General discussion and conclusions

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The salt marsh of Schiermonnikoog
around the 9th creek.
(photo by Rijkswaterstaat, www.kustfoto.nl)
8.1 Introduction

The work presented in this thesis has addressed the aim of: 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. Based on this aim, more specific questions were posed in Chapter 1 (Figure 1.3). In this chapter, I will discuss the results of the previous chapters in view of these questions.

First, I will evaluate the use of natural $\gamma$-radiation for the spatial characterisation of salt-marsh sediment. This consists of answering the following questions: are there variations in $\gamma$-radiation at and around the salt marsh? If yes, what are these variations related to? Does the application of the method have advantages over already established methods?

Based on these results and those from the large database of soil cores, section 8.3 addresses the questions related to salt-marsh development. This concerns the environmental conditions, sediment type and quantity, sediment sources and spatial and temporal patterns.

In the final section, I will give suggestions for applications and future research.

8.2 Radiometric characterisation of sediment at and around the salt marsh

8.2.1 Radiometry question 1: Variations in $\gamma$-radiation

The first question to be answered in evaluating the radiometric method is: are there variations in environmental $\gamma$-radiation at and around salt marshes? In Chapters 4 and 5, it was shown that the answer to this is positive. Variations ranged from a factor two (in situ on the salt marsh) to a factor eight (in situ island-wide).

8.2.2 Radiometry question 2: Relations with known parameters

The second step is to understand these variations, by establishing relations with known parameters.

In Chapter 4 it was found that the sediment on the barrier island of Schiermonnikoog consists of two groups differing in radiometric fingerprints: a coarse-grained sediment group (sand) with low activity concentrations of natural radionuclides and a fine-grained group (consisting of very fine sand, silt and mud) with relatively high activity concentrations.

On the island, the groups occur in two geometries (Figure 8.1, the cross-sections). The two sediment types can be mixed, such as on the intertidal flats (left panels), or the fine-grained sediment forms a top layer of variable thickness overlying coarse-grained sediment, as on the salt marsh (right panels). The relation between the intensity of the $\gamma$-radiation detected at the surface and the relative presence of the two groups depends on the geometry. When the two groups are mixed, the detected activity concentration increases linearly with increasing admixture of the fine-grained...
The sediment groups have a spread around their mean activity concentrations (the ovals in the figures), leading to uncertainty in the relations (the dashed lines). This is translated in the uncertainties in the derived sediment composition (the horizontal, grey dashed lines).

In case the fine-grained group overlies the coarse-grained group, the apparent activity concentrations increase exponentially to a maximum with increasing thickness of the top layer (middle right figure). This is understood in terms of the generation and absorption of $\gamma$-rays in a semi-infinite geometry, and can be largely described using the analytical two-layer model from Chapter 5.

Figure 8.1. Schematic overview of apparent activity concentrations on the soil surface, detected by an in-situ detector (cylinder), as a function of sediment geometry and water content. Left panels: the case where the soil is a homogeneous mixture of the two sediment groups. Right panels: the case where the soil consists of a layer of fine-grained sediment (black) on top of coarse-grained sediment (grey). The percentages give the proportions of the two sediment groups within the upper 50 cm of soil. The activity concentrations and range of the two sediment groups is given at 0% and 100%. The solid lines give the average relation between sediment composition and apparent activity concentration, the black dashed lines the extremes. All relations in between the dashed lines are in principle possible. The horizontal, grey dashed lines give the ‘correct’ $C_{\text{surface}}$ for sediment containing 25% of the fine-grained group, where the projection on the horizontal axis is the uncertainty in the derived sediment composition.
A complicating factor in the detection of sediment $\gamma$-radiation is that sediments on barrier islands exhibit spatial and temporal variations in porosity and water saturation, leading to a large range of water contents. Moreover, the water content of sediment tends to vary non-linearly with grain size (Flemming and Delafontaine, 2000). The effect is that, under normal field conditions, the ranges of activity concentrations of the two groups overlap (Chapter 3). The intensity of the detected $\gamma$-radiation (and thus the derived apparent activity concentrations) decreases linearly with increasing absolute water content. Consequently, it becomes difficult to distinguish the two sediment groups or assess their degree of mixing from in-situ $\gamma$-radiation, if the water content of the sediment is not known (lower left panel of Figure 8.1), as seen in the island-wide survey in Chapter 4. In case the water content is known, however, and can be assumed homogeneous within the view of the detector, the dry activity concentrations can be derived easily and with reasonable uncertainty using the relation presented in Chapter 3. The effect of variations in water content in a layered situation is given in the lower right panel of Figure 8.1. In such situations, the water content tends to vary within the view of the detector. A correction is then not possible and the relation between in-situ radiation and thickness of the top layer may not be straightforward, as seen in Chapter 5.

8.2.3 Radiometry question 3: Evaluation and application of the radiometric method

The final step in the application of sediment $\gamma$-radiation as a tool on salt marshes is to determine whether the method has added value with respect to established measurement techniques, according to the requirements given in section 1.4.

The method allows distinguishing between sand and fine-grained sediment, which constitute the base and top layer of the salt marsh, respectively. On the salt marsh, it was possible to use in-situ $\gamma$-radiation for reproducing the general trend in top-layer thickness, as measured from soil cores, within a factor two to four. Although the uncertainty in the soil-corer (manual) method turned out to be somewhat larger than expected (1 – 2 cm instead of 1 cm, see Chapter 7), the uncertainties in the radiometric method are still too large to compete with the traditional soil coring. Therefore, the radiometric method is not suited for measuring accretion rates on the scale of months to a few years, as required for quantifying marsh sedimentation. The causes for this are the one-dimensional schematisation of the model and spatial and temporal variations in the wet activity concentrations and bulk density of the sediment. The first may be optimised (see section 8.4.4), but the second cannot really be influenced. Therefore, the method is most suited for quick-scans (e.g. from an airplane if flying low), producing qualitative maps of top-layer thickness in potentially less time than with soil cores.

The use of the radiometric method for identifying sediment sources and sinks turned out to be limited for the scale of a barrier island. For the sand, there was an indication of a second source or transport pathway associated with an older dune arc, but virtually all fine-grained sediment from Schiermonnikoog belonged to one radiometric sediment group. The sand of each of the Dutch Frisian islands has its own
characteristic pattern of in-situ radiation (De Meijer et al., 1989). This means the identification of transport patterns using the radiometric method may therefore be more suitable for larger scales than in this thesis or on islands with a more complex history (De Meijer and Donoghue, 1995).

The survey on the intertidal flats showed that in areas with homogeneous water content even small variations in mixing between the groups can be detected. Traditionally, grain-size maps of the intertidal flats, used in studies on e.g. sediment dynamics and shellfish ecology, are constructed using sediment samples. The radiometric method was able to – at least qualitatively – reproduce known patterns of grain-size distribution on the intertidal flats, with higher spatial resolution than existing maps and much less sampling effort. The method is therefore a potential improvement for mapping sediment types of the intertidal flats.

In this thesis, two types of in-situ detector were used. Which detector is most suitable for a specific survey depends on the requirements of the survey and the characteristics of the survey area: do total count rates give enough information or is information on the individual radionuclides necessary? The answer to this question follows preferably from a pilot study, involving sample analysis on the correlation between radionuclides and the variation in the presence of $^{137}\text{Cs}$.

8.3 Salt-marsh development

The second part of this thesis concerned the formation and development of salt marshes on barrier islands. Here, I will discuss the findings in relation to the schematic development of barrier-island marshes as described in Chapter 1.

8.3.1 Initial salt-marsh formation

The environmental conditions during salt-marsh formation vary spatially within a marsh (Chapter 6). Part of the marsh develops under calm conditions and part under conditions rough enough for the transport of sand, or with considerable bioturbation. The spatial distribution of the conditions is related to the slope of the underlying sand surface, in combination with the presence of dunes or artificial sand dikes that provide shelter from overwash and aeolian activity from the direction of the open sea.

8.3.2 Further marsh development

As the marsh evolves, the top layer increases in thickness and forms spatial patterns that may change in size and structure through time. There are at least three hierarchical levels in these spatial patterns. Virtually the same spatial patterning is observed in the sand layers within the top layer, further discussed in the next section: small sand patches together form larger patches within a catchment, which on the island scale form the spatial pattern described in Chapter 6.

This hierarchical patterning indicates that controls on sedimentation act on all spatial scales (c.f. for instance Allen, 2000), depicted in Figure 8.2. On the largest scale
(number 1 in Figure 8.2), base elevation is the initial control on inundation frequency and duration, setting the potential for future sedimentation. The influence of the base elevation decreases during marsh development, when independent accretionary patterns develop. Still, the base elevation remains expressed in the marsh surface through the top layer (Chapter 7). The independent patterns are most probably created by the ongoing creek development including levee development and lateral marsh growth, affecting the catchment and sub-catchment scales in the shore-normal and shore-parallel directions (numbers 2 in Figure 8.2). Both processes are partly related to base elevation, and they affect the distance of a certain location on the marsh to the nearest sediment source, which is the second important control on marsh accretion (e.g. Stoddart et al., 1989; French and Spencer, 1993; Esselink et al., 1998; Friedrichs and Perry, 2001; Temmerman et al., 2003; Van Proosdij et al., 2006).

Finally, on the local scale (numbers 3 in Figure 8.2), vegetation may create irregularities on the marsh surface and lead to variations in current velocity (Van Straaten, 1954; Ehlers et al., 1993; Reineck and Gerdes, 1996; Möller et al., 1999; Langlois et al., 2003; Neumeier and Amos, 2006).

Patterns in short-term accretion rates (described by French et al., 1995 and Van Proosdij et al., 2006) may differ from those in top-layer thickness. The ambient driving forces and conditions will be more pronounced in short-term accretion rates than in top-layer thickness, which is the accumulated outcome of all past conditions. It was not possible to obtain short-term accretion rates from the current large-scale dataset, as the simplified method of calculating accretion rates from Chapter 6 (equation 6.1 used for the dating of the sand layers) introduces too much uncertainty to use for quantitative interpretation.
One of the initial questions was to identify sources and sinks of sediment in relation to salt-marsh rejuvenation. Unfortunately, with both the radiometric and corer methods, it was not possible to recognise sources and sinks of the fine-grained sediment within the marsh of Schiermonnikoog. Although there were spatial and vertical variations in radionuclide activity concentrations within the marsh sediment, these did not have any consistent pattern. Further, the radiometric fingerprint of the sediment seems to be homogeneous within the Dutch Wadden Sea. The most probable explanation for the small-scale variations in radionuclide concentrations are variations in the hydrodynamic conditions under which the sediment was deposited.

8.3.3 High-energy events
During severe storms, waves and currents may take up sand from the intertidal flats and creek bed and deposit it on the marsh surface, within a limited distance from the salt-marsh edge and creeks. Water from the open sea may breach though the dunes and deposit sand eroded from the beach and dunes. Sand from dunes or areas left bare by overwash may be taken up by the wind and deposited on the marsh. The occurrence of sand-depositing storms on Schiermonnikoog has been approximately decadal, although an increase in sand deposition and extreme tide levels were observed in the past few decades. This may be related to the overall increase in high-tide levels in the Dutch Wadden Sea (Dijkema et al., 1990).

The locations with most sand layers resemble those where top-layer thickness is generally largest: along the salt-marsh edge and creek levees (Figure 6.6 and Figure 7.4). Exceptions are where sand layers were deposited by overwash and by wind. The patterns for both types of sediment reflect the proximity to the sources of the sand, wind and water.

The sand layers were mostly deposited at the time a certain marsh area was relatively young. This indicates that, again in analogy with the fine-grained sediment, creek development, lateral marsh growth and further dune building affect the accessibility of the marsh to sand, wind and water.

Artificial sand dike
The artificial sand dike on Schiermonnikoog has blocked sand transport by overwash and wind from the open sea towards the salt marsh, altering the pattern of sand layers. For the spatial patterns of top-layer thickness such an influence was however not found. From the research in this thesis, it cannot be concluded whether the sand dike on Schiermonnikoog has been a benefit or a threat to the marsh. Initially, it generated rapid marsh growth, but the marsh growth has continued outside the influence of the sand dike and in spite of partly breaching of the dike. This suggests that on Schiermonnikoog, the building of the dike was well-timed in relation to geomorphological changes attributed to other large-scale developments, such as closing off the Lauwerszee south of Schiermonnikoog and sand nourishments at the updrift island of Ameland.
8.3.4 Comparison with other barrier-island marshes in the Wadden Sea
Most of the findings were based on measurements from Schiermonnikoog, which is a long-term study site for salt-marsh ecology and was therefore the first choice for conducting field research. The surveys involving soil cores on Terschelling and Skallingen show that, on the investigated high and middle marsh (sub-catchment scale), the general pattern is comparable. There are only small differences between the islands in past environmental conditions as identified from the sediment record and spatial patterns in accretion. The relation between top-layer thickness and in-situ $\gamma$-radiation was also comparable between the investigated marshes (Chapter 5). It is therefore expected that the findings on marsh development are applicable to other barrier islands in at least the Wadden Sea area.

8.4 Outlook

8.4.1 Radiometric mapping of sediment and salt-marsh accretion
In this thesis, only small parts of the salt marsh were surveyed with $\gamma$-ray detectors. Figure 8.3 gives the predicted total count rates if in-situ $\gamma$-radiation would be mapped with the PANDORA detector on the entire marsh of Schiermonnikoog, based on the Scintrex measurements of Chapter 4, the detailed study of Chapter 5 and the spatial pattern of top-layer thicknesses from Chapter 7. Although the map resembles the spatial pattern of top-layer thickness (Figure 7.4), the maps are not identical because the relation between top-layer thickness and in-situ radiation is non-linear and the maximum detectable layer thickness is about 40 cm. Layer thicknesses larger than

![Figure 8.3. Predicted total count rates for the PANDORA detector on the salt marsh of Schiermonnikoog. The calculations are based on the pattern of top-layer thickness of Chapter 7 and the model and parameters of Chapter 5.](image-url)
approximately 20 cm are therefore less distinguishable. In the field, the internal variation in activity concentrations and water content within the top and base layers will cause further deviations.

Sand layers within the top layer (Chapter 6) may affect the level of detected radiation at the soil surface, compared to a homogeneously fine-grained top layer, by diluting the overall activity concentrations of the top layer. The size of this effect is a function of the thickness of the entire top layer, the thickness of the interspersed sand layers and the depth of the sand layers. Because of this multiple dependence, it is not possible to resolve sand layers within the top layer from in-situ radiation without additional information. From the surveys of Chapter 5, it is expected that on the island of Schiermonnikoog the variations in top-layer thickness and variations in activity concentrations within the fine-grained sediment group will dominate in-situ radiation.

The in-situ apparent activity concentrations of $^{137}\text{Cs}$ on the salt marsh appear to be related to the burial depth of the enriched layers. Therefore it may be possible to use in-situ measurements for mapping accretion rates since $^{137}\text{Cs}$ deposition (c.f. Tyler, 1999). This method should be validated at the specific site before application, as it probably involves the same uncertainties related to variations in water content and bulk density as the radiometric determination of top-layer thickness. Additionally, the distribution of $^{137}\text{Cs}$ deposition, especially that resulting from the Chernobyl accident, should be known.

### 8.4.2 Relevance for other types of tidal salt marsh

To evaluate the use of natural $\gamma$-radiation on marshes in an estuarine setting, a pilot study was carried out on a freshwater marsh and a salt marsh in the Scheldt estuary (Belgium and the Netherlands, De Groot, 2005). In these surveys, total count rates from the Scintrex GIS-5 detector were compared to sediment composition as estimated in the field. This did not reveal any correlation between sediment composition and in-situ $\gamma$-radiation within either of the two marshes. However, count rates were higher in the freshwater marsh than in the salt marsh, which may reflect the mineralogical difference between freshwater and marine mud (Van Straaten, 1954). The results indicate that the relation between in-situ $\gamma$-radiation and sediment composition on these estuarine marshes differs from that on the investigated barrier-island marshes.

Sand layers around creeks and the salt marsh edge also occur on marshes that are bordered at their landward end by a seawall (Ehlers et al., 1993; Esselink et al., 1998). Overwash is a process only occurring on barrier-island marshes, and thus sand layers associated with overwash are only expected there.

In salt marshes that are drained by regular, artificial ditches, the spatial patterns in sedimentation are more regular than in marshes that have natural creek systems (see Esselink et al., 1998). The patterns will also exhibit hierarchy, as the same forcings on all levels occur as described for barrier-island marshes.
8.4.3 Implications for management

Currently, there is much interest in the importance of overwash deposits for the functioning of salt marshes on barrier islands, related to presence of artificial sand dikes on the Dutch Frisian islands (Eleveld, 1999; Samenwerkingsverband Het Tij Geleerd, 2007b; De Leeuw et al., 2008; Ten Haaf and Buijs, 2008). The exploratory study of Chapter 6 indicated that the total contribution of sand to the salt marsh on Schiermonnikoog is, with less than ten percent, limited. The contribution of washover deposits will be in the order of one or two percent, so that under the current conditions, the active marsh does not rely on washover sediment for keeping pace with sea-level rise. For the development of the distal end of the island as a whole, however, the contribution of washover may be much more important (Godfrey and Godfrey, 1974; Ehlers, 1988b; Eleveld, 1999), for instance by creating accommodation space for marsh growth and introducing landscape variety. It should be stressed that the findings from this thesis concern the ‘active’ salt marsh, i.e. the area with salt-marsh vegetation that still receives fine-grained sedimentation. If parts of the washover complexes are considered to belong to the salt marsh, which is sometimes done from a floristic point of view, the importance of overwash for salt-marsh sedimentation is – logically – larger. Discussions concerning e.g. washover reconstruction (e.g. Samenwerkingsverband Het Tij Geleerd, 2007b) should therefore be clear in this respect.

As a consequence of the complex patterns in accretion, it is difficult to assess how representative accretion measurements are for a certain area (Chapter 7). Accretion measurements from a small scale (e.g. within 50 m²) should therefore preferably not be used for a much larger area (e.g. several km²), for instance for predicting marsh

![Figure 8.4. Simulated spectra of $^{40}$K (as ratios to a homogeneous sediment bed) for a sediment bed consisting of two layers with increasing top-layer thickness (values indicated in the plots). Left panel: radionuclides in the top layer; right panel: radionuclides in the base layer.](image-url)
resilience in relation to sea-level rise. Measurement layouts should be suited to the studied spatial scale and processes, and ideally cover the entire gradient in base elevation and shore-parallel extent of the area of interest. This may seem obvious, but because of the limited accessibility of salt marshes, measurements locations are often chosen as single transects or small clusters of high-density measurements. In both cases, the spatial variation in accretion may be underestimated considerably. The measurement error (i.e. uncertainty without any spatial component) in core measurements of top-layer thickness is 1 to 2 cm. This followed from Chapters 6 from the intermediate and gradual transitions that cover two third of the salt-marsh area and from the variograms from Chapter 7.

A potential application of the radiometric method is sediment mapping on the intertidal flats, as done in Chapter 4. In the Dutch Wadden Sea, there is concern about the change in ecosystem functioning related to e.g. shellfisheries and the disappearance of mussel beds and seagrass beds (Samenwerkingsverband Het Tij Geleerd, 2007a). These changes may be reflected in sediment composition. A method that can quickly map the intertidal flats on sand and mud may therefore benefit the ongoing research on these subjects.

8.4.4 Suggestions for future research

This thesis has given more understanding of the use of in-situ $\gamma$-radiation on sites with complicated lithology such as the salt marsh, and of spatial patterns of sediment and environmental dynamics during salt-marsh development. Based on these results, several suggestions for further research are given.

Improving the two-layer model

One of the remaining questions is the applicability of the two-layer model in Chapter 5, related to the mismatch between manual and radiometric top-layer thickness. The model is a one-dimensional schematisation of a three-dimensional geometry and may therefore not take into account all necessary three-dimensional aspects of the generation and attenuation of $\gamma$-rays. We performed an exploratory analysis to identify the effect of the schematisation and to set directions for further research. For this, we simulated a flat-bed geometry with a stepwise increasing top layer using the code MCNPX, described in Chapter 3. In a first series, the radionuclides were present in the top layer only and in the second series in the base layer only. The final spectra were broadened with a Gaussian function to model the resolution of the PANDORA detector (see Chapter 3). Here, results are shown for $^{40}$K.

With increasing thickness of the radionuclide-containing top layer, as expected the intensity of the spectra increases (left panel of Figure 8.4). In addition, the shape of the spectra changes in the sense of a changing ratio between the peak and continuum parts. In the case where the radionuclides are present in the base layer only (right panel of Figure 8.4), spectral intensity decreases with increasing top-layer thickness and the peak-to-Compton ratio is low. The spectra of $^{232}$Th and $^{238}$U (not shown) give similar results.
Full-Spectrum Analysis, used for the analysis of the PANDORA spectra in Chapter 5, uses standard spectra that represent homogeneous distributions of radionuclides in the soil and assumes invariant spectral shape. The observed change in spectral shape with changing layer thickness means that the analysis results for such geometries are less reliable, although the degree to which should be determined from further analysis. This may also explain the poorer performance of the standard-spectra based radiometric quantities in determining top-layer thickness compared to total count rates.

The changes in spectral shape contain information on sediment characteristics or radionuclide distribution in the soil. This was previously done by using in-situ detectors with good energy resolution to determine layer thicknesses and the ratio between activity concentrations in the top and base layer (Thummerer and Jacob, 1998). Further, detailed spectral features were used to determine the vertical distribution of $^{137}$Cs and wet bulk density of the soil (Tyler et al., 1996; Tyler et al., 2001). Whether such analyses are possible for BGO-type detectors would be a subject for further study.

The relation between simulated spectral intensity, as ratio with an infinitely thick layer ($\beta_j$ from Chapter 5), and top-layer thickness follows the same trend as the results from the two-layer model (Figure 8.5). However, for $^{40}$K the radiometric layer thickness overestimates the real layer thickness for most of the detectable range. For $^{232}$Th and $^{238}$U (not shown), the two-layer model overestimates small layer thicknesses, whereas large layer thicknesses are underestimated. Therefore, a nuclide-specific, constant effective attenuation coefficient, as proposed in the two-layer model, may not be sufficient to describe the attenuation of $\gamma$-rays in a three-dimensional flatbed geometry.

![Figure 8.5](image.png)

**Figure 8.5.** Spectral content (as ratio with homogeneous sediment) as a function of top-layer thickness, from simulated spectra of $^{40}$K (dots). The two-layer model (solid lines) is plotted for sediment with the same composition and using the regular mass-attenuation coefficients, in analogy with Chapter 5 ($\mu/\rho$ from Berger et al., 2007). Spectral content is summed over the region 0.2 – 2.8 MeV.
To be able to use in-situ radiation quantitatively for the determination of layer thickness, more study is needed on the two-layer model. Such study might involve further simulations, combined with experiments using a more controlled situation and less internal variation within the layers than on the salt marsh, for instance the asphalt setup described in Van der Graaf et al. (2004). Additionally, FSA may be carried out with sets of standard spectra representing various layered situations, where the set that fits best to the measured spectrum gives the thickness of the layers. For application on the salt marsh, however, the natural variations in the activity concentration within the top layer will always remain a limiting factor.

**Spatial patterns in salt-marsh accretion**
Models of salt-marsh sedimentation recently begin to include the spatial dimension of sedimentation (e.g. Temmerman et al., 2005b; Kirwan and Murray, 2007). The soil-corer measurements described in this thesis form an excellent dataset for calibrating and validating such modelling. In addition, the hierarchical spatial patterns in long-term accretion could be related to those in vegetation and the development of creek networks. Further unravelling the feedbacks between elevation, inundation, plant community composition, canopy height and density (including the effect of grazing, e.g. Kuijper, 2004) and top-layer thickness would give more insight into their related spatial patterns and relative importance (see for example the model study by Temmerman et al., 2007 and the experimental work on an artificially drained marsh by Esselink et al., 1998). Recently, new studies have started at the University of Groningen on the spatial and temporal aspects of salt-marsh accretion on Schiermonnikoog and Ameland, which include the relation with marsh vegetation.

Finally, as discussed before, the long-term role of overwash and the effect of its blocking by artificial sand dikes is still uncertain for the barrier islands in the Wadden Sea. For gaining more insight, the field study described in this thesis may be extended to include various islands within the Wadden Sea. Long-term lateral and vertical marsh growth should then be studied in relation to the presence and absence of washover, sand dikes and larger-scale processes such as inlet dynamics, sand nourishments, development of green beaches and tidal range. Together with the work of this thesis, such results would give a stronger basis for the management of salt marshes and their surroundings on barrier islands.