issues. Together with three major sand barriers (fig. 4-1) they act as wave breaker during storms and high tides that reduce the wave energy at the shoreline of the islands and the mainland (Hofstede 1999).

In contrast to the dyked Hallig marshes, frequently flooded tidal marshlands have the ability to adapt to a certain degree of sea-level-rise (SLR), if the hydrographical, geomorphological and sedimentological parameters are appropriate. Their adaptability generally depends on a variety of parameter like the tidal range, inundation frequency, sediment availability and on adequate transport mechanisms (Allen 2000, D’Alpaos et al. 2007, Kirwan et al. 2010, Andersen et al. 2011, D’Alpaos et al. 2011) as well as on rates of subsidence (Vink et al. 2007) and autocompaction (Cahoon et al. 2006). At least the vertical marshland accretion driven by adequate sediment deposition has to compensate SLR. In case of the Hallig marshlands, hydrographical, geomorphological, and sedimentological processes are affected by a variety of human interventions and modifications. Block revetments protect the marsh against further erosion. Summer dykes decrease the inundation frequency and therefore limit the sediment input to the marsh plain. The tidal channel system was straightened and equipped with tidal gates, what must have influenced the sediment distribution patterns. Today uncertainness about those relations and a lack of data prevent for a discussion about the adaptation capacity of those “anthropogenic” marshlands to SLR.

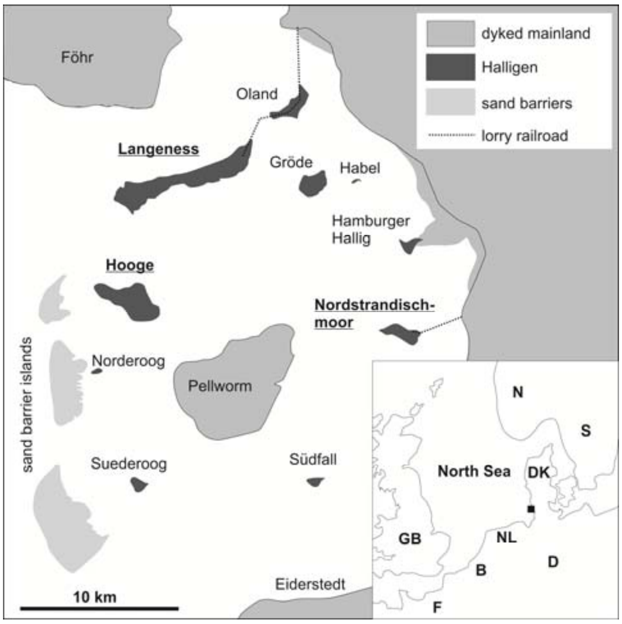

Figure 4-1: Location map showing the northern most region of the German Wadden Sea between the peninsula of Eiderstedt (south) and island Föhr (north). The three Halligen, correspondent to this paper are labeled in bold. Outline map of the North Sea Region: N=Norway, S=Sweden, DK= Denmark, NL= Netherlands, D=Germany, B=Belgium, F=France, GB=Great Britain, black rectangle= study area.

The present paper provides knowledge about short to long term marshland accretion, spatial distribution patterns of flood sediments and the adaptation capacity of the Halligen Hooge, Langeness and Nordstrandischmoor to recent sea-level change. Results are based on methodology, described in Schindler et al. (2014a). The present paper combines sediment trap measurements of annual short-term accretion rates (2010 – 2013) and its spatial distribution with a ^{210}Pb and ^{137}CS dating campaign on 12 percussion cores to infer long term accretion rates.

4.2 STUDY AREA

The Halligen with a total area of approximately 23 km^2 are located between the island Föhr in the North and the peninsula Eiderstedt in the South (fig. 4-1). The tidal flats are divided by large tidal channels and bordered by sand barrier islands to the North Sea. The mesotidal regime has a tidal range of 2 to 4 meters. The present shape of the North Frisian Wadden Sea and its coastline was formed by a number of catastrophic storm surges as well as land reclamation activities (Reise 2005). Two catastrophic surge events, the so-called 1st and 2nd “Grote Mandränke” (i.e. *big drowning of many people*) in 1362 and 1634 had a tremendous impact on the landscape. Major tidal channels were generated that cut into former marshland and huge parts of the settled marshland drowned and disappeared. The isolated Halligen as remnants of the former coherent marshland are a direct consequence of the second event in 1634 (Ahrendt 2007).

The present study focuses on the Halligen Hooge, Langeness and Nordstrandischmoor (fig. 4-1). At the beginning of the 20th century, the larger Halligen Hooge and Langeness were encompassed by low dykes to keep the hinterland dry during fair weather conditions (i.e. summer months) (Müller and Fischer 1917). Only during westerly storms which usually occur in winter time (October to March) the islands are flooded. Gauge records, dating back to the 1950s, show that the inundation frequency on the three Halligen could vary between 0 to 28 times per year, depending on the weather situation and individual coastal protection and hydrological management strategies. By reason of the dyke itself and closing tidal gates with rising tides, Hooge and Langeness need much higher gauge levels to be flooded than Nordstrandischmoor. There, on top of the stone paved marshland edge, water permeable block or gravel revetments act as wave-breakers. The western marsh edge merges to a large sedimentation field. A specific lifestyle has been developed through the centuries on the Halligen. Today the Halligen are inhabited by approximately 300 residents. Houses are built on top of artificial dwelling mounts, so-called “Warften”, to protect habitants and their goods. Their height varies between 4.5 to 5.0 m above sea-level (German Ordnance Level, GOL).

4.3 SEA-LEVEL-RISE

Rising mean sea-levels (MSL) will increase the likelihood of coastal flooding around the world (Seneviratne et al. 2012). Recent analyses highlighted that the global MSL rose by 2.0 mm/a between 1971 and 2010 (Church et al. 2013). In general, rates of SLR are having a considerable temporal and spatial variability (e.g. Church et al. 2004, 2008, Dangendorf et al. 2012, 2013).

In the German Bight, the relative mean sea-level (RMSL) was for example estimated by Wahl et al. (2011). From observational data they calculated rates of sea-level-rise between 2.1 ± 0.7 (Emden) and 4.6 ± 0.8 mm/a (Wyk, Föhr) for the period from 1971 to 2008. With regard to historic tide gauge records dating back to the middle of the 19th century, these rates were not unusual but indicate a more rapid increase at the North Frisian coast compared to the southern parts of the German bight (Wahl et al. 2011). Projections of possible future mean sea-levels have also been assessed on global (Church et al. 2013 for a review) or regional scales as e.g. in the northeast Atlantic Ocean (Katsman et al. 2008, Slangen et al. 2014). The 5th assessment report (AR5) of the

IPCC (2013) suggests a model and scenario dependent range of 0.26 to 0.82 m (2.0 – 15.7 mm/a) in global sea-level-rise (SLR) until 2081 to 2100 relative to 1986 to 2005 (Church et al. 2013).

As MSL rises, it also affects higher water levels by shifting the entire frequency distribution to a higher base level (i.e. events of a given height occur more frequently) (Hunter 2010). In the German Bight, Mudersbach et al. (2013) found that the trends in high water levels exceeded those in MSL significantly from the mid-1950s to approximately 1990. This indicates the presence of nonlinear interactions between the different sea-level components which, however, cannot yet be explained entirely. For investigations dealing with such changes and first explanations see for example Arns et al. (2014).

With regard to the intention of this paper, the regional mean high water (MHW, i.e. the annual average of all peak high water levels) trend is regarded to be the most important hydrographical parameter for the Halligen and tidal marshland in general as the water level of the MSL is lower than today's ground level of all Halligen, which the MHW by contrast is currently about to approach.

4.4 METHODS

4.4.1 SEDIMENT DEPOSITION AND ACCRETION RATES FROM SEDIMENT TRAPS (2010 – 2013)

A broad description of the methodological development is provided in Schindler et al. (2014a). In summary, the agricultural usage of the marshland as well as restrictions by the World Heritage Administration (German Wadden Sea) prevents for long-term measurements of marshland accretion rates. Therefore deposition rates, quantified by the combined use of temporal sediment trap installations (one litre LDPE bottles and small synthetic turf mats of 20 x 30 cm), had to be translated into rates of vertical marshland accretion, utilizing results of a soil survey (bulk dry density; BDD and loss on ignition; LOI) on 12 percussion cores. For the field measurements (2010 – 2013) 141 observation points (71 at Langeness, 46 at Hooge and 24 at Nordstrandischmoor) were equipped during the winter seasons.

4.4.2 RADIOMETRIC MEASUREMENTS ON SEDIMENT CORES: ^{137}CS AND ^{210}PB DATING

12 sediment cores (Langeness n = 6, Hooge n = 4, Nordstrandischmoor n = 2) with length between 74 to 100 cm were taken in March and October 2011 (fig. 4-2) by use of plastic tubes (120 cm length, 10 cm in diameter). After halving, cleaning and photo documentation, the core was sliced

into increments of 1 cm (surface to 25 cm depth) to 5 cm (> 25 cm depth), dried and grinded. Depending on their mass, samples were filed in plastic tins of 6.9 to 35.3 cm^3, afterwards sealed an allowed to rest at least 3 weeks before the measurements to reach equilibrium between ^{226}Ra and ^{214}Bi (Goodbred and Kuehl 1998). The gamma-ray measurements on ^{137}Cs (661.7 keV), ^{210}Pb (46.6 keV) and ^{214}Pb (295.2 and 351.9 keV) were performed by the Laboratory for Radioisotopes (ISOLAB in Göttingen, Germany) with three low background Ge(Li)detectors. The measurement time was 250000 s (2.9 days).

All cores showed two peaks in ^{137}Cs activity which are considered to represent the maximum fallout during atmospheric nuclear weapon testes in 1963 and the 1986 nuclear power plant accident in Chernobyl, Ukraine (Callaway et al. 1996, Kirchner and Ehlers 1998, Schuerch et al. 2012). For the ^{210}Pb dating the CRS model was applied (Appleby and Oldfield, 1978, 1983). Using the CIC model is not appropriate for the Hallig marshlands due to the irregular occurring floodings with highly variable sedimentation rates. The dating horizon (deepest dateable sediment layer) was defined by the excess ^{210}Pb activity decreasing under the cumulated measurement error for ^{210}Pb and ^{214}Pb.

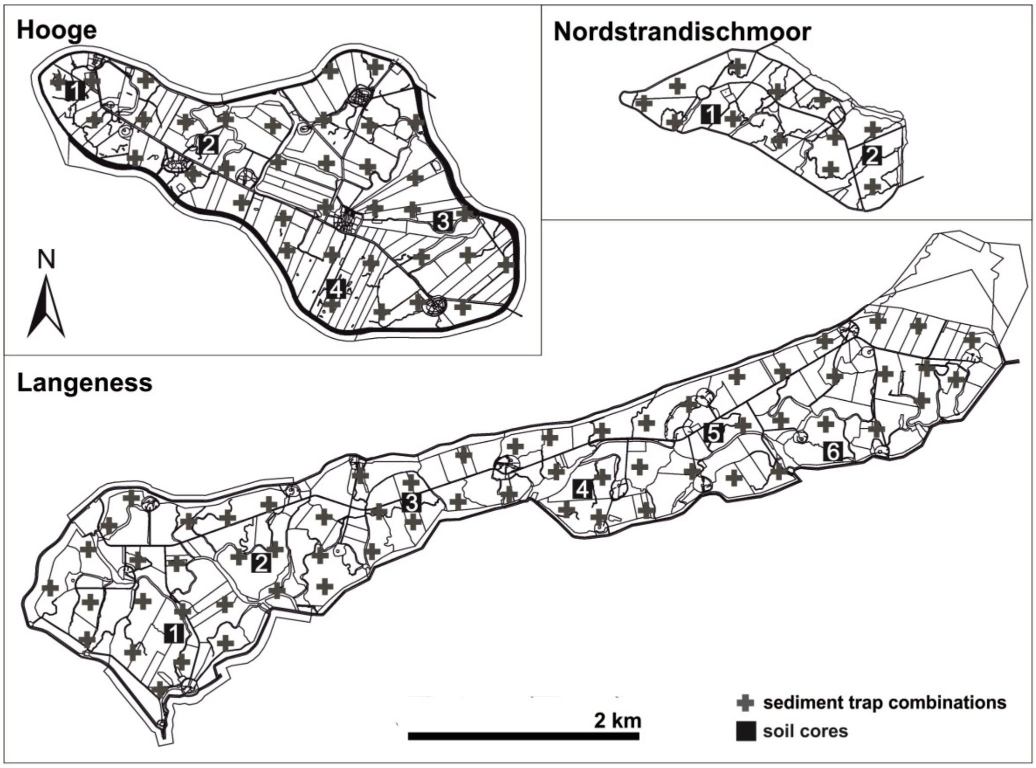

Figure 4-2: Location map showing the positions of sediment trap combinations (dark grey crosses) and soil coring positions (numbered black rectangles). In total 61 (Langeness), 36 (Hooge) and 12 (Nordstrandischmoor sediment traps and 12 sediment core locations (2 Nordstrandischmoor, 4 Hooge, 6 Langeness) were established.

Sediment deposition rates (kg/m^2/a) can be calculated from results of the CRS method by age and mass of the core increments. When translating deposition rates into rates of accretion (vertical length per time), a certain degree of soil compaction down core has to be considered. Due to BDD increasing and LOI decreasing with depth (Craft et al. 1993, Bartholdy et al. 2010b, Schindler et al. 2014a), deeper sediment layers would indicate for lower accretion rates than shallow ones (Bartholdy et al. 2010). Therefore we rescaled the thickness of single core increments by average norm values of BDD and LOI. To enable comparability with accretion rates calculated on recent sediment depositions (cf. chapter 4.4.1) we likewise employed norm values correspondent to the "anthropogenic" marsh soil layers younger than 1915.

4.4.3 SPATIAL DATA INTERPOLATION AND VISUALIZATION

Distribution maps of sediment accretion can provide important information about the spatial variability of sediment accumulation data on the Halligen. Furthermore, they enhance comparability to previous studies dealing with the spatial distribution of sediment depositions on tidal marshlands (e.g. French 1995, Temmerman 2003, D'Alpaos et al. 2007, Bartholdy et al. 2004, Bartholdy et al. 2010a, De Groot et al. 2011). In order to display distribution patterns, the GIS software packages Surfer 9 (Golden Software, Inc.) and ArcGis 10 (Esri, Inc.) have been used. 2D contour maps are calculated via point kriging interpolation without drift. This approach enables best results while computing data based on a "semi" regular grid configuration (Asselman and Middelkoop 1995). Additional spatial information was provided by the „Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig Holstein" (LKN-SH). These data contain aerial images and digital ground models (DGM) based on light detection and ranging (LIDAR) measurements.

4.4.4 STATISTICAL EVALUATION

To compare data collectives (for example ^{137}Cs versus ^{210}Pb dates), the t-test for independent samples was used. Further linear regression analyses to reveal correlations between the sediment deposition and spatial parameters (e.g. inundation depth, distance to marshland margin, revetments, tidal gates). All statistical evaluations were performed by the software packages SPSS Statistics 17.0 (SPSS, Inc.) and Grapher 8.8 (Golden Software, Inc.).

4.5 RESULTS

4.5.1 RADIOMETRIC MEASUREMENTS

In each of the 12 sediment cores, two distinct peaks of ^{137}Cs activity were found in the upper 20 cm (fig. 4-3). The radiation intensity of those peaks is in a range between 35.4 to 170.2 Bq/kg. ^{137}Cs peaks at Nordstrandischmoor occur deeper under the surface due to higher yearly sedimentation rates. Below depths of 12 cm (Hooge and Langeness) to 20 cm

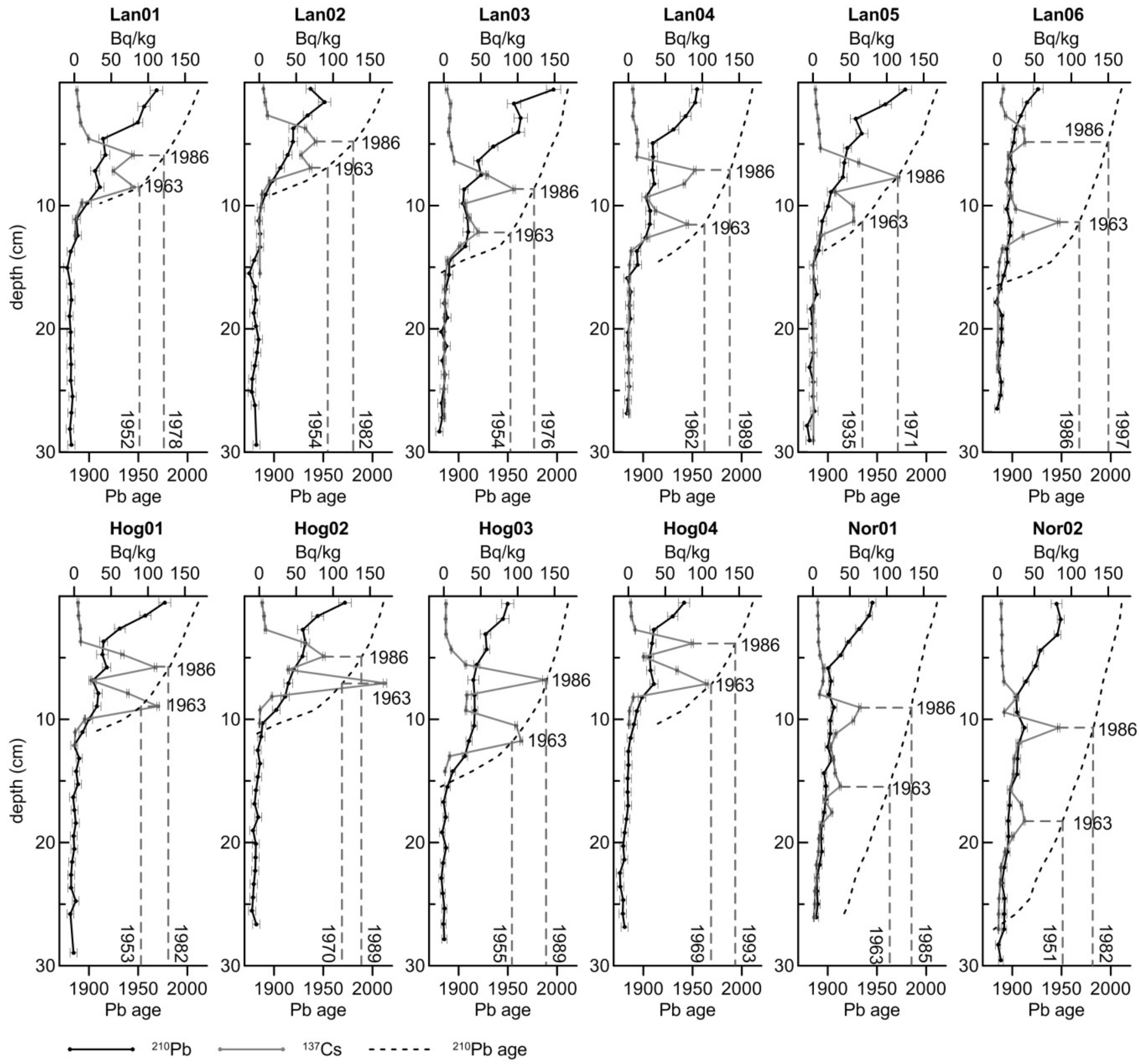

Figure 4-3: Excess ^{210}Pb (black line), ^{137}Cs (grey line) and ^{210}Pb age (dashed black line) versus depth in all 12 sediment cores. Horizontal error bars are one sigma errors resulting from the gamma ray measurements. Depths are medium depth of the measured core increment, rectified for the core compaction rate, resulting from percussion coring. The upper ^{137}Cs peak is supposed to be a result of the Chernobyl nuclear accident (1986). The lower peak to nuclear weapon tests before the comprehensive nuclear-test-ban treaty (1963).

(Nordstrandischmoor), where marsh sediments were deposited before the nuclear fission age, the ^{137}Cs activity decreases below the detection limit. The excess ^{210}Pb curves are mainly decreasing from surface with depth (fig. 4-3). At Hooge and Langeness, the excess ^{210}Pb age versus depth line drops steeply by depth what is equivalent to lower accretion rates. For Nordstrandischmoor the depth versus time line and therefore accretion rates are more stable. It is also visible from figure 4-3 that the agreement between lead and cesium ages is mostly adequate. However, ^{137}Cs ages especially for cores Lan01 Lan02 and Lan03, tend to younger sediment ages compared to the ^{210}Pb dates. This is contrary to previous studies dealing with ^{137}Cs and ^{210}Pb data (Schuerch et al. 2012) who supposed a downwards relocation of ^{137}Cs to be responsible for older ages compared to ^{210}Pb data. For Hooge as well as Nordstrandischmoor a better agreement has been achieved.

4.5.2 SHORT TO LONG-TERM DEPOSITION AND ACCRETION RATES

Inundation events mainly occur during the winter months from October to March. Therefore, winter sediment deposition based on sediment trap measurements can be regarded as representative for the whole year (e.g. summer 2012 to summer 2013). Average annual marshland accretion rates between 2010 to 2013 vary from 0.7 to 4.4 mm/a depending on the individual Halligen as well as frequency of storm surge events (i.e. storm activity) of the respective winter season (fig. 4-4). In years of high storm activity such as 2011 to 2012, marshland accretion rates at Nordstrandischmoor are more than twice the rates as at Langeness and Hooge.

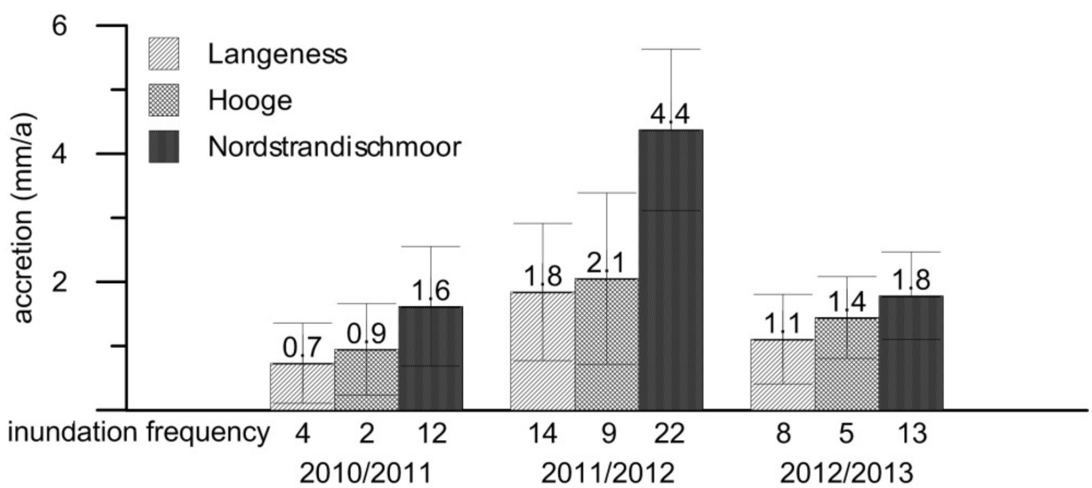

Figure 4-4: Annual average marshland accretion rates during the observation period (October to March 2010 to 2013) in comparison to the inundation frequency. For reason that inundations mostly occur during the winter month, accretion rates can be regarded as representative for the whole year.

In years with lower storm activity (i.e. 2010 – 2011, 2012 – 2013) accretion rates at Nordstrandischmoor are still the highest, but the difference to the bigger Halligen is smaller. In all three years the values for accretion rates are lowest at Langeness, moderate at Hooge and highest at Nordstrandischmoor. Even though a higher storm surge activity at Langeness compared to Hooge would suggest for higher accretion rates at Langeness.

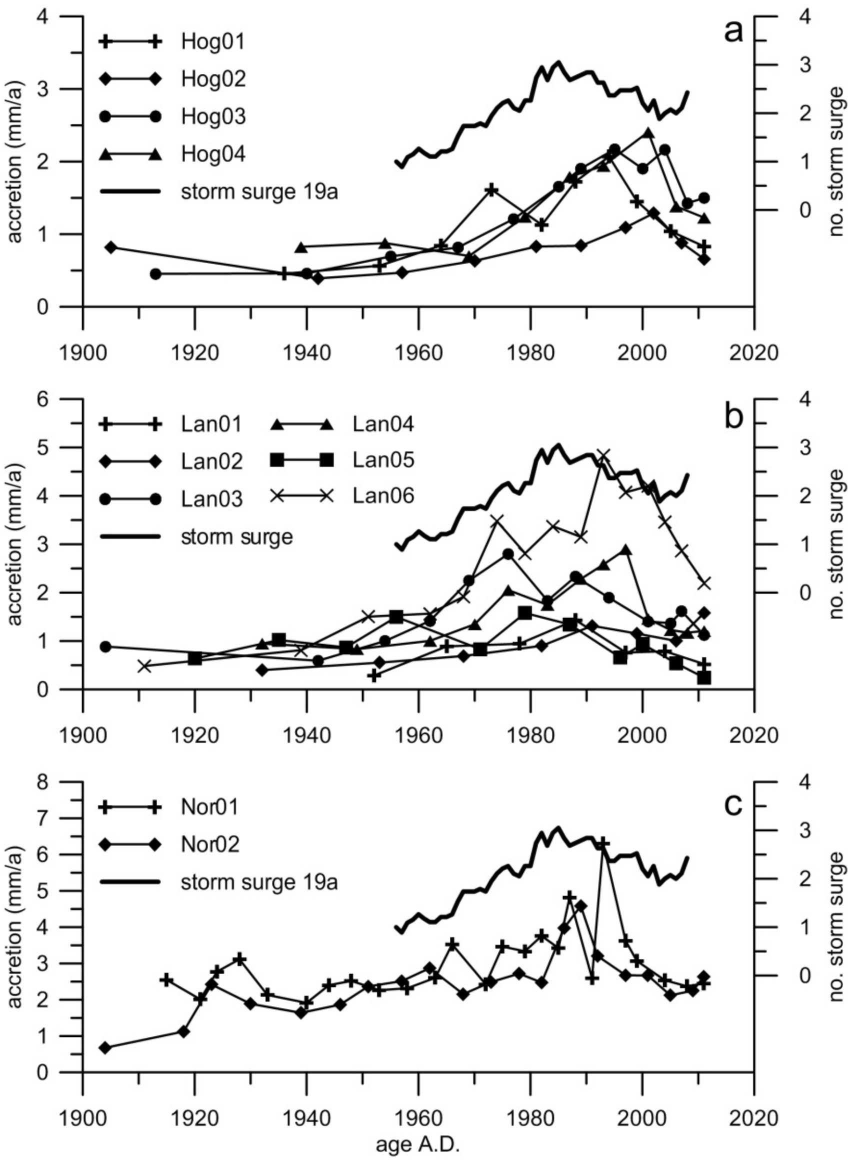

Figure 4-5: Comparison of vertical accretion rates at (a) Hooge, (b) Langeness and (c) Nordstrandischmoor with the storm surge frequency. Accretion rates are based on the constant rate of supply (CRS) method for excess ^{210}Pb according to Appleby and Oldfield (1978, 1983). All 12 cores and all depth down to the dating horizon are shown. The storm surge frequency is calculated as a 19 year running mean based on the yearly number of gauge levels exceeding an threshold of 1.54 m above MHW at the gauge station Wyk on the island Föhr.

Long-term accretion rates derived from the CRS dating model have been found variable in space (different locations on different Hallig marshlands) and time as well (fig. 4-5a,b,c). Nevertheless, the development of accretion rates on different Halligen obviously shows some similarities. During the first half of the 20th century accretion rates don not exceed 1 mm/a at Hooge, 2 mm/a at Langeness and 3.5 mm/a at Nordstrandischmoor. Approximately 1960 rates start to increase and reach the highest values between 1980 and 2000. For some periods at Hooge and Langeness accretion rates are more than double compared to dates before 1960. During the first decade of the 21st century, rates decline to values slightly above the level before 1960. The development of the accretion rates seems to follow the development of the storm surge frequency that had likewise a maximum during the eighties of the 20th century. The 19 year moving average of the storm surge frequency was calculated by the number of gauge levels (station Wyk on Föhr, 1951 – 2011) exceeding a threshold of 1.54 m above MHW level. The threshold represents the average summer dyke height of Hallig Hooge and is nearly consistent with the administrational definition of a storm surge which is defined as MHW + 1.50 m. Combining excess ^{210}Pb and ^{137}Cs data (by calculating average values of ^{137}Cs and ^{210}Pb data of an identic time scale) (tab. 4-1) confirms that marshland accretion during the second half of the 20th century (1963 – 1986 and 1986 – 2011) was above average compared to a time span of 1915 to 2011. Comparing 1963 to 1986 against 1986 to 2011, all investigated Halligen show stagnant accretion rates.

Table 4-1: Comparison of former marshland accretion rates according to ^{137}Cs and ^{210}Pb datings with recent field measurements.

	^{137}Cs/^{210}Pb **1963 – 1986** (mm/a)	**^{137}Cs/^{210}Pb** **1986 – 2011** (mm/a)	**^{210}Pb** **1915 – 2011** (mm/a)	**sediment trapping** **2010 – 2013** (mm/a)
Hooge	1.3 ± 0.7	1.4 ± 0.6	1.0 ± 0.3	1.5 ± 0.9
Langeness	1.9 ± 0.9	1.6 ± 0.7	1.2 ± 0.3	1.2 ± 0.8
N. Moor	3.1 ± 1.9	3.2 ± 1.6	2.6 ± 0.9	2.6 ± 0.9

4.5.3 SPATIAL DISTRIBUTION OF ACCRETION RATES (2010 – 2013)

Sediment distribution maps visualize the spatial variability of sediment deposition and illustrate contrasting distribution patterns between the individual Halligen (fig. 4-6). Accretion values are calculated as three year averages (2010 – 2013) on both sediment traps type A and B. Hooge shows increasing accretion rates from the windward southwest side to the leeward north and northeast side of the marsh island. Eye-catching is a band of observation points located at the southwestern marsh edge where accretion rates are lowest (0.7 – 1.1 mm/a). At Langeness, in the eastern and western part of the Hallig sediment accretion rates are highest near the marshland margin. Points of highest accretion are located close to the two biggest channel outlets "Osterwehl" (3.8 mm/a) and "Der Jelf" (3.4 mm/a). With increasing distance to the edge, accretion rates are decreasing to values < 1 mm/a. Also at the mid part of the Hallig, where the distance from southern to northern edge is smallest, rates are very low (< 1 mm/a). Due to its small extend, Nordstrandischmoor has only 12 grid (400 x 400 m) observation points. Accretion data shows a more or less random spatial distribution.

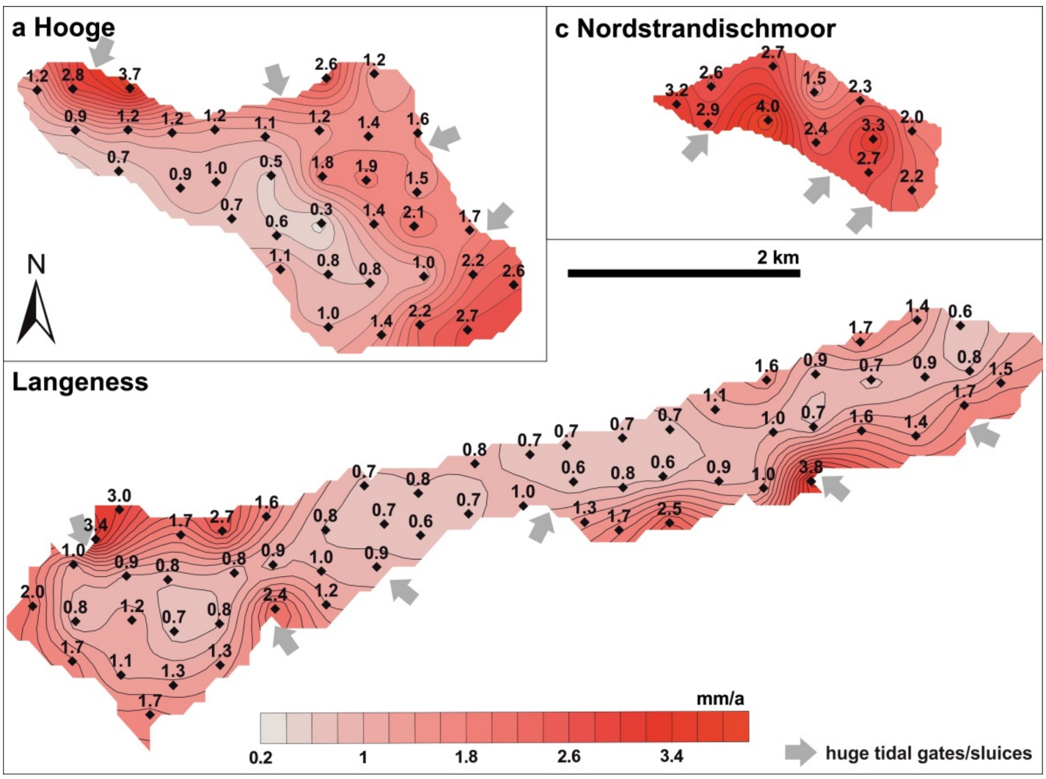

Figure 4-6: 2D contour maps of accretion rates. The displayed map is calculated by average values of a three year lasting field campaign (2010 – 2013) via linear point kriging interpolation without drift. Average lateral distance between the observation points is 400 m.

4.6 DISCUSSION

4.6.1 ACCRETION RATES

A good agreement were found between the used methods to calculate long term and short term marshland accretion rates by ^{137}Cs, ^{210}Pb dating and sediment traps, respectively (tab. 4-1). High standard deviations are resulting from a high spatial variability in sediment deposition rates, effecting short- and long-term measurements, as well as moderate variations between deposition and accretion rates calculated on ^{210}Pb and ^{137}Cs. Compared to previous studies dealing with vertical accretion and surface elevation change in tidal marshlands, accretion rates in general seem to be in a typical range. For the salt marshes along the coastline of the federal state of Schleswig-Holstein, Suchrow et al. (2012) calculated a positive average elevation change of 0.6 mm/a for a time span of 19 to 21 years. At a Danish back barrier salt marsh on the peninsula of Skallingen, comparable accretion rates of 2 to 4 mm/a (Bartholdy et al. 2004) and 1.9 mm/a (Andersen et al. 2011) have been observed by ^{210}Pb/^{137}Cs sediment dating. Close to our study site, Schuerch et al. (2012) reported mean annual sedimentation rates of 1.0 to 2.8 mm/a for a salt marsh at the south-eastern coast of the island Sylt during the 20th century with an strong increase in marshland accretion during the 1980s and 1990s comparable to our ^{210}Pb data. Stock (2011) calculated slightly higher surface elevation changes of 6.18 mm/a by use of sedimentation erosion tables (SET) and sedimentation erosion bars (SEB) on the Hamburger Hallig, close to our study site. A local source for sediments that could be responsible for the higher sedimentation rates could be large sedimentation fields eastwards of the Hamburger Hallig.

There are strong hints that the distinct increase of marshland accretion rates during the 1980s and 1990s (fig. 4-5), is driven by a higher storm surge frequency. But, proofing for a relation between accretion rates and storm surge frequency by linear regression analyses revealed only for 4 out of 12 cores (2 at Hooge, 2 at Langeness) a reliable but mostly weak correlation. The best correlation shows core Lan02 (R^2 = 0.97, $p < 0.01$, n = 6). Furthermore there is a high error for the accretion rates calculated on data of the CRS method (not shown in figure 4-5 by reason of readability). Average ^{210}Pb accretion rates for 1915 to 2011 (tab. 4-1) reveal RSD values of 35 to 67 %. At Nordstrandischmoor where the water impermeable revetment height is only 0.70 m above MHW, a correlation between storm surge frequency (as defined in chapter 4.5.2) and marshland accretion could not be proven. Those results are in accordance with previous studies postulating that the persistence of salt marshes is closely related to storm events (Stumpf 1983, Andersen and Pejrup 2001, Schuerch et al. 2013). Our results suggest a dependency of marshland accretion to more extreme surge events in case of higher water impermeable revetments (e.g. Hooge and Langeness). Marshlands with lower revetments (e.g. Nordstrandischmoor) are less dependent from the rare extreme events. At Nordstrandischmoor, a parameter that could result in a higher inundation frequency and sediment deposition is the reconstruction of water permeable revetments. Nowadays, the old block revetments are gradually replaces by higher gravel ramparts, fixed by two-component adhesives. Recently, there is no data available about their sediment retention potential.

Further on, the effect of varying ratios between shoreline length and the total area (LA-ratio) of the Hallig on sediment deposition has to be discussed (tab. 4-2). At Hooge and Langeness the ratio is similar with 2.04 km/km² (Hooge) and 2.27 km/km² (Langeness). The annual sediment transport over the marshland edge, calculated as mass per shoreline section (t/km/a) is comparable too (Langeness 293 t/km/a, Hooge 364 t/km/a). At Nordstrandischmoor the LA-ratio is double that of Hooge i.e. 4.17 km/km², whereas the sediment transport is about 1.3 times higher, i.e. 479 t/km/a. The higher LA-ratio of Nordstrandischmoor could explain the more homogeneous distribution of sediment deposition on Nordstrandischmoor compared to Hooge and Langeness. Nevertheless, the higher deposition rate has to be explained by higher sediment transport rates over the marshland margin. These could be due to differences in revetment construction and heights and/or a possibly higher concentration of suspended matter in the inundation water.

Table 4-2: Comparison of shoreline length, total area and sediment transport rates calculated as mass per shoreline section and year.

	shoreline length (L) (km)	**Area (A)** (km^2)	**LA-ratio** (km/km^2)	**transport rate** (t/km/a)
Hooge	11.1	5.46	2.04	364
Langeness	21.2	9.24	2.27	293
N. Moor	6.8	1.63	4.17	479

4.6.2 SPATIAL DISTRIBUTION

Even though the horizontal distance between the observation points is rather high (400 x 400 m), spatial distribution patterns of sediment depositions are comparable to gradients found on natural undyked salt marshes. In general, accretion rates are decreasing significantly with increasing distance to the marshland margin and with increasing distance to tidal channels (Temmerman et al. 2003, D'Alpaos et al. 2007, Bartholdy et al. 2010a). On the Halligen, our observations also indicate high sediment deposition rates to some near shore areas (fig. 4-6). But surprisingly these are not consequently attached to the dominant western wind direction. Statistical data analysis on the relation between accretion and spatial variables (e.g. inundation depth, distance to marshland margin, revetments, tidal gates) indicated two major variables that affect the sediment accretion patterns. Those are the distance to major tidal gates, which are draining the marshland after an inundation and the distance to the marshland margin. In both cases, decreasing distance results in a statistically proven increase of sediment deposition ($p < 0.05$). However, the relation for distance to tidal gates is only significant at Hooge, whereas the relation for distance to the marshland margin is only significant at Langeness.

A relation between marshland elevation and accretion could not be statistically proven, by reason of the low lateral and spatial accuracy of the GPS measurements as well as the DGM data. But a visual comparison of the spatial distribution maps with the DGM reveals that highest accretion rates at Hooge seem to correlate with low surface elevations, whereas high marshland accretion at Langeness seems to take place adjacent to the marshland edge. Furthermore, observation points distant to the margin of Langeness but adjacent to a major channel do not show higher accretion rates than observation points which are both, distant to marshland margin and channel system. Hence, Langeness seems to be a "transport limited landscape" (D'Alpaos et al. 2007) where the limitation for sufficient vertical accretion at the hinterland seems to be an obstructed tidal channel system, typically equipped with tidal gates that close automatically at rising tides. Nevertheless, and likewise to Hooge observation points of highest marshland accretion are always adjacent to a tidal outlet. For this observation two scenarios seem to be possible. (1) At the beginning of an inundation, flood water is streaming over the dyke or revetment and converges into near gate channels. Channel sediment, which mobilizes due to high flow turbulent currents, is deposited at adjacent meadows. (2) After an inundation the dyked marshland could drain only throughout the channel outlets. Therefore a post storm surge sediment relocation by effluent inundation water in direction of the outlets could presently not be neglected. Different vegetation patterns, influencing sediment deposition can also be neglected by reason of a homogeneous vegetation pattern, being mostly a short grazed meadow. At Hallig

Nordstrandischmoor neither a relation between spatial sediment accretion and lateral distance to the marsh edge or channel outlets, nor to marshland elevation/inundation height could be found.

4.6.3 ADAPTATION CAPACITY AND FUTURE PERSPECTIVES

All data on marshland accretion since the beginning of the 20th century have shown that the Hallig islands are in sedimentological imbalance to sea-level rise. Hydrographical parameter and sediment distribution pattern are affected by human interventions. The establishment of summer dykes and tidal gates nearly 100 years ago enabled an intensification of land use and decreased wave height during flood events (Mai et al. 1998). On the other hand there is clear evidence that those coastline protection constructions are disturbing the native balance between MHW increase and vertical marsh accretion. In general the hydrographical and sedimentological conditions of the North Sea basin must be regarded as beneficial. A tidal range of ~ 3 m in combination with a high concentration of suspended sediments should result in high adaptation capacities of tidal marshlands to rising sea-levels (Kirwan et al. 2010). However, recent analyses point to considerable differences in the development of water levels and the vertical marshland growth as highlighted in fig. 4-7. The figure shows trend estimates of the MSL, the MHW and the highest annual high water (HHW) at Wyk tide gauge. The left part of the figure shows linear trend estimates of observed water levels between 1952 and 2009 (i.e. three nodal cycles), highlighting that the MHW trend (5.0 ± 0.33 mm/a) roughly amounts to twice the MSL trend (2.6 ± 0.39 mm/a). The HHW trend (6.6 ± 3.8 mm/a) is even larger, amounting to 2.5 times the MSL trend. The figure further indicates that higher water level percentiles tend to have a larger variance than the lower ones (see e.g. Mudersbach et al. 2013), causing larger uncertainties in the trend estimates. For comparison, the average height of a summer dyke (which is assumed having a constant height) as well as the non-stationary vertical accretion rates of Hallig Hooge (1.0 ± 0.3 mm/a), Hallig Langeness (1.2 ± 0.3 mm/a) and Hallig Nordstrandischmoor (2.6 ± 0.9 mm/a) between 1915 and 2011 are plotted.

The observed surface elevation growth especially for Hooge and Langeness was neither able to keep pace with the changes in mean nor in highest water levels. Only Nordstrandischmoor which has the lowest standard or protection due to the absence of a dyke reveals an accretion rate close to the increase in RMSL. The lower right side of the figure (i.e. the period covering 2009 – 2100) shows mean sea-level projections that have recently been used in the IPPC’s Fifth Assessment report (Church et al. 2013, Slangen et al. 2014). The projections shown here consider two different emission scenarios. These are the RCP 4.5, which is a scenario in which the radiative forcing stabilizes at ~ 4.5 W/m² shortly after 2100 (see e.g. Clarke et al. 2007) and the RCP 8.5, for which the radiative forcing reaches > 8.5 W/m² by 2100 (see Riahi et al. 2007). The RMSL shows a progressive increase, indicating that future SLR will likely exceed the observed rates. These projections are only valid for the MSL. Possible changes during the 21st century in higher water levels such as the MHW and the HHW are usually assumed to be dominated by changes in MSL (see e.g. Hunter 2010). However, these findings are not valid for the German Bight (see e.g. Mudersbach et al. 2013, Arns et al. 2014) and there are no robust estimates of future high water levels available. This is why we used the MSL projections and shifted them linearly to the MHW and HHW respectively (see the blue and red lines of the MHW and HHW as well as their likely range which covers 5 to 95 % of the modelling results as reported in the AR5). To approximate nonlinearities, we added the trend differences between the MSL and the MHW or the HHW.

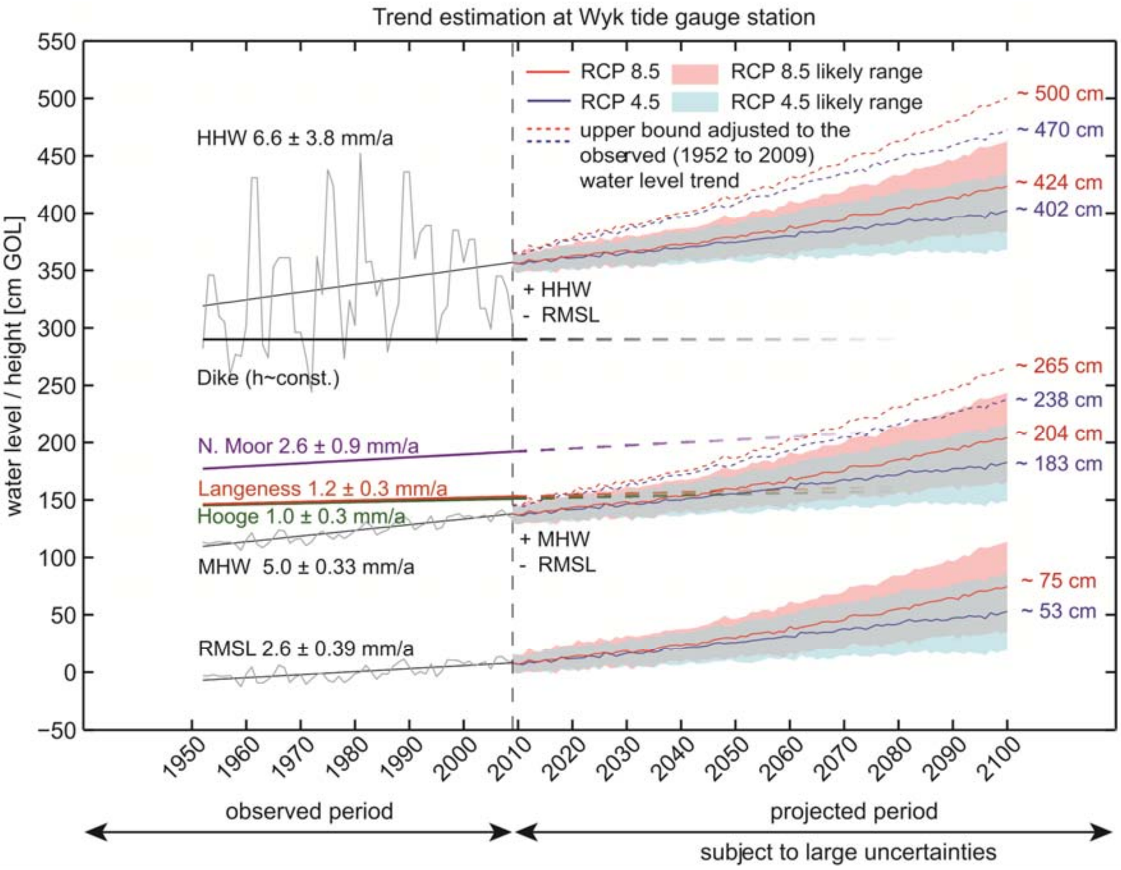

Figure 4-7: Observed (1952 – 2009) and projected (2009 – 2100) water levels based on the "Representative Concentration Pathway" (RCP) scenarios 4.5 and 8.5 of the IPPC's "Fifth assessment Report" (AP5, 2013) in comparison to the marshland accretion rates of Hooge, Langeness and Nordstrandischmoor. By reason that no robust estimates for high water levels at the German Bight are available, the RMSL projection was shifted linearly to MHW and HHW respectively (red and blue lines as well as their likely range, 5 to 95 %). To adjust the upper bound of the RCP 4.5 and 8.5 scenario to the study site, the differences between RMSL and the MWH / HHW of the observed water levels (1952 – 2009) was added to the RMSL (dashed red and blue lines).

This, however, is only considered for the upper boundary of the likely range, yielding a range of water level scenarios that approximately consider nonlinear changes in the high water levels of the German Bight.

Regarding the linear extrapolation of the vertical marshland accretion (which is a simple assumption), accretion rates would be expected to increase by reason of a higher storm surge frequency. But there is still a lack of knowledge about storm surge intensity (especially extreme events due to a non-linear HHW increase) driving sediment supply as well as transport and deposition. Furthermore the ongoing discussion about an improvement of coastline protection constructions on the Halligen (which are contemplate to take advantage by the outcome of these research) will sooner or later result in an revetment/dyke adjustment, having in turn effects on the inundation frequency. Nevertheless, by facing the present divergency between MHW and marshland accretion (especially for Hooge and Langeness) it seems to be unlikely that a further increasing water level results in a multiple times higher marshland accretion. For example, Hallig Hooge would have to increase marshland accretion far beyond the factor 5, which is the current proportion between MHW increase (5 ± 0.33 mm/a, 1951 – 2011) and marshland accretion (1.0 ± 0.3 mm/a). Consequences of such imbalance would be increasing water levels on the marshland during storm surges and increasing hydrodynamic forces both to the marsh surface and to the dwelling mounts. A second point which has to be considered is an increasing wave runup at the slopes of the artificial dwelling mounds, because higher water depth would allow for more wave action. To strengthen the Halligen against rising water and storm surge levels a combination of two different strategies seems to be feasible. (1) At the short term, to strengthen the dwelling mounts and increasing their height by coastal engineering constructions should result in a better hazard protection for inhabitants and their goods. (2) At the long term, the future persistence of the Halligen can only be ensured, if the balance between marshland accretion and increasing water levels can be re-established by well adapted management strategies. Either by an increase of the inundation frequency by deconstruction of dykes and destructed tidal channels or an artificial sediment input to the marshland.

4.7 CONCLUSIONS

The main goal of the current study was to gain knowledge about the recent and past adaptation capacity of the North Frisian Hallig marshlands to a rising sea-level. To combine sediment datings based on the radio nuclides ^{137}Cs and ^{210}Pb with field measurements of sediment deposition have been proven to be a powerful tool to (1) provide data about vertical marshland accretion rates on the North Frisian Halligen and (2) to analyze spatial distribution patterns of sediment accretion. Based on the results the main conclusions can be summarized as follows:

1. Artificial coastal protection structures like summer dykes, block revetments and tidal gates are decreasing flood frequencies and disturb a sufficient sediment input to the marshland. In turn, Halligen with a low standard of protection (e.g. Nordstrandischmoor which is undyked and not fully encompassed by a revetment) revel the highest adaptation capacity to rising water levels. Spatial distribution patterns of sediments are affected by matters of transportation due to the hydrological management of the Halligen. An obstructed tidal channel system seems to prevent an effective sediment distribution to the hinterland.

2. Vertical marshland accretion since the beginning of the 20^{th} century is in a disequilibrium with increasing water levels at the study site. Especially the MHW and HHW develop much faster than MSL which already exceeds marshland accretion at Hooge and Langeness. If this trend could not be changed, the increasing gap, especially between HHW level and marsh surface reinforces hydrodynamic forces on the marshland. This would result in an increased hazard potential for the habitants and their goods.

3. New strategies have to be developed, discussed and tested to change the disequilibrium between marshland accretion and rising water levels. The focus has to be set on well adapted, long term management strategies to strengthen vertical marshland accretion and sediment accumulation processes, consistent with the special needs of the local habitants. Hallig Nordstrandischmoor could hold as a positive example that protection standards, which are regarded to be less effective (e.g. the absence of dykes) are not equivalent to a high hazard potential but a chance to support marshland accretion. Engineering actions to strengthen the artificial “Warften” are important measures to enhance the hazard protection standard on the short term.

ACKNOWLEDGEMENTS

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CHAPTER 5 REACTIVATION OF TIDAL CHANNELS AS A TOOL TO ENHANCE MARSHLAND ACCRETION

5.1 SEDIMENT TRANSPORT LIMITATION

Marshland topography (except artificial relief elements like Warften and dykes) is a result of spatial highly variable sediment depositions by reason of inhomogeneous transport processes. At natural marshlands, sediments are distributed via the marshland edge and a wide branched tidal channel system (D'Alpaos et al. 2007, Bartholdy et al. 2010a). Therefore accretion rates are highest adjacent to channels and margins, while rates are decreasing more distant to the sediment source. DGMs based on airborne LIDAR measurements of the year 2005 (fig. 5-1) reveal clear relief elements on the Halligen. Beside characteristic wide banks alongside of the major tidal channels (lateral extension 20 – 50 m) a distinct elevation rise within 100 to 200 m distance to the marshland edge is visible. The latter shapes the cross section profile of the Halligen like a flattened bowl with a decrease in surface elevation from the edge to the hinterland. Therefore, the general topography of the Halligen is comparable to those of uninhabited salt marshes in a natural state (cf. Temmerman et al. 2003, D'Alpaos et al. 2007, Bartholdy et al. 2010a). Analyses on the variability of short-term (2010 – 2013) spatial sediment accretion (chapter 4.5.3,

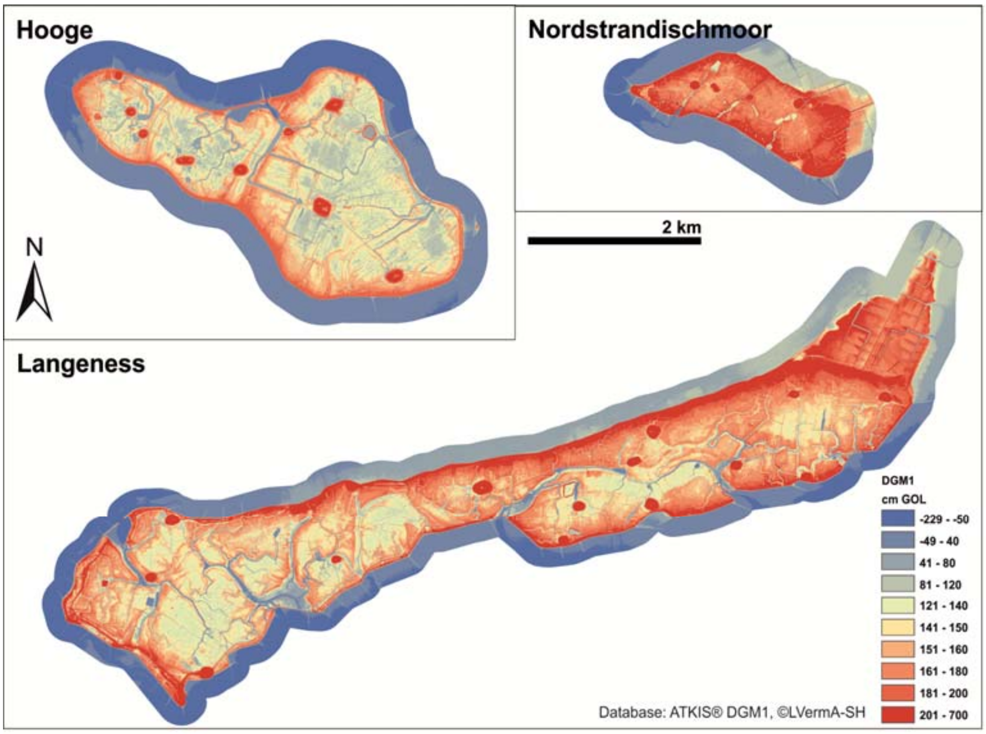

Figure 5-1: DGMs of Hooge, Langeness and Nordstrandischmoor based on LIDAR data (2005) with a spatial resolution of 1 x 1 m.

Schindler et al. 2014b) also reveal highest marshland accretion rates to be consequently attached to the marshland edge. Nevertheless, observation points distant to the Hallig margins but adjacent to a major channel system do not show higher accretion rates than observation points which are both, distant to marshland margin and channel system. Furthermore field measurements of the small scale sediment deposition variability along tidal channels and the marshland edge (fig. 5-2) indicate that variations in sediment deposition are recently limited to the first meters adjacent to the possible sediment source. At Nordstrandischmoor higher sedimentation rates occur obviously in a distance of 0 to 14 (max. 24 m) to the block revetment. For the tidal channel at Langeness, an interaction between sedimentation and the channel structure seems to be limited to a distance of 5 m. Due to this limitation of sediment transport, the broader relief structures as described before are nowadays not supported by sediment deposition. Hence, their origin has to be of an older date. These observations confirm the assumption to regard the Halligen as “transport limited landscapes” (D’Alpaos et al. 2007). Insufficient sediment transport mechanisms by an obstructed channel system result in a lag of marshland accretion distant to the sediment source (Schindler et al. 2014b).

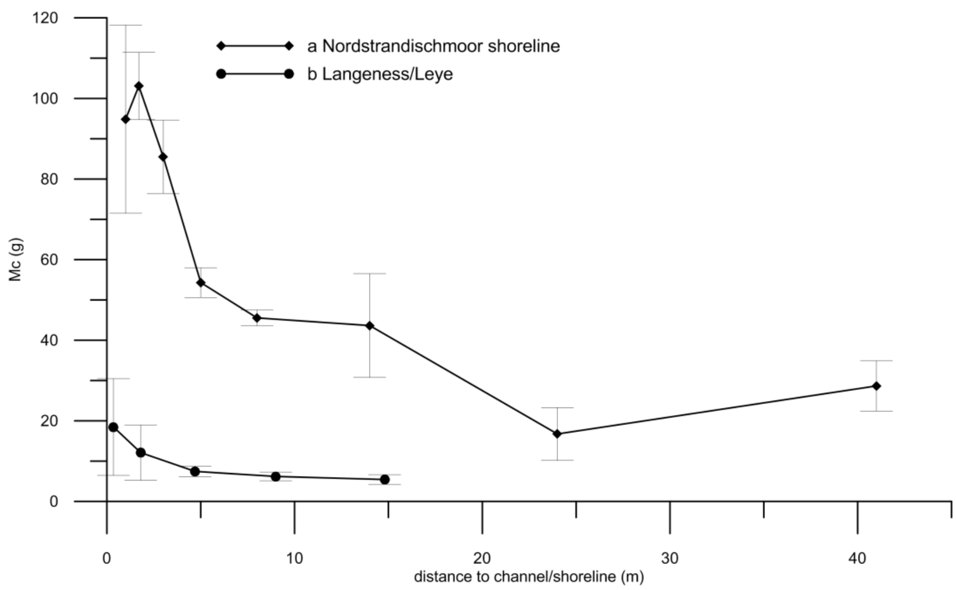

Figure 5-2: Clastic sediment deposition (Mc) during the stormy season from October 2011 to March 2012 as a function of: (a) increasing distance to the block revetment on the marshland edge of Nordstrandischmoor, (b) increasing distance to the tidal channel “Leye” on Langeness. Deposition data is calculated as average values on (a) three lines of sediment traps type A (bottle) and (b) six lines of sediment traps type A (bottle).

5.2 REACTIVATION OF A TIDAL CHANNEL SYSTEM (LANGENESS)

5.2.1 METHODS

With regard to the transport limitation, it is obvious to test if the reactivation of the tidal channel system during high or storm tides could be an adequate measure to enhance sediment transport to the inner marshland. For that purpose, the field experiment “Osterwehl” was established. Between 25th to 27th of March 2013 and 09th to 11th of January 2014 the tidal gates at the “Osterwehl” on Hallig Langeness were kept open (fig. 5-3) and the suspended sediment concentration was measured. For that purpose an ASM-IV-L (Argus GmbH) optical backscatter devise was mounted in the channel ~ 50 m landwards of the tidal gates. It contains 192 infrared emitters and sensors with a vertical distance of 1 cm fitted into a pale of stainless steel. By reason that higher sediment concentrations were expected during measurements conducted in January 2014, the sensor sensitivity was changed from 0 – 500 mg/l to 0 – 5000 mg/l. Measurement cycles were set to 30 seconds. To calculate average sediment concentrations, the ASM-IV-L measurements were filtered for artefacts due to not submersed sensors or blind sensors. The filtering was conducted using an Excel-macro-routine by V. Karius (see affiliation of co-authors). The algorithm to distinguish between data and artefacts is based on appropriate threshold values for the standard deviation of ten moving averages of the order 10 of each sensor time series.

Figure 5-3: Open gates at the tidal channel system “Osterwehl” (Langeness). Gates are fixed by wooden beams against a closing by water inflow. Photo by M. Deicke (2013).

5.2.2 RESULTS AND DISCUSSION

During the first measurement campaign (25th – 27th of March 2013), five tidal cycles ranging from neap to normal MHW were measured. Sediment concentrations of the seawater streaming into the channel system were within a range of 100 to 200 mg/l. During the second measurement campaign (09th – 11th of January 2014), conducted for four tide cycles, the first two tides were exceeding the normal MHW level by ~ 0.5 m due to heavy wind from westward directions. Thus, a higher volume of water passed the gates towards the Hallig. Tide number 3 and 4 reached comparable gauge levels (around MHW) to the first measurement campaign conducted in March 2013. Figure 5-4 illustrates the suspended sediment concentrations measured by the ASM-IV-L backscatter device. The colour image illustrates the temporal as well as vertical backscatter variability (concentration of solids in mg/l). Yellow to red bands of highest reflections occur due to organic flotsam caught by the sensor-pale. The shift from bluish (water) to solid green colours of medium reflections (air) are tracing the changing water level due to the tide (left y-axis). The black signatures indicate for the average concentration of solids in the water column (right y-axis) calculated on the processed and corrected raw data (colour image).

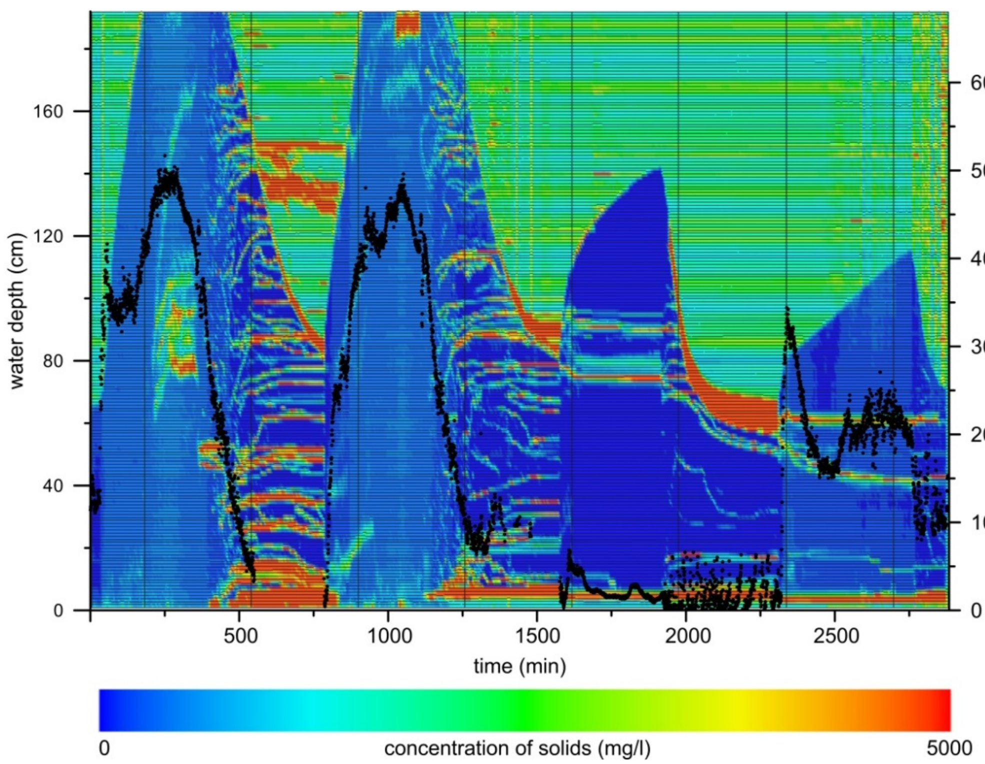

Figure 5-4: Mean suspended sediment concentration (black signatures) at the tidal channel system "Osterwehl" (Langeness) in mg/l during four tide (09th to 11th of January 2014). The coloured image illustrates the temporal backscatter variability (also given in mg/l) due to sensor height above the channel bed. Measurements were conducted by an ASM-IV-L (Argus GmbH) optical backscatter device. The measurement cycle was set to 30 seconds with a sensor sensitivity of 0 – 5000 mg/l.

It is apparent that flood stream sediment concentrations during the raised tides no. 1 and 2 are noticeable higher (400 – 500 mg/l) compared to measurements conducted by MHW-conditions. Eye-catching are low transport rates (max. 50 mg/l) during tide no. 3 after the weather has calmed down. Water level and sediment concentrations of tide no. 4 (approx. 200 mg/l) are well comparable to values measured during the first campaign in March 2013. Furthermore, sediment concentrations tend to increase fast at the beginning of the flood stream. When the reversal point of the tide is reached and the flood stream turns to ebb tide, sedimentation processes are decreasing the suspended sediment concentrations abruptly. Therefore a sediment input to the channel system takes place, which increases in dependence to rising tides. Regarding those observations it seems to be obvious to expect further increasing sediment concentrations during storm surge conditions. Measurements above the marsh surface of Hallig Nordstrandischmoor during a storm surge in November 2011 revealed suspended sediment concentrations of > 400 mg/l, being comparable to the "Osterwehl" data. Nevertheless, the measured sediment concentrations during spring tide as well as storm surge conditions, are fare exceeding the threshold of Kirwan et al. (2010) (being 30 mg/l), for marsh sustainability during a high rate of SLR (> 20 mm/a). Summing up, it can be reasoned that the suspended sediment concentration seems to be appropriate to enhance marshland accretion by reactivation of the tidal channel system during advantageous weather conditions. To evaluate this measure, a field survey to quantify sediment deposition rates adjacent to active channel systems is highly recommended.

CHAPTER 6 DISCUSSING THE RECENT SITUATION AND FUTURE PERSPECTIVES OF THE HALLIGEN

6.1 HALLIGEN AS AN ANTHROPOGENIC ENVIRONMENT

The recent appearance of the Halligen (especially of Hooge and Langeness) is equivalent to a man-made environment. As a response on environmental threats (more precisely frequent inundations and a loss of land due to erosion, Müller and Fischer 1917), coastal protection constructions were established at the beginning of the 20th century. The recent study shows clearly that there is a strong relation between those anthropogenic activities and hydrological factors at least controlling sediment dynamics. The artificial heightening (block revetments and dykes) of the marsh edge decreases the annual inundation frequency (Schindler and Willim 2014, chapter 2). Gauge level thresholds for an inundation event range between + 88 cm (Nordstrandischmoor) and + 136 cm (Hooge) above MHW, clearly indicating that inundations are related to high intensity storm events (figure 4-5, Schindler et al. 2014b). In contrast to those rare events, the low marshland elevations of + 15 cm (Hooge) to + 37 cm (Nordstrandischmoor) above MHW level would indicate for a pioneer marsh in transition to the low marsh zone that benefits more from a huge inundation frequency than from storm strength (Schuerch et al. 2012). Also vegetation mappings revealed that plant communities on the low elevated meadows and fallows tend to less salt tolerant species of the upper salt marsh (Natho 2007, Petersen 2011.) Therefore we argue that the hydrological management has preserved a marshland, showing hydrological, topographical as well as botanical characteristics typical for the development stage of the higher saltmarsh, on an elevation level indicative for the pioneer marsh below the spring high water level. Also previous studies have suggested human activities to have negative influences on marshland sediment dynamics (e.g. Flemming and Bartholomä 1997, Flemming 2002) and their adaptation to changing environmental conditions in general (Reise 2005). Nevertheless, without coastline constructions, in particular to protect the Halligen against further erosion, the Halligen probably would be completely vanished until today. Hence, they are a metastable environment which has been preserved by human activities until today and which future persistence relies on the appropriate adaptation of recent management strategies to changing environmental conditions.

6.2 THE RECENT ADAPTATION OF THE HALLIGEN TO SEA-LEVEL-RISE

The adaptation of tidal marshlands to SLR depends on different parameters effecting sediment dynamics. In summary those are sediment availability, inundation frequency, and adequate transport mechanisms (Allen 2000, D'Alpaos et al. 2007, Kirwan et al. 2010, Andersen et al. 2011, D'Alpaos et al. 2011). The short- to long term measurements on sediment deposition and vertical accretion have gained the outcome that the recent hydrological management at least results in an insufficient sediment input (chapter 4, Schindler et al. 2014b) and a transport limitation of sediment towards the hinterland (chapter 5). The lack of sediment input by reason of the inundation frequency is inversely related to the standard of protection, defined by the individual dyke (Hooge 1.54 m above MHW and Langeness 0.98 m above MHW) or revetment height (Nordstrandischmoor 0.70 m above MHW) (chapter 2, Schindler and Willim 2014). Nowadays, the total decrease in inundation frequency due to the heightening of the marshland edge is exceeding 90 %. In case of Hallig Hooge the gauge level threshold for an inundation (136 cm above recent MHW level) is reached two times per year (2001 – 2010). Without the dyke, ~ 130 inundations per year would have happened in the same time. The undyked Hallig Nordstrandischmoor shows an inundation frequency which is multiple times higher (15 inundations per year, 2001 – 2010) than Hooge (2 inundations per year, 2001 – 2010). As discussed in chapter 5, the transport limitation obviously results from an obstructed channel system. Tidal gates are closing automatically by rising tides, obstructing the channel system from the sediment source (i.e. the tidal flats adjacent to the marshland). Therefore sedimentation mainly takes place at the marshland edge whereas summer dykes and block revetments could be regarded as an additional barrier for sediment transport. For Hooge and Langeness, the recent lack of accretion (1915 – 2011) in relation to the RMSL rise at the nearby gauge station Wyk, Föhr (2.6 mm/a, 1952 - 2011) is 1.4 to 1.6 mm/a or 120 to 160 % (figure 4-7). At Nordstrandischmoor, where sediment dynamics are less affected by humans, marsh accretion seems to keep pace with RMSL rise (both being 2.6 mm/a). Most interesting for the persistence of the Halligen is the development of the MHW level (5.0 ± 0.3 mm/a), which is a determining factor for the inundation frequency, as well as the HHW level (6.6 ± 3.6) as an indicator for the inundation magnitude. The hydrographical data reveal a striking non-linearity for the high water levels. These are not necessarily dominated by the RMSL trend (Mudersbach et al. 2013, Arns et al. 2014). Also Hallig Nordstrandischmoor, which has the highest adaptation capacity of the three investigated Halligen, cannot compensate the hydrological changes. Based those findings, it is reasoned that the recent hydrological management (especially at Hooge and Langeness) is disadvantageous for the general objective to adapt the marshland to SLR.

6.3 SHALLOW AND DEEP SUBSIDENCE

While referring to sediment dynamics in relation to SLR, the subject of autocompaction as well as isostatic adjustment has to be addressed (cf. figure 1-3). Considering BDD as well as LOI values of the correspondent marsh soil in the calculation of accretion rates (chapter 3, Schindler et al. 2014a), the part of shallow subsidence resulting from decomposition of organic substance is already taken into account (cf. Cahoon et al. 2006, Bartholdy et al. 2010b). A second process which can result in shallow subsidence of young marshlands is peat compaction (Long et al. 2006). Geoengineering surveys (10 reports) provided by the LKN-SH reveal peat formations of 0.7 to 2.2 m thickness only on Hallig Nordstrandischmoor. That information is only punctual and cannot be generalized for the respective Hallig. Nevertheless, reports about the expected subsidence due to building measures also point to higher rates of subsidence on Nordstrandischmoor than on Hooge and Langeness. Considering deeper subsidence due to isostatic movements, there is still a lack of knowledge. Vink et al. (2007) calculated the zone of highest isostatic forebulge subsidence to be on a SSW to NNO axis from the shore of Lower Saxony towards the Dogger Bank. Rates of subsidence decrease in direction of the study area and the former Scandinavian ice shield, until subsidence turns to uplift. Mörner (1980) points the tilting axis to follow a line from Rügen to the north-western coast of Denmark. Therefore, the isostatic movement for the study area is probably limited to a range of 0 to 7.5 m (0 – 0.9 mm/a) for the last 8000 years. Now considering that the process of isostatic forebulge subsidence tends to slow down during the last 5000 years, it can be reasoned that this process is negligible for the North Frisian Wadden Sea. Furthermore Vink et al. (2007) calculated rates of subsidence to be only ~ 0.4 mm/a during the last 5000 years at the German bight. Therefore we expect accretion data to be almost comparable to the elevation change in total.

6.4 FUTURE PERSPECTIVES AND OBJECTIVES

As already mentioned, the future projection of the water levels until 2100 by use of the IPCCs (2013) RMSL scenarios in comparison to the recent marshland accretion until 2011 (figure 4-7) is a simplification. The adaptation of RMSL trends of the northern Atlantic to the German Bight is not undoubtable as well as the linear projection of the observed accretion rates. For the latter, a positive feedback between inundations and sediment deposition is expected to result in an increase of marshland accretion rates (Schindler et al. 2014b in accordance to Stumpf 1983, Andersen and Pejrup 2001, Schuerch et al. 2013). But it seems unlikely that the increasing gap, especially between marshland accretion and the MHW level (> 5.0 ± 0.3 mm/a) as well as the HHW level (6.6 ± 3.8 mm/a) until 2100, will be compensated by enhanced accretion rates.

In consequence, an increase in wave height and period due to higher water levels on the Hallig and a declining wave transmission at the summer dyke (Mai et al. 1998) will result in higher hydrodynamic forces on the marshland and the Warften. Therefore alternative concepts of coastal protection strategies should be developed. In detail, a combination of constructional short-term measures to strengthen the Warften against rising tides and well adapted management strategies to enhance marshland accretion on the long-term could be feasible.

Short-term measures

Recently, the most critical hazard during heavy storms is the wave surge at the Warften, posing a risk for buildings, machinery and livestock. To increase the elevation of the complete dwelling mount is highly cost- and time-intensive and would result in reconstruction of buildings and infrastructures. Therefore the methods of choice have to be cheap and easy to install constructions that would increase the present hazard protection standard of individual Warften. Individual solutions will be developed and tested by hydraulic engineers.

Long-term perspectives

The major outcome of the present study provides the scientific base to discuss long-term strategies for the Halligen. It is obvious that their future persistence depends on the balance of sediment dynamics to environmental changes controlled by inundation frequency and magnitude (Allen 2000, Cahoon et al. 2002b, Nolte et al. 2013). Because of the close interdependency between human activities and inundation frequency (chapter 2, Schindler and Willim 2014), the recent hydrological management strategies have to be regarded as a major cause for the disadvantageous situation of the Halligen (chapter 4, Schindler et al. 2014b). Therefore, the main objective for the upcoming decades is a careful revision of the hydrological management strategy to re-establish (if possible) the sedimentological balance of the marshland while preserving an adequate standard of hazard protection.

First thoughts are addressed on the general need for a heightened marshland edge by dykes or block revetments. By dykes, the hinterland is kept dry during fair weather conditions (i.e. summer months) (chapter 2, Schindler and Willim 2014). This aspect is of high interest for economic reason. It guarantees farming as well as the accessibility of the Halligen by tourists. The second important aspect is that the heightening lowers hydrodynamic forces during storm surges by wave transmission at the marshland edge (Mai 1998). Both functions are essential for the Hallig and their inhabitants. As to remove those structures completely is out of question, it is still possible to improve them for new requirements. Major aspects are the critical height as well as the water and sediment permeability. To lower the summer dyke (especially at Hallig Hooge) would increase the inundation frequency and sediment input. To calculate a critical height is a matter of statistic calculation involving hydrographical as well as sedimentological data. It is defined by an adequate flood protection during the summer month and the threshold for a gauge level related to a sufficient sediment transport. If the focus of future protection strategies could be shifted towards wave transmission instead of flood retention, the replacement of impermeable dykes by water and sediment permeable block or gravel revetments could be feasible. Modern constructions like the Elastocoast® (BASF) gravel revetment (fig. 2-3b) are recently tested by the Department of river and Coastal Engineering (University Hamburg-Harburg) on their durability as well as on flow rate and sediment transport capacity.

An additional approach to enhance sediment transport to the marshland is the reactivation of the tidal channel system as tested by a field experiment described in chapter 5. Whether this renaturation measure is a successful approach or not is also a matter of the general adaptation capacity of tidal marshes to SLR. There is an ongoing controversial discussion about this topic. With regard to calculations of Bartholdy et al. (2004) who expected the inner marsh of the peninsula of Skallingen, Denmark to drown by a constant short-term SLR of 4.2 mm/a, even the moderate increase of the RMSL to ~ 53 cm GOL (until 2100) due to the IPCC (2013) RCP 4.5 scenario (~ 75 cm GOL, RCP 8.5 scenario) is critical for the persistence of the Halligen. In contrast, further studies predict Dutch tidal marshes (Essink et al. 2005) as well as tidal marshes in general (Kirwan et al. 2010) to survive at SLR rates ranging from > 8.5 mm/a to > 20 mm/a. Also the high tidal range of the study cite (~ 3.5 m), which has a strong interdependency to sediment supply (cf. Kirwan et al. 2010, Kirwan and Guntenspergen 2010), has to be regarded as beneficial. The implementation of such a strategy is the second critical point. In detail this involves financial aspects for the reactivation of obstructed tidal channels and ditches as well as the willingness of the inhabitants to cope with an increased inundation frequency. To limit economic damage, inundations are only acceptable during times of low farming activity and tourism (i.e. winter month). This in turn increases the need for engineering solutions which allows to temporally open channel systems.

To develop constructive solutions for the Halligen, the discussion started above has to be forced by local decision makers and the inhabitants themselves. To do so, it is necessary to realize that inundations and storm surges are not solely a hazard for the Halligen and their inhabitants but also a natural hydrological phenomenon that is essential to keep sediment accretion in balance to SLR.

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APPENDIX

(A) GAUGE LEVEL ANALYSES

Gauge station	**WW**
Wyk/Föhr (Langeness)	1952-1961

gauge level	**WW**									
PNP cm	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
600	488	491	446	485	481	490	477	449	436	591
610	404	382	347	376	372	383	368	324	324	495
620	299	279	259	269	259	279	263	215	223	381
630	218	168	184	183	178	189	176	135	138	274
640	148	107	135	129	129	146	112	85	88	168
650	107	73	89	89	90	105	78	57	51	107
660	79	48	64	65	67	68	51	44	31	68
670	63	27	47	47	48	49	41	30	23	47
680	45	12	32	36	39	41	29	21	16	29
690	35	10	20	24	29	24	24	15	11	22
700	24	6	14	17	21	16	19	12	5	15
710	16	6	10	13	19	13	15	8	4	7
720	9	3	9	11	14	11	10	5	2	7
730	8	3	7	11	12	7	7	2	1	4
LU_Nord 737	7	3	6	8	10	6	3	2	0	3
LU_A-Lan 740	6	2	6	8	10	6	2	2	0	3
750	4	1	3	6	9	4	1	2	0	2
vLU_Nord 759	4	1	3	6	5	4	1	2	0	2
760	4	1	3	6	5	4	0	2	0	2
770	1	1	2	5	4	1	0	2	0	2
vLU_A-Lan 773	1	1	2	4	3	0	0	2	0	2
780	0	1	2	3	3	0	0	0	0	1
790	0	0	2	3	2	0	0	0	0	1
800	0	0	2	3	2	0	0	0	0	1
810	0	0	2	2	1	0	0	0	0	0
820	0	0	1	0	0	0	0	0	0	0
830	0	0	1	0	0	0	0	0	0	0
840	0	0	1	0	0	0	0	0	0	0
850	0	0	0	0	0	0	0	0	0	0
860	0	0	0	0	0	0	0	0	0	0
870	0	0	0	0	0	0	0	0	0	0
880	0	0	0	0	0	0	0	0	0	0
890	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0
910	0	0	0	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Wyk/Föhr 1962-1971
(Langeness)

gauge level	**WW**									
PNP cm	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
600	526	411	436	485	525	563	500	466	516	464
610	429	293	352	384	437	485	424	367	431	365
620	321	204	247	275	335	388	315	270	332	269
630	234	134	172	202	244	296	227	183	243	189
640	172	91	118	138	165	208	152	105	183	117
650	124	59	78	97	118	153	110	76	124	73
660	86	40	53	67	87	113	77	49	84	54
670	55	26	36	47	68	91	48	34	64	43
680	36	16	26	31	45	61	36	25	44	28
690	30	14	19	21	25	50	27	17	34	18
700	23	12	12	17	17	39	18	13	26	16
710	16	9	8	13	12	32	14	10	19	11
720	14	6	7	10	8	26	11	4	11	7
730	11	4	7	9	6	16	9	2	10	6
LU_Nord 737	8	2	7	8	6	15	9	2	8	5
LU_A-Lan 740	8	2	5	6	5	15	9	2	8	5
750	8	1	4	4	5	10	7	2	8	3
vLU_Nord 759	8	0	3	3	3	8	4	2	4	1
760	8	0	3	3	3	8	3	2	3	1
770	7	0	3	2	3	5	3	0	2	0
vLU_A-Lan 773	7	0	2	1	3	5	3	0	2	0
780	4	0	2	0	3	4	1	0	1	0
790	4	0	0	0	3	4	1	0	1	0
800	3	0	0	0	3	4	1	0	0	0
810	3	0	0	0	3	4	1	0	0	0
820	2	0	0	0	1	4	1	0	0	0
830	1	0	0	0	1	3	1	0	0	0
840	1	0	0	0	1	3	1	0	0	0
850	1	0	0	0	1	3	1	0	0	0
860	1	0	0	0	0	1	1	0	0	0
870	1	0	0	0	0	0	0	0	0	0
880	1	0	0	0	0	0	0	0	0	0
890	1	0	0	0	0	0	0	0	0	0
900	1	0	0	0	0	0	0	0	0	0
910	1	0	0	0	0	0	0	0	0	0
920	1	0	0	0	0	0	0	0	0	0
930	1	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Wyk/Föhr 1972-1981
(Langeness)

gauge level PNP cm	**WW** 1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
600	463	536	531	560	504	515	531	523	552	570
610	362	430	439	478	404	407	448	438	462	493
620	270	315	335	380	307	295	348	340	356	380
630	179	221	248	291	209	210	258	239	260	274
640	109	145	182	215	145	140	181	146	177	199
650	74	95	131	159	99	101	133	91	128	146
660	47	59	90	121	65	60	86	55	89	105
670	29	39	68	87	47	38	62	40	66	79
680	20	30	54	66	33	24	48	29	51	61
690	15	18	36	50	28	17	38	19	37	46
700	11	12	33	34	19	11	28	9	27	32
710	7	7	26	25	13	9	21	4	19	22
720	5	4	22	16	12	6	16	4	11	15
730	5	3	18	13	8	4	12	4	6	11
LU_Nord 737	4	2	14	12	7	3	10	4	4	9
LU_A-Lan 740	4	2	12	10	6	3	10	4	3	8
750	1	0	11	8	6	3	7	2	2	6
vLU_Nord 759	1	0	7	6	6	2	7	1	2	4
760	1	0	7	6	6	2	7	1	2	4
770	1	0	6	5	6	0	7	1	2	3
vLU_A-Lan 773	1	0	6	5	6	0	7	1	2	1
780	0	0	6	5	6	0	7	0	1	1
790	0	0	6	4	5	0	4	0	1	1
800	0	0	6	3	4	0	3	0	1	1
810	0	0	6	2	2	0	2	0	1	0
820	0	0	5	2	2	0	2	0	1	0
830	0	0	5	0	2	0	1	0	0	0
840	0	0	4	0	2	0	0	0	0	0
850	0	0	1	0	2	0	0	0	0	0
860	0	0	1	0	2	0	0	0	0	0
870	0	0	0	0	2	0	0	0	0	0
880	0	0	0	0	2	0	0	0	0	0
890	0	0	0	0	2	0	0	0	0	0
900	0	0	0	0	2	0	0	0	0	0
910	0	0	0	0	2	0	0	0	0	0
920	0	0	0	0	2	0	0	0	0	0
930	0	0	0	0	1	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station	**WW**
Wyk/Föhr (Langeness)	1982-1991

gauge level PNP cm	**WW** 1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
600	577	602	530	551	524	563	612	610	620	562
610	518	529	452	458	463	505	542	541	563	462
620	397	457	352	344	388	413	456	442	467	377
630	291	342	268	240	288	314	368	363	368	268
640	209	261	188	157	198	230	265	279	275	195
650	151	199	137	108	141	158	190	201	205	123
660	108	150	98	68	94	114	140	137	161	99
670	78	118	72	42	63	83	99	91	117	68
680	54	89	53	27	49	65	76	62	89	56
690	42	71	38	15	38	42	49	44	71	41
700	31	60	32	11	29	24	37	30	59	29
710	18	46	26	9	22	20	27	23	51	23
720	12	31	20	7	21	12	20	19	39	18
730	8	26	18	4	13	6	12	13	32	15
LU_Nord 737	7	23	16	4	9	5	10	10	26	10
LU_A-Lan 740	7	21	16	4	8	4	9	9	26	10
750	7	14	11	3	7	3	7	6	21	8
vLU_Nord 759	5	13	9	2	5	2	6	6	17	3
760	5	13	9	2	5	2	6	6	17	3
770	2	10	7	2	3	1	5	6	16	3
vLU_A-Lan 773	2	10	7	1	3	1	3	6	15	3
780	2	8	7	1	2	0	3	3	13	3
790	2	7	4	1	2	0	2	3	9	2
800	2	7	3	1	2	0	1	3	8	2
810	2	7	2	0	2	0	0	1	7	2
820	2	5	2	0	1	0	0	1	6	2
830	2	4	1	0	1	0	0	0	5	1
840	2	3	1	0	1	0	0	0	4	1
850	1	1	1	0	0	0	0	0	4	1
860	1	0	0	0	0	0	0	0	4	1
870	1	0	0	0	0	0	0	0	4	1
880	1	0	0	0	0	0	0	0	4	1
890	1	0	0	0	0	0	0	0	3	1
900	1	0	0	0	0	0	0	0	3	0
910	1	0	0	0	0	0	0	0	2	0
920	1	0	0	0	0	0	0	0	2	0
930	1	0	0	0	0	0	0	0	1	0
940	1	0	0	0	0	0	0	0	0	0
950	1	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Wyk/Föhr 1992-2001
(Langeness)

gauge level	**WW**									
PNP cm	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
600	580	583	606	640	525	644	620	644	655	629
610	497	498	524	574	438	574	564	569	614	568
620	395	408	434	467	345	487	494	488	548	486
630	300	298	339	392	233	368	405	373	436	381
640	221	203	254	300	146	257	306	282	310	281
650	165	151	178	231	87	180	208	195	230	197
660	104	106	123	173	55	118	140	141	150	118
670	78	80	94	127	30	79	93	96	99	81
680	60	60	69	92	18	65	69	59	70	49
690	45	50	53	68	11	44	42	41	58	31
700	33	41	42	45	7	30	30	31	44	20
710	23	36	25	31	4	24	24	18	35	12
720	16	29	18	25	3	18	19	17	25	9
730	12	24	11	20	2	13	16	13	21	8
LU_Nord 737	9	21	9	19	2	10	12	10	15	7
LU_A-Lan 740	9	20	9	15	2	10	11	8	14	7
750	6	17	6	13	1	6	10	5	9	5
vLU_Nord 759	5	13	6	10	1	5	8	4	9	4
760	4	13	6	8	1	5	8	4	9	4
770	3	10	6	4	0	5	6	3	8	2
vLU_A-Lan 773	3	10	6	4	0	5	5	3	7	2
780	3	9	6	3	0	5	3	2	4	1
790	2	7	5	1	0	2	2	2	3	1
800	1	5	5	1	0	2	2	1	3	1
810	1	4	5	0	0	1	1	1	3	1
820	1	3	5	0	0	0	0	1	2	1
830	1	2	2	0	0	0	0	1	2	1
840	1	1	1	0	0	0	0	1	2	1
850	1	1	1	0	0	0	0	1	2	1
860	1	1	1	0	0	0	0	1	1	0
870	0	1	1	0	0	0	0	1	1	0
880	0	1	1	0	0	0	0	1	1	0
890	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0
910	0	0	0	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Wyk/Föhr 2002-2012
(Langeness)

gauge level	**WW**									
PNP cm	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
600	640	599	626	619	590	642	646	604	608	629
610	598	536	585	555	546	604	608	542	556	581
620	528	458	506	471	480	532	541	467	490	504
630	429	361	415	376	382	451	447	379	384	409
640	326	266	318	271	285	343	341	272	275	294
650	221	175	230	188	203	260	263	182	199	207
660	164	110	146	133	127	196	200	123	130	127
670	124	62	91	96	74	156	148	85	77	89
680	92	41	62	68	36	102	102	56	48	56
690	68	29	43	48	23	74	81	34	23	39
700	47	19	35	35	14	52	51	21	13	26
710	29	11	25	24	10	39	39	14	9	19
720	21	7	15	22	6	30	31	11	6	13
730	15	3	12	18	4	22	21	6	5	7
LU_Nord 737	13	2	11	16	4	18	16	5	4	6
LU_A-Lan 740	12	0	11	15	4	17	14	5	4	4
750	11	0	8	9	3	14	12	3	3	3
vLU_Nord 759	8	0	5	7	2	10	8	3	3	2
760	6	0	5	7	2	9	8	3	3	2
770	4	0	2	6	2	5	7	3	1	2
vLU_A-Lan 773	4	0	2	6	0	4	7	3	1	2
780	3	0	1	5	0	3	4	3	1	2
790	3	0	1	5	0	3	3	2	1	2
800	2	0	1	2	0	2	3	0	1	2
810	2	0	1	2	0	2	3	0	0	2
820	1	0	0	0	0	2	2	0	0	2
830	1	0	0	0	0	2	2	0	0	1
840	1	0	0	0	0	2	0	0	0	0
850	1	0	0	0	0	0	0	0	0	0
860	1	0	0	0	0	0	0	0	0	0
870	1	0	0	0	0	0	0	0	0	0
880	0	0	0	0	0	0	0	0	0	0
890	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0
910	0	0	0	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0
960	0	0	0	0	0	0	0	0	0	0

Gauge station	**WW**									
Hooge/Anleger (Hooge)	1978-1987									
gauge level	**WW**									
PNP cm	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
600	554	574	620	601	598	616	539	563	543	564
610	483	529	563	534	545	559	469	476	476	508
620	384	451	471	449	442	475	383	379	411	424
630	285	357	368	327	319	376	301	275	321	331
640	210	258	261	241	236	282	220	183	213	239
650	146	167	180	170	163	206	151	107	148	155
660	98	96	119	126	111	157	107	72	92	117
670	62	57	79	85	78	117	67	45	61	77
680	48	33	61	66	53	87	54	28	45	50
690	37	23	44	49	38	65	44	15	39	36
700	29	10	29	38	29	54	31	11	26	23
710	18	6	24	23	17	38	24	7	19	13
720	13	4	14	13	10	29	20	6	15	6
730	11	4	7	11	8	22	15	4	12	5
740	8	3	4	8	7	16	10	3	8	2
750	7	2	2	7	6	12	8	3	6	1
760	7	2	2	4	3	8	7	2	5	0
770	7	1	2	2	2	8	6	1	3	0
LU_Hooge 773	7	0	2	1	2	7	6	1	3	0
780	7	0	1	1	2	7	3	1	1	0
790	4	0	1	1	2	7	3	1	1	0
800	3	0	1	1	2	6	2	1	1	0
vLU_Hooge 806	3	0	1	0	2	5	2	0	1	0
810	3	0	1	0	2	4	1	0	1	0
820	1	0	0	0	2	3	1	0	1	0
830	0	0	0	0	2	2	1	0	1	0
840	0	0	0	0	1	0	0	0	0	0
850	0	0	0	0	1	0	0	0	0	0
860	0	0	0	0	1	0	0	0	0	0
870	0	0	0	0	1	0	0	0	0	0
880	0	0	0	0	1	0	0	0	0	0
890	0	0	0	0	1	0	0	0	0	0
900	0	0	0	0	1	0	0	0	0	0
910	0	0	0	0	1	0	0	0	0	0
920	0	0	0	0	1	0	0	0	0	0
930	0	0	0	0	1	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Hooge/Anleger 1988-1997
(Hooge)

gauge level	**WW**									
PNP cm	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
600	627	630	645	570	606	596	617	650	544	647
610	556	578	596	492	544	536	551	606	472	575
620	490	495	520	384	458	446	463	507	366	495
630	397	411	424	294	343	340	376	421	260	377
640	300	329	326	205	251	237	287	325	157	263
650	209	235	242	142	182	166	200	249	99	177
660	154	162	178	103	129	115	143	187	61	111
670	109	108	132	75	84	87	102	138	33	76
680	76	72	97	56	67	64	69	94	19	61
690	53	48	75	42	43	49	50	65	10	36
700	37	30	62	29	36	38	35	46	6	29
710	24	24	49	23	26	33	18	31	3	19
720	17	15	40	18	17	29	14	24	3	16
730	11	12	34	14	10	24	11	20	2	11
740	7	8	26	10	6	18	7	16	2	7
750	6	6	20	7	6	17	6	12	1	5
760	4	6	16	3	4	12	6	9	1	4
770	4	6	14	3	3	10	6	4	1	4
LU_Hooge 773	3	4	14	3	3	9	6	4	0	3
780	3	3	13	3	3	8	6	3	0	3
790	1	3	9	2	1	5	6	1	0	2
800	0	3	8	2	1	5	5	1	0	1
vLU_Hooge 806	0	1	7	2	1	4	5	1	0	0
810	0	1	7	2	1	4	4	1	0	0
820	0	0	5	1	1	3	3	1	0	0
830	0	0	5	1	1	2	1	0	0	0
840	0	0	4	1	1	1	1	0	0	0
850	0	0	4	1	0	1	1	0	0	0
860	0	0	4	1	0	1	1	0	0	0
870	0	0	3	1	0	1	1	0	0	0
880	0	0	3	0	0	1	1	0	0	0
890	0	0	3	0	0	0	0	0	0	0
900	0	0	2	0	0	0	0	0	0	0
910	0	0	2	0	0	0	0	0	0	0
920	0	0	2	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0

Gauge station Hooge/Anleger (Hooge) — **WW** 1998-2007

gauge level PNP cm	1998	1999	2000	2001	2002 (**WW**)	2003	2004	2005	2006	2007
600	626	652	653	630	643	614	617	613	591	639
610	583	593	619	575	596	552	560	551	551	594
620	503	515	546	490	531	471	472	478	483	523
630	432	412	444	392	449	393	389	385	384	450
640	319	309	331	290	345	289	287	278	287	347
650	235	208	230	210	247	200	190	193	208	258
660	147	145	156	134	178	121	124	134	134	200
670	99	95	97	85	119	63	79	96	73	149
680	68	57	69	49	90	46	55	63	39	97
690	47	43	53	29	58	33	41	39	19	69
700	30	27	38	19	38	20	32	27	14	46
710	22	17	29	12	27	13	21	23	9	37
720	17	16	21	8	18	6	15	19	6	26
730	14	10	15	8	14	4	11	14	4	19
740	10	8	9	7	12	1	9	10	4	14
750	10	5	9	6	8	0	7	7	4	10
760	6	2	8	3	5	0	3	5	2	8
770	4	2	4	2	4	0	2	5	0	4
LU_Hooge 773	4	2	4	1	4	0	1	5	0	4
780	3	2	4	1	3	0	1	5	0	3
790	3	2	3	1	2	0	1	2	0	2
800	2	1	3	1	2	0	0	1	0	2
vLU_Hooge 806	1	1	3	1	2	0	0	1	0	2
810	0	1	2	1	1	0	0	0	0	2
820	0	1	2	1	1	0	0	0	0	2
830	0	1	2	1	1	0	0	0	0	2
840	0	1	2	1	1	0	0	0	0	0
850	0	1	2	0	1	0	0	0	0	0
860	0	1	1	0	1	0	0	0	0	0
870	0	1	0	0	0	0	0	0	0	0
880	0	1	0	0	0	0	0	0	0	0
890	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	0	0	0	0
910	0	0	0	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Hooge/Anleger 2008-2012
(Hooge)

gauge level	**WW**			
PNP cm	2008	2009	2010	2011
600	635	602	606	625
610	598	541	563	575
620	525	463	489	514
630	439	376	401	419
640	331	264	301	299
650	253	178	216	221
660	193	122	141	137
670	143	83	85	96
680	102	55	48	61
690	74	32	25	44
700	49	20	14	22
710	40	13	9	18
720	25	9	6	10
730	17	4	4	6
740	13	4	4	4
750	10	3	3	2
760	7	3	1	2
770	6	3	1	2
LU_Hooge 773	4	2	1	2
780	3	1	1	2
790	3	1	0	2
800	2	0	0	2
vLU_Hooge 806	2	0	0	2
810	2	0	0	2
820	2	0	0	1
830	1	0	0	0
840	1	0	0	0
850	0	0	0	0
860	0	0	0	0
870	0	0	0	0
880	0	0	0	0
890	0	0	0	0
900	0	0	0	0
910	0	0	0	0
920	0	0	0	0
930	0	0	0	0
940	0	0	0	0

Gauge station **WW**
Strucklahnungshörn 1995-2004
(N.Moor)

gauge level PNP cm	WW 1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
600	676	595	680	646	680	687	669	673	666	666
610	659	570	662	630	664	670	644	656	649	640
620	635	524	614	589	633	645	604	628	603	616
630	585	457	554	541	568	615	554	585	543	571
640	509	376	476	484	496	555	479	523	478	508
650	417	287	377	415	403	464	390	441	406	440
660	346	198	274	316	321	360	309	355	309	357
670	268	126	193	236	229	264	211	261	235	265
680	197	80	136	159	161	189	143	180	148	182
690	141	51	90	98	110	118	85	136	87	115
700	100	29	68	70	73	81	56	94	59	78
710	64	15	49	51	52	60	37	68	39	51
720	49	9	34	36	35	47	24	44	27	37
730	32	7	26	24	22	32	13	31	20	31
740	25	3	16	18	16	25	11	23	12	22
LU_N.Moor 745	21	2	15	17	13	22	10	20	11	17
750	20	2	14	14	13	18	8	17	11	16
760	16	2	11	12	10	12	8	12	4	15
vLU_N.Moor 761	16	2	10	12	10	12	8	12	3	15
770	13	2	6	12	6	9	7	12	0	8
780	9	1	4	8	6	8	7	9	0	7
790	7	1	4	5	3	8	3	5	0	4
800	5	1	4	3	3	6	2	4	0	3
810	3	0	3	3	2	4	1	2	0	1
820	2	0	2	2	2	3	1	2	0	1
830	1	0	1	1	1	3	1	1	0	1
840	1	0	0	0	1	3	1	1	0	0
850	1	0	0	0	1	2	1	1	0	0
860	1	0	0	0	1	2	1	1	0	0
870	0	0	0	0	1	2	1	1	0	0
880	0	0	0	0	1	2	0	1	0	0
890	0	0	0	0	1	1	0	1	0	0
900	0	0	0	0	1	1	0	1	0	0
910	0	0	0	0	1	1	0	0	0	0
920	0	0	0	0	1	1	0	0	0	0
930	0	0	0	0	0	1	0	0	0	0
940	0	0	0	0	0	1	0	0	0	0
950	0	0	0	0	0	0	0	0	0	0

Gauge station **WW**
Strucklahnungshörn 2005-2011
(N.Moor)

gauge level	**WW**						
PNP cm	2005	2006	2007	2008	2009	2010	2011
600	666	642	683	674	661	651	663
610	641	622	659	653	627	620	640
620	594	587	628	622	589	591	609
630	533	540	583	584	530	542	556
640	467	471	522	514	457	472	498
650	379	398	459	443	377	389	405
660	298	312	368	351	293	297	314
670	218	227	276	253	198	201	232
680	158	147	207	196	131	129	147
690	108	80	155	143	93	86	107
700	80	47	110	104	64	44	63
710	53	25	78	77	41	31	46
720	36	19	57	57	26	16	30
730	25	11	40	41	19	11	20
740	22	8	29	30	10	10	16
LU_N.Moor 745	20	7	28	25	9	8	12
750	19	6	25	25	7	6	8
760	13	5	19	18	4	4	5
vLU_N.Moor 761	13	5	18	18	4	4	5
770	11	4	12	13	4	3	5
780	10	3	11	9	3	2	2
790	9	2	7	7	3	2	2
800	5	1	4	5	3	1	2
810	4	0	4	4	2	0	2
820	1	0	2	2	1	0	2
830	1	0	2	2	0	0	2
840	1	0	2	2	0	0	1
850	1	0	2	2	0	0	1
860	1	0	2	1	0	0	0
870	0	0	1	1	0	0	0
880	0	0	0	1	0	0	0
890	0	0	0	1	0	0	0
900	0	0	0	0	0	0	0
910	0	0	0	0	0	0	0
920	0	0	0	0	0	0	0
930	0	0	0	0	0	0	0
940	0	0	0	0	0	0	0
950	0	0	0	0	0	0	0

(B) SHORT TERM SEDIMENT DEPOSITION AND ACCRETION MEASUREMENTS

ABBREVIATIONS

Ms	total mass of solids
Org	organics
Mc	mass of clastic solids
Acc	vertical accretion
EZ	single sediment trap
FF	sediment trap in cluster field

Hallig	**year**
Langeness	2010/2011

sample ID		**A (bottle)**					**B (mat)**			
		Ms [g]	**Org [%]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**	**Ms [g]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**
Lan-11-F-01	EZ	2.53	9.14	2.30	3.25	0.59	12.03	10.93	1.82	0.33
Lan-10-F-02	EZ	2.25	14.50	1.92	2.71	0.49	9.11	7.79	1.30	0.24
Lan-10-F-03	EZ									
Lan-10-F-04	EZ						9.99	9.30	1.55	0.28
Lan-10-F-05	EZ	1.52	10.02	1.37	1.93	0.35	8.72	7.84	1.31	0.24
Lan-10-F-06	EZ	1.43	10.52	1.28	1.81	0.33	9.96	8.91	1.49	0.27
Lan-10-F-07	EZ	2.10	8.39	1.92	2.71	0.49	12.88	11.80	1.97	0.36
Lan-10-F-08	EZ	3.15	6.57	2.94	4.15	0.76	17.24	16.11	2.68	0.49
Lan-10-F-09	EZ	5.42	8.03	4.98	7.03	1.28	39.89	36.68	6.11	1.11
Lan-10-F-10	EZ	1.10	5.83	1.04	1.46	0.27	12.51	11.78	1.96	0.36
Lan-10-F-11	EZ	1.45	11.55	1.28	1.81	0.33	10.18	9.01	1.50	0.27
Lan-10-F-12	EZ	1.33	11.21	1.18	1.67	0.30	5.38	4.77	0.80	0.14
Lan-10-F-13	EZ	1.62	7.45	1.50	2.11	0.38	7.11	6.58	1.10	0.20
lan-10-F-14	EZ						24.50	22.79	3.80	0.69
Lan-10-F-15	EZ	2.05	10.17	1.84	2.60	0.47	18.76	16.85	2.81	0.51
Lan-10-F-16	EZ	3.77	7.02	3.50	4.94	0.90	82.20	76.42	12.74	2.32
Lan-10-F-17	EZ	4.42	5.44	4.18	5.89	1.07	42.12	39.82	6.64	1.21
Lan-10-F-18	EZ	6.35	5.23	6.02	8.49	1.55	40.28	38.18	6.36	1.16
Lan-10-F-19	EZ	1.93	5.60	1.83	2.58	0.47	14.84	14.01	2.34	0.43
Lan-10-F-20	EZ	1.80	8.65	1.64	2.32	0.42	9.00	8.22	1.37	0.25
Lan-10-F-21	EZ	1.58	10.69	1.41	2.00	0.36	10.63	9.49	1.58	0.29
Lan-10-F-22	EZ						15.23	14.17	2.36	0.43
Lan-10-F-23	EZ	1.75	10.74	1.56	2.20	0.40	16.63	14.84	2.47	0.45
Lan-10-F-24	EZ	1.57	8.69	1.43	2.02	0.37	12.53	11.44	1.91	0.35
Lan-10-F-25	EZ	1.47	4.71	1.40	1.97	0.36	13.48	12.85	2.14	0.39
Lan-10-F-26	EZ	3.02	9.52	2.73	3.85	0.70	15.44	13.97	2.33	0.42
Lan-10-F-27	EZ	3.57	8.26	3.27	4.62	0.84	34.23	31.40	5.23	0.95
Lan-10-F-28	EZ	13.94	6.07	13.09	18.47	3.36	139.76	131.28	21.88	3.99
Lan-10-F-29	EZ	6.89	3.74	6.63	9.35	1.70	39.06	37.60	6.27	1.14
Lan-10-F-30	EZ	7.47	3.33	7.22	10.19	1.86	66.19	63.99	10.66	1.94
Lan-10-F-31	EZ	2.15	5.94	2.02	2.85	0.52	11.94	11.23	1.87	0.34
Lan-10-F-32	EZ									
Lan-10-F-33	EZ	4.53	6.06	4.26	6.01	1.09	25.26	23.73	3.96	0.72
Lan-10-F-34	EZ	1.40	7.22	1.30	1.83	0.33	9.21	8.54	1.42	0.26
Lan-10-F-35	EZ	1.47	6.95	1.37	1.93	0.35	16.55	15.40	2.57	0.47

Lan-10-F-36	EZ	1.57	8.69	1.43	2.02	0.37	11.01	10.06	1.68	0.31
Lan-10-F-37	EZ	2.25	6.46	2.11	2.97	0.54	18.56	17.36	2.89	0.53
Lan-10-F-38	EZ	3.22	4.93	3.06	4.32	0.79	20.84	19.81	3.30	0.60
Lan-10-F-39	EZ	3.82	4.79	3.63	5.13	0.93	41.19	39.22	6.54	1.19
Lan-10-F-40	EZ	4.93	3.01	4.79	6.75	1.23	56.85	55.14	9.19	1.67
Lan-10-F-41	EZ	6.05	3.52	5.84	8.24	1.50	91.39	88.17	14.70	2.68
Lan-10-F-42	EZ	2.13	7.51	1.97	2.78	0.51	11.70	10.82	1.80	0.33
Lan-10-F-43	EZ	1.87	9.27	1.69	2.39	0.44	16.80	15.25	2.54	0.46
Lan-10-F-44	EZ	1.40	10.74	1.25	1.76	0.32	8.85	7.90	1.32	0.24
Lan-10-F-45	EZ	1.53	1.35	1.51	2.13	0.39	9.33	9.21	1.53	0.28
Lan-10-F-46	EZ	1.60	1.35	1.58	2.23	0.41	9.42	9.29	1.55	0.28
Lan-10-F-47	EZ	1.58	4.46	1.51	2.13	0.39	18.61	17.78	2.96	0.54
Lan-10-F-48	EZ	2.17	5.90	2.04	2.88	0.52	17.54	16.51	2.75	0.50
Lan-10-F-49	EZ						34.60	32.19	5.36	0.98
Lan-10-F-50	EZ	1.68	5.25	1.60	2.25	0.41	15.14	14.35	2.39	0.44
Lan-10-F-51	EZ	4.70	4.15	4.51	6.36	1.16	55.51	53.21	8.87	1.62
Lan-10-F-52	EZ	1.60	5.46	1.51	2.13	0.39	9.68	9.15	1.53	0.28
Lan-10-F-53	EZ	1.95	10.62	1.74	2.46	0.45	9.77	8.73	1.46	0.27
Lan-10-F-54	EZ						18.91	17.59	2.93	0.53
Lan-10-F-55	EZ	2.07	6.12	1.94	2.74	0.50	65.91	61.87	10.31	1.88
Lan-10-F-56	EZ	5.40	3.48	5.21	7.36	1.34	27.81	26.84	4.47	0.81
Lan-10-F-57	EZ	3.15	3.96	3.03	4.27	0.78	23.30	22.38	3.73	0.68
Lan-10-F-58	EZ	3.45	9.93	3.11	4.39	0.80	17.23	15.52	2.59	0.47
Lan-10-F-59	EZ	3.85	6.90	3.59	5.06	0.92	23.35	21.74	3.62	0.66
Lan-10-F-60	EZ	5.15	4.86	4.90	6.91	1.26	61.58	58.59	9.76	1.78
Lan-10-F-61	EZ									
Lan-10-F-62	FF	2.60	5.14	2.47	3.48	0.63	13.91	13.19	2.20	0.40
Lan-10-F-63	FF	2.57	5.19	2.43	3.43	0.63	17.48	16.58	2.76	0.50
Lan-10-F-64	FF	2.38	4.11	2.29	3.23	0.59	14.45	13.86	2.31	0.42
Lan-10-F-65	FF	2.28	6.39	2.14	3.02	0.55	15.10	14.14	2.36	0.43
Lan-10-F-66	FF	2.30	4.92	2.19	3.09	0.56	16.46	15.65	2.61	0.47
Lan-10-F-67	FF	3.52	6.49	3.29	4.64	0.85	43.64	40.80	6.80	1.24
Lan-10-F-68	FF	2.88	5.34	2.73	3.85	0.70	52.77	49.95	8.33	1.52
Lan-10-F-69	FF	2.62	4.49	2.50	3.53	0.64	47.79	45.64	7.61	1.39
Lan-10-F-70	FF	2.92	7.55	2.70	3.81	0.69	47.84	44.23	7.37	1.34
Lan-10-F-71	FF	2.90	8.72	2.65	3.74	0.68	63.34	57.82	9.64	1.76

Hallig **year**
Hooge 2010/2011

sample ID		A (bottle)					B (mat)			
		Ms [g]	Org [%]	Mc [g]	Mc [t/ha]	Acc [mm/a]	Ms [g]	Mc [g]	Mc [t/ha]	Acc [mm/a]
Hog-11-F-01	EZ	2.32	40.38	1.38	1.95	0.39	38.44	22.92	3.82	0.76
Hog-10-F-02	EZ	10.82	3.78	10.41	14.69	2.94	27.60	26.55	4.43	0.89
Hog-10-F-03	EZ	9.02	7.00	8.39	11.83	2.37	77.82	72.38	12.06	2.41
Hog-10-F-04	EZ	4.58	4.22	4.39	6.20	1.24	28.93	27.71	4.62	0.92
Hog-10-F-05	EZ	4.17	5.69	3.93	5.55	1.11	15.61	14.72	2.45	0.49
Hog-10-F-06	EZ	2.22	1.35	2.19	3.09	0.62	19.30	19.04	3.17	0.63
Hog-10-F-07	EZ	3.18	2.38	3.11	4.39	0.88	8.07	7.88	1.31	0.26
Hog-10-F-08	EZ	2.95	2.46	2.88	4.06	0.81	11.08	10.81	1.80	0.36
Hog-10-F-09	EZ	4.53	1.35	4.47	6.31	1.26	12.11	11.94	1.99	0.40
Hog-10-F-10	EZ	4.12	9.34	3.73	5.27	1.05	13.93	12.63	2.10	0.42
Hog-10-F-11	EZ									
Hog-10-F-12	EZ	5.60	9.86	5.05	7.12	1.42	11.54	10.41	1.73	0.35
Hog-10-F-13	EZ	8.04	8.51	7.35	10.37	2.07	73.10	66.88	11.15	2.23
Hog-10-F-14	EZ	3.32	2.83	3.22	4.55	0.91	11.48	11.15	1.86	0.37

Hog-10-F-15	EZ						14.34	13.19	2.20	0.42
Hog-10-F-16	EZ	2.10	7.61	1.94	2.74	0.55	8.84	8.16	1.36	0.27
Hog-10-F-17	EZ	1.48	9.11	1.35	1.90	0.38	6.53	5.93	0.99	0.20
Hog-10-F-18	EZ	5.27	9.78	4.75	6.71	1.34	54.42	49.10	8.18	1.64
Hog-10-F-19	EZ	3.07	4.56	2.93	4.13	0.83	16.26	15.52	2.59	0.52
Hog-10-F-20	EZ	3.33	9.73	3.01	4.25	0.85	12.26	11.06	1.84	0.37
Hog-10-F-21	EZ	1.55	41.66	0.90	1.28	0.26	21.24	12.39	2.07	0.41
Hog-10-F-22	EZ	1.25	13.19	1.09	1.53	0.31	12.27	10.65	1.77	0.35
Hog-10-F-23	EZ	1.33	12.45	1.17	1.65	0.33	8.63	7.56	1.26	0.25
Hog-10-F-24	EZ	4.18	9.99	3.77	5.31	1.06	19.91	17.92	2.99	0.60
Hog-10-F-25	EZ	5.23	6.69	4.88	6.89	1.38	22.39	20.90	3.48	0.70
Hog-10-F-26	EZ	4.92	4.02	4.72	6.66	1.33	19.45	18.67	3.11	0.62
Hog-10-F-27	EZ	2.27	4.97	2.15	3.04	0.61	27.88	26.49	4.42	0.88
Hog-10-F-28	EZ	1.62	6.43	1.51	2.13	0.43	11.24	10.52	1.75	0.35
Hog-10-F-29	EZ	1.20	4.09	1.15	1.62	0.32	10.77	10.33	1.72	0.34
Hog-10-F-30	EZ	1.78	6.88	1.66	2.34	0.47	11.02	10.26	1.71	0.34
Hog-10-F-31	EZ	4.12	2.55	4.01	5.66	1.13	39.59	38.58	6.43	1.29
Hog-10-F-32	EZ	8.45	6.99	7.86	11.09	2.22	54.44	50.63	8.44	1.69
Hog-10-F-33	EZ	2.08	1.35	2.06	2.90	0.58	28.21	27.83	4.64	0.93
Hog-10-F-34	EZ	3.47	7.51	3.21	4.52	0.91	29.42	27.21	4.53	0.91
Hog-10-F-35	EZ	5.62	1.35	5.54	7.82	1.56	83.60	82.47	13.75	2.75
Hog-10-F-36	EZ	8.85	3.39	8.55	12.07	2.41	101.00	97.58	16.26	3.25
Hog-10-F-37	FF	4.80	24.98	3.60	5.08	1.02				
Hog-10-F-38	FF	4.38	11.48	3.88	5.48	1.10				
Hog-10-F-39	FF	4.97	8.96	4.52	6.38	1.28				
Hog-10-F-40	FF	5.70	10.00	5.13	7.24	1.45				
Hog-10-F-41	FF	5.10	9.41	4.62	6.52	1.30				
Hog-10-F-42	FF	5.32	3.82	5.11	7.22	1.44				
Hog-10-F-43	FF	12.20	4.45	11.66	16.45	3.29				
Hog-10-F-44	FF	10.47	6.37	9.80	13.83	2.77				
Hog-10-F-45	FF	9.89	4.34	9.46	13.34	2.67				
Hog-10-F-46	FF	11.49	4.93	10.92	15.41	3.08				

Hallig	**year**
N.Moor	2010/2011

sample ID				**A (bottle)**				**B (mat)**		
		Ms	**Org**	**Mc**	**Mc**	**Acc**	**Ms**	**Mc**	**Mc**	**Acc**
		[g]	**[%]**	**[g]**	**[t/ha]**	**[mm/a]**	**[g]**	**[g]**	**[t/ha]**	**[mm/a]**
Nor-11-F-01	EZ	21.72	3.50	20.96	29.57	3.56				
Nor-10-F-02	EZ	8.59	5.12	8.15	11.50	1.39				
Nor-10-F-03	EZ	7.91	6.32	7.41	10.45	1.26				
Nor-10-F-04	EZ	3.96	6.06	3.72	5.25	0.63				
Nor-10-F-05	EZ	4.03	8.19	3.70	5.22	0.63				
Nor-10-F-06	EZ	18.21	4.12	17.46	24.63	2.97				
Nor-10-F-07	EZ	14.06	3.91	13.51	19.06	2.30				
Nor-10-F-08	EZ	10.67	3.94	10.25	14.46	1.74				
Nor-10-F-09	EZ	7.12	6.04	6.69	9.44	1.14				
Nor-10-F-10	EZ	3.98	10.05	3.58	5.05	0.61				
Nor-10-F-11	EZ	11.25	3.82	10.82	15.26	1.84				
Nor-10-F-12	EZ	8.69	7.25	8.06	11.37	1.37				
Nor-10-F-14	FF	6.54	4.89	6.22	8.78	1.06				
Nor-10-F-13	FF	6.63	5.43	6.27	8.85	1.07				
Nor-10-F-15	FF	6.61	4.84	6.29	8.87	1.07				
Nor-10-F-16	FF									
Nor-10-F-17	FF	6.66	5.56	6.29	8.87	1.07				
Nor-10-F-18	FF	3.63	8.82	3.31	4.67	0.56				

Nor-10-F-19	FF	3.64	7.42	3.37	4.75	0.57
Nor-10-F-20	FF					
Nor-10-F-21	FF	2.82	7.80	2.60	3.67	0.44
Nor-10-F-22	FF	3.26	7.06	3.03	4.27	0.52

Hallig	**year**
Langeness	2011/2012

sample ID		**A (bottle)**					**B (mat)**			
		Ms [g]	**Org [%]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**	**Ms [g]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**
Lan-11-F-01	EZ	7.64	11.62	6.75	9.53	1.73	64.02	56.57	9.43	1.72
Lan-11-F-02	EZ	4.46	24.65	3.36	4.74	0.86	28.67	21.60	3.60	0.66
Lan-11-F-03	EZ									
Lan-11-F-04	EZ	10.94	10.83	9.76	13.76	2.51	108.42	96.68	16.11	2.93
Lan-11-F-05	EZ	5.01	14.33	4.29	6.05	1.10	65.89	56.44	9.41	1.71
Lan-11-F-06	EZ	6.81	24.02	5.17	7.30	1.33	34.49	26.21	4.37	0.80
Lan-11-F-07	EZ	7.21	12.58	6.30	8.89	1.62	49.39	43.17	7.20	1.31
Lan-11-F-08	EZ									
Lan-11-F-09	EZ	8.47	10.87	7.55	10.65	1.94	90.10	80.30	13.38	2.44
Lan-11-F-10	EZ	2.70	13.36	2.34	3.30	0.60	33.93	29.39	4.90	0.89
Lan-11-F-11	EZ	4.68	18.77	3.80	5.36	0.98	38.53	31.30	5.22	0.95
Lan-11-F-12	EZ	4.95	16.19	4.15	5.85	1.07				
Lan-11-F-13	EZ	9.02	14.77	7.69	10.85	1.98	55.29	47.13	7.85	1.43
lan-11-F-14	EZ	6.57	12.31	5.76	8.13	1.48	45.20	39.63	6.61	1.20
Lan-11-F-15	EZ	3.70	13.15	3.21	4.53	0.83	44.09	38.29	6.38	1.16
Lan-11-F-16	EZ	6.43	9.91	5.79	8.17	1.49	81.77	73.66	12.28	2.24
Lan-11-F-17	EZ	7.40	12.28	6.49	9.16	1.67	70.38	61.73	10.29	1.87
Lan-11-F-18	EZ	9.13	17.92	7.49	10.57	1.93	96.83	79.48	13.25	2.41
Lan-11-F-19	EZ	4.11	7.67	3.79	5.35	0.98	38.29	35.35	5.89	1.07
Lan-11-F-20	EZ	6.04	13.58	5.22	7.36	1.34	55.68	48.12	8.02	1.46
Lan-11-F-21	EZ	5.92	12.58	5.18	7.30	1.33	57.70	50.44	8.41	1.53
Lan-11-F-22	EZ	4.04	12.80	3.52	4.97	0.91	51.69	45.07	7.51	1.37
Lan-11-F-23	EZ	3.12	13.33	2.70	3.81	0.69	42.10	36.49	6.08	1.11
Lan-11-F-24	EZ	5.29	11.90	4.66	6.58	1.20	48.98	43.15	7.19	1.31
Lan-11-F-25	EZ	4.46	11.98	3.93	5.54	1.01	41.06	36.15	6.02	1.10
Lan-11-F-26	EZ	7.24	12.83	6.31	8.90	1.62	49.03	42.73	7.12	1.30
Lan-11-F-27	EZ	5.65	13.60	4.88	6.89	1.25	67.88	58.65	9.78	1.78
Lan-11-F-28	EZ	14.77	6.21	13.85	19.54	3.56	150.02	140.71	23.45	4.27
Lan-11-F-29	EZ	18.47	9.43	16.73	23.60	4.30	243.62	220.65	36.77	6.70
Lan-11-F-30	EZ	18.00	5.70	16.97	23.95	4.36	185.24	174.68	29.11	5.30
Lan-11-F-31	EZ	13.68	10.48	12.25	17.28	3.15	95.37	85.38	14.23	2.59
Lan-11-F-32	EZ	12.23	6.45	11.44	16.14	2.94	83.90	78.49	13.08	2.38
Lan-11-F-33	EZ	11.09	8.09	10.19	14.38	2.62	85.97	79.01	13.17	2.40
Lan-11-F-34	EZ	6.32	12.12	5.55	7.84	1.43	54.26	47.69	7.95	1.45
Lan-11-F-35	EZ	4.26	13.50	3.68	5.20	0.95	52.19	45.14	7.52	1.37
Lan-11-F-36	EZ	5.23	12.30	4.59	6.47	1.18	40.16	35.22	5.87	1.07
Lan-11-F-37	EZ	4.74	11.64	4.19	5.91	1.08	44.88	39.65	6.61	1.20
Lan-11-F-38	EZ	6.12	12.41	5.36	7.56	1.38	55.95	49.01	8.17	1.49
Lan-11-F-39	EZ	7.13	10.57	6.38	9.00	1.64	64.29	57.50	9.58	1.75
Lan-11-F-40	EZ						75.64	66.68	11.11	2.02
Lan-11-F-41	EZ	13.83	6.99	12.86	18.15	3.31	120.50	112.08	18.68	3.40
Lan-11-F-42	EZ	7.04	8.83	6.42	9.05	1.65	57.68	52.58	8.76	1.60
Lan-11-F-43	EZ	7.02	11.79	6.19	8.74	1.59	48.76	43.01	7.17	1.31
Lan-11-F-44	EZ	6.80	11.41	6.02	8.50	1.55	62.88	55.71	9.28	1.69
Lan-11-F-45	EZ	7.31	10.47	6.54	9.23	1.68	47.80	42.79	7.13	1.30

Lan-11-F-46	EZ	6.80	12.21	5.97	8.42	1.53	42.73	37.51	6.25	1.14
Lan-11-F-47	EZ	7.85	10.87	7.00	9.87	1.80	56.75	50.58	8.43	1.54
Lan-11-F-48	EZ	6.66	8.08	6.12	8.64	1.57	55.05	50.60	8.43	1.54
Lan-11-F-49	EZ	10.47	7.14	9.72	13.72	2.50	86.89	80.68	13.45	2.45
Lan-11-F-50	EZ	5.29	8.73	4.83	6.81	1.24	39.08	35.67	5.94	1.08
Lan-11-F-51n	EZ	7.68	11.43	6.80	9.60	1.75	54.19	48.00	8.00	1.46
Lan-11-F-52	EZ						46.18	40.71	6.78	1.24
Lan-11-F-53	EZ	7.03	11.99	6.19	8.73	1.59	53.18	46.80	7.80	1.42
Lan-11-F-54n	EZ	24.92	9.22	22.62	31.91	5.81	220.93	200.55	33.43	6.09
Lan-11-F-55	EZ	5.67	10.95	5.05	7.12	1.30	62.92	56.02	9.34	1.70
Lan-11-F-56	EZ	10.20	8.31	9.35	13.19	2.40	104.44	95.75	15.96	2.91
Lan-11-F-57	EZ	6.83	9.76	6.16	8.69	1.58	59.63	53.80	8.97	1.63
Lan-11-F-58	EZ	9.39	11.35	8.32	11.74	2.14	59.74	52.96	8.83	1.61
Lan-11-F-59	EZ	10.42	11.18	9.26	13.06	2.38	72.95	64.80	10.80	1.97
Lan-11-F-60	EZ	7.49	13.17	6.50	9.17	1.67	99.52	86.41	14.40	2.62
Lan-11-F-61	EZ	6.62	14.77	5.64	7.96	1.45	49.43	42.13	7.02	1.28
Lan-11-F-62	FF	7.86	7.71	7.25	10.23	1.86	59.77	55.16	9.19	1.67
Lan-11-F-63	FF	8.13	8.77	7.42	10.46	1.91	55.88	50.98	8.50	1.55
Lan-11-F-64	FF	7.61	8.44	6.97	9.83	1.79	55.78	51.07	8.51	1.55
Lan-11-F-65	FF	7.04	8.87	6.42	9.05	1.65	57.79	52.66	8.78	1.60
Lan-11-F-66	FF	7.30	6.98	6.79	9.58	1.74	47.32	44.01	7.34	1.34
Lan-11-F-67	FF	5.37	12.16	4.72	6.65	1.21	61.53	54.04	9.01	1.64
Lan-11-F-68	FF	5.34	10.88	4.76	6.71	1.22	72.29	64.42	10.74	1.96
Lan-11-F-69	FF	5.48	11.11	4.87	6.87	1.25	63.07	56.06	9.34	1.70
Lan-11-F-70	FF	5.58	13.82	4.81	6.78	1.24	87.34	75.27	12.54	2.28
Lan-11-F-71	FF	5.20	10.95	4.63	6.53	1.19	72.81	64.84	10.81	1.97

Hallig	**year**
Hooge	2011/2012

sample ID		**A (bottle)**					**B (mat)**			
		Ms	**Org**	**Mc**	**Mc**	**Acc**	**Ms**	**Mc**	**Mc**	**Acc**
		[g]	**[%]**	**[g]**	**[t/ha]**	**[mm/a]**	**[g]**	**[g]**	**[t/ha]**	**[mm/a]**
Hog-11-F-01	EZ	7.74	13.75	6.68	9.42	1.88	64.54	55.67	9.28	1.86
Hog-11-F-02	EZ	16.82	8.15	15.45	21.80	4.36	139.60	128.22	21.37	4.27
Hog-11-F-03	EZ	19.25	13.75	16.60	23.42	4.69	209.10	180.36	30.06	6.01
Hog-11-F-04	EZ	16.06	6.62	15.00	21.16	4.23	209.10	195.25	32.54	6.51
Hog-11-F-05	EZ	5.61	11.72	4.95	6.99	1.40	58.54	51.68	8.61	1.72
Hog-11-F-06	EZ	5.09	20.76	4.03	5.69	1.14	37.64	29.82	4.97	0.99
Hog-11-F-07	EZ	7.91	11.55	7.00	9.87	1.97	76.82	67.94	11.32	2.27
Hog-11-F-08	EZ	8.37	12.69	7.31	10.31	2.06	56.17	49.04	8.17	1.63
Hog-11-F-09	EZ	6.98	11.07	6.21	8.76	1.75	49.35	43.89	7.31	1.46
Hog-11-F-10	EZ	4.90	12.29	4.30	6.06	1.21	29.27	25.67	4.28	0.86
Hog-11-F-11	EZ	5.16	13.75	4.45	6.28	1.26	47.29	40.79	6.80	1.36
Hog-11-F-12	EZ	11.27	15.22	9.55	13.48	2.70	70.78	60.01	10.00	2.00
Hog-11-F-13	EZ									
Hog-11-F-14	EZ	3.17	15.64	2.67	3.77	0.75	21.94	18.51	3.09	0.62
Hog-11-F-15	EZ	5.31	14.31	4.55	6.42	1.28	38.84	33.28	5.55	1.11
Hog-11-F-16	EZ	5.88	17.90	4.83	6.81	1.36	36.19	29.71	4.95	0.99
Hog-11-F-17	EZ	2.46	13.45	2.13	3.00	0.60	36.19	31.32	5.22	1.04
Hog-11-F-18	EZ	10.53	16.43	8.80	12.41	2.48	60.31	50.40	8.40	1.68
Hog-11-F-19	EZ	16.96	18.38	13.84	19.53	3.91	124.32	101.46	16.91	3.38
Hog-11-F-20	EZ	11.77	11.96	10.36	14.62	2.92	81.51	71.76	11.96	2.39
Hog-11-F-21	EZ	2.72	15.77	2.29	3.23	0.65	22.33	18.81	3.13	0.63
Hog-11-F-22	EZ	1.90	16.35	1.59	2.24	0.45	16.57	13.86	2.31	0.46

Hog-11-F-23	EZ									
Hog-11-F-24	EZ	9.19	13.75	7.93	11.18	2.24	73.75	63.61	10.60	2.12
Hog-11-F-25	EZ	14.14	7.95	13.02	18.36	3.67	96.52	88.85	14.81	2.96
Hog-11-F-26	EZ	14.80	13.29	12.83	18.10	3.62	76.19	66.07	11.01	2.20
Hog-11-F-27	EZ	2.34	11.78	2.06	2.91	0.58	17.53	15.46	2.58	0.52
Hog-11-F-28	EZ	4.95	19.21	4.00	5.64	1.13	32.22	26.03	4.34	0.87
Hog-11-F-29	EZ	4.58	13.75	3.95	5.57	1.11	44.99	38.80	6.47	1.29
Hog-11-F-30	EZ						50.21	43.32	7.22	1.44
Hog-11-F-31	EZ	14.98	12.82	13.06	18.42	3.69	119.62	104.28	17.38	3.48
Hog-11-F-32	EZ	15.14	14.23	12.99	18.32	3.66	105.28	90.30	15.05	3.01
Hog-11-F-33	EZ	2.80	12.28	2.46	3.47	0.69	24.38	21.39	3.56	0.71
Hog-11-F-34	EZ	7.81	21.90	6.10	8.61	1.72	44.93	35.09	5.85	1.17
Hog-11-F-35	EZ	8.14	11.32	7.22	10.18	2.04	88.90	78.83	13.14	2.63
Hog-11-F-36	EZ	10.01	8.87	9.12	12.87	2.57	92.06	83.89	13.98	2.80
Hog-11-F-37	FF	9.29	9.75	8.38	11.83	2.37	49.76	44.91	7.49	1.50
Hog-11-F-38	FF						53.55	46.21	7.70	1.54
Hog-11-F-39	FF	12.17	13.75	10.50	14.81	2.96	79.57	68.64	11.44	2.29
Hog-11-F-40	FF	8.42	13.42	7.29	10.28	2.06	79.57	68.90	11.48	2.30
Hog-11-F-41	FF	8.00	12.82	6.97	9.84	1.97	62.58	54.55	9.09	1.82
Hog-11-F-42	FF	3.01	23.76	2.29	3.24	0.65	29.06	22.16	3.69	0.74
Hog-11-F-43	FF	3.82	12.58	3.34	4.71	0.94	26.45	23.12	3.85	0.77
Hog-11-F-44	FF	3.63	13.75	3.13	4.42	0.88	28.27	24.38	4.06	0.81
Hog-11-F-45	FF						32.88	28.37	4.73	0.95
Hog-11-F-46	FF	3.89	11.09	3.46	4.88	0.98	28.37	25.22	4.20	0.84

Hallig	**year**
N.Moor	2011/2012

sample ID		**A (bottle)**					**B (mat)**			
		Ms [g]	**Org [%]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**	**Ms [g]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**
Nor-11-F-01	EZ	24.48	8.37	22.43	31.65	4.19	138.35	126.77	21.13	2.80
Nor-11-F-02	EZ	29.54	8.59	27.00	38.09	5.04	233.94	213.83	35.64	4.72
Nor-11-F-03	EZ	33.43	10.13	30.04	42.38	5.61	196.30	176.40	29.40	3.89
Nor-11-F-04	EZ	17.45	13.50	15.10	21.30	2.82	160.36	138.72	23.12	3.06
Nor-11-F-05	EZ	36.88	10.63	32.96	46.50	6.15	234.96	209.99	35.00	4.63
Nor-11-F-06	EZ	19.64	7.98	18.07	25.50	3.37	188.25	173.22	28.87	3.82
Nor-11-F-07	EZ	52.27	10.48	46.79	66.01	8.74	267.63	239.59	39.93	5.28
Nor-11-F-08	EZ						178.71	159.99	26.66	3.53
Nor-11-F-09	EZ	43.41	11.72	38.32	54.06	7.15	189.62	167.40	27.90	3.69
Nor-11-F-10	EZ	27.21	14.32	23.31	32.89	4.35	127.58	109.31	18.22	2.41
Nor-11-F-11	EZ	25.29	9.55	22.87	32.27	4.27	201.38	182.14	30.36	4.02
Nor-11-F-12	EZ	24.13	9.99	21.72	30.64	4.05	194.05	174.67	29.11	3.85
Nor-11-F-14	FF	22.77	13.26	19.75	27.86	3.69	161.35	139.95	23.33	3.09
Nor-11-F-13	FF	22.48	9.40	20.37	28.73	3.80	177.24	160.58	26.76	3.54
Nor-11-F-15	FF	26.79	10.34	24.02	33.89	4.48	153.77	137.87	22.98	3.04
Nor-11-F-16	FF	23.97	10.52	21.45	30.26	4.00	182.83	163.60	27.27	3.61
Nor-11-F-17	FF	25.42	9.50	23.01	32.46	4.29	166.06	150.29	25.05	3.31
Nor-11-F-18	FF	18.85	12.98	16.40	23.14	3.06	172.11	149.77	24.96	3.30
Nor-11-F-19	FF	31.17	14.31	26.71	37.68	4.99	151.07	129.45	21.57	2.86
Nor-11-F-20	FF	17.19	12.91	14.97	21.12	2.80	152.00	132.38	22.06	2.92
Nor-11-F-21	FF	17.25	12.90	15.02	21.20	2.81	179.64	156.47	26.08	3.45
Nor-11-F-22	FF	16.72	8.79	15.25	21.51	2.85	156.23	142.49	23.75	3.14
Nor-11-F-23	FF	33.75		30.23	42.65					
Nor-11-F-24	FF	29.93		26.81	37.82					
Nor-11-F-25	FF	30.81		27.60	38.93					

Nor-11-F-26	FF	30.57		27.38	38.63
Nor-11-F-27	FF	19.10		17.11	24.14

Hallig	**year**
Langeness	2012/2013

sample ID		**A (bottle)**					**B (mat)**			
		Ms	**Org**	**Mc**	**Mc**	**Acc**	**Ms**	**Mc**	**Mc**	**Acc**
		[g]	**[%]**	**[g]**	**[t/ha]**	**[mm/a]**	**[g]**	**[g]**	**[t/ha]**	**[mm/a]**
Lan-12-F-01	EZ	8.84	8.42	8.10	11.42	2.08	69.01	63.20	10.53	1.92
Lan-12-F-02	EZ	3.03	13.20	2.63	3.71	0.68	20.71	17.97	3.00	0.55
Lan-12-F-03	EZ									
Lan-12-F-04	EZ	8.07	11.27	7.16	10.10	1.84	56.90	50.48	8.41	1.53
Lan-12-F-05	EZ						32.09	28.59	4.77	0.87
Lan-12-F-06	EZ	2.99	11.86	2.64	3.72	0.68	26.64	23.48	3.91	0.71
Lan-12-F-07	EZ	3.27	11.08	2.91	4.10	0.75	28.40	25.26	4.21	0.77
Lan-12-F-08	EZ	3.78	9.52	3.42	4.82	0.88	34.03	30.79	5.13	0.93
Lan-12-F-09	EZ	4.75	9.78	4.29	6.05	1.10	48.46	43.72	7.29	1.33
Lan-12-F-10	EZ	4.17	11.19	3.70	5.22	0.95	46.98	41.72	6.95	1.27
Lan-12-F-11	EZ	3.38	10.65	3.02	4.26	0.78	34.54	30.86	5.14	0.94
Lan-12-F-12	EZ	3.85	11.86	3.39	4.79	0.87	35.53	31.32	5.22	0.95
Lan-12-F-13	EZ	6.69	11.11	5.95	8.39	1.53	47.39	42.12	7.02	1.28
lan-12-F-14	EZ	3.86	18.81	3.13	4.42	0.81	37.85	30.73	5.12	0.93
Lan-12-F-15	EZ	2.75	11.27	2.44	3.44	0.63	24.34	21.60	3.60	0.66
Lan-12-F-16	EZ	5.02	10.14	4.51	6.36	1.16	55.74	50.09	8.35	1.52
Lan-12-F-17	EZ	4.67	9.77	4.21	5.94	1.08	48.00	43.32	7.22	1.31
Lan-12-F-18	EZ	5.28	13.45	4.57	6.45	1.17	67.54	58.46	9.74	1.77
Lan-12-F-19	EZ									
Lan-12-F-20	EZ	3.15	12.26	2.76	3.90	0.71	23.30	20.44	3.41	0.62
Lan-12-F-21	EZ	3.08	10.10	2.77	3.91	0.71	29.04	26.10	4.35	0.79
Lan-12-F-22	EZ	2.83	16.55	2.36	3.33	0.61	27.37	22.84	3.81	0.69
Lan-12-F-23	EZ	2.23	12.11	1.96	2.77	0.50	23.79	20.91	3.49	0.63
Lan-12-F-24	EZ	3.20	13.13	2.78	3.92	0.71	23.57	20.48	3.41	0.62
Lan-12-F-25	EZ	1.92	11.52	1.70	2.40	0.44	20.75	18.36	3.06	0.56
Lan-12-F-26	EZ	3.02	13.25	2.62	3.70	0.67	29.03	25.18	4.20	0.76
Lan-12-F-27	EZ	2.90	14.38	2.48	3.50	0.64	31.90	27.31	4.55	0.83
Lan-12-F-28	EZ	10.87	4.51	10.38	14.64	2.67	162.32	154.99	25.83	4.70
Lan-12-F-29	EZ	11.66	5.02	11.07	15.62	2.85	121.40	115.30	19.22	3.50
Lan-12-F-30	EZ	8.46	5.30	8.01	11.30	2.06	79.18	74.99	12.50	2.28
Lan-12-F-31	EZ						68.31	60.87	10.14	1.85
Lan-12-F-32	EZ									
Lan-12-F-33	EZ	6.26	8.19	5.75	8.11	1.48	47.51	43.62	7.27	1.32
Lan-12-F-34	EZ	2.29	13.42	1.98	2.80	0.51	21.80	18.87	3.15	0.57
Lan-12-F-35	EZ	2.73	10.99	2.43	3.43	0.62	22.94	20.42	3.40	0.62
Lan-12-F-36	EZ	2.13	10.85	1.90	2.68	0.49	16.04	14.30	2.38	0.43
Lan-12-F-37	EZ	2.27	11.35	2.01	2.84	0.52	15.62	13.85	2.31	0.42
Lan-12-F-38	EZ	3.07	9.06	2.79	3.94	0.72	27.50	25.01	4.17	0.76
Lan-12-F-39	EZ	4.74	12.71	4.14	5.84	1.06	54.01	47.14	7.86	1.43
Lan-12-F-40	EZ	6.60	6.39	6.18	8.72	1.59	68.52	64.14	10.69	1.95
Lan-12-F-41	EZ	8.44	4.17	8.09	11.41	2.08	79.60	76.28	12.71	2.32
Lan-12-F-42	EZ	4.41	6.12	4.14	5.84	1.06	39.08	36.69	6.11	1.11
Lan-12-F-43n	EZ	3.14	10.83	2.80	3.95	0.72	26.63	23.74	3.96	0.72
Lan-12-F-44	EZ	2.58	14.34	2.21	3.12	0.57	20.51	17.57	2.93	0.53
Lan-12-F-45	EZ	2.24	19.28	1.81	2.55	0.46	19.92	16.08	2.68	0.49
Lan-12-F-46	EZ	3.04	13.82	2.62	3.70	0.67	42.20	36.37	6.06	1.10

Lan-12-F-47	EZ	3.80	12.14	3.34	4.71	0.86	32.42	28.48	4.75	0.86
Lan-12-F-48	EZ	2.65	11.83	2.34	3.30	0.60	25.18	22.20	3.70	0.67
Lan-12-F-49	EZ	9.17	3.81	8.82	12.44	2.27	101.82	97.94	16.32	2.97
Lan-12-F-50	EZ									
Lan-12-F-51n	EZ	3.06	10.46	2.74	3.87	0.70	27.52	24.64	4.11	0.75
Lan-12-F-52	EZ	2.30	16.09	1.93	2.72	0.50	18.61	15.62	2.60	0.47
Lan-12-F-53	EZ	2.06	15.77	1.74	2.45	0.45	17.96	15.13	2.52	0.46
Lan-12-F-54n	EZ	3.07	10.75	2.74	3.87	0.70	22.34	19.93	3.32	0.61
Lan-12-F-55	EZ	3.65	9.12	3.32	4.68	0.85	31.51	28.64	4.77	0.87
Lan-12-F-56	EZ	5.73	6.47	5.36	7.56	1.38	47.12	44.08	7.35	1.34
Lan-12-F-57	EZ	4.18	8.10	3.84	5.42	0.99	44.12	40.55	6.76	1.23
Lan-12-F-58	EZ									
Lan-12-F-59	EZ	3.91	9.90	3.52	4.97	0.91	33.51	30.19	5.03	0.92
Lan-12-F-60	EZ	5.23	8.73	4.77	6.73	1.23	57.55	52.53	8.75	1.59
Lan-12-F-61	EZ	8.17	11.89	7.20	10.16	1.85	84.78	74.70	12.45	2.27
Lan-12-F-62	FF									
Lan-12-F-63	FF	4.96	5.86	4.67	6.59	1.20	48.49	45.65	7.61	1.39
Lan-12-F-64	FF	4.75	7.58	4.39	6.19	1.13	44.21	40.86	6.81	1.24
Lan-12-F-65	FF	4.98	11.04	4.43	6.25	1.14	45.68	40.63	6.77	1.23
Lan-12-F-66	FF	4.72	6.03	4.44	6.26	1.14	44.52	41.83	6.97	1.27
Lan-12-F-67	FF	3.75	21.28	2.95	4.16	0.76	41.78	32.89	5.48	1.00
Lan-12-F-68	FF	3.26	10.74	2.91	4.11	0.75	42.98	38.37	6.39	1.16
Lan-12-F-69	FF	3.63	11.75	3.20	4.52	0.82	41.68	36.78	6.13	1.12
Lan-12-F-70	FF	3.82	18.11	3.13	4.41	0.80	51.88	42.49	7.08	1.29
Lan-12-F-71	FF	3.60	11.26	3.19	4.51	0.82	54.53	48.39	8.06	1.47

Hallig	**year**
Hooge	2012/2013

sample ID		**A (bottle)**					**B (mat)**			
		Ms	**Org**	**Mc**	**Mc**	**Acc**	**Ms**	**Mc**	**Mc**	**Acc**
		[g]	**[%]**	**[g]**	**[t/ha]**	**[mm/a]**	**[g]**	**[g]**	**[t/ha]**	**[mm/a]**
Hog-12-F-01	EZ	4.15	13.10	3.61	5.09	1.02	44.96	39.07	6.51	1.30
Hog-12-F-02	EZ	9.46	7.93	8.71	12.29	2.46	65.86	60.63	10.11	2.02
Hog-12-F-03	EZ	13.58	7.91	12.51	17.64	3.53	105.89	97.52	16.25	3.25
Hog-12-F-04	EZ	5.36	7.99	4.93	6.96	1.39				
Hog-12-F-05	EZ									
Hog-12-F-06	EZ	4.05	9.65	3.66	5.16	1.03	29.57	26.72	4.45	0.89
Hog-12-F-07	EZ	4.05	11.40	3.59	5.06	1.01	26.52	23.50	3.92	0.78
Hog-12-F-08	EZ	4.81	11.48	4.26	6.01	1.20	31.96	28.29	4.72	0.94
Hog-12-F-09	EZ	4.64	12.12	4.08	5.75	1.15	31.75	27.90	4.65	0.93
Hog-12-F-10	EZ	6.46	11.77	5.70	8.04	1.61	40.42	35.66	5.94	1.19
Hog-12-F-11	EZ	5.08	15.50	4.29	6.06	1.21	38.29	32.36	5.39	1.08
Hog-12-F-12	EZ	4.40	12.25	3.86	5.45	1.09				
Hog-12-F-13	EZ	4.80	13.78	4.14	5.84	1.17	33.78	29.12	4.85	0.97
Hog-12-F-14	EZ	3.26	11.11	2.90	4.09	0.82				
Hog-12-F-15	EZ	4.41	12.89	3.84	5.42	1.08	37.08	32.30	5.38	1.08
Hog-12-F-16	EZ	4.56	13.07	3.96	5.59	1.12	48.94	42.55	7.09	1.42
Hog-12-F-17	EZ	2.51	13.10	2.18	3.08	0.62	13.75	11.95	1.99	0.40
Hog-12-F-18	EZ	9.01	12.90	7.85	11.07	2.21	52.95	46.12	7.69	1.54
Hog-12-F-19	EZ						47.98	42.61	7.10	1.42
Hog-12-F-20	EZ	5.84	18.40	4.77	6.72	1.34	38.25	31.21	5.20	1.04
Hog-12-F-21	EZ	4.61	11.71	4.07	5.74	1.15	38.63	34.11	5.68	1.14
Hog-12-F-22	EZ	5.30	11.85	4.67	6.59	1.32	27.80	24.51	4.09	0.82
Hog-12-F-23	EZ									

Hog-12-F-24	EZ	5.22	11.79	4.60	6.50	1.30	37.97	33.49	5.58	1.12
Hog-12-F-25	EZ	7.86	11.19	6.98	9.85	1.97	62.21	55.25	9.21	1.84
Hog-12-F-26	EZ	5.08	11.87	4.48	6.32	1.26	44.21	38.96	6.49	1.30
Hog-12-F-27	EZ						71.88	63.84	10.64	2.13
Hog-12-F-28	EZ	4.63	12.17	4.07	5.74	1.15	27.64	24.27	4.05	0.81
Hog-12-F-29	EZ	3.84	11.92	3.38	4.77	0.95	24.76	21.81	3.63	0.73
Hog-12-F-30	EZ	5.35	11.26	4.75	6.70	1.34	33.29	29.54	4.92	0.98
Hog-12-F-31	EZ	6.97	9.00	6.34	8.95	1.79	55.94	50.91	8.48	1.70
Hog-12-F-32	EZ	8.12	6.59	7.59	10.70	2.14	85.90	80.24	13.37	2.67
Hog-12-F-33	EZ	5.90	9.18	5.36	7.56	1.51	52.33	47.52	7.92	1.58
Hog-12-F-34	EZ	7.09	8.17	6.51	9.19	1.84				
Hog-12-F-35	EZ	8.28	8.64	7.56	10.67	2.13	78.10	71.35	11.89	2.38
Hog-12-F-36n	EZ	8.74	6.23	8.20	11.56	2.31	91.48	85.78	14.30	2.86
Hog-12-F-37	FF	5.72	12.28	5.02	7.08	1.42	34.02	29.84	4.97	0.99
Hog-12-F-38	FF	5.22	10.79	4.66	6.57	1.31	35.39	31.57	5.26	1.05
Hog-12-F-39	FF	5.36	9.74	4.84	6.83	1.37	35.05	31.64	5.27	1.05
Hog-12-F-40	FF	5.42	14.47	4.64	6.54	1.31	32.83	28.08	4.68	0.94
Hog-12-F-41	FF									
Hog-12-F-42	FF	5.30	11.85	4.67	6.59	1.32	88.69	78.18	13.03	2.61
Hog-12-F-43	FF	10.35	4.96	9.84	13.88	2.78	93.55	88.91	14.82	2.96
Hog-12-F-44	FF	9.32	5.86	8.77	12.38	2.48	86.61	81.53	13.59	2.72
Hog-12-F-45	FF	8.43	5.12	8.00	11.28	2.26	78.39	74.37	12.40	2.48
Hog-12-F-46	FF	9.73	4.99	9.24	13.04	2.61	89.92	85.43	14.24	2.85

Hallig	**year**
N.Moor	2012/2013

sample ID		**A (bottle)**					**B (mat)**			
		Ms [g]	**Org [%]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**	**Ms [g]**	**Mc [g]**	**Mc [t/ha]**	**Acc [mm/a]**
Nor-12-F-01	EZ	15.18	5.68	14.32	20.20	2.67	114.01	107.53	17.92	2.37
Nor-12-F-02	EZ	9.34	7.63	8.63	12.17	1.61	59.81	55.25	9.21	1.22
Nor-12-F-03	EZ	13.67	8.60	12.49	17.63	2.33	100.25	91.63	15.27	2.02
Nor-12-F-04	EZ	5.51	14.48	4.71	6.65	0.88	44.59	38.13	6.36	0.84
Nor-12-F-05	EZ	5.74	15.18	4.87	6.87	0.91	35.60	30.20	5.03	0.67
Nor-12-F-06	EZ	12.29	8.06	11.30	15.94	2.11	101.37	93.20	15.53	2.06
Nor-12-F-07	EZ	16.52	6.00	15.53	21.91	2.90	125.94	118.38	19.73	2.61
Nor-12-F-08	EZ	11.19	6.39	10.48	14.78	1.96	95.32	89.23	14.87	1.97
Nor-12-F-09	EZ									
Nor-12-F-10	EZ									
Nor-12-F-11	EZ	10.49	9.28	9.52	13.43	1.78	112.85	102.37	17.06	2.26
Nor-12-F-12	EZ	7.96	12.06	7.00	9.88	1.31	63.54	55.88	9.31	1.23
Nor-12-F-14	FF	9.04	11.85	7.97	11.24	1.49	61.63	54.33	9.05	1.20
Nor-12-F-13	FF	8.02	7.49	7.42	10.47	1.39	54.39	50.32	8.39	1.11
Nor-12-F-15	FF	8.22	8.25	7.54	10.64	1.41	59.93	54.99	9.17	1.21
Nor-12-F-16	FF	7.49	9.44	6.78	9.57	1.27	63.04	57.09	9.51	1.26
Nor-12-F-17	FF	8.21	8.34	7.53	10.62	1.40	56.70	51.97	8.66	1.15
Nor-12-F-18	FF	9.36	11.38	8.29	11.70	1.55	71.20	63.09	10.52	1.39
Nor-12-F-19	FF	8.38	9.63	7.57	10.68	1.41	66.81	60.38	10.06	1.33
Nor-12-F-20	FF	8.29	10.02	7.46	10.52	1.39	68.86	61.96	10.33	1.37
Nor-12-F-21	FF	7.81	20.60	6.20	8.75	1.16	59.00	46.84	7.81	1.03
Nor-12-F-22	FF	9.01	12.84	7.85	11.08	1.47	61.47	53.57	8.93	1.18

(C) 137CS AND 210PB DATING

ABBREVIATIONS

dept korr	revised depth
^{210}Pb	radiation of ^{210}Pb
^{214}Pb	radiation of ^{214}Pb
^{137}Cs	radiation of ^{137}Cs
BDD	bulk dry density
LOI	loss on ignition
t	calculated year of deposition

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core ID Hog-11-K-01	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Hog-11-K 01-01	0.24	137.05	14.39	5.24	0.36	36.56	2011
Hog-11-K 01-02	0.79	114.79	18.33	5.89	0.39	25.14	2005
Hog-11-K 01-03	1.45	79.86	17.98	8.33	0.42	20.84	1999
Hog-11-K 01-04	2.47	59.67	19.78	8.94	0.73	13.53	1994
Hog-11-K 01-05	3.66	53.65	15.57	65.09	0.60	16.36	1988
Hog-11-K 01-06	4.71	63.99	19.96	110.09	0.62	19.85	1982
Hog-11-K 01-07	5.90	41.39	16.26	23.08	0.74	14.04	1973
Hog-11-K 01-08	7.05	50.36	17.69	72.83	0.57	21.09	1964
Hog-11-K 01-09	8.02	46.08	15.14	113.57	0.60	22.35	1953
Hog-11-K 01-10	9.22	35.16	15.33	14.39	0.82	17.20	1936
Hog-11-K 01-11	10.75	29.84	18.40	1.38	0.87	10.20	1905
Hog-11-K 01-12	12.68	18.35	18.35	0.72	1.12	5.82	
Hog-11-K 01-13	15.30	24.19	17.41	<	1.51	4.80	
Hog-11-K 01-14	18.19	23.29	20.67	<	1.38	5.44	
Hog-11-K 01-15	20.76	22.54	17.45	<	1.20	5.08	
Hog-11-K 01-16	23.26	19.21	20.70	<	1.30	5.16	
Hog-11-K 01-17	25.81	20.74	20.26	<	1.25	5.25	
Hog-11-K 01-18	28.34	19.34	17.19	<	1.28	5.22	
Hog-11-K 01-19	31.08	16.22	16.95	<	1.45	4.42	
Hog-11-K 01-20	33.83	15.28	15.23	<	1.29	4.20	
Hog-11-K 01-21	36.83	14.16	17.08	<	1.68	4.03	
Hog-11-K 01-22	39.62	14.11	18.28	<	1.09	4.13	
Hog-11-K 01-23	42.12	12.61	16.65	<	1.37	2.81	
Hog-11-K 01-24	44.92	18.96	16.90	<	1.39	4.75	
Hog-11-K 01-25	47.49	10.94	16.00	<	1.16	3.77	
Hog-11-K 01-30	56.05	15.80	16.76	<	1.45	3.26	
Hog-11-K 01-35	70.82	12.94	17.68	<	1.44	2.72	
Hog-11-K 01-40	85.69	17.99	19.11	<	1.46	2.83	
Hog-11-K 01-45	100.44	21.35	25.62	<	1.42	3.06	
Hog-11-K 01-50	114.63	13.39	21.33	<	1.36	3.28	
Hog-11-K 01-55	128.94	18.01	16.72	<	1.45	2.87	
Hog-11-K 01-60	143.54	17.43	18.42	<	1.41	2.74	

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core ID **Hog-11-K-02**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Hog-11-K 02-01	0.12	128.77	12.68	3.79	0.22	47.46	2011
Hog-11-K 02-02	0.49	93.01	14.13	6.28	0.40	45.09	2007
Hog-11-K 02-03	1.02	76.34	17.18	8.36	0.39	29.46	2002
Hog-11-K 02-04	1.75	71.75	9.38	61.97	0.52	23.52	1997
Hog-11-K 02-05	2.54	71.97	13.67	87.48	0.46	29.17	1989
Hog-11-K 02-06	3.36	60.13	13.80	39.21	0.57	24.71	1981
Hog-11-K 02-07	4.22	51.83	12.47	170.18	0.50	29.94	1970
Hog-11-K 02-08	4.97	46.27	11.31	17.20	0.48	29.00	1957
Hog-11-K 02-09	6.06	37.26	14.34	1.07	0.79	16.15	1942
Hog-11-K 02-10	7.96	22.64	18.30	0.52	1.16	6.65	1905
Hog-11-K 02-11	10.50	24.01	21.37	<	1.33	5.61	1876
Hog-11-K 02-12	13.09	17.68	19.86	<	1.20	5.63	
Hog-11-K 02-13	15.60	21.98	21.14	<	1.25	6.11	
Hog-11-K 02-14	18.22	21.90	23.66	<	1.31	5.34	
Hog-11-K 02-15	20.84	19.14	23.56	<	1.25	5.69	
Hog-11-K 02-16	23.41	16.44	22.70	0.46	1.26	5.76	
Hog-11-K 02-17	26.01	20.90	22.33	<	1.26	4.76	
Hog-11-K 02-18	28.69	14.50	22.82	<	1.32	4.67	
Hog-11-K 02-19	31.37	17.74	22.42	<	1.25	4.13	
Hog-11-K 02-20	34.03	17.42	22.40	<	1.29	3.25	
Hog-11-K 02-21	36.63	18.16	23.66	<	1.19	3.60	
Hog-11-K 02-22	39.21	15.80	23.25	<	1.28	3.91	
Hog-11-K 02-23	42.01	10.55	18.98	<	1.39	2.73	
Hog-11-K 02-24	44.80	14.26	24.02	<	1.26	3.83	
Hog-11-K 02-25	47.42	19.13	23.23	<	1.25	4.36	

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core ID **Hog-11-K-03**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Hog-11-K 03-01	0.26	96.45	9.88	2.84	0.32	35.24	2011
Hog-11-K 03-02	0.77	94.34	14.33	2.62	0.32	36.37	2008
Hog-11-K 03-03	1.44	74.66	18.21	2.77	0.44	23.78	2004
Hog-11-K 03-04	2.36	77.77	19.81	9.89	0.51	20.72	2000
Hog-11-K 03-05	3.46	67.27	22.57	29.72	0.59	17.61	1995
Hog-11-K 03-06	4.46	62.47	22.43	137.19	0.43	24.64	1989
Hog-11-K 03-07	5.54	61.45	19.94	31.23	0.67	17.78	1985
Hog-11-K 03-08	6.84	58.05	16.29	29.87	0.61	19.67	1977
Hog-11-K 03-09	7.93	57.88	16.76	98.15	0.51	25.35	1967
Hog-11-K 03-10	8.93	52.25	18.28	104.82	0.54	21.02	1955
Hog-11-K 03-11	10.06	47.28	18.97	7.76	0.61	18.21	1940
Hog-11-K 03-12	11.39	31.64	19.41	1.72	0.68	14.89	1913
Hog-11-K 03-13	13.30	27.67	22.85	0.99	1.04	7.86	1882
Hog-11-K 03-14	15.71	24.71	24.97	0.51	1.06	7.28	
Hog-11-K 03-15	18.18	25.76	23.10	<	1.08	6.97	
Hog-11-K 03-16	20.73	22.88	25.14	0.70	1.13	7.02	
Hog-11-K 03-17	23.19	24.54	21.43	<	1.01	6.71	
Hog-11-K 03-18	25.76	22.12	23.15	0.40	1.21	6.04	

Hog-11-K 03-19	28.37	19.10	22.35	<	1.05	6.65	
Hog-11-K 03-20	30.81	21.62	23.10	<	1.06	6.21	
Hog-11-K 03-21	33.49	23.67	22.88	<	1.24	5.81	
Hog-11-K 03-22	36.13	22.65	23.12	<	1.01	5.49	
Hog-11-K 03-23	38.51	21.45	20.82	<	1.02	5.48	
Hog-11-K 03-24	41.20	23.86	21.70	<	1.26	4.79	
Hog-11-K 03-25	44.03	23.76	23.63	<	1.15	5.22	
Hog-11-K 03-30	51.93	22.42	23.89	0.46	1.12	5.14	
Hog-11-K 03-35	65.13	21.76	25.58	<	1.13	4.84	
Hog-11-K 03-40	78.41	22.44	20.35	<	1.13	4.90	
Hog-11-K 03-45	91.68	24.62	26.18	<	1.12	4.51	
Hog-11-K 03-50	104.69	27.21	24.64	<	1.07	4.28	
Hog-11-K 03-55	116.83	21.57	24.54	<	0.98	4.51	
Hog-11-K 03-60	128.04	28.55	22.06	<	0.92	4.77	

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core ID **Hog-11-K-04**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Hog-11-K 04-01	0.28	91.15	15.60	3.20	0.37	29.75	2011
Hog-11-K 04-02	0.93	72.37	12.30	4.07	0.46	26.75	2006
Hog-11-K 04-03	2.23	47.35	13.06	8.98	0.96	10.93	2001
Hog-11-K 04-04	3.75	50.04	17.94	86.67	0.64	16.67	1993
Hog-11-K 04-05	5.04	46.55	17.56	20.56	0.75	14.14	1987
Hog-11-K 04-06	6.37	47.15	17.11	65.77	0.70	18.58	1979
Hog-11-K 04-07	7.54	52.05	17.63	106.34	0.64	22.19	1969
Hog-11-K 04-08	8.73	37.36	18.96	6.63	0.71	16.67	1954
Hog-11-K 04-09	10.45	29.97	18.49	1.41	1.08	9.57	1939
Hog-11-K 04-10	12.87	25.09	17.34	0.59	1.30	5.32	1913
Hog-11-K 04-11	15.51	22.99	20.22	<	1.25	5.77	
Hog-11-K 04-12	18.24	23.51	23.75	<	1.38	5.26	
Hog-11-K 04-13	20.88	23.54	23.44	<	1.17	6.40	
Hog-11-K 04-14	23.38	23.92	24.82	<	1.26	6.54	
Hog-11-K 04-15	26.07	21.12	22.17	<	1.37	6.71	
Hog-11-K 04-16	28.73	22.02	22.41	<	1.23	6.12	
Hog-11-K 04-17	31.54	18.07	20.60	<	1.48	4.67	
Hog-11-K 04-18	34.44	19.47	24.61	0.49	1.31	6.07	
Hog-11-K 04-19	37.25	11.53	18.60	<	1.38	2.98	
Hog-11-K 04-20	40.16	14.37	19.89	<	1.37	4.29	
Hog-11-K 04-21	42.95	12.93	24.44	<	1.30	5.28	
Hog-11-K 04-22	45.87	15.65	26.50	<	1.47	2.96	
Hog-11-K 04-23	48.99	17.85	25.03	<	1.47	3.00	
Hog-11-K 04-24	51.79	19.09	26.84	<	1.19	5.41	
Hog-11-K 04-25	54.28	21.85	27.06	<	1.21	5.67	
Hog-11-K 04-30	63.07	14.87	21.90	<	1.44	4.32	
Hog-11-K 04-35	77.52	16.54	19.95	<	1.32	4.28	
Hog-11-K 04-40	91.87	15.49	17.63	<	1.42	4.30	
Hog-11-K 04-45	106.24	17.18	23.25	<	1.33	4.71	
Hog-11-K 04-50	120.19	16.55	19.32	<	1.33	3.63	
Hog-11-K 04-55	133.51	20.22	22.96	<	1.21	4.64	
Hog-11-K 04-60	147.09	20.41	24.41	<	1.39	4.32	

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core ID **Lan-11-K-01**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 01-01	0.17	128.95	17.70	3.26	0.23	37.60	2011
Lan-11-K 01-02	0.64	118.67	24.39	5.66	0.37	33.19	2004
Lan-11-K 01-03	1.29	109.42	23.34	8.30	0.41	25.91	1997
Lan-11-K 01-04	2.37	66.80	27.77	19.32	0.71	14.92	1988
Lan-11-K 01-05	3.69	69.79	27.85	79.39	0.61	18.09	1978
Lan-11-K 01-06	4.85	58.86	30.84	52.76	0.60	20.34	1965
Lan-11-K 01-07	6.01	57.18	22.90	81.09	0.63	20.99	1952
Lan-11-K 01-08	7.26	42.01	24.51	9.78	0.65	15.27	1911
Lan-11-K 01-09	9.09	31.24	28.52	1.58	1.08	8.69	
Lan-11-K 01-10	11.44	25.18	20.52	1.16	1.07	6.45	
Lan-11-K 01-11	13.77	21.49	26.29	<	1.02	6.44	
Lan-11-K 01-12	15.99	23.92	33.44	<	0.99	7.54	
Lan-11-K 01-13	18.21	22.09	27.45	<	1.02	7.28	
Lan-11-K 01-14	20.33	19.88	24.01	<	0.89	7.03	
Lan-11-K 01-15	22.34	17.93	24.52	<	0.94	7.73	
Lan-11-K 01-16	24.45	20.37	25.39	<	0.97	7.02	
Lan-11-K 01-17	26.57	18.01	23.53	<	0.94	6.75	
Lan-11-K 01-18	28.56	22.49	26.87	<	0.84	6.90	
Lan-11-K 01-19	30.53	20.65	25.50	<	0.93	7.10	
Lan-11-K 01-20	32.40	24.77	27.08	<	0.76	6.93	
Lan-11-K 01-21	34.23	19.76	23.58	<	0.87	6.21	
Lan-11-K 01-22	36.15	19.17	25.19	<	0.86	6.90	
Lan-11-K 01-23	38.09	21.65	25.85	<	0.89	6.96	
Lan-11-K 01-24	40.13	21.52	27.02	<	0.95	6.65	
Lan-11-K 01-25	42.25	25.29	25.43	<	0.95	6.73	

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core ID **Lan-11-K-02**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 02-01	0.40	93.16	23.62	5.62	0.53	22.67	2011
Lan-11-K 02-02	1.13	113.42	25.02	8.25	0.45	25.50	2006
Lan-11-K 02-03	1.91	87.25	21.76	11.22	0.59	20.60	1999
Lan-11-K 02-04	2.99	72.05	26.09	62.58	0.77	16.98	1991
Lan-11-K 02-05	4.24	68.45	22.73	76.33	0.79	18.85	1982
Lan-11-K 02-06	5.39	62.67	23.97	56.29	0.64	17.90	1968
Lan-11-K 02-07	6.49	50.34	21.82	69.44	0.72	15.81	1953
Lan-11-K 02-08	7.76	41.29	23.97	14.00	0.82	15.54	1932
Lan-11-K 02-09	9.22	33.78	25.31	3.69	0.91	10.96	1898
Lan-11-K 02-10	11.00	24.96	22.95	1.98	1.10	8.09	
Lan-11-K 02-11	12.85	23.56	24.33	0.63	0.97	8.65	
Lan-11-K 02-12	14.59	24.70	23.61	<	0.99	10.09	
Lan-11-K 02-13	16.35	21.54	20.69	<	1.02	10.04	
Lan-11-K 02-14	17.93	18.71	25.78	<	0.78	9.99	
Lan-11-K 02-15	19.58	18.08	31.59	0.75	1.08	8.17	
Lan-11-K 02-16	21.53	18.57	24.69	<	1.08	6.71	
Lan-11-K 02-17	23.57	21.41	26.02	<	1.16	6.66	
Lan-11-K 02-18	25.59	17.95	25.69	<	1.06	6.65	

Lan-11-K 02-19	27.48	20.40	24.71	<	1.01	6.16	
Lan-11-K 02-20	29.50	22.24	23.09	<	1.21	6.35	
Lan-11-K 02-21	31.54	23.06	25.89	<	1.03	5.72	
Lan-11-K 02-22	33.44	18.98	24.86	<	1.04	6.47	
Lan-11-K 02-23	35.40	19.17	28.57	<	1.11	5.35	
Lan-11-K 02-24	37.55	18.14	28.27	<	1.24	6.31	
Lan-11-K 02-25	39.63	23.06	28.89	<	1.03	6.01	
Lan-11-K 02-30	45.96	17.84	21.63	<	1.16	4.65	
Lan-11-K 02-35	56.58	24.26	27.24	<	1.13	4.80	
Lan-11-K 02-40	66.85	23.43	24.45	<	1.08	4.64	
Lan-11-K 02-45	77.30	21.22	27.39	<	1.16	4.09	
Lan-11-K 02-50	87.87	16.16	29.79	<	1.11	4.66	
Lan-11-K 02-55	98.30	20.18	23.80	<	1.13	4.09	
Lan-11-K 02-60	109.20	18.03	25.43	<	1.20	3.80	

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core ID **Lan-11-K-03**	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 03-00	0.20	159.57	11.01	3.81	0.31	37.96	2011
Lan-11-K 03-01	0.59	110.76	15.62	9.22	0.28	37.40	2007
Lan-11-K 03-02	1.04	121.21	17.00	8.22	0.40	35.95	2005
Lan-11-K 03-03	1.79	116.15	15.32	6.67	0.61	24.99	2001
Lan-11-K 03-04	2.85	89.44	22.50	10.14	0.66	17.88	1994
Lan-11-K 03-05	4.01	67.93	21.66	14.12	0.67	17.01	1988
Lan-11-K 03-06	5.24	73.04	22.73	58.87	0.71	14.56	1983
Lan-11-K 03-07	6.84	48.79	21.51	95.13	1.05	12.35	1976
Lan-11-K 03-08	8.58	43.03	16.85	28.28	0.88	16.30	1969
Lan-11-K 03-09	9.98	50.13	18.12	34.13	0.73	17.81	1962
Lan-11-K 03-10	11.22	51.50	18.39	46.54	0.69	17.17	1954
Lan-11-K 03-11	12.93	46.60	17.50	21.20	1.20	11.65	1942
Lan-11-K 03-12	15.17	25.88	18.41	5.14	1.16	7.21	1904
Lan-11-K 03-13	17.32	26.36	19.29	2.09	1.01	5.05	1879
Lan-11-K 03-14	19.32	22.53	19.92	1.23	1.03	8.70	
Lan-11-K 03-15	21.59	22.81	22.17	1.93	1.31	7.33	
Lan-11-K 03-16	23.82	24.73	20.16	0.73	0.97	6.76	
Lan-11-K 03-17	25.83	20.89	24.14	0.77	1.08	6.97	
Lan-11-K 03-18	28.03	26.12	22.51	0.64	1.15	6.16	
Lan-11-K 03-19	30.33	18.89	20.97	<	1.18	6.04	
Lan-11-K 03-20	32.47	23.19	21.47	0.44	0.98	6.24	
Lan-11-K 03-21	34.56	22.86	23.08	0.44	1.12	5.82	
Lan-11-K 03-22	36.99	19.78	22.88	0.46	1.31	4.66	
Lan-11-K 03-23	39.41	17.05	19.13	0.59	1.10	5.25	
Lan-11-K 03-24	41.55	13.82	19.93	<	1.06	6.19	
Lan-11-K 03-25	48.17	22.27	24.85	0.42	1.12	5.83	

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core ID Lan-11-K-04	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 04-01	0.17	107.01	13.88	5.89	0.27	36.04	2011
Lan-11-K 04-02	0.53	108.32	18.00	7.45	0.28	33.88	2008
Lan-11-K 04-03	0.97	93.42	15.72	6.04	0.38	33.49	2005
Lan-11-K 04-04	1.49	78.93	17.82	10.80	0.38	29.68	2001
Lan-11-K 04-05	2.38	47.74	14.88	12.73	0.73	15.25	1997
Lan-11-K 04-06	3.55	46.28	12.71	11.63	0.64	11.86	1993
Lan-11-K 04-07	4.73	46.66	14.24	90.18	0.70	12.40	1989
Lan-11-K 04-08	5.98	52.54	17.71	75.71	0.73	12.53	1983
Lan-11-K 04-09	7.22	42.37	18.59	24.58	0.70	13.97	1976
Lan-11-K 04-10	8.37	48.40	19.15	37.03	0.64	13.78	1970
Lan-11-K 04-11	9.56	44.94	15.83	79.94	0.73	12.03	1962
Lan-11-K 04-12	10.90	43.14	20.12	25.29	0.78	8.89	1949
Lan-11-K 04-13	12.64	27.85	16.34	3.54	1.10	6.19	1932
Lan-11-K 04-14	14.68	29.17	16.62	1.75	1.05	4.36	1910
Lan-11-K 04-15	16.79	14.77	16.17	1.00	1.16	3.84	
Lan-11-K 04-16	18.97	20.13	17.16	1.21	1.12	3.74	
Lan-11-K 04-17	21.14	19.81	18.27	0.59	1.14	4.37	
Lan-11-K 04-18	23.37	20.65	18.18	<	1.19	3.49	
Lan-11-K 04-19	25.44	15.56	16.26	<	0.98	5.15	
Lan-11-K 04-20	27.40	20.57	21.68	0.64	1.09	4.74	
Lan-11-K 04-21	29.42	20.98	19.69	0.53	1.03	4.62	
Lan-11-K 04-22	31.44	18.84	18.94	<	1.08	4.71	
Lan-11-K 04-23	33.63	19.74	18.53	<	1.22	3.91	
Lan-11-K 04-24	35.60	18.04	18.43	<	0.84	5.17	
Lan-11-K 04-25	37.44	18.39	20.60	0.61	1.09	4.04	

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Langeness

core ID Lan-11-K-05	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 05-01	0.07	142.53	17.48	3.27	0.13	53.63	2011
Lan-11-K 05-02	0.28	112.02	13.84	4.32	0.20	33.17	2006
Lan-11-K 05-03	0.61	75.25	17.40	6.88	0.27	37.06	2000
Lan-11-K 05-04	1.11	85.44	19.19	8.61	0.40	26.18	1996
Lan-11-K 05-05	1.92	67.10	20.37	10.13	0.56	19.02	1987
Lan-11-K 05-06	3.09	65.47	23.09	62.11	0.76	16.70	1979
Lan-11-K 05-07	4.37	61.09	20.60	116.11	0.67	17.89	1971
Lan-11-K 05-08	5.68	44.59	19.99	30.20	0.80	16.68	1956
Lan-11-K 05-09	6.91	42.00	21.63	54.69	0.56	16.66	1947
Lan-11-K 05-10	8.18	40.24	27.53	55.24	0.83	15.81	1935
Lan-11-K 05-11	9.68	35.05	24.42	9.40	0.81	13.55	1920
Lan-11-K 05-12	11.31	30.90	23.23	3.11	0.89	9.63	1897
Lan-11-K 05-13	13.52	23.74	23.54	0.58	1.33	6.10	
Lan-11-K 05-14	15.98	24.87	23.57	0.67	1.10	6.41	
Lan-11-K 05-15	18.05	29.32	24.28	<	0.97	8.01	
Lan-11-K 05-16	20.03	21.17	23.86	0.67	1.02	7.68	
Lan-11-K 05-17	22.30	23.53	24.28	<	1.25	7.11	
Lan-11-K 05-18	24.46	21.46	21.73	<	0.90	7.30	

Lan-11-K 05-19	26.45	24.27	23.63	<	1.07	6.74	
Lan-11-K 05-20	28.58	21.35	26.01	<	1.05	6.99	
Lan-11-K 05-21	30.62	23.55	23.14	<	0.98	6.31	
Lan-11-K 05-22	32.56	22.41	22.42	<	0.94	5.79	
Lan-11-K 05-23	34.81	24.07	22.27	<	1.27	5.83	
Lan-11-K 05-24	37.24	16.88	24.66	<	1.10	4.96	
Lan-11-K 05-25	39.28	19.31	23.76	0.60	0.88	5.47	

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core ID Lan-11-K-06	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Lan-11-K 06-01	0.46	74.30	19.07	7.79	0.58	18.89	2011
Lan-11-K 06-02	1.35	59.09	19.13	4.96	0.49	14.55	2007
Lan-11-K 06-03	2.34	52.49	20.89	10.83	0.65	10.12	2004
Lan-11-K 06-04	3.68	43.19	19.38	35.39	0.84	8.50	2001
Lan-11-K 06-05	5.26	39.11	17.26	36.77	0.92	8.29	1997
Lan-11-K 06-06	6.99	32.23	15.61	15.01	0.98	6.57	1993
Lan-11-K 06-07	8.75	38.41	16.88	14.16	0.97	9.15	1989
Lan-11-K 06-08	10.41	33.75	16.45	12.25	0.88	8.48	1984
Lan-11-K 06-09	11.94	36.72	19.53	18.01	0.85	11.44	1979
Lan-11-K 06-10	13.69	29.18	16.88	24.64	1.10	7.15	1974
Lan-11-K 06-11	15.30	33.36	15.62	82.88	0.70	10.91	1968
Lan-11-K 06-12	16.78	33.34	16.53	34.67	0.97	9.86	1962
Lan-11-K 06-13	18.52	28.34	15.75	6.42	0.97	7.82	1951
Lan-11-K 06-14	20.51	28.14	14.74	2.61	1.19	5.29	1939
Lan-11-K 06-15	22.51	22.60	14.10	1.24	0.96	5.60	1911
Lan-11-K 06-16	24.47	18.40	15.00	1.36	1.13	4.13	1875
Lan-11-K 06-17	26.59	14.41	16.36	0.62	1.11	2.96	
Lan-11-K 06-18	28.85	21.15	15.20	<	1.25	3.02	
Lan-11-K 06-19	31.24	20.32	15.03	<	1.25	3.03	
Lan-11-K 06-20	33.72	22.74	17.34	0.37	1.36	3.86	
Lan-11-K 06-21	36.56	17.49	16.18	<	1.63	2.58	
Lan-11-K 06-22	39.24	17.54	16.07	0.40	1.17	2.53	
Lan-11-K 06-23	41.76	21.95	16.75	<	1.46	3.19	
Lan-11-K 06-24	44.48	20.62	16.59	<	1.39	2.32	
Lan-11-K 06-25	47.20	17.91	18.50	<	1.44	2.45	

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core ID Nor-11-K-01	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Nor-11-K 01-01	0.35	104.22	23.66	6.45	0.59	15.15	2011
Nor-11-K 01-02	1.22	100.80	24.64	6.75	0.83	13.38	2008
Nor-11-K 01-03	2.31	84.92	22.48	7.47	0.96	12.69	2004
Nor-11-K 01-04	3.25	71.71	23.92	7.42	0.56	9.89	1999
Nor-11-K 01-05	4.31	60.12	22.87	9.63	1.08	8.73	1997
Nor-11-K 01-06	5.56	40.85	20.59	14.15	0.84	5.97	1993
Nor-11-K 01-07	6.65	39.14	17.73	8.79	0.81	5.30	1991
Nor-11-K 01-08	7.71	52.80	24.54	63.41	0.79	8.06	1987

Nor-11-K 01-09	8.70	44.96	21.57	54.66	0.74	6.98	1985
Nor-11-K 01-10	9.76	46.89	23.29	31.11	0.88	7.46	1982
Nor-11-K 01-11	10.98	43.11	23.09	24.19	1.00	7.74	1979
Nor-11-K 01-12	12.26	49.70	24.33	28.07	0.97	8.61	1975
Nor-11-K 01-13	13.52	38.06	23.01	30.02	0.98	6.98	1972
Nor-11-K 01-14	14.80	39.73	22.00	37.16	0.98	7.97	1966
Nor-11-K 01-15	16.04	39.61	22.35	15.47	0.95	8.97	1963
Nor-11-K 01-16	17.22	38.84	23.62	25.68	0.89	8.51	1958
Nor-11-K 01-17	18.36	34.16	22.33	10.46	0.87	8.06	1953
Nor-11-K 01-18	19.47	33.48	22.60	8.14	0.84	8.13	1948
Nor-11-K 01-19	20.53	33.25	21.48	7.47	0.79	7.98	1944
Nor-11-K 01-20	21.65	28.34	19.47	4.70	0.93	6.49	1940
Nor-11-K 01-21	22.81	24.81	19.46	5.21	0.82	6.15	1933
Nor-11-K 01-22	23.92	25.13	19.74	2.71	0.86	5.34	1928
Nor-11-K 01-23	24.97	24.29	17.83	2.28	0.72	5.01	1924
Nor-11-K 01-24	26.04	23.62	19.26	1.28	0.89	4.68	1921
Nor-11-K 01-25	27.17	24.16	18.96	1.55	0.79	4.65	1915
Nor-11-K 01-30	30.92	23.87	21.01	1.41	0.96	5.08	1911
Nor-11-K 01-35	37.98	19.50	23.67	0.94	1.14	4.59	
Nor-11-K 01-40	45.72	24.45	22.14	<	1.16	4.26	
Nor-11-K 01-45	53.85	21.42	21.77	<	1.25	4.04	
Nor-11-K 01-50	62.19	19.97	22.74	<	1.21	3.39	
Nor-11-K 01-55	70.13	20.94	24.22	<	1.14	4.38	
Nor-11-K 01-60	77.68	22.87	25.44	<	1.10	4.10	

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core ID Nor-11-K-02	depth korr [cm]	^{210}Pb [Bq/kg]	^{214}Pb [Bq/kg]	^{137}Cs [Bq/kg]	BDD [g/cm^3]	LOI [%]	t [year]
Nor-11-K 02-01	0.24	100.36	20.32	4.95	0.35	15.92	2011
Nor-11-K 02-02	0.94	105.25	19.73	5.18	0.65	15.92	2009
Nor-11-K 02-03	1.84	101.20	20.13	6.06	0.63	14.65	2005
Nor-11-K 02-04	2.85	80.52	22.53	5.92	0.77	12.56	2001
Nor-11-K 02-05	4.01	71.52	20.05	6.91	0.81	10.94	1997
Nor-11-K 02-06	5.09	57.34	18.85	8.62	0.64	10.45	1992
Nor-11-K 02-07	6.30	46.96	21.61	26.86	0.95	7.22	1989
Nor-11-K 02-08	7.74	48.82	22.51	9.04	0.92	7.15	1986
Nor-11-K 02-09	9.03	56.40	20.14	82.67	0.77	9.63	1982
Nor-11-K 02-10	10.22	50.35	21.48	28.36	0.81	8.68	1978
Nor-11-K 02-11	11.45	47.70	20.73	22.25	0.81	9.58	1973
Nor-11-K 02-12	12.75	46.82	20.41	21.26	0.91	8.86	1968
Nor-11-K 02-13	14.16	33.99	17.18	16.86	0.94	7.61	1962
Nor-11-K 02-14	15.61	34.67	18.39	32.50	0.95	7.42	1957
Nor-11-K 02-15	16.94	35.15	20.84	36.43	0.79	9.28	1951
Nor-11-K 02-16	18.24	30.80	15.77	21.06	0.93	8.77	1946
Nor-11-K 02-17	19.67	35.89	22.59	10.11	0.95	8.58	1939
Nor-11-K 02-18	21.05	27.14	18.07	4.57	0.86	8.39	1930
Nor-11-K 02-19	22.27	24.82	18.91	3.96	0.74	8.27	1923
Nor-11-K 02-20	23.65	28.63	18.90	2.01	1.04	6.51	1918
Nor-11-K 02-21	25.22	29.48	20.27	1.62	0.98	6.47	1904
Nor-11-K 02-22	26.78	26.17	17.30	1.37	1.01	5.63	1881
Nor-11-K 02-23	28.35	20.07	19.26	<	1.00	5.57	
Nor-11-K 02-24	30.04	22.40	17.89	<	1.14	5.29	
Nor-11-K 02-25	31.85	22.60	16.75	<	1.14	4.13	

Nor-11-K 02-30	36.80	22.47	18.50	<	1.02	5.04
Nor-11-K 02-35	44.89	26.30	24.77	<	1.03	5.45
Nor-11-K 02-40	53.15	22.88	21.06	<	1.06	4.97
Nor-11-K 02-45	61.56	23.63	20.52	<	1.06	4.85

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Ph.D.-student at the Department of Sedimentology & Environmental Geology,
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