Chapter 5

Radiometric determination of top-layer thickness on salt marshes

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Abstract
Barrier-island salt marshes in Northwest Europe generally consist of a layer of fine-grained marsh deposits on top of sand, the thickness of which is related to marsh development and vegetation succession. The activity concentrations of the $\gamma$-ray emitting natural primordial radionuclides ($^{40}$K, $^{232}$Th and $^{238}$U) are often higher in the top layer than in the underlying sand bed. Based on this, we investigated the applicability of in-situ measurements of $\gamma$-radiation for mapping top-layer thickness. We use a simple analytical, 1D two-layer model, based on the emission and absorption of $\gamma$-radiation in the two layers. 
On the island of Schiermonnikoog (NL), we measured $\gamma$-radiation in situ with a large bismuth-germanate detector and a small portable NaI (Tl) detector. Data were collected at several other sites with the small detector only. With these results, we calculated the radiometric top-layer thickness and compared it with traditionally (corer-based) obtained values. The degree to which radiometric layer thickness could reproduce traditional top-layer thickness varied. The performance was best when using total count rates and for layer thickness between 10 and 40 cm. The method is affected by the naturally occurring variations in the composition and water content of marsh sediment, which makes it most suitable for quick-scans of layer thickness.
5.1 Introduction

On barrier islands in Northwest Europe, tidal salt marshes generally consist of a top layer of predominantly fine-grained mineral deposits (silt) on top of a base layer of sand (Dijkema, 1987b). Traditionally, top-layer thickness is measured using a soil corer. This method is relatively simple but requires a lot of handwork when larger areas need to be mapped and the method relies on the presence of a marked transition in grain-size. Therefore, we investigate the use of another potentially useful technique for determining layer thickness on salt marshes: that of in-situ environmental $\gamma$-radiation.

Most sediments contain natural radionuclides that emit $\gamma$-radiation: $^{40}$K, $^{232}$Th and $^{238}$U. The concentrations of these radionuclides are related to sediment properties such as grain size and provenance (De Meijer, 1998). In addition, the anthropogenic gamma-emitter $^{137}$Cs is often present as the result of atmospheric nuclear weapon tests and the reactor accident at Chernobyl. Its presence may be used to date the history of sedimentation (e.g. Walling and He, 1997; Tyler, 1999). In Chapter 4 we found that on the island of Schiermonnikoog (NL), two radiometric sediment groups are present: a coarse-grained group with low radioactivity and a fine-grained group with high radioactivity. On the salt marsh, the top layer consists of this fine-grained sediment and the base layer of coarse-grained sediment. Therefore in-situ radiation intensity should in principle be related to the thickness of the top layer.

The aim of this chapter is to determine whether top-layer thickness on salt marshes can be measured in-situ using natural $\gamma$-radiation. For that, we will model the marsh as a two-layer system where $\gamma$-ray contributions of the top and base layer together determine the radiometric signal at the soil surface. The situation of a layered soil has previously been addressed with a ‘two-line method’ by Thummerer and Jacob (1998). That method uses the ratio of primary photons from spectra obtained with an HPGe detector. However, not all detectors used in in-situ surveys have the high energy resolution of an HPGe detector, so that the two-line method cannot be used universally. Therefore we will use a method that is based on total count rates and apparent activity concentrations and is in principle applicable with any detector. This two-layer model has previously been applied successfully for measuring the thickness of asphalt layers in road construction (Van der Graaf et al., 2004).

After introducing the two-layer model, we will describe the measurements of the relevant parameters for the model on the salt marsh of Schiermonnikoog. With these parameters, we determine the radiometric layer thickness and compare this to the thickness obtained from soil coring. Finally, to test the reproducibility of the results and general application of the method, we apply the method on several other salt marshes in the international Wadden Sea.
5.2 Two-layer model

Salt marshes on barrier islands can be generalised as systems consisting of two homogeneous layers: a top layer of fine-grained sediment overlying a base layer of sand, each with characteristic radionuclide concentrations. Each (sediment) layer acts as a source of $\gamma$-radiation and as an attenuator of the radiation emitted by the underlying sediment. In the two-layer model, the radiation transport is schematised in one dimension. The three-dimensional effects from multiple scattering and radiation originating under an angle with the vertical are incorporated in an effective mass-attenuation coefficient (Greenfield et al., 1989; De Meijer, 2003).

In short the two-layer model can be described as follows. Consider a detector which is efficiency calibrated for an infinite thick layer with activity concentration $C_{j,\infty}$ of radionuclide $j$. The calibration includes the self-absorption taking place in the layer. On the surface of a layer with finite thickness $d$ (cm), an apparent activity concentration $C_{j,\text{surface}}$ is measured, depending on mass thickness $\rho d$ of the layer (where mass thickness is the product of thickness $d$ and bulk density $\rho$ (g cm$^{-3}$) of the layer):

$$C_{j,\text{surface}}(d) = C_{j,\infty} \left(1 - e^{-\left(\frac{\mu}{\rho}\right)_{\text{eff},j} \rho d}\right), \quad (5.1)$$

in which $\left(\frac{\mu}{\rho}\right)_{\text{eff},j}$ (cm$^2$ g$^{-1}$) is the effective mass-attenuation coefficient which describes the attenuation of the $\gamma$-rays within the layer. In the energy range of the $\gamma$-radiation emitted by the natural radionuclides, the predominant interaction of $\gamma$-rays with matter is Compton scattering, described by the Klein-Nishina formula (Knoll, 2000). The cross-section per unit of mass is (in first-order) $Z$-independent. Consequently $\left(\frac{\mu}{\rho}\right)_{\text{eff},j}$ is almost independent of atomic number, but depends on the energy of the $\gamma$-radiation (see also Chapter 3).

When a top layer with a finite thickness $d$ and bulk density $\rho_{\text{top}}$ is placed on top of a base layer with an infinite thickness (right panel of Figure 5.1), the apparent concentration on top of the two layers is assumed to be composed of two parts.

1) The $\gamma$-rays from the top layer with activity concentration $C_{j,\text{top}}$, including self-absorption within the top layer, yield an apparent concentration according to equation 5.1:

$$C_{j,\text{surface}}(d) = C_{j,\text{top}} \left(1 - e^{-\left(\frac{\mu}{\rho}\right)_{\text{eff},j} \rho_{\text{top}} d}\right) \quad (5.2)$$

2) The $\gamma$-rays from the infinitely thick base layer $C_{j,\text{base}}$, attenuated by absorption in the top layer lead to an apparent concentration of:

$$C_{j,\text{surface}}(d) = C_{j,\text{base}} e^{-\left(\frac{\mu}{\rho}\right)_{\text{eff},j} \rho_{\text{top}} d} \quad (5.3)$$

The apparent concentration on top of the two layers, $C_{j,\text{surface}}$, is the sum of the previous two contributions:
\[
C_{j,\text{surface}} (d) = C_{j,\text{top}} + (C_{j,\text{base}} - C_{j,\text{top}}) e^{-(\mu/\rho)_{\text{eff},j} \rho_{\text{top}} d},
\]

(5.4)

This relation between apparent activity concentration and top-layer thickness is depicted in the upper right panel of Figure 5.1 for the case where \(C_{j,\text{top}} > C_{j,\text{base}}\). In the absence of a top layer, \(C_{j,\text{surface}}\) is equal to the activity concentration in the base layer \((C_{j,\text{base}})\). With increasing top-layer thickness, \(C_{j,\text{surface}}\) increases due to the second term in equation 5.4 until the top layer eventually attains a thickness where it absorbs all radiation from the base layer, and \(C_{j,\text{surface}}\) becomes equal to the activity concentration in the top layer \((C_{j,\text{top}}, \text{ upper left panel of Figure 5.1})\). This thickness is also the maximum detectable layer thickness using in-situ \(\gamma\)-radiation and depends on the values of \((\mu/\rho)_{\text{eff},j}\) and \(\rho_{\text{top}}\). If we take the practical value of this thickness as where \(C_{j,\text{surface}}\) is 95 % of the value of \(C_{j,\text{top}},\) this thickness is found when \((\mu/\rho)_{\text{eff},j} \rho_{\text{top}} d\) is equal to 3 (lower left panel of Figure 5.1). The maximum detectable layer thickness can then be calculated if \((\mu/\rho)_{\text{eff},j}\) and local \(\rho_{\text{top}}\) are known.

In this chapter the radiometric layer thickness is calculated from the apparent concentration on top of the two layers by rewriting equation 5.4 into

\[
d_{\text{rm},j} = \frac{1}{(\mu/\rho)_{\text{eff},j} \cdot \rho_{\text{top}}} \ln \left( \frac{C_{j,\text{top}} - C_{j,\text{base}}}{C_{j,\text{top}} - C_{j,\text{surface}}} \right),
\]

(5.5)

where \(d_{\text{rm},j}\) is the radiometric calculated top-layer thickness based on radionuclide \(j\). The activity concentrations can be replaced by total count rates \((TC)\) if desired.

In addition to using the individual radionuclides, the two-layer model can be rewritten such that top-layer thickness can be derived directly from the measured spectra. In Chapter 4 we defined the contribution from the low-activity sediment group to the total activity sample concentration as \(\alpha_j\) (equation 4.2). We can do the same for the contribution of the base layer to the apparent activity concentrations at the surface:

\[
\alpha_j = \frac{C_{j,\text{surface}} - C_{j,\text{top}}}{C_{j,\text{base}} - C_{j,\text{top}}}. \tag{5.6}
\]

When we combine this with equation 5.4, we get

\[
\alpha_j = e^{-(\mu/\rho)_{\text{eff},j} \rho_{\text{top}} d}. \tag{5.7}
\]

For the analysis of spectra from the PANDORA detector (see below), we use Full-Spectrum Analysis (FSA, see Chapter 2). In FSA, measured spectrum \(S\) with channels \(i\) is regarded as the sum of the contributions of all radionuclides plus the spectral background \((Bg)\):

\[
S(i) = \sum_j C_j X_j (i) + Bg(i), \tag{5.8}
\]

in which \(C_j\) is the activity concentration and \(X_j\) the standard spectrum of nuclide \(j\).
Substituting equation 5.6 gives (in analogy with Chapter 4):

\[ S(i) = \sum_j \alpha_j (C_{j,\text{base}} - C_{j,\text{top}}) X_j(i) + \sum_j C_{j,\text{top}} X_j(i) + Bg(i) \]  

(5.9)

The spectra of \( Bg(i) \), \( \sum_j C_{j,\text{top}} X_j(i) \) and \( \sum_j (C_{j,\text{base}} - C_{j,\text{top}}) X_j(i) \) are fixed, which leaves the factors \( \alpha_j \) to be determined in a least-squares fit. Because theoretically \( \alpha \) should be the same for all three natural radionuclides, their contributions can be added and \( \alpha \) can be determined directly from the spectra. On the salt marsh, \( C_{j,\text{top}} \) is expected to be larger than \( C_{j,\text{base}} \) and to avoid spectra with negative numbers, equation 5.9 is rewritten in terms of the contribution of the top layer to the in-situ radiation, \( \beta_j = 1 - \alpha_j \). The apparent activity concentration of the anthropogenic \(^{137}\text{Cs} \) needs to be fitted independently, as sample analysis indicated that its presence is location dependent. This leads to:

\[ S(i) = \beta \sum_j (C_{j,\text{top}} - C_{j,\text{base}}) X_j(i) + C_{^{137}\text{Cs}} X_{^{137}\text{Cs}}(i) + \sum_j C_{j,\text{base}} X_j(i) + Bg(i) \],  

(5.10)

in which \( X_{^{137}\text{Cs}} \) is the standard spectrum of \(^{137}\text{Cs} \).

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**Figure 5.1.** Right panel: schematic drawing of a two-layered system. A top layer with thickness \( d \) overlies a semi-infinite base layer. Both top and base layers emit \( \gamma \)-radiation (depicted by arrows), of which part is absorbed and/or scattered by the intermediate sediment layer before it reaches the soil surface and the detector. The layers have activity concentrations \( C \) and bulk density \( \rho \). Upper left panel: expected apparent activity concentrations on top of a two-layered system, as a function of top-layer thickness. Lower left panel: apparent activity concentration in percent of the activity concentration of the top layer, as a function of the product of mass-attenuation coefficient, bulk density and top-layer thickness. The maximum detectable layer thickness (\( d_{\text{max}} \)) is indicated (see text).
5.3 Measurements and study sites

The main part of this chapter deals with measurements carried out in April 2006, on a transect called TP06 on the barrier island of Schiermonnikoog (see Chapter 2). Subsequently the general applicability of the two-layer model is tested on several other measurement sites on Schiermonnikoog, Terschelling, Skallingen and Westerhever.

5.3.1 Main study site

The main study site TP06 is a 160 m long transect on Schiermonnikoog. It is located between the high marsh and the levee of a major creek, so that the top-layer thickness increases along this transect in the direction of the creek. Along the transect, the parameters necessary for the two-layer model were determined: $C_{j,\text{base}}, C_{j,\text{top}}, C_{j,\text{surface}}, d$ and $\rho_{\text{top}}$.

In-situ radiation ($C_{j,\text{surface}}$)

In-situ radioactivity ($C_{j,\text{surface}}$) was measured with two detectors: the Scintrex GIS-5 and PANDORA detectors. The Scintrex GIS-5 detector is a portable detector displaying total count rates (see Chapter 2). During the surveys, the detector was placed on top of the soil. Scintrex recordings were taken at 86 locations along the transect. Counting times were 200 seconds or more, which for the measured count rates results in statistical uncertainties of less than 2%. Background was subtracted (see Chapter 2).

The PANDORA detector (see for a description of the detector and analysis method Chapter 2) was also positioned on the ground, with an arbitrary part of the cylinder wall facing the soil. In total, 36 PANDORA measurements were carried out, their locations along the transect based on the variation found with the Scintrex GIS-5 detector and measurements of top-layer thickness. Measurement times were at least 10 minutes.

Figure 5.2. The location of the measurement sites on Schiermonnikoog (NL).
per location, ensuring that the statistical uncertainties in the activity concentrations of $^{232}\text{Th}$, $^{40}\text{K}$ and $^{238}\text{U}$ were below 3%. A measurement at $x = 146$ m (local top-layer thickness of 79 cm, which means that the detector will only detect $\gamma$-rays from the top layer) was used for calibration and was therefore left out of the rest of the analysis. Full-Spectrum Analysis was used to convert the obtained spectra into total count rates and apparent activity concentrations of $^{40}\text{K}$, $^{232}\text{Th}$, $^{238}\text{U}$ and $^{137}\text{Cs}$. Net total count rates were determined by correcting the spectra for drift and summing the spectral content over the range $0.2 – 2.8$ MeV. Initially, the apparent activity concentrations were determined with respect to the wet sediment. Based on the variation in water content in the soil (see below) we will decide whether we can reliably convert these values to dry activity concentrations. A second type of Full-Spectrum Analysis was carried out with standard spectra for the base and top layer so that the relative contribution of the top layer to the total in-situ radiation ($\beta$) could be determined (equation 5.10).

During the majority of the radiometric measurements there was no precipitation, except for the last PANDORA measurements. Rain may introduce radon progeny and thus affect $^{238}\text{U}$ concentrations and total count rates. However, there was no notable increase in the $^{238}\text{U}$ levels at the affected measurement points compared to surrounding points that were measured under dry conditions.

Activity concentrations of top and base layer ($C_{j,\text{top}}$ and $C_{j,\text{base}}$).

The activity concentrations of the top ($C_{j,\text{top}}$) and base ($C_{j,\text{base}}$) layer were determined from sediment samples. Samples were taken from soil cores at seven locations along the transect. The locations were chosen to represent the variability along the transect, based on measurements with the Scintrex GIS-5 detector and soil-corer. PVC tubes of 50 cm length and either 10 or 7.5 cm diameter were driven into the soil and subsequently dug out. Compaction was a few cm at most. The cores were transported to the laboratory where they were cut into slices of approximately equal contributions to the $\gamma$-ray spectra of the PANDORA detector, based on Monte-Carlo simulations (Chapter 3). These increments were 0 – 2.5 cm, 2.5 – 7.5 cm, 7.5 – 17.5 cm, and 17.5 – 32.5 cm from the top of the core. One core was cut up into equal increments of 2.5 cm. Only (visually) pure samples of top or base layer were taken. This resulted in a total of 39 samples: 26 from the top layer and 13 from the base layer. The samples were measured without further preparation in 100 ml pillboxes or Marinelli beakers of 0.5 or 1.0 litre on a hyper-pure germanium (HPGe) detector (see Chapter 2). Because the samples were not sealed before measuring, the activity concentrations for $^{238}\text{U}$ may be underestimated. Therefore $^{238}\text{U}$ is only used in an indicative way in further analysis. After HPGe analysis, the samples were dried for 24 h at 105°C to determine the absolute water content $w_a$ (equation 3.5) and activity concentrations of the dry sediment (equation 3.6).

The values for $C_{j,\text{base}}$ and $C_{j,\text{top}}$ for the two-layer model were based on the sample activity concentrations. The values of $TC_{\text{base}}$ and $TC_{\text{top}}$ for the PANDORA detector were determined from:
Box 5.1 Sample activity concentration and Scintrex GIS-5 detector response

To determine the relation between Scintrex total count rate and sediment activity concentrations, in 2003 and 2004 samples were taken alongside Scintrex measurements on various sites on Schiermonnikoog with homogeneous sediment. The samples were analysed on an HPGe detector.

Assuming equal efficiencies for detection of any $\gamma$-ray and a homogeneous distribution of the radionuclides in the sediment, in first order the total count rate is proportional to the sum of the multiplicity values $p_j$ (i.e. the average number of $\gamma$-rays emitted per becquerel) and activity concentrations $C_j$ of the radionuclides:

$$TC = b + c \sum_j p_j C_j$$  \hspace{1cm} (5.12)

where $b$ represents a contribution to the count rate from the background and $c$ is a scaling factor representing detector efficiency. The relation between $TC_{\text{net}}$ (counts per second, cps) and $\sum_j p_j C_j$ from the selected samples is plotted in Figure 5.3. The data points lie on a straight line which indicates that samples and in-situ count rates can effectively be described by equation 5.12. A weighted regression yields:

$$TC_{\text{Scintrex, net}} = -5.0 + 0.58 \sum_j p_j C_j.$$  \hspace{1cm} (5.13)

The negative value of the intercept indicates that the experimentally measured background (Chapter 4) may be too high. For the range of count rates measured on Schiermonnikoog, this will not lead to negative count rates.

![Figure 5.3. Relation between Scintrex total net count rates (vertical axis) and activity concentrations from sediment samples, expressed as $\sum p_j C_j$ (see text). The uncertainties in count rates are smaller than the dots.](image)
where $X_{ij}$ is the standard spectrum with channels $i$ of radionuclide $j$. The values for parameter $\beta$ in equation 5.10 are $\beta_{\text{top}} = 1$ and $\beta_{\text{base}} = 0$.

For the Scintrex GIS-5 detector, standard spectra are not available. To determine $T_{C_{\text{base}}}$ and $T_{C_{\text{top}}}$, the relation between sample activity concentrations and Scintrex response was determined (Box 5.1) and subsequently applied with samples from the measurement site.

To determine whether the top and base layer consist of radiometric homogeneous sediment of the same types as described in Chapter 4, we calculated mixing coefficients $\alpha_j$ from the dry activity concentrations for all samples and radionuclides using equation 4.2. For the values of $C_{j,1}$ and $C_{j,2}$ we used the fingerprints of the coarse-grained and fine-grained group, respectively, as identified in Chapter 4.

**Water content and bulk density ($w_a$ and $\rho$)**

Sediment bulk density and in-situ water content were measured by driving metal rings of 100 cc into the soil. This was done at the walls of the holes left by the PVC cores and at five other locations where holes were dug. Four samples per core location were taken at several depths, the exact depths depending on the location of the silt-sand contact. Wet bulk density $\rho_{\text{wet}}$ was calculated from equation 3.7. Subsequently the samples were dried for 24 h at 105°C to determine the absolute water content $w_a$ (equation 3.5). The uncertainties in bulk density and water content, due to compaction or insufficient filling of the rings, were estimated to be about 5%. Wet bulk density $\rho_{\text{dry}}$ and porosity $\varepsilon$ were calculated from equations 3.8 and 3.9.

**Effective attenuation coefficient ($\mu/\rho$)$_{\text{eff},j}$**

The nuclide-specific, effective mass-attenuation coefficients $(\mu/\rho)_{\text{eff},j}$ for $^{40}$K and $^{137}$Cs in a semi-infinite geometry were approximated by the standard mass-attenuation coefficients. The reason for this is that the net effects of multiple scattering and radiation originating under an angle with the vertical are not known. The mass-attenuation coefficients were derived from the online database XCOM (Berger et al., 2007), using the emitted $\gamma$-ray energy and a sediment mixture consisting of 50% water and 50% quartz. This composition is an approximation of the sediment in the top layer of the main measurement site, of which the average water content is $0.49 \pm 0.09$. The attenuation coefficients for the decay series of $^{232}$Th and $^{238}$U were based on the effective $\gamma$-ray energies of these series, calculated in Chapter 3 from simulations. For the total count rates, the effective mass-attenuation coefficient depends on the relative amounts in which the radionuclides are present in the sediment. It is unpractical to determine a new coefficient for each individual measurement point. Therefore we used the relative contributions of the individual radionuclides to TC PANDORA to weight the (effective) energies of the individual radionuclides. This gave $E_{\text{eff}} = 0.91$ MeV for the total count rates of the PANDORA and Scintrex GIS-5 detectors.
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Top-layer thickness ($d_{\text{man}}$)
Top-layer thickness was measured manually ($d_{\text{man}}$) using a small soil corer, which is the traditional way (Chapter 2). Layer thickness was measured at distances of 0, 25, 50, 75 and 100 cm from the measurements with the PANDORA detector in four directions, and additionally every metre along the transect. Top-layer thickness was averaged over the manual measurements inside a 1 m radius around a radiometric measurement. This radius is based on calculations of the volume ‘viewed’ by the PANDORA detector (Chapter 3). The uncertainty in the average was defined as the standard deviation, using the precision of the measurements as lower limit.

To describe marsh geomorphology, soil elevation was measured at the same positions as top-layer thickness (see Chapter 2).

5.3.2 Other study sites
The main measurement site TP06 represents a relative small area of marsh. To assess whether the results from that location apply to barrier-island marshes in general, we tested the two-layer model on several other marsh sites in the Wadden Sea (see also Chapter 2). At Schiermonnikoog four other transects of variable marsh age were located (SCH_T0, SCH_G5, SCH_G7 and SCH_G14, Figure 5.2). On Terschelling, west of Schiermonnikoog, two transects were investigated (TERS_T3 and TERS_T4, 53°26´N, 5°28´E). Skallingen, the barrier spit that forms the northern end of the international Wadden Sea, supplied two transects (SKAL_03 and SKAL_T2, 55°30´N, 8°20´E). The Westerhever salt marsh (54°22'N, 8°38'E), on which transect W was situated, lies along the mainland coast of Germany. At these transects, measurements were made of in-situ radioactivity with the Scintrex GIS-5 detector, sediment activity concentrations in samples and manual top-layer thickness. Measurement spacing varied. The values for $TC_{\text{base}}$ and $TC_{\text{top}}$ were determined with equation 5.13 from at least one set of samples of top and base layer at or near the site. Bulk density and mass-attenuation coefficient of the individual transects were not known and therefore the values of TP06 were used. Top-layer thickness was averaged over all corer measurement within 1 m from the detector measurement. On SKAL_03 only the total thickness of the fine layers was available instead of total layer thickness. However, on Skallingen these thicknesses are generally the same (see Chapter 6).

5.4 Results

5.4.1 Measurement results and model parameters for the main study site
Marsh geomorphology
The topography of the main study site TP06 reflects the transition from high marsh ($x = 0$ m) to a levee ($x = 160$ m) (Figure 5.4). The thickness of the top layer ranges from around 3 cm at the high marsh to over 1 m at the creek levee. At the high marsh ($0 – 10$ m) the top layer is only a few cm thick and contains quite some organic material. Between $x = 10$ m and $x = 110$ m the marsh elevation is constant and top-layer
thickness ranges from 10 to 20 cm. Often, a thin sand layer of around one cm thick is present in the lower part of the top layer. The part between $x = 110$ and 150 m consists of an alternation of ridges and elongated, moist areas in between, more or less perpendicular to the transect. Top-layer thickness increases from 20 to 100 cm. The transect ends at the levee of a major creek which forms an elevated ridge, with a top layer of approximately 100 cm thick. On the landward side of the levee, the lower part of the top layer consists of an alternation of coarser and finer layers.

Sediment water content and bulk density
Water content, wet and dry bulk density and porosity differ between the top and the base layer (Figure 5.5). The values are all more or less constant in the base layer whereas in the top layer there is variation at the sample locations and along the transect. Water content ranges from 0.09 to 0.64 by mass. It is around 0.2 in the base layer and decreases from around 0.6 to around 0.4 along the transect in the top layer (Figure 5.5). The magnitude of the variation in water content and the difference between top and base layer mean that it is not possible to correct the in-situ activity concentrations from the PANDORA and Scintrex GIS-5 detectors for water content within acceptable uncertainties. Therefore all in-situ apparent activity concentrations will be given with respect to the wet sediment (c.f. Chapter 3).

The wet bulk density of the top layer varies considerably at the measurement points and along the transect, ranging from 0.66 to 1.77 g cm$^{-3}$ (Figure 5.5), and increases overall slightly along the transect. As input value for the two-layer model we take the transect average of the average bulk density per measurement point in the top layer, giving $1.24 \pm 0.20$ g cm$^{-3}$. The variations in wet bulk density are caused by a combination of variations in water content and dry bulk density. The increase in dry bulk density from $x = 0$ m to $x = 160$ m along the transect is related to the decreasing porosity of the top layer (Figure 5.5).
Sediment activity concentrations of top and base layer

The wet activity concentrations (\(^{40}\text{K}, {^{232}\text{Th}}, \text{and} {^{238}\text{U}}\) and the \(^{232}\text{Th} / {^{238}\text{U}}\) ratio) derived from sediment samples are in most cases higher in the top layer than in the base layer and vary internally within the layers (Figure 5.6). The wet activity concentrations of top and base layer overlap at some sample locations for \(^{40}\text{K}\) and \(^{238}\text{U}\). The wet activity concentrations in the top layer on average increase along the transect and vary within a factor 1.6 for the \(^{232}\text{Th} / {^{238}\text{U}}\) ratio, 2 for \(^{40}\text{K}\) and \(^{232}\text{Th}\) and 2.4 for \(^{238}\text{U}\). In the base layer the wet activity concentrations vary within a factor 1.3 (the \(^{232}\text{Th} / {^{238}\text{U}}\) ratio), 1.5 (\(^{40}\text{K}\)), 1.8 (\(^{232}\text{Th}\)) and 1.9 (\(^{238}\text{U}\)) and do not have a trend. The wet activity concentrations of \(^{137}\text{Cs}\) have a different pattern, with low values in the base layer and variations up to an order of magnitude in the top layer. This is consistent with the episodic deposition of \(^{137}\text{Cs}\) in combination with the continuous accretion of the salt marsh, resulting in enriched layers within the sediment.

The dry activity concentrations vary within the two layers, but do not increase along the transect like the wet activity concentrations do (Figure 5.7). The difference between the base and top layer is larger than for the wet activity concentrations. The different pattern of wet and dry activity concentrations indicates that sediment water content is in part responsible for the increase in wet activity concentrations along the transect.

Figure 5.5. Sediment properties for the top layer (filled circles) and base layer (open circles) along the main study site. Upper left: in-situ water content; upper right: wet bulk density; lower left: porosity and lower right: dry bulk density. Error bars represent the estimated uncertainty of 5%.
The mixing coefficients $\alpha_j$ from the base layer fall, as expected, within the coarse-grained group of Schiermonnikoog sediment (Figure 5.8). The mixing coefficients of the top layer for $^{40}$K and $^{238}$U are in general consistent with the pure fine-grained group, centred around $\alpha_j = 0$. For $^{232}$Th the values of $\alpha_j$ are shifted towards negative values\(^1\) (Figure 5.8). The shift suggests that part of the measurement site contains sediment from the tail of the distribution described in Chapter 4.

\(^{1}\) The samples from this chapter were not sealed so that radon escape may influence the $^{238}$U concentrations. Hence we will not elaborate on the values for $^{238}$U and $^{232}$Th/$^{238}$U.

Figure 5.6. Wet activity concentrations $C_j$ in the top (filled circles) and base layer (open circles) of the main measurement site, derived from sediment samples. Error bars represent measurement uncertainties.
We will calculate radiometric layer thickness with the average wet activity concentration of all core averages\(^2\) as values for \(C_{j,\text{base}}\) and \(C_{j,\text{top}}\). The values of \(T_{C,\text{base}}\) and \(T_{C,\text{top}}\) for the PANDORA and Scintrex GIS-5 detectors are determined from these samples and equations 5.11 and 5.13. Based on the standard deviations per core site, the uncertainty in the hypothetical count rates is estimated to be about 20%.

\(^2\) Because the number of samples from top or base layer is different between the cores, this method prevents bias introduced by the number of samples.
The activity concentrations, count rates and $\beta$ (further called radiometric quantities) obtained from the in-situ measurements with the PANDORA and Scintrex GIS-5 detectors increase along the transect, except for $^{137}$Cs. This increase coincides with the increase in top-layer thickness along the transect (left panels of Figure 5.9), whereas the reversed pattern of $^{137}$Cs probably reflects the increasing burial depth of this radionuclide. The total count rates follow the same pattern as the three natural radionuclides and are therefore dominated by the contributions from these radionuclides. Similar to the results from the entire island (Chapter 4), most radiometric quantities are strongly positively correlated; only correlations with $^{137}$Cs are less good and reverse to the others (Table 4.3). Because of the high correlation coefficients, the individual radionuclides will provide approximately the same information and total count rates may be used for characterising the sediment (c.f. Chapter 4).

The values of the radiometric quantities rise exponentially to a maximum with increasing top-layer thickness (right panels of Figure 5.9). This agrees with the expected pattern and indicates that the two-layer model can potentially be applied.

Figure 5.8. Histograms of mixing coefficient $\alpha_j$ in the top layer (black bars) and base layer (grey bars) from sediment samples taken along the main measurement site. The values are based on the dry activity concentrations. For comparison, the histograms of $\alpha_j$ from the fingerprints of Schiermonnikoog sediment (Chapter 4) are given in the grey outline.

In-situ radiation

The activity concentrations, count rates and $\beta$ (further called radiometric quantities) obtained from the in-situ measurements with the PANDORA and Scintrex GIS-5 detectors increase along the transect, except for $^{137}$Cs. This increase coincides with the increase in top-layer thickness along the transect (left panels of Figure 5.9), whereas the reversed pattern of $^{137}$Cs probably reflects the increasing burial depth of this radionuclide. The total count rates follow the same pattern as the three natural radionuclides and are therefore dominated by the contributions from these radionuclides. Similar to the results from the entire island (Chapter 4), most radiometric quantities are strongly positively correlated; only correlations with $^{137}$Cs are less good and reverse to the others (Table 4.3). Because of the high correlation coefficients, the individual radionuclides will provide approximately the same information and total count rates may be used for characterising the sediment (c.f. Chapter 4).

The values of the radiometric quantities rise exponentially to a maximum with increasing top-layer thickness (right panels of Figure 5.9). This agrees with the expected pattern and indicates that the two-layer model can potentially be applied.
Figure 5.9. Upper panel: average top-layer thickness on the main measurement site. Left panels: *in-situ* total count rates, apparent activity concentrations and relative contribution of top layer $\beta$ measured with the PANDORA and Scintrex GIS-5 detectors. Right panels: relation between top-layer thickness and *in-situ* radiation.
Figure 5.9. Continued.
Figure 5.9. Continued.
The maximum value is reached at top-layer thicknesses between 30 and 40 cm, except for $^{40}\text{K}$, which levels off between 40 and 50 cm top-layer thickness. This maximum detectable layer thickness coincides with the theoretical maximum detection depths (calculated from bulk density and mass-attenuation coefficients, section 5.2) for $^{40}\text{K}$, $^{\beta}$, TC PANDORA and TC Scintrex (Table 5.1). The actual detection depth is higher (40 – 50 cm) than the calculated one for $^{232}\text{Th}$, $^{238}\text{U}$ and their ratio, based on the effective energies of 0.62 and 0.58 MeV for these two decay series. We therefore choose practical maximum detection depths of 45 cm (for $^{40}\text{K}$) and 35 cm (for the other radiometric quantities) that will be used as cut-off in the calculations of the radiometric top-layer thickness in the next section.

There are a large number of observations with top-layer thickness between 10 and 20 cm. Part of these values follow the expected curve, but the ones measured at the stretch between $x = 20$ and $x = 100$ m on the transect are lower than expected (i.e. the cluster of data points in the right panels of Figure 5.9). This indicates that this part of the transect may have different radiometric properties than the rest. Based on Figure 5.5, Figure 5.6 and Figure 5.7, wet bulk density is the most likely candidate.

Table 5.1. Correlations (Spearman’s $\rho$, as the data are non-normal) between in-situ radiometric quantities. Between PANDORA variables $N = 35$ and for correlations with Scintrex $N = 31$. All correlations are significant at the 0.001 level.

<table>
<thead>
<tr>
<th></th>
<th>TC PANDORA</th>
<th>$^{40}\text{K}$</th>
<th>$^{232}\text{Th}$</th>
<th>$^{238}\text{U}$</th>
<th>$^{137}\text{Cs}$</th>
<th>$^{\beta}$</th>
<th>TC Scintrex</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC PANDORA</td>
<td>1.000</td>
<td>0.929</td>
<td>0.885</td>
<td>0.869</td>
<td>-0.585</td>
<td>0.911</td>
<td>0.946</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>0.929</td>
<td>1.000</td>
<td>0.945</td>
<td>0.788</td>
<td>-0.698</td>
<td>0.985</td>
<td>0.962</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>0.885</td>
<td>0.945</td>
<td>1.000</td>
<td>0.737</td>
<td>-0.786</td>
<td>0.968</td>
<td>0.909</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0.869</td>
<td>0.788</td>
<td>0.737</td>
<td>1.000</td>
<td>-0.649</td>
<td>0.805</td>
<td>0.808</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>-0.585</td>
<td>-0.698</td>
<td>-0.786</td>
<td>-0.649</td>
<td>1.000</td>
<td>-0.755</td>
<td>-0.607</td>
</tr>
<tr>
<td>$^{\beta}$</td>
<td>0.911</td>
<td>0.985</td>
<td>0.968</td>
<td>0.805</td>
<td>-0.755</td>
<td>1.000</td>
<td>0.948</td>
</tr>
<tr>
<td>TC Scintrex</td>
<td>0.946</td>
<td>0.962</td>
<td>0.909</td>
<td>0.808</td>
<td>-0.607</td>
<td>0.948</td>
<td>1.000</td>
</tr>
</tbody>
</table>

5.4.2 Radiometric top-layer thickness: main study site
Two-layer model with homogeneous layers
With the parameter values determined in the previous section, we calculated the radiometric layer thickness $d_{m}$ separately for all radiometric quantities from the in-situ measurements (Figure 5.10 and Table 5.2). The radiometric layer thickness largely follows the increase along the transect of the manual thickness, but the values do not always agree. Between $x = 20$ and $x = 100$ m, the radiometric layer thickness generally underestimates the manual layer thickness, often by more than a factor two. This is the same group of data points having relatively low apparent activity concentrations in Figure 5.9. On the rest of the transect, the agreement between radiometric and manual thickness varies. For manual layer thicknesses over 20 cm, most radiometric layer
Figure 5.10. Comparison of manual (open circles) and radiometric (filled circles) layer thickness on the main measurement site. The radiometric thickness is calculated for homogeneous layers with constant values of $C_{j,\text{base}}$, $C_{j,\text{top}}$ and $\rho_{\text{top}}$. The maximum of each vertical axis represents the cut-off thickness for the radiometric thickness. To preserve clarity, the in general large uncertainties in radiometric layer thickness are omitted.
Table 5.2. Model parameters for the calculation of top-layer thickness on the main measurement site and model performance, for homogeneous layers (with $\rho_{\text{top}} = 1.24 \text{ g cm}^{-3}$) and individual core locations. The total number of data points is 35 for the PANDORA quantities and 86 for TC Scintrex. For the $\chi^2$ test the uncertainties in $d_{\text{rm}}$ are taken into account and radiometric top-layer thicknesses over $d_{\text{max}}$ were omitted. If $p$ exceeds the significance level of 0.05, the manual and radiometric layer thicknesses are considered statistically equal.

<table>
<thead>
<tr>
<th>Radiometric variable</th>
<th>$E_{\text{eff}}$ (MeV)</th>
<th>$\mu/\rho$ (cm$^2$ g$^{-1}$)</th>
<th>XCOM detection, cm</th>
<th>$d_{\text{max}}$ (95% theoretical)</th>
<th>$d_{\text{max}}$ (practical)</th>
<th>$C_{j,\text{base}}$ (Bq kg$^{-1}$) and $T_{C_{j,\text{base}}}$ (cps)</th>
<th>$C_{j,\text{top}}$ (Bq kg$^{-1}$) and $T_{C_{j,\text{top}}}$ (cps)</th>
<th>$N$ (valid)</th>
<th>$\chi^2$</th>
<th>$p$</th>
<th>$N$ (valid)</th>
<th>$\chi^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC Pandora</td>
<td>0.91 a)</td>
<td>0.0703</td>
<td>34</td>
<td>35</td>
<td></td>
<td>165 ± 33</td>
<td>271 ± 54</td>
<td>27</td>
<td>0.3</td>
<td>1.0</td>
<td>5</td>
<td>0.95</td>
<td>0.82</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>1.46</td>
<td>0.0554</td>
<td>44</td>
<td>45</td>
<td></td>
<td>199 ± 14</td>
<td>249 ± 36</td>
<td>27</td>
<td>0.4</td>
<td>1.0</td>
<td>4</td>
<td>1.38</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>0.62 b)</td>
<td>0.0839</td>
<td>29</td>
<td>35</td>
<td></td>
<td>7.2 ± 1.4</td>
<td>14.1 ± 2.5</td>
<td>26</td>
<td>1.1</td>
<td>1.0</td>
<td>6</td>
<td>0.73</td>
<td>0.95</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>0.59 b)</td>
<td>0.0858</td>
<td>28</td>
<td>35</td>
<td></td>
<td>6.3 ± 1.3</td>
<td>8.8 ± 1.9</td>
<td>26</td>
<td>1.2</td>
<td>1.0</td>
<td>5</td>
<td>17.6</td>
<td>0.001</td>
</tr>
<tr>
<td>$^{232}$Th/$^{238}$U</td>
<td>0.61 c)</td>
<td>0.0848</td>
<td>29</td>
<td>35</td>
<td></td>
<td>1.14 ± 0.07</td>
<td>1.63 ± 0.15</td>
<td>16</td>
<td>1.5</td>
<td>1.0</td>
<td>4</td>
<td>0.15</td>
<td>0.93</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.91 a)</td>
<td>0.0703</td>
<td>34</td>
<td>35</td>
<td></td>
<td>0</td>
<td>1</td>
<td>26</td>
<td>1.0</td>
<td>1.0</td>
<td>6</td>
<td>2.1</td>
<td>0.72</td>
</tr>
<tr>
<td>TC Scintrex</td>
<td>0.91 a)</td>
<td>0.0703</td>
<td>34</td>
<td>35</td>
<td></td>
<td>26 ± 5</td>
<td>53 ± 11</td>
<td>61</td>
<td>0.4</td>
<td>1.0</td>
<td>6</td>
<td>0.77</td>
<td>0.94</td>
</tr>
</tbody>
</table>

a) approximation based on relative contributions of individual radionuclides on the measurement site
b) from Monte-Carlo simulations in Chapter 3
c) average of $^{232}$Th and $^{238}$U
d) using the average activity concentrations from Figure 5.6
thicknesses are overestimated and become higher than the cut-off value. At the end of the transect TC Scintrex underestimates high layer thicknesses. For part of the data points, top-layer thickness cannot be calculated because $C_{j,\text{surface}}$ is equal to or higher than $C_{j,\text{top}}$, or the radiometric layer thickness is higher than the cut-off value. The $^{232}\text{Th}/^{238}\text{U}$ ratio performs worst in this respect. The total count rates from the PANDORA and Scintrex GIS-5 detectors perform better than the quantities derived from Full-Spectra Analysis involving standard spectra ($^{40}\text{K}$, $^{232}\text{Th}$, $^{238}\text{U}$, $^{232}\text{Th}/^{238}\text{U}$ and $\beta$).

The agreement between radiometric and manual top-layer thickness was tested using $\chi^2$ tests taking into account the uncertainties in $d_{\text{rm}}$. These uncertainties are very large, with relative values of over 100%. Consequently, for all parameters the radiometric and manual top-layer thicknesses are statistically the same ($p \geq 0.05$ in Table 5.2, values above the cut-off are omitted). However, because the uncertainties in the radiometric layer thickness are so large, this statistical result fails to reflect the visual disagreement between manual and radiometric layer thickness.

Varying $C_{j,\text{base}}$ and $C_{j,\text{top}}$ along the transect according to linear fits through the sample activity concentrations did not improve the visual agreement of manual and radiometric top-layer thickness.

Two-layer model for individual core locations
The previous results suggest that the sediment composition may be too variable to describe with constant or linearly varying activity concentrations. Therefore, we calculated radiometric layer thickness individually for the six measurement points where local $C_{j,\text{base}}$, $C_{j,\text{top}}$ and $\rho_{\text{top}}$ are known from sediment samples (Figure 5.11). Again, the large uncertainties lead to a statistically good agreement between radiometric and manual top-layer thickness, except for $^{238}\text{U}$ (Table 5.2). However, compared to the uncertainties in $d_{\text{man}}$ the agreements are not good. Top-layer thickness calculated from $\beta$ follows the trend along the transect best, although it is at least a factor two too low.

Optimising the middle part of the transect
Top-layer thickness between $x = 20$ and $x = 100$ m on the transect was almost invariably underestimated. To identify possible causes for the mismatch, we iteratively varied the values of $C_{j,\text{base}}$, $C_{j,\text{top}}$ and $(\mu/\rho)_{\text{eff},j}\rho_{\text{top}}$ in the calculations. The values of all three parameters need to be lowered in order to obtain more matching thicknesses, often outside the range of expected values. It is not possible to derive values of $d_{\text{rm}}$ within the uncertainties of $d_{\text{man}}$ for the entire transect using one set of values for $C_{j,\text{base}}$, $C_{j,\text{top}}$ and $(\mu/\rho)_{\text{eff},j}\rho_{\text{top}}$. Wet bulk density is indeed lower on this part of the transect than elsewhere, but not enough to account for the entire underestimation of top-layer thickness (Figure 5.5). Lower values for $C_{j,\text{base}}$ and $C_{j,\text{top}}$ are not expected from sample analysis (Figure 5.6). The cause for the structural mismatch at this part of the transect is therefore not clear.
Figure 5.11. As Figure 5.10 but with the radiometric thickness calculated individually for the six locations where local $C_{j,\text{base}}$, $C_{j,\text{top}}$ and $\rho_{\text{top}}$ are known from sediment samples.
5.4.3 Radiometric top-layer thickness on other salt-marsh sites

To assess whether the results from the main measurement site are representative for barrier-island marshes in the Wadden Sea, we repeated the measurements with the Scintrex GIS-5 detector on other marsh sites. Values for \( T_{C_{\text{base}}} \) and \( T_{C_{\text{top}}} \) were based on samples (Table 5.3). Uncertainties were estimated to be 5% because, except for \(^{137}\text{Cs}\), the uncertainties in sample radionuclide activity concentrations are all below this percentage. The dry sample activity concentrations were converted into mixing coefficients \( \alpha_j \) and were compared to the radiometric fingerprints of Schiermonnikoog. The majority of sample activity concentrations fall in the range observed on Schiermonnikoog, and the ones deviating did not show a clear geographical pattern.

The sites had various ranges of observed top-layer thicknesses (Figure 5.12). The relation between in-situ total count rates and manual top-layer thickness follows the expected pattern at the locations SCH_G7, SCH_G14, TERS_T3, TERS_T4 and W (compare the left panels of Figure 5.12 with Figure 5.1). At other sites the data points form clusters. This is reflected in the performance of the two-layer model, which is visually best for the same sites, especially TERS_T3, TERS_T4 and W, even though part of the data points cannot be reproduced within a factor two (right panels of Figure 5.12). At most study sites, the radiometric thickness overestimates the manual thickness. This is most pronounced at dune sites (right part of SCH_G5 and SCH_G7, left part of TERS_T3 and some points in SCH_G14), the intertidal flats, pioneer zones and very young marshes on Schiermonnikoog (SCH_T0 and left parts of SCH_G5, SCH_G7 and SCH_G14), which have relatively high total count rates. The overestimation at SKAL_T2 may be caused by calibration samples that are not representative, as the sample values are low compared to the other samples from Skallingen and elsewhere. Statistically, manual and radiometric top-layer thickness was the same at all sites (\( p \geq 0.05 \) in Table 5.3). Again, the uncertainties in \( d_{\text{rm}} \) are so large that this has not much practical value.

### Table 5.3. Parameter values and model performance for the other measurement sites.

Radiometric top-layer thicknesses over 35 cm were omitted. Manual and radiometric top-layer thickness are considered statistically the same if \( p \geq 0.05 \).

<table>
<thead>
<tr>
<th>transect</th>
<th>location</th>
<th>( T_{C_{\text{base}}} )</th>
<th>( T_{C_{\text{top}}} )</th>
<th>( N ) (total)</th>
<th>( N ) (valid)</th>
<th>( \chi^2 )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCH_T0</td>
<td>Schiermonnikoog</td>
<td>25.7 ± 1.3 (^{a)})</td>
<td>34.8 ± 1.7 (^{a)})</td>
<td>61</td>
<td>47</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>SCH_G5</td>
<td>Schiermonnikoog</td>
<td>25.7 ± 1.3</td>
<td>34.8 ± 1.7</td>
<td>21</td>
<td>16</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>SCH_G7</td>
<td>Schiermonnikoog</td>
<td>25.7 ± 1.3</td>
<td>44 ± 2</td>
<td>27</td>
<td>26</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>SCH_G14</td>
<td>Schiermonnikoog</td>
<td>28.9 ± 1.4</td>
<td>47 ± 2</td>
<td>29</td>
<td>21</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>TERS_T3</td>
<td>Terschelling</td>
<td>24.8 ± 1.2</td>
<td>46 ± 2</td>
<td>40</td>
<td>40</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>TERS_T4</td>
<td>Terschelling</td>
<td>23.7 ± 1.2</td>
<td>50 ± 3</td>
<td>40</td>
<td>40</td>
<td>2.7</td>
<td>1.0</td>
</tr>
<tr>
<td>SKAL_03</td>
<td>Skallingen</td>
<td>26.6 ± 1.3</td>
<td>41 ± 2</td>
<td>20</td>
<td>20</td>
<td>3.8</td>
<td>1.0</td>
</tr>
<tr>
<td>SKAL_T2</td>
<td>Skallingen</td>
<td>15.3 ± 0.8</td>
<td>33.1 ± 1.7</td>
<td>40</td>
<td>25</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>W</td>
<td>Westerhever</td>
<td>28.8 ± 1.4</td>
<td>64 ± 3</td>
<td>11</td>
<td>10</td>
<td>4.4</td>
<td>0.82</td>
</tr>
</tbody>
</table>

\(^{a)}\) Because there were no samples available for SCH_T0, values from the nearby SCH_G5 were used.
5.5 Discussion

5.5.1 General
The aim of this chapter was to investigate how well top-layer thickness on salt marshes can be determined using in-situ $\gamma$-radiation, combined with an analytical two-layer model. We found that at most of the studied marsh sites, the level of in-situ radioactivity is related to the thickness of the top layer of marsh deposits. The shape of this relation shows the effect of the generation and absorption of $\gamma$-ray in the two layers and follows the relation described by the model. However, the degree to which radiometric layer thickness reproduced manual top-layer thickness was variable. There are two main possible causes for this. These are the variations in sediment composition on the test sites and the intrinsic properties of the two-layer model. We will discuss these here.

5.5.2 Salt-marsh properties
Earlier studies found the two-layer model a very promising method for determining layer thickness from in-situ measurements (Van der Graaf et al., 2004). Compared to these earlier studies, the two layers on the salt marsh are less well defined. On the main study site, the top layer consists of the fine-grained sediment described in Chapter 4 and the base layer of the coarse-grained sediment. Despite internal variations, the two layers can be distinguished based on their dry activity concentrations. However, water content varies significantly within and differs between the two layers, leading to a large variation in wet activity concentrations around their means. Consequently the top and base layers cannot always be distinguished radiometrically and considerable uncertainty is introduced in the radiometric layer thickness. Additionally, the bulk density varies both vertically within the top layer and along the transect, as the result of variations in water content and porosity. This causes uncertainty in the degree of attenuation of the $\gamma$-radiation and thus radiometric layer thickness.

Our sample spacing was in the order of 10 – 20 m, whereas in-situ detectors receive radiation from a soil volume with a radius of approximately one metre. It is therefore possible that there are variations in activity concentrations and/or bulk density within the transect that affect the in-situ apparent activity concentrations but that were not sampled.

Even when the above uncertainties are taken into account, the cause of the structural underestimation of the layer thickness on the middle part of the main study site, with layer thicknesses between 10 and 20 cm, remains unclear.

5.5.3 Two-layer model
The two-layer model is an analytical, one-dimensional model that describes a complex, three-dimensional situation. Some three-dimensional processes may not be taken fully into account, leading to uncertainty in the calculated layer thicknesses. These uninvestigated effects include the following.

- We used the attenuation coefficients defined for a one-dimensional narrow-beam
Figure 5.12. Left panels: in-situ total count rate measured with the Scintrex GIS-5 detector as a function of top-layer thickness for various sites in the Wadden Sea (for Schiermonnikoog locations see Figure 5.2). The uncertainties in total count rates are generally smaller than the dots. Right panels: radiometric (black) and manual (grey) top-layer thickness along the transects. The maximum on the vertical axis represent the cut-off in radiometric thickness.
Figure 5.12. Continued
geometry. However, the in-situ apparent activity concentrations are derived from entire spectra rather than only the full-energy peak, in a three-dimensional setting. It may be necessary to incorporate the effect of the multiple scattering of the radiation in the soil into the attenuation coefficients.

- The average path length through the top layer of the radiation reaching the detector is larger in a three-dimensional situation than in a one-dimensional one. Radiometric measurements may therefore underestimate the real layer thickness.
- The shape of the detected spectra may depend on top-layer thickness. This would affect the apparent activity concentrations, as these are derived from Full-Spectrum analysis using standard spectra. This might explain the lesser performance of the quantities based on standard spectra compared to the total count rates (section 5.4.2).
- Variations in bulk density within the view of the detector may affect detector response and thus radiometric layer thickness.

The above effects are partly counteracting and are not straightforward to deal with analytically. Monte-Carlo simulations are an appropriate tool in such situations. In Chapter 8 some preliminary simulations will be discussed in view of these effects.

### 5.6 Conclusions

On barrier-island salt marshes in Northwest Europe, in-situ natural γ-radioactivity is generally related to the thickness of the layer of fine-grained marsh deposits. Due to the good correlation between the natural radionuclides, the total radiation at the soil surface gives generally enough information.

We used an analytical two-layer model to calculate the thickness of the top layer from in-situ radioactivity. The degree to which radiometric layer thickness could reproduce top-layer thickness measured with a soil corer varied. The radiometric method works best for top-layer thicknesses of less than 40 cm and for situations with a clear difference between the activity concentrations of the two layers. The method is sensitive to variations in activity concentrations and bulk density in especially the top layer. Such variations occur naturally on salt marshes as a result of variations in dry activity concentrations, water content and bulk density.

More study is needed on the following points:

- how to incorporate three-dimensional effects of radiation transport in the currently one-dimensional two-layer model;
- the effect of variations in sediment composition within the view of the detector on detected radioactivity.

Concluding, when taking into account the uncertainties caused by variations in marsh sediment, measurements of γ-radiation on layered salt marshes are most suited as quick-scan of top-layer thickness. This can for example be done by mapping an area from a vehicle or airplane at low altitude.
Radiometric determination of top-layer thickness