Chapter 1

Introduction

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The salt marsh of Schiermonnikoog.
1.1 Introduction: salt marshes

Coastal salt marshes are areas vegetated by salt-tolerant plant species that are subject to periodic flooding as a result of fluctuations in the level of the adjacent saline-water bodies (Adam, 1990) (Figure 1.1). Salt marshes are dynamic systems that are characterised by a balance between vertical accretion and erosion, and a feedback between vegetation and sedimentation (e.g. Pethick, 1992; Torres et al., 2006; Doody, 2008). On barrier-island salt marshes, which are the focus areas of this thesis, sedimentation ranges from a few mm to a few cm per year and consists of predominantly fine-grained mineral sediment (French, 2006). The sediment is imported by the flooding waters and, to a small extent, produced locally in the form of organic matter by vegetation. During the growth of a marsh, a creek system develops and the marsh may experience lateral accretion and/or erosion.

Salt marshes are of high ecological value. Their environmental dynamics and salinity gradients create habitats for specific plant and animal species (Bakker et al., 2005; Doody, 2008). Salt marshes are sources and sinks of various nutrients and sediments and function as nursery areas for fish, thereby having an impact on ecosystems in the adjacent coastal waters (e.g. Mitsch, 1994; Dausse et al., 2005). Finally, by absorbing wave energy, salt marshes have an important function for coastal protection (Brampton, 1992; Möller et al., 1999; Doody, 2008).

Figure 1.1. Aerial view of part of the salt marsh on Schiermonnikoog (NL) in 2006. Photo: Rijkswaterstaat, www.kustfoto.nl.
There are several threats to the existence and functioning of salt marshes. First there are the natural processes that may lead to drowning or lateral erosion of the marsh, such as local lack of sediment, sea-level rise and changes in (wave) climate (Doody, 2008). Secondly, there is the direct or indirect impact of human activities, in the form of progressive embankments and fixation with brushwood groyne, ditches and sand dikes. As a consequence, in Northwest Europe the area of salt marshes and the area suitable for new marsh development have substantially reduced within the past centuries (Dijkema, 1987a). The establishment of new marshes is very limited and during sea-level rise, salt marshes that are bounded by a seawall at their landward side may become ‘squeezed’ between the intertidal flats and the seawall. Limited new marsh growth and reduction of the natural dynamics lead to the ageing of the present marshes, a loss of pioneer and young marsh area and therefore possibly the disappearance of organisms characteristic of the younger successional stages (Esselink et al., 2000; Bakker et al., 2005).

Salt-marsh management aims at mitigating the above effects. The current trend in management is to allow natural dynamics within the boundaries of safety (Bakker et al., 2005; Samenwerkingsverband Het Tij Geleerd, 2007b). This requires knowledge on the dynamics of such marshes, both spatially and temporally.

1.2 Salt-marsh development on barrier islands

Salt marshes on barrier islands in Northwest Europe generally consist of a vegetated layer of predominantly silt and clay, on top of coarser-grained sediment such as sand (Dijkema, 1987b). Their development goes schematically as follows (Figure 1.2, Olff et al., 1997). The process starts when a sandbar emerges from the sea (Figure 1.2A). Initially, the hydrodynamic conditions on this sandbar are rough and during storms, overwash may occur from the open sea towards the back-barrier area. Aeolian activity leads to the formation of dunes, which gradually shelter part of the sandbar from the open sea (Figure 1.2B). Where the bed level is high enough, generally above mean high tide (MHT), halophytic pioneer vegetation starts to grow. This is the onset of marsh sedimentation (Figure 1.2C). The vegetation further reduces local hydrodynamics such that fine-grained sediment is deposited and a top layer of fine-grained marsh deposits develops. The resulting increase in soil elevation and nutrient availability lead to more favourable conditions for plant growth and increased vegetation productivity. The vegetation canopy hence becomes denser, resulting in more sediment trapping. In the initial stages of marsh development, accretion rates are high. However, the increase in soil elevation reduces inundation frequency and duration, and after some time sedimentation rates decrease. The marsh eventually grows towards an equilibrium level around highest astronomical tide or mean high water level (Allen, 1990; Van Wijnen and Bakker, 2001; Temmerman et al., 2004). The accretion causes a steepening of the seaward edge of the marsh, where wave action may eventually lead to the formation of an eroding marsh cliff (Figure 1.2D, e.g. Van Straaten, 1954; Van de Koppel et al.,
From estuaries, salt-marsh cycling or rejuvenation is reported, where after a certain period of vertical and lateral growth, the marsh erodes from the seaward edge until a new equilibrium is reached and the marsh expands again (Pringle, 1995; Allen, 2000; Van der Wal et al., 2008).

Sedimentation on barrier-island salt marshes is variable in time and space. The sand surface underlying the marsh slopes down from the dunes towards the salt-marsh edge and determines the typical marsh zonation (De Leeuw et al., 1993). The top layer is thin at the toe of the dunes and increases in thickness towards the intertidal flats (Figure 1.2), typically ranging between 0 – 50 cm. The presence of a creek network gives rise to further spatial variations in sedimentation rate. Unique for barrier-island marshes is the process of overwash, in which water from the open sea locally breaches through the dunes during major storms. Sediment eroded from the beach and dunes may be deposited into the salt marsh, resulting in washover deposits. On many of the north-western European barrier islands, washover activity is nowadays blocked by the construction of artificial sand dikes.

Figure 1.2. Schematic development of a barrier-island salt marsh (from Olff et al., 1997). The dark layer represents the fine-grained sediment deposited onto the sandy subsoil. See text for further explanation.
1.3 Aim of this thesis

The spatial complexity of marsh accretion makes that knowledge is still lacking on especially the long-term effect of the interplay of accretion processes and their spatial expression (e.g. Allen, 2000; French, 2006). This leads to the aim of this thesis, which is:

* gaining more insight into the development of salt marshes on barrier islands, 
* through the spatial characterisation of salt-marsh sediment, 
* using a combination of established and new measurement techniques. 

More specifically, the following questions will be addressed in this thesis:

- Under which environmental conditions does salt-marsh formation commence and does marsh growth continue?
- What type of sediment is deposited and at what rate?
- What are the local and regional sources of salt-marsh sediment? Can we identify sources and sinks as indication for salt-marsh rejuvenation?
- What are the spatial patterns in environmental conditions and sediment? Does this have implications for the scaling up of small-scale measurements?
- How is the above related to marsh development?
- Can insight in marsh development be improved by introducing a new method for the characterisation of salt-marsh sediment: *in-situ* measurements of natural radioactivity?

1.4 Measurement techniques

Established methods to characterise marsh sediment include soil coring and taking samples. With a soil corer, the thickness and lithology of the marsh top layer can be described visually with a precision of 0.1 – 0.5 cm and an estimated accuracy of less than one cm. Top-layer thickness gives information on the nutrient availability for plant growth and on sedimentation rates. Sedimentation rates are typically in the order of millimetres per year and are derived by measuring repeatedly or above a horizon with known age. When measured at intervals of at least five years, accretion rates give an indication of the ability of a marsh to keep pace with sea-level rise. For accretion rates for shorter time intervals (e.g. one year), core measurements are not considered precise enough. In such cases, methods such as the sedimentation-erosion bar (Van Duin et al., 1997) can be used. These consist of many measurements of soil-elevation change within several metres from a local benchmark. This averages out small-scale variation, leading to high precision but with limited spatial coverage.

The grain-size distribution determined from sediment samples gives information on the environmental conditions during which the sediment was deposited. The level of detail of such distributions depends on the used analysis method. On barrier-island marshes, the most important distinction is that between sand and fine-grained sedi-
ment. Sediment grain size is additionally used to infer sediment pathways and sources. Alternative methods for inferring sediment sources are measurements on hydrodynamics and mineral composition.

The described methods are very labour-intensive so that a trade-off has to be made between spatial resolution, spatial covering and temporal sampling frequency. For example, determining top-layer thickness together with soil elevation on a 50 m × 200 m grid with 600 points covering the salt marsh (7 km²) of Schiermonnikoog (NL) takes around two months for two people. The spatial and temporal variations in sedimentation on barrier-island salt marshes introduce the need for a large number of measurements to characterise sedimentation. Therefore, a new method was sought that is capable of mapping top-layer thickness and/or accretion rates with comparable precision to the soil corer method, and which allows yearly or even monthly repeated mapping with high spatial resolution (order of tens of metres). The method should be able to distinguish at least between sand and mud, and should be able to assess accretion rates. The in-situ measurement of natural γ-radiation has the potential to meet these requirements, and may additionally be capable of identifying sediment sources and sinks. This method is described in the next section.

1.5 Environmental γ-radioactivity

Most sediments contain small amounts of radionuclides that emit γ-radiation. The most abundant radionuclides of natural origin are 40K and the members of the decay series of 232Th and 238U. These primordial radionuclides were formed in supernovae preceding the formation of our solar system. They are still detectable because their half-life times are comparable to the age of the Earth (4.5 · 10⁹ a). The amount of radionuclides in sediment depends on the constituting mineral types and mineral provenance. In addition to the natural radionuclides, sediment may contain anthropogenic radionuclides such as 137Cs. An important source of these radionuclides is release into the atmosphere by two anthropogenic events: atomic bomb testing around 1960 and the Chernobyl nuclear-reactor accident in 1986. Subsequently the radionuclides were deposited on the Earth’s surface mainly by rain.

The relation between sediment properties and γ-radiation means that measurements of γ-radiation can be used for studies on e.g. sedimentology, transport patterns and the distribution of rock types. In coastal areas, it was used for studying provenances, large-scale transport, selective sorting and grain size of sediments (e.g. De Meijer et al., 1997; Macdonald et al., 1997; De Meijer, 1998; De Meijer et al., 2001; Ligero et al., 2001; Anjos et al., 2006; Tsabaris et al., 2007). For this, the concept of the radiometric fingerprint was introduced. This is the characteristic set of radionuclide activity concentrations for a specific sediment or sediment fraction (De Meijer et al., 1990; De Meijer and Donoghue, 1995; De Meijer, 1998). Radiometric fingerprints were initially constructed for heavy minerals in sand, leading to the identification of regions with similar fingerprints, often separated by rivers or inlets. Measurements in coastal
areas with a larger range of sediment grain sizes than the previous studies (and typically considering a smaller geographical area) led to the identification of fingerprints for a number of grain-size fractions (Venema and De Meijer, 2001; Van Wijngaarden et al., 2002b). In the Dutch coastal zone, the activity concentrations of $^{40}$K, $^{232}$Th and $^{238}$U are on average a factor two to six higher in mud than in sand. Therefore, with the application of newly-developed towed seabed detectors (e.g. Jones, 2001) it became possible to map $\gamma$-radiation \textit{in situ} with a high density of data points, resulting in detailed maps of the occurrence of sand and mud. The availability of this type of detectors together with the successful application of $\gamma$-radiation in coastal settings was the incentive to use environmental $\gamma$-radiation for the characterisation of salt-marsh sediment in this thesis.

In this thesis, the focus lies on the natural radionuclides, which will be used to characterise sediment in terms of grain size and sediment source. Previously, the application of environmental $\gamma$-radiation on salt marshes has mainly concerned dating of the sediment and determining accretion rates, using $^{210}$Pb (a radionuclide from the $^{238}$U series), $^{137}$Cs and other anthropogenic radionuclides such as $^{241}$Am (e.g. Ehlers et al., 1993; Wheeler et al., 1999; Tyler, 1999; Dyer et al., 2002; Bartholdy et al., 2004; Harvey et al., 2007). Except for correcting for background radiation, in those studies the contributions of $^{40}$K, $^{232}$Th and $^{238}$U were not taken into account.

Since the radiometric characterisation of sediment is relatively novel and has not been applied on salt marshes before, the emphasis will be more on the development and testing of the method than on the derivation of sediment characteristics over a large area. The secondary aim of this thesis is therefore:

\textit{evaluating the use of natural $\gamma$-radiation for the spatial characterisation of salt-marsh sediment.}

This evaluation consists of answering the following questions:

- \textit{Are there variations in $\gamma$-radiation on the salt marsh?}
  Only if there are significant variations, $\gamma$-radioactivity measurements will yield information.

- \textit{If so, are the observed variations related to known parameters, or otherwise explainable?}
  For the interpretation of the data it is necessary to compare the measurements with the results from established measurement techniques, so that the radiometric results can be ‘translated’ into other variables.

- \textit{Has the application of the method added value with respect to existing techniques?}
  Introducing a new measurement technique is only worthwhile if it provides an improvement in terms of more precision, accuracy, information, time-effectiveness and/or cost-effectiveness.
1.6 Outline of this thesis

This thesis consists of three parts. First the measurement methods, their principles and the field sites are described in Chapter 2. The second part (Chapters 3 – 5) concerns the assessment of using \( \gamma \)-radiation as a tool for salt-marsh research, and identifying possible applications. The last part focuses on spatial and temporal patterns in sediment and accretion on salt marshes using traditional methods (Chapter 6 and 7). Figure 1.3 gives a schematic overview of the topics addressed in the individual chapters.

The main study site of this thesis is the island of Schiermonnikoog, the Netherlands. This island supports marshes of various known ages (a so-called chronosequence), allowing long-term marsh development to be studied. The island will be used as a model island for the barrier islands in the Wadden Sea. Replicating part of the measurements on the island of Terschelling (NL) and the peninsula of Skallingen (DK) will give an indication on whether the results are indeed representative for other islands in the Wadden Sea.

Several of the surveys of natural radioactivity concern in-situ measurements. Based on the geomorphology of barrier islands, it is expected that sediment bulk density and water content vary spatially and temporally. As this may affect detector response, in Chapter 3, Monte-Carlo simulations are used for a sensitivity analysis on the effects of water content and density on \( \gamma \)-ray spectra and the size of the detected sediment volume. Comparing the simulation results with sample data from Schiermonnikoog will give an indication of the expected uncertainties in in-situ measurements due to variable field conditions and therefore serves as boundary conditions for the following measurements.

Figure 1.3. Schematic overview of topics dealt with in this thesis and the corresponding chapters.
Chapter 4 describes large-scale spatial variations in $\gamma$-radiation on the island of Schiermonnikoog. The surveys include the entire island, so that possible pathways of sediment connected to the salt marsh may be identified. To understand the observed patterns of $\gamma$-radiation, these will be related to grain-size measurements so that the radiometric fingerprints can be determined. An application of the method is given by mapping grain-size variations on the intertidal flats using in-situ $\gamma$-radiation.

Chapter 5 focuses on the use of in-situ $\gamma$-radioactivity on the salt marsh. Based on the results of Chapter 4, the relation between the thickness of the top layer of marsh deposits and in-situ $\gamma$-radiation is further explored. It is assessed how well top-layer thickness can be determined from in-situ measurements, using a simple analytical model for the emission and absorption of $\gamma$-radiation in the soil.

In Chapter 6, spatial variations in salt-marsh sediment are described from a large database of soil-corer measurements. The occurrence of sand within the otherwise fine-grained sediment is used as indication for the conditions under which salt-marsh development started and the importance of high-energy events during the development of the salt marsh. The spatial patterns in sand occurrence are used to infer the sources of the sand.

Marsh development is further explored in Chapter 7. The sizes of spatial patterns associated with net long-term accretion are determined on marshes of various ages, using geostatistics. This results in a conceptual model of pattern development through time. The measurements cover several spatial scales, which gives insight into the degree to which small-scale measurements can be scaled up.

Finally, the General discussion and conclusions (Chapter 8) combines the results from the radiometric and non-radiometric surveys, to answer the questions on salt-marsh development outlined before. The applicability of the radiometric method is discussed and suggestions for future application are given.