The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

MSc Thesis – Final Report

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20-04-2012
Preface

This thesis is a description of the research carried out in order to complete the Double Degree Programme in Hydraulic Engineering and Water Resources Management at Delft University of Technology and at the National University of Singapore. It covers a study to the effect of bioturbation on the erodibility of fine sediments in Lake Markermeer. The research has been carried out mainly at Deltares in the Netherlands and partly at SDWA¹ in Singapore. The experiments were performed at the FCL² laboratory at Deltares and financed by Ecoshape, Building with Nature project NMU2.1.

This thesis would not have been possible without the help of many people. First of all I would like to thank Miguel de Lucas Pardo, my daily supervisor for being greatly involved with my work, always willing to guide me and for his enthusiasm. And I would also like to thank the other committee members, prof. dr. ir. J.C. Winterwerp, ir. T. Vijverberg, F. Cozzoli and dr. ir. B.C. van Prooijen, for their enthusiasm and their valuable comments on my thesis. I also would like to thank the FCL team, Kees and Saskia, for their assistance during the experiments and not to forget, Marinus Hom, who made it possible to gamma radiate our mud samples.

Furthermore I would like to thank dr. Sin Tsai Min and dr. Chew Soon Hoe for supervising while I was in Singapore, and prof. H.F. Cheong for taking the effort of grading.

To end with I would like to thank the Deltares- and DDP-students for being nice colleagues and last but not least my parents and all my sisters for their support.

Enjoy reading this report!

Marieke Bakker

April 2012

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Summary

Lake Markermeer is a large and shallow lake in the center of the Netherlands. The lake was originally part of the Zuiderzee, a sea inlet of the North Sea. After closure of the Afsluitdijk in 1932, the area turned into a freshwater basin. Lake Markermeer was created by the construction of the Houtribdijk in 1976. The lake is an important ecosystem, especially for water birds. The main problem in Lake Markermeer is its decreasing ecological value. High turbidity levels are believed to be one of the reasons for the alarming ecological state.

The lake is characterized by a high load of suspended sediments. The hydrodynamics in the lake is driven by wind, resulting in waves and currents. The waves have a large impact on the lake bottom due to the shallowness. Secondly, there is a layer of soft mud present at the bottom that can be easily resuspended. As a result, wind-induced waves stir up the sediment and wind-induced currents distribute the suspended sediments over the lake. Hence, a turbid lake is created.

This study focusses on the erodibility of the sediment bed. Bed sediments in Lake Markermeer consist mainly of clay and loam. During the Zuiderzee period fine sediments were deposited in the sheltered bay, currently the Markermeer area. These old marine deposits are called Zuiderzee deposits. On top of these sediments a layer of soft mud is found. The soft mud originates mainly from eroded Zuiderzee deposits, however Zuiderzee deposits are well consolidated and very stiff, and therefore it is unlikely they were eroded due to the hydrodynamic forcing in the lake. It remains unknown how the soft mud layer has been created from erosion of the Zuiderzee deposits.

The soft mud layer can be further divided into two layers. The lower layer consists of anoxic mud, characterized by a black color and is about 10 cm thick. The top layer is very thin, only a few mm, and consists of oxic mud, colored brown-yellow. The color and chemical properties of the sediment are driven by redox reactions occurring in soil. According to Vijverberg (2010), the sediment concentration in the lake is dominated by resuspension of the oxic mud layer. It is unknown why the oxic mud layer is easily eroded.

An often mentioned factor that possibly could affect sediment erodibility is the activity of biota. Bioturbation, crawling and burrowing animals, possibly influence the strength of the soil. This leads to the following research question:

‘To what extent affects biota the erodibility of the near bed sediments in Lake Markermeer?’

The effect of bioturbation on sediment erodibility was tested through erosion experiments. Erosion experiments were performed on several samples with biota and one sample without biota. Five samples were taken from the soft mud layer, one of them was defaunated by gamma radiation. One sample was taken from the Zuiderzee deposits.

Sediment cores with a diameter of 10 cm were used for the experiments. Soil samples with the same diameter were taken from the bottom of Lake Markermeer, allowing minimal disturbance of the soil sample. Biota was obtained by sieving the soil samples. Tubifex worms and Ostracoda were the main biota found.
An U-GEMS microcosm was used for the erosion experiments. A combination of a central suction and rotating disk provides a quasi-uniform bed shear stress on the sediment bed. An erosion experiment consists of nine steps of one minute with increasing bed shear stresses. The eroded material is removed from the microcosm with the central suction and the turbidity of the outflowing water is measured with an Oslim. The Oslim measures the attenuation of the intensity of an infra-red light beam through suspended particles.

A series of experiments was performed for every sample. At the start an erosion experiment is performed, before biota would disturb the bed. In order to do this we first removed the oxic layer we found on the field, leading to a smooth and not bioturbated surface. Then biota is added and the sample is stored for 2 days, during this period biota reworks the sediment and simultaneously the top layer gets oxidized. Thereafter an erosion experiment is performed on the bioturbated and oxidized sample. Finally the oxidized layer is removed again and the whole procedure is repeated for a bioturbation period of 4, 6 and 8 days respectively.

The results of the erosion experiments showed a clear difference between the defaunated sample and the bioturbated sample. Erodibility increased after n days of bioturbation, while for the control experiment, the defaunated sample, erodibility decreased after n days. The results also showed that the effect of bioturbation on erodibility is a function of time, the total eroded mass increases with increasing bioturbation period. From this we can conclude that biota indeed affects the erodibility of near-bed sediments in Lake Markermeer. Our experimental results showed that erosion increased with a factor of 3 to 18 after 8 days of bioturbation compared to erosion at the start.

Moreover, observations showed that bioturbation increases the thickness of the oxidized layer. For the bioturbated samples the thickness of the oxidized layer increased with bioturbation period, from 1 to 2.5 mm. An oxidized layer also developed for the defaunated sample, but the thickness didn’t increase in time and reached a value of only 1 mm. These results also showed that oxidized sediment is not necessarily resulting in high erosion and again supports our first hypothesis, bioturbation and not oxidation is increasing the erodibility of the oxic mud layer.

The results of the erosion experiments on the Zuiderzee deposits also showed the effect of bioturbation on erodibility. Zuiderzee deposits showed minor erosion during the experiment at the start and significant erosion during the experiment after bioturbation. Though, erosion rates were much lower compared to the previous experiments, revealing the strength of the Zuiderzee deposits. Again the effect of bioturbation on the erodibility was a function of time.

An important bioturbation mechanism is the production of fecal pellets by Tubifex worms, these worms feed at a certain depth in the black anoxic mud layer and produce easy erodible fecal pellets at the surface. Other mechanisms that might be taking place are disturbance of the soil resulting in a less compacted soil layer and increased roughness due to protrusions. Another noteworthy observation is the erosion type, decreasing erosion rates were observed for increasing shear stresses, this indicates that erosion is limited by the amount of sediments that is available for erosion. Important parameters influencing the bioturbation rate are probably temperature and biota density.
From this research we can conclude that bioturbation makes a certain amount of sediments available for erosion as a function of time, thereby affecting the erodibility of the oxic mud layer and the Zuiderzee deposits. We believe bioturbation is also important for the sediment dynamics in the lake. We hypothesize that bioturbation is an explanation for the high erodibility of the oxic mud layer and bioturbation have also enhanced the erosion of the Zuiderzee deposits, thereby creating the soft mud layer. However, extrapolation to the situation in the field is rather difficult, although a causal relationship has been demonstrated between bioturbation and erodibility, this does not necessarily imply that bioturbation-induced erosion is a dominant mechanism. Another important mechanism in Lake Markermeer is the frequent resuspension of bottom sediments. Due to the frequent resuspension events, there is a certain amount of sediment that is continuously involved in resuspension-deposition loops.
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1 Introduction

1.1 Problem definition

1.1.1 Lake Markermeer

Lake Markermeer is a large shallow lake, located between the provinces Noord-Holland and Flevoland in the Netherlands. It is part of the IJsselmeer area, which consists of Lake IJsselmeer, Lake Markermeer, IJmeer and the border lakes in Flevoland, (Vijverberg 2008). The IJsselmeer area used to be a sea inlet of the North Sea. It was transformed into a fresh water basin after closure of the Afsluitdijk. Lake Markermeer was created by the construction of the Houtribdijk.

Figure 1-1 IJsselmeer area, including Lake Markermeer, www.wikipedia.nl

The lake area is of great ecological value. It is as an important habitat for water birds. The lake is also of great importance for the fresh water supply and for safety against flooding. Nowadays the lake is also used extensively for sailing and other water sports. Furthermore, the lake is used for fishery and transport of goods, (Vijverberg 2008).

1.1.2 Ecological deterioration

The main problem in Lake Markermeer is its ecological deterioration. A decrease in the population of mussels, ‘the crash’, occurred in the 1990s, (RIZA 2003). This event is one of the first signs for the ecological decline. After the crash, also other species, particularly the population of fish-, shell- and zoobenthos eating birds, have declined, (Noordhuis 2010). In 2009, the lake becomes part of the Natura 2000. This means the European Union considers the lake as a valuable habitat that requires protection. Furthermore, there are plans to develop an integral future design of the Lake Markermeer, including building in or around the lake. A healthy ecosystem is a requirement before these plans can be realized.
The sources and solutions for the decreasing ecological value are not well known. A better understanding of the ecosystem in the Markermeer is necessary, in order to find a way to improve the ecological situation. Therefore various research projects are studying the situation in the lake. ANT and BwN are two of those projects. ANT stands for ‘autonomous declining trend’ and focus on the ecologic aspect. BwN stands for ‘building with nature’. Part of ANT and BwN is a PhD research about the fine sediment dynamics in Lake Markermeer. This MSc thesis is embedded in that PhD.

1.1.3 High turbidity level

Lake Markermeer is characterized by a high level of suspended sediments. The high turbidity level is suspected to have an overall negative effect on the ecosystem, (Noordhuis 2010). The reason for the high turbidity levels can be explained by a combination of factors. The hydrodynamics in the lake is wind driven, resulting in waves and currents. Lake Markermeer is relatively shallow and therefore the waves reach the bottom and stir up the sediment. Besides, there is a soft mud layer present at the bottom of the lake, these sediments are easily resuspended. As a result, the wind-induced waves bring the fine sediments into suspension and the wind-driven currents distribute the suspended sediments over the whole lake. Hence, a turbid lake is created.

<table>
<thead>
<tr>
<th>Lake</th>
<th>background concentration</th>
<th>maximum concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markermeer</td>
<td>30 (mg/l)</td>
<td>250 (mg/l)</td>
</tr>
<tr>
<td>Ketelmeer</td>
<td>5 (mg/l)</td>
<td>100 (mg/l)</td>
</tr>
<tr>
<td>Lake Balaton (Hungary)</td>
<td>15 (mg/l)</td>
<td>170 (mg/l)</td>
</tr>
</tbody>
</table>

Table 1-1 Comparison Suspended Matter concentration for different lakes, (Noordhuis 2010)

Lake Markermeer is very turbid compared to other lakes. The turbidity values show a large scatter in the range of 0-300 mg/l. The average concentration of suspended sediments is 50 mg/l, (Van Kessel 2008).

Figure 1-2 - Overview of TSM (Total Suspended Matter) and Secchi depth observations at Markermeer Midden in the period 1982-2008, (Van Kessel 2008)
The water-bed exchange processes, i.e. erosion and deposition, are important processes to understand the present-day high turbidity level. Sediment erosion is forced by the hydrodynamics in the lake. The erodibility is determined by the sediment characteristics, (Winterwerp and Van Kesteren 2004). This research will focus on the erodibility of the sediment.

The historical development of the lake is important for the understanding of the origin of the fine sediments. During the time the lake area was still an inlet sea, the Markermeer area was a sheltered bay. The limited hydrodynamics allowed the deposition of fine sediments. From the moment of the closure, the fine sediments got trapped and remained in the lake basin. These sediments are called the Zuiderzee deposit.

On top of the Zuiderzee deposits, a soft mud layer is present. During the last decades, the layer thickness has increased and shifted more to the east and deeper side of the lake, (Lenselink and Menke 1995). The soft mud layer consists mainly of eroded Zuiderzee deposits. However the Zuiderzee deposits are very stiff and it is unlikely they have eroded under the hydrodynamics in the lake, it remains unknown how the soft mud layer has been created during the past decades.

![Figure 1-3 - Location of the soft mud layer and its thickness (in m) in 1988, (Van Duin 1992)](image)

Another interesting site characteristic is the existence of a very thin oxic mud layer over a large part of the lake bottom, discovered by both Van Duin (1992) and Vijverberg (2008). The very thin oxic mud layer is colored brown-yellow and oxidized, while the soft mud layer below is colored black and in a reduced state. The oxidized and reduced state of the mud is determined by redox reactions occurring in the soil. The reactions are a result of decomposition of organic matter by bacteria. As a consequence of these reactions, the soft mud layer is anoxic. The figure below shows a schematization of the bed composition.
According to Vijverberg (2010) the sediment concentration in Lake Markermeer is dominated by erosion and deposition of the oxidized layer. This mobile layer can resuspend into the water column during already moderate wind conditions: e.g. wind speed Bft 3. The soft mud layer only gets mobilized during storms, see Figure 1-5.

1.2 Objective and hypotheses

An often-mentioned factor that could be of importance in the upper fine sediment layer is the activity of biota, a collective noun for all life. Biota, in the form of digging worms or rooted plants can have a severe effect on the sediment dynamics, (Le Hir, Monbet et al. 2007).

The research objective of this thesis is to increase the understanding of the influence of biota on the fine sediment dynamics in Lake Markermeer. The underlying objective is to find causes for the decreasing ecological value and the assumed related high turbidity levels. The focus is on biologic processes in the water-sediment interface that influence the erodibility of the sediment, this leads to the following research question:

‘To what extent affects biota the erodibility of the near bed sediments in Lake Markermeer?’
The first step is to identify the specific biologic processes affecting the erodibility. The second step would be to quantify the effect of different processes.

Recent laboratory experiments (De Lucas Pardo 2011), have shown the formation of an oxic top layer with a certain equilibrium thickness from a soft mud layer in the reduced state, showing the dynamic equilibrium of the oxic and reduced state of the mud. Other experiments showed an increased water content of the oxic mud layer compared to the anoxic mud layer. However, the influence of oxidation on the sediment properties is only small and could not be held responsible for changing sediment properties.\(^3\) We believe that the oxidized state of the sediment might be an indication for the presence of life; the oxic top layer provides the circumstances for animal life to become active. Hence, the burrowing and crawling of benthic fauna, so called ‘bioturbation’, could possibly be the initiator of the increasing water content and high erodibility of the oxic mud layer. This results in the following hypothesis:

\textit{Hypothesis 1: Bioturbation is taking place in the oxidized layer and is responsible for the increase in erodibility of this layer}

At a large part of the lake the Zuiderzee deposits are covered by the anoxic soft mud layer. We assume biota cannot be active in this anoxic environment. However, at some parts the Zuiderzee deposits are at the water interface. It would be interesting to see the development of this soil layer when oxic conditions are present. The theory is that an oxidized layer will develop where bioturbation can take place. Similar to the process described above, the activity of biota will influence the bed strength. Possibly bioturbation can explain the formation of the soft mud layer from the Zuiderzee deposits.

\textit{Hypothesis 2: When Zuiderzee deposits are at the water interface, the top layer will get oxidized and bioturbation will increase the erodibility of this top layer}

\subsection{1.3 Approach and set up of the report}

The hypotheses are tested through laboratorial experiments. To test the effect of bioturbation on the erodibility, erosion experiments are performed on several Markermeer mud samples, with and without animal life.

This chapter has introduced the problem definition and research objective. Chapter 2 will describe the literature review. Chapter 3 will give a description of the study area: Lake Markermeer. Chapter 4 will describe the material and methods used for the experiments. Chapter 5 will present the results and the discussion. Finally, chapter 6 will give the conclusions and recommendations.

\(^3\) discussion with Prof dr Peter M.J. Herman, 01-06-2011
2 Literature review

2.1 Cohesive sediments

2.1.1 Properties

Cohesive sediments are a mixture of clay, silt, (fine) sand, organic material and sometimes gas, (Winterwerp and Van Kesteren 2004). The most important difference with non-cohesive sediments is the existence of internal forces; the sediment particles tend to stick together. This is the reason why mud is a sticky substance and suspended mud particles form flocs in the water column.

Cohesion is also a soil property by itself; it is a measure of the internal strength. If a soil sample is submitted to shear stresses, $\tau$, under various normal pressures, $p$; it turns out that cohesive sediment is able to withstand a certain stress without deformation, (Partheniades 2009), (van Rijn 1990). This stress ($c_h$) is called cohesion, also yield stress.

![Figure 2-1 - Shear strength envelop for cohesive soils, (Partheniades 2009)](image)

The cohesive behavior is determined by the clay particles, the organic material and the properties of the pore water, (Winterwerp and Van Kesteren 2004). Clay particles tend to stick together due to electro-statical forces and form aggregates, also called flocs. The electro-statical forces play a role because of the flat shape and small size of the clay minerals, leading to a very high specific surface area and an electrical charge distribution that interacts with the surrounding water, (Winterwerp and Van Kesteren 2004).

![Figure 2-2 - Comparison of different type of sediment, Montserrat [2011]](image)

The interparticle attractive forces exist out of Van Der Waals, hydrogen and cation bonds, (Partheniades 2009). Clay minerals usually carry a negative electric charge on their faces and sometimes a positive charge on their edges, (Partheniades 2009). These charged faces interact with the positive cation concentration in the
surrounding pore water. Organic material, like poly-saccharides, plays a role due to their ability to adhere to clay particles, (Winterwerp and Van Kesteren 2004).

Cohesive sediments consist of clay minerals; the most common are kaolinite, illite, smectite and montmorillonite, and chloride. The most common method to determine if a particle is a clay, silt, sand or gravel particle is to determine the grain size. Then there exist several classifications which relate soil type to grain size. Important to keep in mind is that in reality clay minerals can also exist for particle sizes larger than 10 µm, see figure below.

Figure 2-3 - Right: classification of particle size, left: example of a mineral distribution as a function of grain size for Mississippi sediments, (Winterwerp and Van Kesteren 2004)

Two other interesting properties of clay are its plasticity and the fact that it loses its strength when it’s remolded. Plasticity is the feature of clayey soil to undergo deformation under stress without breaking, in case of a very high water content even liquefaction can takes place. Remolding destroys the existing bonds and thus a decrease of the strength. The reverse process, the regaining of all or a great part of their strength after remolding, is known as thixotropy, (Partheniades 2009).

2.1.2 Processes

Two specific processes characteristic for cohesive sediment are flocculation and consolidation. Flocculation is the forming of aggregates or flocs from different clay particles. The structure of these flocs is very open, hence the water content is very high (around 90%). Consolidation is a process of soil compaction under the influence of gravity, whereby pore water is squeezed out and the strength of the soil increases, (van Rijn 1990). This typically occurs when flocs from the water column settle and deposit at the bed.

Figure 2-4 - (a) clay particle, (b) individual floc (c) floc group (d) consolidating bed deposit, lecture Winterwerp
The figure below shows the main processes in the aquatic cohesive sediment environment, including common sediment processes, like erosion, deposition, settling and turbulent suspension.

![Diagram of sediment processes](image)

**Figure 2-5 - Different processes in a cohesive sediment environment, (Whitehouse 2000)**

If the instantaneous shear stress exceeds the critical shear stress for erosion, $\tau_e$, resuspension will occur, if it falls below the critical shear stress for deposition, $\tau_d$, deposition will occur. Flocculation leads to bigger flocs that will settle faster, unless they will break up due to a high shear flow near the bed or moved upwards by turbulent mixing, they will deposit on the bed. Freshly deposit mudflocs contain a lot of water, hence the top soil layer will be fluid mud. The deeper layer of the sediment bed will be partially consolidated. Turbulent mixing on the one hand induces particle collision, thus enhances flocculation (and faster settling and deposition), on the other hand it provides energy to keep the sediments in suspension.

2.1.3 **Erodibility**

Erosion of cohesive sediments is rather different than erosion of non-cohesive sediment. Initiation of motion for non-cohesive sediments is studied extensively. The Shields curve is a well-known method to determine the initiation of motion. It assumes the critical shear stress for erosion to be dependent on the particle diameter and the density of the material. This approach is not valid for cohesive sediments due to the internal forces between the particles.

One of the most important factors regarding the strength of cohesive soils in the natural environment is the degree of consolidation; this is represented by the water content. The very top fresh material has a lower critical value than material further down in the bed, (Bengtsson and Hellström 1992). According to Winterwerp (2004), the water bed exchange processes are to a large extent governed by the erodibility of the upper mm-cm of the bed and a thin layer of eroded material can cause already a substantial increase of the turbidity.
Next to this, the erodibility is defined by a number of physical, geochemical and biological properties of the sediment and surrounding pore water.

![Conceptual model of the sediment properties that affect sediment erodibility.](Grabowski, Droppo et al. 2011)

The erodibility decreases for increasing temperature, pH value, sand concentrations, whilst the erodibility increases for increasing clay content, organic content and salinity, (Winterwerp and Van Kesteren 2004). Also biology can have a severe effect on the erodibility, see chapter 2.2.

Erosion of cohesive sediments is typically described as a function of a certain erosion threshold, \( \tau_e \), and an erosion rate parameter, \( M \) or \( E_f \). Mehta. and Partheniades (1982) defined two types of erosion, type I, limited erosion, and type II, unlimited erosion.

Type I (limited erosion): 

\[
E = E_f \exp \left( \frac{\alpha}{\tau_e} \left( \frac{\tau_b - \tau_e}{\tau_e} \right)^\beta \right) \quad \text{for} \quad \tau_b \geq \tau_e
\]

Type II (unlimited erosion): 

\[
E = M \left( \frac{\tau_b - \tau_e}{\tau_e} \right) \quad \text{for} \quad \tau_b \geq \tau_e
\]

Type I is described by an exponentially decaying erosion rate in time. Consequently for a certain shear stress, the suspended sediment concentration will approach a constant magnitude. Type II erosion is described by a constant erosion rate in time. Which implies no equilibrium in sediment concentration is reached for type II, erosion continues as long as a certain shear stress is applied.

### 2.1.4 Oxidized – reduced mud layer

The chemical reactions occurring in mud are generated because bacteria and other microorganism degrade organic material. ‘Lake sediments are the major sites of microbial degradation of detrital organic matter and biogeochemical recycling of nutrients’, (Wetzel 2001). During this degradation, redox reactions occur; chemical reactions in which electrons are exchanged. The reducing component, first preference is oxygen, will gain...
electrons while the oxidating component, the organic matter, will lose electrons. The figure below gives an overview of the reactions occurring in order of preference.

<table>
<thead>
<tr>
<th>Electron acceptor</th>
<th>Reaction by which organic matter is oxidized</th>
<th>Relative yield of energy</th>
<th>Characteristic H₂ concentration (μM in solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O² in O₂</td>
<td>CH₄ + O₂ → CO² + H₂O</td>
<td>100 O</td>
<td></td>
</tr>
<tr>
<td>N⁵⁺ in NO₃⁻</td>
<td>5CH₂O + 4NO₃⁻ → 4HCO₃⁻ + 2N₂ + CO₂ + 3H₂O</td>
<td>93 &lt;0.1</td>
<td></td>
</tr>
<tr>
<td>N⁵⁺ in NO₃⁻</td>
<td>2CH₂O + NO₃⁻ + H₂O → 2HCO₃⁻ + NH₄⁺</td>
<td>87 &lt;0.1</td>
<td></td>
</tr>
<tr>
<td>Mn⁴⁺ in MnO₂</td>
<td>CH₂O + 3CO₂ + H₂O → 2MnO₂ + 2H₂O + 4HCO₃⁻</td>
<td>84 0.5</td>
<td></td>
</tr>
<tr>
<td>Fe³⁺ in Fe(OH)₃</td>
<td>CH₂O + 7CO₂ + 4Fe(OH)₃ → 4Fe²⁺ + 8HCO₃⁻ + 3H₂O</td>
<td>84 0.5</td>
<td></td>
</tr>
<tr>
<td>S⁶⁺ in SO₄²⁻</td>
<td>2CH₂O + SO₄²⁻ → H₂S + 2HCO₃⁻</td>
<td>6 1-2</td>
<td></td>
</tr>
<tr>
<td>C⁰ in CH₂O</td>
<td>2CH₂O → CH₄ + CO₂ (Methanogenesis)</td>
<td>3 5-10</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-7 - Common redox reactions in the oxidation of organic matter, (Railsback 2011)**

These reactions use and produce certain chemical products, creating the characteristic profile as shown below.

**Figure 2-8 - Characteristic profiles of various chemical parameters in the upper part of the bed, (Winterwerp and Van Kesteren 2004), after (Fenchel and Riedl 1970)**

Usually, cohesive sediments contain a lot of organic matter and intrusion of oxygen is limited due to the small grain size, therefore bacterial metabolism rapidly produces anoxic, reducing conditions. The reduced layer is black due to the presence iron sulfides and is also known as the ‘black zone’ or ‘sulfide zone’, (Fenchel and Riedl 1970). The oxidized layer is maintained close to the surface where free oxygen is available and is yellowish due to the presence of ferric iron, (Fenchel and Riedl 1970).

The thickness of the oxidized layer is above all determined by the availability of oxygen; when oxygen supply is cutoff, the oxidized layer turns black. In a natural environment, the oxidized layer can still vary from several mm’s to a few cm. Mortimer (1941) believed the thickness of the oxidized layer to be a result of the balance between the reducing power of the mud and the rate of diffusion of oxygen into the mud. The rate of oxygen diffusion is then influenced by the water volume above the mud surface and the degree of turbulence within this water body. Gorham (1958) continued on this research and also recognized the importance of turbulent displacement of the uppermost sediments. From his laboratory experiments and field observations he showed a
substantial increase of the oxidized layer due to turbulent displacement. He also observed orange-oxidized channels in the top 10-20 mm of the mud, caused by the introduction of air by tubificid worms.

2.2 Activity of biota

The activity of biota can have a severe effect on their environment. Jones (1994) defined the term ‘ecosystem engineer’; an organism that modifies their habitat. A well-known example is the beaver; they alter their environment by building dams in the river.

This research focusses on the effect of zoobenthos on bed sediments. Zoobenthos are all animals that live in or on aquatic sediments, (Meysman, Middelburg et al. 2006). Zoobenthos can be further divided into microzoobenthos (smaller than 63 µm), meiozoobenthos (between 63 µm and 1 mm) and macrobenthos (greater than 1 mm), (Meysman, Middelburg et al. 2006). Vegetation is scarce in Lake Markermeer, therefore this effect will be neglected. Scheffer (1998) showed that also fish can induce high turbidity levels in lakes, see paragraph 2.3. However, this mechanism is not considered important in Lake Markermeer. The specific fish species have low abundance and even decreased during the past years, (Noordhuis 2010).

The first scientist who noticed the effect of biota on the soil was Darwin (1881). He demonstrated that earthworms could displace large amount of sediments and stated they could play a major role in soil formation. At that time his work was not well recognized, but nowadays it is well cited. New interest in the interaction between biota and sediment was developed only a few decades ago, (Rhoads 1974; Aller 1978; Mc Call 1982). Nowadays the effect of biota on sediment is well recognized. A number of experimental studies quantified the effect of biota on sediment. Despite this availability of data, hydraulic engineers rarely consider the effect in sediment modeling. One of the difficulties is biodiversity; there are many different species and strong heterogeneity, (Le Hir, Monbet et al. 2007). Besides, biologic processes are complex, organisms relate to each other and their environment. Therefore biologic processes often non-linear and possibly there is positive feedback within the system, (Knaapen 2003). Moreover, biologic processes vary in time, often daily and with the season. Another challenge is to couple the biologic and physical processes simultaneously.

2.2.1 Bioturbation

Bioturbation are all processes that involve the particle displacement of sediment induced by all kind of activities of organisms, Le Hir (2007). Sometimes the term bioturbation is defined more extensive as the biological reworking of soils and sediment by all kind of organisms, (Meysman, Middelburg et al. 2006; Nogaro, Mermillod-Blondin et al. 2009). For this research the more strict definition is used.

Bioturbation can alter the sediment through the following mechanisms;

I. sediment disturbance, thereby increasing the porosity and water content and decreasing the compactness of the soil

II. the production of fecal pellets at the surface, thereby creating a layer of fluffy material that is easily erodible

III. altering the roughness of the sediment bed, thereby changing the relation between hydrodynamics and bottom shear stress
Generally the first two bioturbation mechanisms result in destabilization of the soil. However there are exceptions, reported by Meadows (1989) and Mc Call (1980). The third mechanisms can result in stabilization or destabilization of the sediment. Important to realize is that the effect of biota on the sediment is in first place is characterized by the species. Different mechanisms can occur simultaneously. Moreover also other effects than bioturbation can be important, these will be described in the next paragraph.

Sediment disturbance can be induced by meio- and macrobenthos. Macrobenthos are probably the most powerful, due to their size and ability to move through a large volume of sediment, (Mc Call 1982). The burrowing and crawling activity of small animals induces random mixing of sediment particles. Deposit feeding behavior results in organized mixing. Deposit feeders are species that actually ingest sediment. Some species feed at the surface and deposit at the bed, others feed at the bed and deposit at the surface. Both types of mixing result in increased water content and a less compact top layer, leading to sediment destabilization, (Knaapen 2003).

Fecal pellets are secreted by deposit feeders. Fecal pellets consist of sediments that are bound by mucus. They are composed mainly of fine particles and often have high water content. Therefore, fecal pellets are easily eroded, (Le Hir, Monbet et al. 2007). The laboratory experiments of Rhoads (1970) clearly showed higher water content and higher resuspension for reworked sediment by deposit feeder Nucula proxima (a marine bivalve mollusk).

Another indirect effect of biota on the sediment dynamics, is the effect of biota on the bed roughness, (Le Hir, Monbet et al. 2007). Protrusions created by benthic fauna change the bed roughness and indirect affect the bottom shear stress. The protrusions can be due to the animals themselves or due to their tubes, tracks, mounds or burrows. Depending on the density and strength of the protrusions this can result in stabilization or destabilization of the bed.

2.2.2 Biota-mediated sediment processes

Besides bioturbation, the following processes are important, biosuspension, biostabilization and biodeposition, Knaapen (2003).
Biosuspension is the suspension of sediment due to the movement or feeding activity of biota. Some specific deposit feeders expel strongly fluidized fecal pellets into the water, Figure 2-10. This results in direct suspension of sediments. Another indirect mechanism is the resuspension due to the movement of animals. If animals cause only a minor uplift of a small particle, this could already result in resuspension of the particle, (Graf and Rosenberg 1997).

Figure 2-10 - (A) Top view of experimental core subjected to 14 days of reworking by Nucula, (B, C and D) Expulsion of watery sediment by Yoldia, Pectinaria and Macoma, (Davis 1993)

Biostabilization is the stabilization of the sediment by all kind of biota. Mussel beds for example have a stabilizing effect on the sediment. Another important mechanism is the production of a biofilm created by microorganism. Microorganism, like bacteria and algae secrete extracellular polymeric substances (EPS) on top of the sediment surface. This slimy biofilm stabilizes the sediment surface and can increase the erosion threshold on muddy bed up to a factor of five, (Le Hir, Monbet et al. 2007).

Figure 2-11 - Diatom biofilm growing on muddy intertidal sediment of the Westerscheldt, (Stal 2010)
However, bioturbation and grazing by surface deposit feeders can destroy the biofilm and counteract the stabilization effect, (Mc Call 1980).

Biodeposition is the filtering of sediment particles from the water column and the subsequent deposition of these particles on the bed. This type of animal is called a filter feeder. Figure 3-13 shows the behavior of typical filter feeders, mussels.

![Mussels, actively filtering](image)

**Figure 2-12 - Mussels, actively filtering, (Van Duren 2006)**

### 2.2.3 Biota and their life styles

The effect of biota on sediment is dependent on the specific species. In the benthic fresh water environment, macrozoobenthos, like oligochaete (worms) and chironomid larvae (larvae of midges) are probably the most dominant bioturbators, (Mc Call 1982). Their life styles will be discussed here. Other important parameters regarding the bioturbation rate are temperature and the density of specific species, (Mc Call 1982).

Tubifex worms are subsurface deposit feeders. They live head down in the sediment and feed at a depth of 2-8 cm below the surface. They selectively ingest clay and silt particles and feed on the attached microflora, primarily bacteria. After the sediments have passed the gut, they are packed together as fecal pellets and deposited at the surface. This type of feeding is also called conveyor belt mixing, (Mc Call 1982).

![Conveyor belt mixing](image)

**Figure 2-13 - Conveyor belt mixing, (Rhoads 1974)**
Schieber (2011) showed the sediment mixing by placing a thin layer of sand on top of organic mud containing Tubifex worms. Tubifex worms prefer environments with a high input organic matter, (Martins, Stephan et al. 2008). The results support the conveyor belt mixing theory, see Figure 2-14. Organic mud is transported upwards by the worms, creating a thick layer of fecal material on top of the sand layer.

Figure 2-14 - Production of fecal matter by Tubifex Tubifex, shown by placing a thin layer of sand on top of the mud. Panel A, B and C show the change in position of the sand layer for day 0, day 6 and day 275 respectively, panel D shows the development of the thickness of fecal matter in time, (Schieber 2011)

Chironomid larvae are larvae of midges. They burrow into bottom sediments, most larvae live in the top 8 to 10 cm. They build tubes that are secreted with silk. These tubes can protrude a few mms above the sediment surface. Chironomid larvae are also very mobile; they can swim in the water column. Their feeding behavior depends, they can act as surface deposit feeder or as filter feeder, (Mc Call 1982). For high densities, chironomid larvae tend to stabilize the sediment, see Figure 2-15. A matrix of tubes and silk threads over the sediment surface will prevent erosion, Ólafsson (2004).
2.3 Ecology in shallow lakes

A turbid lake is considered as an unhealthy system in general. Scheffer (1998) discovered the occurrence of two alternative stable equilibriums: a turbid, non-vegetated and algae rich state and a clear water and vegetated state. The clear water state of the lake is characterized by a high biodiversity with characteristic algae, vegetation and fauna, (STOWA 2008) and is the desired healthy state of the lake. The turbid state is turbid, due to suspended sediments and algae and is dominated by only a few species.

According to Scheffer (1998), a crucial factor in the change from one equilibrium to another is the nutrient load (mostly N and P). A high nutrient load induces algal blooms that increase the organic suspended matter and thus the turbidity. This is not a linear relation in shallow lakes: the ecosystem is resistant to changes. This is called the hysteresis effect; the way to and from the equilibrium state follows a different path, see Figure 2-16.

Figure 2-15 - Relationship between the shear strength and larval/pupal densities at the top 0-1 cm of the bed, (filled samples + regression lines represent measurement from experimental set up, empty symbols represents measurements from lake sediments) , (Ólafsson and Paterson 2004)
Figure 2-16 – Alternative stable states: clear water dominated by water plants and turbid water dominated by algae, (x-axis represents nutrients, y-axis represents algae), (Jaarsma, Klinge et al. 2008)

Water plants play a crucial role in the hysteresis process. In a clear lake, the water stays clear, because the plants take up the nutrients and keep the bottom sediment in place. While in a turbid lake, the water stays turbid, because algae and resuspended sediment reduce the light penetration and in this way prevent the comeback of vegetation.

Figure 2-17 - Main feedback loops thought to be responsible for the existence of alternative equilibriums in shallow lake ecosystems, (Scheffer, Hosper et al. 1993)

Biomanipulation has proved to be one of the most successful measures to let a turbid shallow lake switch to an alternative clear state, (Scheffer 1998). The ‘bream-case’ is a well-known successful example of biomanipulation. Bream is a fish that feeds at the bottom and induces sediment resuspension while feeding. In case of a fish community that is dominated by bream, high turbidity levels show up. Consequent removal of this fish leads almost direct to an increasing transparency, (Scheffer, Hosper et al. 1993).
3 Lake Markermeer, a site description

3.1 History
The Zuiderzee was a sea inlet that came into being in the thirteenth century. Several storm surges caused flooding and connected various inland lakes to the North Sea in that period, creating the Zuiderzee. A period of recovery occurred after this event, with a less aggressive storm climate. The Dutch people started to protect themselves against the water by building dikes and during the VOC-period they gained new land by creating polders. Despite all this, some flooding still occurred from time to time. Finally, a big flooding event in the nineteenth century led to the decision to build a closure dam, the Afsluitdijk. The construction of the dam was finalized in July 1932. From that moment on, the former Zuiderzee was called the Ijsselmeer and gradually turned into a freshwater basin. After that some regions of the lake were turned into polders: the Wieringermeer polder, the Noordoostpolder and Flevoland, (Noordhuis 2010).

Figure 3-1 - Left: closure of the Afsluitdijk in 1932, right: present situation, (Deltares 2011)
In the case of the Noordoostpolder and Flevoland, border lakes were maintained around the polders to reduce the drop in groundwater level of the hinterland. The original plan was also to drain the Markermeer. For that reason, the Houtribdijk was constructed in 1976 at the boundary of a sandy and clayey bottom, to make optimal use of the fertile clayey bottom for agricultural purpose, (Noordhuis 2010). However, this polder was never constructed, due to changing needs, and it is now assured that Lake Markermeer will remain as a lake.

3.2 Geology
During the Zuiderzee period there was a landward flux of fine sediments due to tide and estuarine circulation. As a result sandy sediments settled in the inlet, nowadays Ijsselmeer, and clay and loam settled in the bay, nowadays Markermeer and Flevoland, (Noordhuis 2010). In the western part of the Markermeer the clay layer is even about 10 m thick, in the east the clay layer is about 5 m thick, (Royal Haskoning 2006). The upper clay layer is known as the Zuiderzee deposit. At some places the old Holocene layer comes to the surface, sandy soil (oudegetijdenafzettingen) in the north near Enkhuizen and some peat (hollandveen) in the west near Marken.
Figure 3-2 – Sediment composition of the Markermeer bed (green=loam, blue=clay, yellow=loamy sand and red=sand), (Royal Haskoning 2006)

On top of the Zuiderzee deposit, a fresher soft mud layer is found. According to Van Duin (1992), this layer consists of eroded material from the Zuiderzee deposits and deposits from the river IJssel. The soft mud layer is also called the top silt layer or Ijsselmeer deposit, (Van Duin 1992; Vijverberg 2008). As shown in Figure 3-3, the soft mud layer is increased in volume and transported to the southeast part of the lake. Lenselink and Menke (1995) demonstrated that at some locations, at the Hoornsche Hop and at the west of the IJmeer, the clayey topsoil is eroded until a marine shell layer.
3.3 Fine sediment characteristics

Within this paragraph, the properties of fine sediments from Lake Markermeer will be shown. Those were determined through laboratory experiments, (De Lucas Pardo 2011). Sampling sides A, B, C, D and E are located in the south, F in the Northeast and G in the middle of the lake. Only the soft mud layer was sampled. In all locations, the anoxic mud layer was collected. The oxic mud layer was collected only at location C, G and E.

Figure 3-3 - Development of the layer thickness of the soft mud layer, years 1958-1994, (Lenselink and Menke 1995)

Figure 3-4 - Composition bed sediments Lake Markermeer
Figure 3-5 shows the water content for each location. In locations in which we found oxic mud, the water content of the oxic mud layer is clearly higher than the anoxic mud layer.

![Figure 3-5 - Water content, (De Lucas Pardo 2011)](image)

The bulk density of the samples ranges from $1.03 \times 10^3 \text{ kg/m}^3$ to $1.57 \times 10^3 \text{ kg/m}^3$, (De Lucas Pardo 2011). The bulk density of the anoxic mud layer is somewhat higher than the bulk density of the oxic mud layer at the same location. The organic matter also shows a significant difference, the content is higher for the oxic mud layer than for the anoxic mud layer. The total sediment composition is presented in Figure 3-6.

![Figure 3-6 - Sediment composition, (De Lucas Pardo 2011)](image)

The clay content is sufficient to induce cohesive behavior of the sediment. The detritus component is rather high. The particle size distribution does not show important changes between the oxic and anoxic layer, but does show spatial variation.
The most profound differences of the oxic mud layer compared to the anoxic mud layer are the increased water content and the increased organic matter content. The high water content is believed to be caused by the activity of bioturbating fauna. The high organic content is believed to be the result of the frequent exchange with the water column.

### 3.4 Bathymetry, hydrology and wind climate

Lake Markermeer is a very shallow lake, with an average depth of 3.6 m and an area of 680 km$^2$, (Vijverberg, Winterwerp et al. 2010).
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

Figure 3-9 - Depth profile of the Markermeer, (Witteveen & Bos 2004)

The lake has relatively steep shores, caused by the fact that it was originally a coastline subject to erosion, (Royal Haskoning 2010).

The residence time of the water is 10 to 15 months. The main fluxes are the in- and outflow from Lake Ijsselmeer, the discharge from the river Eem, water that is drained from or pumped to the surrounding polder area, and precipitation and evaporation. From hydraulic point of view, the lake is considered as a closed system, (Noordhuis 2010).

Wind data from station Schiphol is the most representative for the Markermeer area, (Van Kessel 2008). The wind from the southwest wind is the most dominant, as shown in the figure below.

Figure 3-10 - Wind rose Schiphol (left) and wind speed and occurrence for different directions (right), (Vijverberg 2008)
The data show some seasonal variation in the wind direction. During springtime, winds usually come from the north, in summer from the west, and in autumn and winter from the southwest, (Vijverberg 2008).

### 3.5 Hydrodynamics and sediment dynamics

The hydrodynamics in Lake Markermeer is driven by wind. The wind produces waves and currents.

Currents are induced by the wind set up. Wind set up is damming up of the water, thereby creating a slope in the water level. The water level differences increases with increasing wind velocity and fetch and decreasing water depth. The wind set up induces a pressure gradient that drives a return current near the bottom. These pressure gradients also induce large scale horizontal circulation. This result in different flow patterns in the upper and lower layer of Lake Markermeer, see Figure 2-10. Turbulent mixing takes place between the different layers, resulting in a complex 3D flow pattern in the lake, (Vijverberg 2008). The large-scale circulating flow patterns change depending on the direction and speed of the wind.

![Figure 3-11 - Large scale flow patterns simulated for different wind direction and a wind speed of 10 m/s (dark blue corresponds to a zero velocity and red to 0.15 m/s), (De Lucas Pardo 2011)](image)

Wind also produces waves. The wave height and wave period are again related to wind velocity, fetch and water depth. Waves produce oscillatory motion and in a shallow environment these will easily reach the bottom. This ‘wave stirring’ will result in erosion of bottom sediments.

![Figure 3-12 - Orbital motion in shallow water, (Zhen-Gang 2008)](image)

Both waves and currents imply a certain stress on the bed. Wave induced stresses are dominant, shown in Table 3-1.
Wind force | BFT | 4  | 5  | 6  | 7  | 8  |
---|---|---|---|---|---|---|
Wind speed | U10 m/s | 6   | 10  | 12  | 15  | 20  |
Number of days that wind speed is exceeded | 280 | 148 | 59  | 17  | 3   |
Shear stress induced by waves | $\tau_w$ Pa | 0.095 | 0.421 | 0.650 | 1.067 | 1.925 |
Shear stress induced by current | $\tau_c$ Pa | 0.067 | 0.067 | 0.067 | 0.067 | 0.067 |
Shear stress induced by both currents and waves | $\tau_{w,c}$ Pa | 0.116 | 0.426 | 0.654 | 1.072 | 1.926 |

Table 3-1 - Estimation of bed shear stress for every wind condition in Lake Markermeer, for calculation method see appendix D

The water bed exchange processes, i.e. erosion and deposition, are important processes for understanding the high turbidity values, as already mentioned in paragraph 1.1.3. Erosion will occur when the bed shear stress exceeds the critical shear stress for erosion, $\tau_e$. Deposition will occur when the bed shear stress falls below the critical shear stress for deposition, $\tau_d$. Van Rijn (1993) reported $\tau_e$ values in the range of 0.05 to 0.80 Pa and $\tau_d$ values of 0.03 to 0.15 Pa for natural muds from the Netherlands.

As described in Appendix D, wave induced shear stresses are an indirect function of wind speed and fetch. This is also revealed by measured data. In the middle of the lake the fetch is more or less constant. In that situation, it appears that turbidity levels increase more or less linearly with increasing wind speeds, see Figure 3-13.

![Figure 3-13 - Scatter plot of turbidity versus wind speed for middle of the lake (FL42), measurements were taken during one month in autumn 2007, (Vijverberg, Winterwerp et al. 2010)](image)

The morphological trend is a net transport of sediment from the western part of the lake to the eastern part in the lake, (Royal Haskoning 2006). The western part is shallower and as a result the impact of waves on the bed is greater. The turbulent motion of the waves keeps the sediments in suspension and the wind-induced currents redistributes the sediment over the lake.
3.6 Ecology

Since the founding in 1932, the IJsselmeer area is experiencing a complex of ecological changes. Most important are the changes in turbidity, changes in nutrients, climate change, intensification of use and the introduction of exotic species, (Noordhuis 2010). At this moment the ecological state is alarming; the bird population has declined strongly last years. Birds have a high trophic level and therefore most developments within the ecosystem relate to the state of the birds. The figure below gives an overview of the aquatic food web of IJsselmeer area.

Lake Markermeer was in a healthier ecological state during the 1980s. There were high densities of Zebra Mussels and a high fish biomass with a good pelagic population of Smelt. There were also large numbers of benthivorous and piscivorous birds.

Since the early 1990s, densities of bivalves have decreased and the remaining mussels are much smaller than they used to be. The total fish biomass decreased in the lake, there seems to be hardly any bream and the amount
of smelt has decreased a lot. Subsequent the numbers of benthivorous and piscivorous birds have dropped. The only positive effect is the increase of macrophytes in shallow areas in both lakes, (Deltares 2011).

Figure 3-16 - Biovolume [ml/m²] of the Zebra Mussel *Dreissena* in Lake Markermeer for 1981, 1993 and 2000, (RIZA 2003)

A combination of low nutrients and limited light extinction has caused the crash in mussel population. The increased turbidity was caused by high sediment resuspension due to temporary bad weather circumstances in that period. Together with the reduced effect of the mussels filtering the suspended sediments, a more turbid state of the lake was created, (RIZA 2003). The transparency even decreased to 20 cm in large parts of the lake, (Noordhuis 2010). The high turbidity value limits the light penetration in the lake. Due to this condition, the diversity of benthic communities is reduced to few, stress-tolerant species.

<table>
<thead>
<tr>
<th>Taxonomic group</th>
<th>Number of species</th>
<th>Taxonomic group</th>
<th>Number of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sponges</td>
<td>2</td>
<td>Damselflies, dragonflies</td>
<td>3</td>
</tr>
<tr>
<td>Cnidaria</td>
<td>5</td>
<td>Heteroptera</td>
<td>4</td>
</tr>
<tr>
<td>Flatworms</td>
<td>6</td>
<td>Beetles</td>
<td>3</td>
</tr>
<tr>
<td>Leeches</td>
<td>8</td>
<td>Chironomidae</td>
<td>40</td>
</tr>
<tr>
<td>Polychaetes</td>
<td>18</td>
<td>Caddisflies</td>
<td>10</td>
</tr>
<tr>
<td>Amphipoda</td>
<td>6</td>
<td>Other insects</td>
<td>5</td>
</tr>
<tr>
<td>Lobsters, crabs, shrimps</td>
<td>5</td>
<td>Spiders, mites</td>
<td>16</td>
</tr>
<tr>
<td>Isopoda Astacidea</td>
<td>7</td>
<td>Bivalvia</td>
<td>18</td>
</tr>
<tr>
<td>Mayflies</td>
<td>5</td>
<td>Snails</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 3-2 - Macrofauna in Lake Markermeer, distribution of number of species per taxonomic group, modified from (Noordhuis 2010)
4 Material and Methods

4.1 Material

4.1.1 Field campaign

Sediment samples were collected from Lake Markermeer. During the field campaign, a specially designed tool was used to obtain the samples. The tool is composed of a 5 m long steel pole with a PVC cylinder attached at its lower end. The sampling method consisted of the pushing of this tool into the lake bed by manpower, and was executed from a boat. The cylinder of the tool and the tube used in the erosion experiments have the same diameter, 10 cm, in order to minimize disturbance of the sediment sample.

![Specially designed tool to obtain the samples](image)

The first field campaign was executed at the 4th of July 2011, in which sample A and B were collected. The second field campaign was executed from the 19th to 23rd of September 2011, of which sample C, D, E and F were collected. The selection of these samples was quite random, only excluding samples with shells in the top layer. All material was stored in a cool and dark environment.
4.1.2 Sediment

The sediment core was pulled from the sampling tube into the experimental tube with help of an extruding piston. The experimental tube needed only a sediment core with a length of ca. 10 cm, allowing multiple samples to be taken from the sampling tube. In total 6 samples were taken to use for the erosion experiments. In most cases the top 10 cm was used, but sometimes a lower layer was used, see table below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Bulk density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Soft mud layer (top part of the sample)</td>
<td>- (1)</td>
</tr>
<tr>
<td>B</td>
<td>Soft mud layer (2)</td>
<td>- (1)</td>
</tr>
<tr>
<td>C</td>
<td>Soft mud layer (top part of the sample)</td>
<td>- (1)</td>
</tr>
<tr>
<td>D</td>
<td>Soft mud layer (top part of the sample)</td>
<td>1280 (3)</td>
</tr>
<tr>
<td>E</td>
<td>Soft mud layer (lower part of the sample)</td>
<td>1220 (3)</td>
</tr>
<tr>
<td>F</td>
<td>Zuiderzee deposit (middle part of the sample)</td>
<td>1230</td>
</tr>
</tbody>
</table>

Table 4-1 - Soil properties of samples used for erosion experiments, (1) soil properties were not determined for samples A, B and C (2) unknown which part of the layer is used (3) bulk density is estimated based on correlation with water content

4.1.3 Biota and water

Biota was obtained from the sediment samples by sieving through a 250 µm and a 500 µm sieve. Abundant biota was Ostracoda (seed shrimps) and Tubifex worms (genus of tubificid oligochaete worms). Besides, Chironomid larvae (larvae of midges), Nematode (roundworms) and Hydrobia ulvae (laver spire shell) were found. Biota in the sample of series B was eliminated by gamma radiation (2.5 kGy) in the Reactor Institute Delft.
Figure 4-3 - *Tubifex Tubifex*, species belonging to *Tubifex* worms, http://watercenter.montana.edu/gallery/detail.asp?iType=25&iPic=1835

Figure 4-4 - *Ostracoda*, http://www.kuleuven-kulak.be/kulakbiocampus/insecten-ongewervelden/vijverfauna/zooplankton/Ostracoda/Ostracoda.htm

Markermeer water was collected in jerry cans during the field campaign. This water was used for the experiments as the properties of the water might influence the strength or behavior of the sediment. The water was filtered through a 45 μm membrane filter before it was used for an erosion experiment, because non-turbid water was necessary for the erosion experiments.

4.2 Experimental set up

The erodibility of the sediment was tested by erosion experiments with the U-GEMS (UMCES2 -Gust Erosion Microcosm System). The U-GEMS is designed for erosion of fine-grained sediment. A combination of a rotating disk and a central suction provides a bed shear stress that is spatially homogeneous, (Green Eyes 2010)
Figure 4-5 - Geometry of the microcosm set-up with the spinning disk and suction outlet, introduced by Dr. Gust (1990), (De Lucas Pardo 2011)

Water will flow into the erosion head from above the rotating disk and flow out through the center of the rotating disk. The rotating disk in the microcosm is magnetically coupled with a rotating disk just above the microcosm that is driven by a motor. Together with the flow induced by the rotating disk a spiral flow pattern is created, inducing a shear stress on the bottom, see left panel of Figure 4-6. The magnitude of the shear stress can be varied by adapting the rotational speed of the disk and the velocity of water flowing out.

Figure 4-6 – Left: flow pattern in the microcosm during experiment, Manual U-GEMS, right: measurement method of an Oslim, (De Lucas Pardo 2011)

The device is able to produce shear stresses from 0.01 to 0.80 Pa. Shear stresses of 0.45 - 0.80 Pa were outside the calibration range, therefore a calibration procedure was performed, (De Lucas Pardo 2011). For this procedure a comparison was made between observed critical shear stress in the microcosm and critical shear stress calculated according Shields-van-Rijn. The criteria used to determine the occurrence of erosion was the initiation of ripples.
Figure 4-7 - Comparison between the 'observed critical shear stress in the microcosm' and the 'critical shear stress according to Shields-van-Rijn, (De Lucas Pardo 2011)

The calibration procedure resulted in the following calibration equation:

$$\text{Bottom shear stress} = \frac{\text{Bottom shear stress in microcosm} - 0.099}{0.93}$$

The erodibility is determined by measuring the sediment concentration in the outflowing water. An Optical Silt Measuring Instrument (Oslim) is used for this operation, see right panel in Figure 4-6. The measurement method is based on the attenuation of the intensity of infra-red light beam by the suspended particles in the fluid. The output signal of the Oslim is Volt. This signal needs to be translated into g/l through a calibration procedure. Subsequently the output signal needs to be converted to erosion flux, g/m2/s. See paragraph 4.4 for these procedures.

The total experimental set up is shown in the figure below. The water flows from the input bucket through a small plastic tube via the pump to the U-GEMS microcosm. If erosion occurs, sediment particles will flush away with the outflowing water. Halfway the tube with outflowing water, the turbidity is measured by the Oslim. At last, the outflowing water and sediments are collected in the outflowing bucket.
4.3 Experimental procedure

4.3.1 Series of experiments

A series of experiments is performed on every sample, Figure 4-9 gives an overview of the repetitive steps.

First an experiment is performed on the anoxic mud layer, to check the erodibility of mud before bioturbation.\(^4\) Furthermore, the procedure provides the same starting conditions for each round of experiments.

\(^4\) Assuming no bioturbation is taking place in the black anoxic mud layer.
To perform an erosion experiment on the anoxic mud, the oxic mud needs to be removed. To accomplish this, the mud sample is pushed to the top of the tube with an extruding piston, where the oxic layer is cut off with a knife, then the sample is lowered and set at the right position with help of the extruding piston. The nut on the piston is tightened to ensure that the O-ring makes a seal with the microcosm tube. Water is added on top of the sample with help of the pump and the plastic tube. Two erosion experiments are performed on the anoxic mud layer. The goal of the first experiment is to remove loose particles, present due to the cutting of the sample and the adding of water. The second experiment is used to represent the erodibility of the anoxic mud layer, see appendix C.3 for details.

After these experiments, biota is added to the sample, followed by a waiting period to give the biota an opportunity to rework the sediment. The waiting time is for the first round of experiments is 2 days. During this time the sample is stored in a cool (ca. 6.5°C) and dark environment. The sample should be exposed to constant conditions during each experiment, these conditions approximate the conditions in the lake. The temperature is the average water temperature of the lake during winter and the darkness represents the limited light penetration due to high turbidity levels.

Next, an erosion experiment is executed on the bioturbated and oxidized mud. The oxic layer is removed and the whole procedure can be repeated with a waiting period of 4, 6 and 8 days respectively.

4.3.2 Erosion experiment

The procedure for an erosion experiment is the following; the erosion head is placed on top and the total system is filled with water. Finally, the rotational disk is set on top of the erosion head and the erosion experiment is executed, which consists of nine steps of one minute. The shear stress is increased incrementally.

<table>
<thead>
<tr>
<th>Step [-]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time [s]</td>
<td>0-60</td>
<td>60-120</td>
<td>120-180</td>
<td>180-240</td>
<td>240-300</td>
<td>300-360</td>
<td>360-420</td>
<td>420-480</td>
<td>480-540</td>
</tr>
<tr>
<td>Applied bottom shear stress [Pa]</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4-2 - Applied bottom shear stress during an erosion experiment

The input parameters to set the bottom shear stress are the flow velocity and the disk rotation. These parameters are calculated using calibration equations presented by Gust, see

\(^5\) The tubes need to be connected in opposite order to fill the total system, because the outflow opening has a lower position than the inflow opening.

\(^6\) For reasons of efficiency
Appendix B: During an erosion experiment the input parameters are changed manually. At the same time, the output of the Oslim is read and saved. The following actions are executed after the experiment. The water level is lowered until it’s possible to remove the erosion head. The erosion head is removed carefully and, together with the Oslim, rinsed with tap water.

4.3.3 Replica series

In total, six series of experiments were executed on different soil samples. To start off, two series were performed: a sample with biota and a sample without biota, series B. Then four replica series were performed with biota, of which one sample contained Zuiderzee deposit.

The routine for adding biota is not the same for all series. For series A and C the routine ‘re-use of biota’ was used. Biota from the natural oxidized layer from the same sample is added to the first experiment. This natural oxidized layer could be up to 3 cm thick. After each experiment the developed oxidized layer is cut off and sieved, and the collected biota is added to the next experiment. The amount of biota decreased during the series of experiments due to mortality caused by manipulation. On top of this, it was observed that Tubifex worms also live in the anoxic mud layer, which made it impossible to count all the worms during the experiment.

After this the routine was improved for series D, E and F. The routine ‘constant Tubifex’ implies the adding of a constant number of Tubifex for each experiment. According to previous observation, 0-20 worms and 0-62 Ostracoda and few other species were present in one sample. Unfortunately, no more living Ostracoda were found in the samples. By that time the field campaign had taken place three and a half months ago, meaning most Ostracoda probably died due to storage circumstances. Based on this information, the choice was made to add a constant amount of 11 Tubifex worms. These worms were collected out of different samples. After the total series of experiments the complete sample, anoxic and oxic mud, was sieved to determine the total amount of worms. Afterwards it was discovered that the amount of biota had gradually increased during the series of experiments.

Furthermore, there are some small differences in the procedures. The first three experiments were not performed in chronological order, for reasons of efficient planning. The chronological order was restored for the last three series. Series C failed because it was exposed to high temperature. Table 4-3 gives an overview of characteristics of each series.

<table>
<thead>
<tr>
<th>Series</th>
<th>Mud type</th>
<th>Biota procedure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Soft mud layer</td>
<td>Re-use of biota</td>
<td>Order of experiments: n= 4,2,6,8</td>
</tr>
<tr>
<td>B</td>
<td>Soft mud layer</td>
<td>No biota</td>
<td>Order of experiments: n= 4,2,6,8</td>
</tr>
<tr>
<td>C</td>
<td>Soft mud layer</td>
<td>Re-use of biota</td>
<td>Failed due to high temperature, order of experiments: n= 4,2,6</td>
</tr>
<tr>
<td>D</td>
<td>Soft mud layer</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
<tr>
<td>E</td>
<td>Soft mud layer</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
<tr>
<td>F</td>
<td>Zuiderzee deposit</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
</tbody>
</table>

Table 4-3 - Replica series, mud type, biota procedure and important details

7 By one sample is meant the natural oxidized top layer, assuming no presence of biota in the black anoxic layer.
4.4 Data processing

4.4.1 Calibration Oslim

The output signal of the Oslim is in Volts. A calibration procedure is performed to relate this signal to a concentration in g/l. This relation is changing per soil type; therefore original Markermeer sediments are used. The Oslim instrument would also be sensitive for different colors, for that reason both the black anoxic mud layer and the yellowish oxic mud layer are tested.

The calibration procedure was the following. Suspensions were created in a 200 ml Erlenmeyer with a concentration of 0, 0.1, 0.3, 0.5, 0.7 and 1 g/l. These suspensions were pumped through the tubes and the Oslim one after another. Simultaneously the suspension was stirred to make sure all sediments were kept in suspension. The corresponding value in Volt was defined after a stable value was reached. This resulted in a linear relation between concentration and output signal, see Figure 4-10.

![Calibration curve, soft mud layer, 22 augustus 2011](image)

Figure 4-10 - Calibration curve of the Oslim for the soft mud layer at 22nd of August 2011

This linear relation can be presented as a linear equation with a certain slope and a certain offset. As turned out after several calibration procedures, these parameters showed quite some variation. The choice was made to measure the offset value prior to every experiment and use an average value for the slope, see Appendix C.1.

This resulted in the following calibration equations:

Calibration equation: \[ C_O = \frac{O_{\text{output}} - O_{\text{offset}}}{4.40} \]

Calibration equation: \[ C_R = \frac{O_{\text{output}} - O_{\text{offset}}}{4.61} \]

Where \( C_O \) is the concentration [g/l] for the oxidized mud layer, \( C_R \) is the concentration for the anoxic mud layer [g/l], \( O_{\text{output}} \) is the output signal of the Oslim [V] and \( O_{\text{offset}} \) is the measured offset value prior to the experiment.
The same procedure was executed for the Zuiderzee deposits. No significant difference was observed for the oxidized Zuiderzee deposits, therefore no distinction was made. The results show a steep slope compared to the soft mud layer, resulting in the following calibration equation.

Calibration equation: \[ C_Z = \frac{O_{\text{output}} - O_{\text{offset}}}{8.95} \]

Where \( C_Z \) is the concentration [g/l] for the Zuiderzee deposits, \( O_{\text{output}} \) is the output signal of the Oslim [V] and \( O_{\text{offset}} \) is the measured offset value prior to the experiment.

![Calibration curve Zuiderzee deposits](image)

**Figure 4-11 - Calibration curve for the Zuiderzee deposits**

### 4.4.2 Data analysis

With help of the calibration equation the output of the Oslim has turned into a concentration in [g/l]. Then the erosion rate can be calculated by multiplying the concentration by the velocity that is valid at that time. As a consequence of the increased shear stress per minute, the flow velocity increases every minute. Table 4-4 presents these velocities.

<table>
<thead>
<tr>
<th>Period [min]</th>
<th>1&lt;sup&gt;st&lt;/sup&gt;</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt;</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt;</th>
<th>4&lt;sup&gt;th&lt;/sup&gt;</th>
<th>5&lt;sup&gt;th&lt;/sup&gt;</th>
<th>6&lt;sup&gt;th&lt;/sup&gt;</th>
<th>7&lt;sup&gt;th&lt;/sup&gt;</th>
<th>8&lt;sup&gt;th&lt;/sup&gt;</th>
<th>9&lt;sup&gt;th&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied bottom shear stress [Pa]</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Flow velocity ([10^3 \text{l/s}])</td>
<td>1.28</td>
<td>1.87</td>
<td>2.57</td>
<td>2.98</td>
<td>3.28</td>
<td>3.50</td>
<td>3.65</td>
<td>3.75</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Table 4-4 - Applied bottom shear stress and flow velocity for each minute during the erosion experiment.

The erosion rate can be calculated by the following formula:

\[ E = \frac{C \cdot U}{A_{\text{sample}}} \]

Where \( E \) is erosion rate in g/(m$^2$*s), \( C \) is the concentration measured by the Oslim in [g/l], \( U \) is the flow velocity in the tube in [l/s] and \( A_{\text{sample}} \) is the area of the sample that is subject to erosion in m$^2$. 
When we look at rough data on erosion rate, a time lag is observed between the expected start of erosion and the measured start of erosion. This time lag is shown in Figure 4-12. From observations we did not notice a response time for the particles to start eroding. Therefore, the time lag should be a consequence of the experimental set up. The sediment particles have to travel a distance of 1 meter from the sediment bed to the Oslim where the sediment particles are measured. Furthermore we expect the pump needs a certain time to accelerate the flow.

The time lag is defined: \( T_{delay} = T_{set up} + T_{pump} \)

\[
T_{delay} = \frac{L_{tube}}{U_{tube} \times 10^{-3} / A_{tube}} + T_{pump}
\]

Where, \( L_{tube} \) is the length that the sediment particles travel through the tube before they reach the Oslim [m]. \( U_{tube} \) is the flow velocity in the tube at that moment in [l/sec]. \( A_{tube} \) is the cross sectional area of the tube in [m²]. \( T_{pump} \) is the time needed for the pump to accelerate the flow in [s]. \( L_{tube} \) and \( A_{tube} \) are measured from the set up. \( U_{tube} \) is known from Table 4-4. \( T_{pump} \) is estimated based on visual observations.

\( L_{tube} = 1 \text{ m}, A_{tube} = 2.376 \times 10^{-5} \text{ m}^2, T_{pump} = 1 \text{ s}. \)

Table 4-5 presents the calculated time lag. As a consequence of the time lag, the duration of one step is not precisely one minute.

<table>
<thead>
<tr>
<th>Step [minute]</th>
<th>1\textsuperscript{st}</th>
<th>2\textsuperscript{nd}</th>
<th>3\textsuperscript{rd}</th>
<th>4\textsuperscript{th}</th>
<th>5\textsuperscript{th}</th>
<th>6\textsuperscript{th}</th>
<th>7\textsuperscript{th}</th>
<th>8\textsuperscript{th}</th>
<th>9\textsuperscript{th}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{delay} ) [s]</td>
<td>20</td>
<td>14</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Start [s]</td>
<td>20</td>
<td>74</td>
<td>130</td>
<td>189</td>
<td>248</td>
<td>308</td>
<td>368</td>
<td>427</td>
<td>487</td>
</tr>
<tr>
<td>End [s]</td>
<td>73</td>
<td>129</td>
<td>188</td>
<td>247</td>
<td>307</td>
<td>367</td>
<td>426</td>
<td>486</td>
<td>540</td>
</tr>
<tr>
<td>Duration [s]</td>
<td>54</td>
<td>56</td>
<td>59</td>
<td>59</td>
<td>60</td>
<td>60</td>
<td>59</td>
<td>60</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 4-5 - Time lag between start of erosion and measured erosion for every step that the bottom shear stress is increased and corresponding

Figure 4-12 – Time lag between expected start of erosion (at the start of a new minute) and measured start of erosion (increase of erosion rate): erosion rate (series A)
Figure 4-13 presents the erosion rate for series A when the time lag is processed. As expected, it shows that the erosion rate immediately increases after the shear stress has increased.

![Figure 4-13 - Erosion rate (Series A), time lag due to experimental procedure is processed](image)

Figure 4-13 - Erosion rate (Series A), time lag due to experimental procedure is processed
5 Results and discussion

First a comparison is presented of a bioturbated mud sample (series A) and a defaunated mud sample (series B). Subsequently the replica series of bioturbated mud samples are presented. Series C is not a representative replica, since it was exposed to a high temperature. Nevertheless series C is presented, because it reveals new insight. Series D and E are two representative replica series, executed on the soft mud layer with only Tubifex worms. The sample of series F consists of Zuiderzee deposit and here also only Tubifex worms are used.

One small change was made for series D, E and F; the procedure to add biota was further adjusted. Moreover the order of the experiments changed, but this is not considered to be relevant. Important to note is that the sediment characteristics of the Markermeer mud vary spatially and in depth. Therefore some deviation in the characteristics of the soil sample between the different replica series cannot be prevented. Table 5-1 presents an overview of the differences between the series of experiments.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mud type</th>
<th>Biota procedure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Soft mud layer</td>
<td>Re-use of biota</td>
<td>Order of experiments: n= 4,2,6,8</td>
</tr>
<tr>
<td>B</td>
<td>Soft mud layer</td>
<td>No biota</td>
<td>Order of experiments: n= 4,2,6,8</td>
</tr>
<tr>
<td>C</td>
<td>Soft mud layer</td>
<td>Re-use of biota</td>
<td>Failed due to high temperature, order of experiments: n= 4,2,6</td>
</tr>
<tr>
<td>D</td>
<td>Soft mud layer</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
<tr>
<td>E</td>
<td>Soft mud layer</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
<tr>
<td>F</td>
<td>Zuiderzee deposit</td>
<td>Constant Tubifex</td>
<td>Order of experiments: n= 2,4,6,8</td>
</tr>
</tbody>
</table>

Table 5-1 - Replica series, mud type, biota procedure and important details

5.1 Bioturbated versus defaunated

5.1.1 Erodibility

The erodibility is studied by plotting the erosion rate [g/m2/s] versus bottom shear stress [Pa]. The shear stress is the forcing parameter and the erosion rate is the response of the sediment sample to this forcing. The higher the erosion rate for a certain shear stress, the more erodible the sample.

The first two series of experiments, A and B, represent a bioturbated and a defaunated mud sample. As shown in Figure 5-1 the erodibility of the bioturbated mud sample is considerably larger than the erodibility of the defaunated mud sample. There is a trend observed for series A, the erodibility increases with bioturbation period, while for series B the erodibility is constant.
Another observed difference is the ratio of the erodibility at the start (anoxic mud layer) and after x days (oxic layer). For the bioturbated sample, the erodibility after x days is always greater than erodibility at the start, while for the defaunated sample the erodibility after x days is always lower than the erodibility at the start.

It is believed that bioturbation is responsible for the increasing erodibility of series A. The increasing trend with bioturbation period can be explained by the increased duration of the bioturbation activity. This is in agreement with Davis (1993) who stated that bioturbation is a function of the type, abundance and reworking time of the fauna. For series B, the erodibility decreased after a certain waiting period, see Figure 5-3. This can be explained in two ways. It could be that most particles available for erosion were already eroded during the first experiment. Second, it could be due to the compaction of the top layer. Just before the start of the experiment, the sample was disturbed by cutting the oxidized top layer. Remolding decreases the strength by destroying the cohesive bonds. Compaction of the surface top layer could account for the regaining of cohesive strength.

A noteworthy observation for the left graph of Figure 5-1 is the decreasing erosion rate for increasing bottom shear stress. It indicates that erosion is limited by the amount of sediment that is available for erosion. This will be discussed in more detail in paragraph 5.3.1.

### 5.1.2 Total eroded mass

Figure 5-2 below shows the development of the total eroded mass during the experiment. The left y-axis shows total eroded mass, the right y-axis shows applied bottom shear stress and the x-axis shows time.
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

Figure 5-2 – Development total eroded mass for bioturbated Markermeer mud, series A

The figure above shows again that the total eroded mass of the bioturbated sample is much higher than the defaunated sample. The top panel of series A also shows the increasing trend of total eroded mass for increasing bioturbation period. However the total eroded mass for the 4 days experiment is lower than the 6 days experiment. But we also observe relatively high erosion at the start for the 6 days experiment. Probably the erodibility shows some variability. Another possibility is that high erosion during the 4 days experiment is explained by the high amount of biota that was present. As a result of the experimental procedure there was a peak in the input of animals for the 4 days experiment, see right panel of Figure 5-5. As mentioned in paragraph 2.2.3, bioturbation is expected to be a function of the amount of animals. The high abundance of animals for the 4 days experiment could have caused more intense bioturbation activity and thus higher erosion rates.

5.1.3 Thickness oxidized layer

During every experiment an oxidized layer develops. Figure 5-4 shows the development of the thickness of the oxidized layer for every experiment.
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

5.1.4 Amount of biota

Biota that was present in the oxidized layer is shown in Figure 5-5. Biota was counted for the natural oxidized layer and after each round of experiment when the oxidized layer was cut off. The left panel shows the development in chronological order. The first experiment that was executed was the 4 days experiment and hereafter the 2 days, 6 days and 8 days experiment were performed.\(^8\) The right panel shows the input for every experiment.

---

\(^8\) It was not possible to perform experiments in the weekend and for that reason the planning would be more efficient if the 4 days experiment was executed first.
A decreasing trend is observed in the number of animals during the total series of experiments, see left panel of Figure 5-5. Most probably animals died due to the manipulation during the experimental procedure. A noteworthy observation is made for the *Tubifex* worms. There are zero worms halfway the experiment, while at the end there are *Tubifex* worms again. This suggests that *Tubifex* worms are not only living in the oxic mud layer, but also in the black anoxic mud layer. Visual observation supports this statement as tubes are visible in the black anoxic mud, see Figure 5-6. However this implies that no accurate measurements on the amount of *Tubifex* worms can be made. Collecting the worms in the anoxic mud layer for counting is not possible prior or during the experiments, because the sample will be destroyed by the sieving procedure. For series D, E and F the method is further improved by counting the amount of biota at the end of the experiments.

The right panel of Figure 5-5 shows a large peak for the 4 days experiment. This is caused by the fact that the experiments were not performed in logical chronological order. This may be the reason for the high eroded mass after the 4 days experiment.
5.2 Bioturbated replica series

5.2.1 Soft mud layer

Figure 5-7 shows the erodibility of replica series D with bioturbated Markermeer mud. Biota that was added to the sample consisted of *Tubifex* worms only.

![Erodibility graph](image)

![Development graph](image)

**Figure 5-7 - Erodibility of bioturbated soft mud layer (series D), top: erosion rate versus shear stress, below: development total eroded mass**

Erodibility again increases with number of days of bioturbation. Furthermore, the erosion rate and cumulative erosion are comparable with series A, the total eroded mass of series D is 84% of series A. Hence, this replica series again demonstrates the effect of bioturbation on the erosion behavior of Markermeer sediment. Moreover, this result shows that *Tubifex* worms are an important bioturbation species, as for this experiment only *Tubifex* worms were added to the sample.

The main difference with the results of series A is the shape of the graphs. The erosion rate shows a peak for 0.3 to 0.4 Pa and decreasing erosion rates for higher shear stresses. This will be further discussed in paragraph 5.3.1.
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

Figure 5-8 shows the erodibility of replica series E with bioturbated Markermeer mud.

![Erodibility bioturbated Markermeer mud replica (series E)]

![Development total eroded mass (series E)]

The erodibility after bioturbation is low for series E compared to series A and D. The total eroded mass of series E is 45% of series D. The mud sample of series E was taken at a lower depth than series D. Therefore it seems logical that consolidation plays a role in the lower erodibility of series E. However this explanation is not supported by the measured soil properties, see paragraph 4.1.2. It could also be the result of the variety occurring in nature. For example, maybe smaller or less productive worms were added to this sample, resulting in lower bioturbation activity.

5.2.2 Zuiderzee deposit

Figure 5-9 shows the erodibility of replica series F with bioturbated Zuiderzee mud. The Zuiderzee deposit is very stiff. This is also observed from the erosion experiment as the mud sample shows minor erosion at the start. After bioturbation small but significant erosion is taking place during the experiment. A clear trend is visible; total eroded mass is increasing with bioturbation period. We observe that erosion especially takes place during the time steps of 0.3 and 0.4 Pa. The erosion rate shows a peak at 0.3 Pa. This is again an indication that erosion is limited by the amount of sediments that are available for erosion, see paragraph 5.3.1.
5.2.3 Thickness of oxidized layer

Figure 5-10 shows the development of the thickness of the oxidized layer. The observations of series D, E and F show good agreement with series A, the thickness increases with bioturbation period.
This again supports our idea that bioturbation increases both the thickness of the oxidized layer and sediments that are available for erosion. Thus in case of bioturbation most probably the eroded layer is related to the thickness of the oxidized layer. Figure 5-11 indeed shows this relation, the scatter plot shows an increasing trend. True, this relation only holds for the bioturbated oxidized layer and not for the defaunated one, series B. Moreover Figure 5-11 gives an idea on the relative thickness that has been eroded. The thickness of the eroded layer was calculated according the following formula: 

\[ d_{\text{eroded}} = \frac{TEM}{\rho} \]

Where \( d_{\text{eroded}} \) is the thickness of the eroded layer in [m], TEM is the total eroded mass in [g/m^2] and \( \rho \) is the soil density in [g/m^3]. The thickness of the eroded layer is approximately 2-10% of the oxidized layer.

![Figure 5-10 - Development oxidized layer in time](image)

![Figure 5-11 - Thickness eroded layer versus thickness oxidized layer](image)

### 5.2.4 Amount of biota

Biota that was added for the experiments of series D, E and F consist only of *Tubifex* worms. Table 5-2 shows the measurement results of the amount of those worms during the experiment. After every round of experiments
11 worms are added to the sample. Therefore the amount of worms is increasing during the total series of experiment. However at the same time worms are dying due to manipulation during the procedure.

<table>
<thead>
<tr>
<th></th>
<th>Series D</th>
<th>Series E</th>
<th>Series F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worms added every experiment</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Worms present at the end</td>
<td>34</td>
<td>29</td>
<td>23</td>
</tr>
<tr>
<td>Worms died</td>
<td>10</td>
<td>15</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 5-2 - Measurement amount of worms during the series of experiments

We assume there are no worms in the black anoxic mud layer at the start and the dying rate is constant per manipulation procedure. Based on these assumptions, an estimate is made on the number of worms that is present during each experiment, see Figure 5-12.

As stated in paragraph 2.2.3, the effect of bioturbation is most likely a function of the amount of animals. For that reason we explore the possibility to explain the variation in erosion by the amount of worms. First of all we assume that the total eroded mass of the oxidized bioturbated samples is induced by bioturbation. As shown before, bioturbation induced erosion is a function of the bioturbation reworking period. To exclude this last effect we calculated the bioturbation induced erosion divided by the bioturbation period. Then we compare the bioturbation induced erosion against the amount of worms.
Figure 5-13 - Total eroded mass versus amount of worms

Figure 5-13 shows that bioturbated induced erosion per bioturbation period is more or less constant per series. This implies that the effect of bioturbation on the erodibility is most probably dependent on the soil properties. No relation is shown between the eroded mass and the amount of worms. However the dataset is quite poor. The amount of worms is only an estimation. Second, the variation between the amounts of animals is rather small. Studies that showed the importance of amount of animals used a much larger density variation, see paragraph 2.2.3.

5.2.5 Effect of temperature on bioturbation activity

During one series of experiments the fridge failed and the sample was subject to temperatures up to 21°. Due to this, series C wouldn’t represent a good replicate to compare with the first series of experiments. For this reason this series was stopped after the 6 days experiment.

However, afterwards the series appears to be of interest to give new insights. The 6 days experiment shows high erosion compared to other experiments, see Figure 5-14. The total eroded mass for the 6 days experiment is 317.14 g/m², an increase of 160% compared to series A.
That let us believe that temperature might be an important factor influencing the bioturbation activity. Mc Call (1982) supports this idea. He states that water temperature is an important determinant of sediment mixing rates by worms.

5.3 Comparison literature review

5.3.1 Type of erosion
The erosion rate, $E$, of cohesive sediments is typically described as a function of a certain erosion threshold, $\tau_e$, and an erosion rate parameter, $M$ or $E_f$. Mehta and Partheniades (1982) defined two types of erosion, type I, limited erosion, and type II, unlimited erosion.

Type I (limited erosion): 

$$E = E_f \exp \left\{ \alpha \left( \frac{\tau_b - \tau_e(z)}{\tau_e(z)} \right)^\beta \right\} \quad \text{for} \quad \tau_b \geq \tau_e$$
Type II (unlimited erosion): \( E = M \left( \frac{\tau_b - \tau_c}{\tau_c} \right)^n \) for \( \tau_b \geq \tau_c \)

The type I erosion formula predicts an exponential decaying erosion rate with time. Erosion rate drops as a result of an increasing critical shear stress with depth. Therefore the total eroded mass will reach an equilibrium value. This type of erosion is often observed during erosion experiments, (Winterwerp and Van Kesteren 2004). The type II erosion formula predicts unlimited erosion. Generally exponent \( n \) is considered unity, resulting in a constant erosion rate when a certain shear stress is applied.

**Figure 5-16 - Erosion rate in time for bioturbated Markermeer mud (series A and D)**

Figure 5-16 shows the erosion rate in time for series A and series D. The erosion pattern seems to be type I erosion during the first minutes. The erosion rate increases when a higher shear stress is applied and then decreases in time. The last minutes show a decreasing erosion rate with increasing shear stress, especially for series D. This indicates that erosion is limited by the amount of sediments that are available for erosion. This implies that bioturbation makes a certain amount of sediment available for erosion. Once these sediments are eroded the erosion rate drops. This theory is supported by Montserrat (2011), he showed that the foraging behavior of *Macoma Balthica* increases the amount of sediment that is available for erosion.

Furthermore Amos (1992) distinguished type IA and type IB erosion. Type IA was associated with the erosion of fecal pellets and only took place in environments with high benthic activity. Type IB was linked with the erosion of rip-clasts and aggregates and occurred at all location for bed stresses between 1-4.4 Pa. Both types were characterized by a rapid increase of erosion immediately after the force was implied, followed by a smooth exponential decay within 3 minutes. Type II erosion only occurred when the uppermost 0.5 mm was eroded. This supports our idea that availability of sediment for erosion is important for the erosion of fecal pellets.

Besides, it shows that limited erosion is dominant in the thin top layer in general.

### 5.3.2 Bioturbation mechanisms

During the experiments we observed the production of fecal pellets. The pellets have the shape of small worms with a length up to 1 cm. Some fecal pellets are still black, indicating that they origin from the black anoxic layer.
For series D, Tubifex worms were the only biota that was added. Consequently these fecal pellets should have been secreted by Tubifex worms. This is supported by literature, see paragraph 2.2.3. Tubifex worms are well-known for their feeding behavior, thereby producing a fecal pellet layer at the surface, see Figure 5-18.

During the erosion experiment we observed that the fecal pellets were eroded first. Figure 5-19 shows the experimental sample of series (A), before and after the erosion experiment. It shows the presence of fecal pellets before the erosion experiment and the absence of fecal pellets after the erosion experiment. Based on observation, also sediment particles were eroded.

Another feature, shown in Figure 5-19, is a scouring hole, the black spot in the right picture. At the black spot the oxidized layer is eroded until the oxidized layer. Scouring or mass erosion occurred occasionally. In most cases mass erosion occurred during the experiment at the start. Sometimes the scouring process continued during the erosion experiment on the bioturbated sample.
After bioturbation we observe the change from a smooth bed to a rough bed with mounds and pits, see Figure 5-20. This roughness could have caused additional turbulence near the bed, causing more erosion. Moreover, loose protrusions and heaps will erode earlier, as they will experience a higher stress.

A big tube appeared after bioturbation for series A. We believe the tube is produced by chironomid larvae, see Figure 5-21. Chironomid larvae were added to the sample only for series A and C, but no tubes were found during series C. The tube didn’t erode during the erosion experiment.
As described in paragraph 2.2.3, chironomid larvae tend to stabilize the sediment, however this stabilizing effect is only observed for high densities, greater than 5000 ind/m². During our experiments we only found 1 or 2 chironomid larvae, resulting in a density of 150-300 ind/m². For that reason we’re not considering this mechanism to be important in our case. However the tube is a large protrusion and could have affected the boundary flow in the experimental set up. Possibly the tube induced near-bed turbulence and caused increased erosion.

We hypothesize that the increased erodibility is a result of all three bioturbation mechanisms. The production of fecal pellets is demonstrated from photographs. We believe that the second mechanism, sediment disturbance by *Tubifex* worms is taking place in the oxic and anoxic layer, resulting in less compacted soil. Moreover, for series A and C, the movement of *Ostracoda* could also have resulted in sediment disturbance of the surface layer. Lastly the heaps and pits created by the activity of biota probably caused increased turbulence near the bed. Now and then scouring occurred, plausible as a result of this increased bed roughness.

### 5.4 Discussion consequences Lake Markermeer

The previous results showed the effect of the activity of biota on the erodibility of sediment. This paragraph will give a first impression about the consequences for the sediment dynamics in Lake Markermeer. As stated in the introduction, chapter one, two knowledge gaps could be explained by the bioturbation phenomenon. First, possibly, the top sediment layer is easy erodible as a result of bioturbation, resulting in high turbidity values in Lake Markermeer. Second, possibly, bioturbation has increased the erodibility of the Zuiderzee deposits during the last decades, thereby explaining the creation of the soft mud layer from eroded Zuiderzee deposits under the current hydrodynamics.

#### 5.4.1 Production of erodible sediments due to bioturbation

In our experiments we observed that bioturbation is creating a certain amount of sediments that are available for erosion. A first estimate will be made on the production of those sediments and their contribution to high turbidity values and the creation of a soft mud layer.
First we have to make a few assumptions. We assume that the erosion during a nine minute experiment is representing the total amount of erosion that is induced by 2, 4, 6 or 8 days of bioturbation. Important to be aware is that this is an underestimate, as erosion was still going on at the end of the experiment, however erosion is expected to drop within several minutes, since erosion is limited by the amount of sediments that are available for erosion. Moreover shear stresses were applied until 0.8 Pa, while in Lake Markermeer shear stresses up to 2 Pa can occur.

Figure 5-22 - Bioturbation reworking rate, total eroded mass [g/m²] versus bioturbation period [days]

Figure 5-22 shows that the total eroded mass increases roughly linearly with increasing bioturbation period. Hence a constant production per day can be determined, resulting in a production of sediments that are available for erosion of 27 g/m²/day. Based on this, we can make an estimate on the contribution of these sediments to the turbidity level in the lake.

\[ TSM_{\text{day}} = \frac{TEM}{h} \]

Where TEM/day is the total eroded mass that is produced per day [g/m²/day], h is the water depth [m] and TSM/day is the production of suspended sediment per day for a square meter water column, in [g/m³] or [mg/l]. When we take the average water depth of 3.5 m, we come to an production of suspended sediment of 7.7 mg/l per day for a square meter water column.

The retraction of suspended sediments due to deposition is unknown, however if we assume that sediments will stay in the water column for about a week, bioturbation induced erosion could result in a turbidity level of about 50 mg/l due to inorganic fraction only. The average concentration in the lake, consisting of both organic and inorganic fraction, is also 50 mg/l, so this implies bioturbation induced erosion could be the source for the high turbidity levels.

---

9 Average value for all experiments of series A and D
Next thing to investigate is if bioturbation induced erosion of the Zuiderzee deposits could explain the creation of the soft mud layer. For that purpose the erosion behavior of the Zuiderzee deposits needs to be studied. We assume again all erosion is induced by bioturbation and the reworked material is a constant number per day. From Figure 5-22 an average production of bioturbation-induced eroded sediments from the Zuiderzee deposit of 3.5 g/m$^2$/day can be calculated. We have to note that these calculations are based on only one experiment. If we assume that the soft mud layer consists only of reworked Zuiderzee deposits, we can calculate the layer thickness that can be produced per year.

$$P_{zuiderzee} = \frac{TEM}{\rho_{zuiderzee}} \cdot \frac{1000 \times 365}{\text{day}}$$

Where $P_{zuiderzee}$ is the production of eroded material [mm/year], TEM/day is the total eroded mass that is produced per day [g/m$^2$/day], $\rho_{zuiderzee}$ is the bulk density of the Zuiderzee deposit, $1230 \times 10^3$ g/m$^3$. This results in a production of reworked sediments of 1 mm/year. Assuming bioturbation became important since the origin of Lake Markermeer, bioturbation could have produced a layer of reworked sediment of around 3.5 cm. According Vijverberg (2010) a soft mud layer of 10 cm is present in Lake Markermeer, hence the influence of bioturbated-induced erosion could have been substantial. Important to mentions is that we here neglected the protective function of the soft mud layer, once a layer of soft mud has developed with a certain thickness, it will protect the Zuiderzee deposits from bioturbation-induced erosion. An important factor regarding bioturbation-induced erosion is temperature, probably leading to even higher erosion rates during summer.

### 5.4.2 Comparison laboratory and field situation

There are some important differences between the experimental set up and the situation in the field. In our experimental set up only erosion was studied, once sediment particles eroded, they were removed from the system, while in Lake Markermeer suspended particles remain in the water column and deposition is also taking place. Furthermore, during storage the sample was exposed to still water conditions, while in the lake frequent resuspension events take place as a result of wind conditions.

Luettich (1990) and Bengtsson (1992) studied wind-induced resuspension in shallow lakes. In both studies bottom sediments were predominantly cohesive. Both authors observe that resuspension is dominated by a thin surface layer of loosely bound sediment that is easy erodible. The layer consists of fine and unconsolidated sediments that are continuously involved in suspension-deposition loops. El Ganaoui (2007) named this layer the fluffy layer. Other authors, (Orvain, Le Hir et al. 2003; Le Hir, Monbet et al. 2007; Montserrat, Suykerbuyk et al. 2011), report of a fluffy top layer as a result of bioturbation. This fluffy layer is a matrix of sediment that is disconnected from the underlying sediment bed. It includes tracks, fecal pellets and mucus and has been shown to be easily resuspended.

We hypothesize both authors are discussing the same fluffy layer. And both processes, bioturbation and frequent resuspension, are the driving mechanisms behind the fluffy layer. An important indicator of the occurrence of bioturbation and frequent resuspension is the thickness of the oxidized layer; both processes increase the amount of oxidized sediments. However, oxidation itself is not a driving mechanism, so one must be careful by using the oxidized state as a characteristic of the fluffy layer. Our experiments showed that bioturbation results in an easy
erodible top layer, but in the field probably also frequent resuspension plays an important role in the maintenance of the easy erodible fluffy layer. A challenging exercise would be to determine which process is dominant, is bioturbation really as important in the field as appears from our experiments?
6 Conclusions and recommendations

6.1 Conclusions

The research objective of this study was to increase the understanding of the influence of biota on the fine sediment dynamics in Lake Markermeer. The research question was: ‘To what extent affects biota the erodibility of the near bed sediments in Lake Markermeer?’

We can conclude that the activity of biota increases the erodibility of the sediment. Experiments showed an increase in erodibility after bioturbation, while the control experiment, the defaunated sample, showed a decrease in erodibility. Next, it appeared that the effect of bioturbation was a function of time, the longer the period for biota to rework the sediment, the higher the erodibility. After 8 days of bioturbation, erosion was 3 to 18 times higher than the erosion at the start.

As stated in chapter 1, sediment dynamics in Lake Markermeer is dominated by erosion and deposition of an oxidized top layer. In the first hypothesis, we stated: Bioturbation is taking place in the oxidized layer and is responsible for the increase in erodibility of this layer.

This study shows that bioturbation was indeed responsible for an increase in erodibility of the top mud layer. However, unlike our assumption in the hypothesis, bioturbation is not only taking place in the oxic mud layer but also in the anoxic mud layer, observations showed that worms also lived in the black anoxic layer. In addition, erosion was limited by the amount of sediments that were available for erosion, which implies that only a very thin top layer was eroded, hence the erodibility of the whole oxic layer was not necessarily affected. A better description would be that bioturbation makes a certain amount of sediments available for erosion.

A noteworthy observation is that bioturbation increased the thickness of the oxidized layer; apparently the movement of biota increases the penetration of oxygen into the mud. However, as was assumed in chapter 1 and supported by our results, there is no causal relation between the oxidized state of the sediment and the high erosion rates. Neither is the oxic state a requirement for life to become active, so one must be careful by using the oxidized state as a characteristic of the easy erodible top layer of a characteristic of bioturbation. However for our experiments the thickness of the oxic mud layer can be used as an indication for the bioturbation history.

For the replica series only Tubifex worms were added, still a similar effect of bioturbation on erodibility was shown, indicating that the worms are an important bioturbation species. During the experiments, we observed the production of fecal pellets by the worms, these fecal pellets were easily erodible and contributed to the total eroded mass. This indicates that the production of fecal pellets by tubifex worms is an important bioturbation mechanism. Other mechanism, like soil disturbance by the activity of biota, possibly affects the strength of the total oxic layer and the anoxic mud layer, but this was not revealed by our experiments. Soil disturbance results in a less compacted soil layer that will be more easily erodible. Observations showed that bioturbation also caused an increased bed roughness, possibly resulting in increased near bed turbulence thereby enhancing erosion.
Figure 6-1 Schematization of important bioturbation mechanism: production of fecal pellets by *Tubifex* worms

The second hypothesis stated: *When Zuiderzee deposits are at the water interface, the top layer will get oxidized and bioturbation will increase the erodibility of this top layer.*

Experiments on the Zuiderzee deposits showed comparable results, the top layer got oxidized and the erodibility of the top layer increased after bioturbation. The only difference was that the sediment was stiffer, which was shown by lower erosion rates. Experiments showed minor erosion at the start and small but significant erosion after bioturbation. Again the effect of bioturbation on the erodibility was a function of time, the longer the period for biota to rework the sediment, the higher the erodibility.

This study demonstrated that bioturbation makes a certain amount of sediments available for erosion. This effect of bioturbation on erodibility is a function of time and affects both the oxic mud layer and the Zuiderzee deposits. We believe the effect of bioturbation is also important for the sediment dynamics in the lake, and possibly bioturbation-induced erosion is one of the reasons for the high turbidity levels. We hypothesize bioturbation is an explanation for the high erodibility of the oxic mud layer and bioturbation have also enhanced the erosion of the Zuiderzee deposits, thereby creating the soft mud layer. However, extrapolation to the situation in the field is rather difficult, although a causal relationship has been demonstrated between bioturbation and erodibility, this does not necessarily imply that bioturbation-induced erosion is a dominant mechanism.

### 6.2 Recommendations

This research about the link between biology and sediment dynamics was the first that has been executed for the situation in Lake Markermear. The study has led to important findings, however improvements can be made and further research is essential to determine the importance of the effect of bioturbation in the field.

We observed that bioturbation mechanisms are characteristic for specific zoobenthos species. We hypothesize *Tubifex* worms are one of the key species in Lake Markermear. Further research is recommended to classify the important bioturbation species and the corresponding bioturbation mechanisms.
Second, it would be interesting to determine the importance of several parameters on the effect of bioturbation on erodibility, most important being temperature and biota density. The influence of temperature on bioturbation possibly induces seasonal variation.

Furthermore we observed that erosion was limited by the amount of sediment that was available for erosion. The erosion behavior needs to be studied in more detail. A first approach would be to increase the time step of the erosion experiment, to check if erosion is indeed reaching equilibrium.

A last challenging exercise would be to extrapolate the effect of bioturbation on the erodibility to the situation in the field. Within Lake Markermeer frequent resuspension events take place as a result of wind conditions, due to these events there is a certain amount of sediment that is continuously involved in resuspension-deposition loops, also resulting in an easy erodible top layer. Both processes are important in Lake Markermeer and the link between those two processes needs to be studied in more detail.
References


Appendix A: Results erosion experiments

A1: Erosion rate versus bottom shear stress

Please note that the scaling of the y-axis is different for every graph.

Erosion rate versus bottom shear stress (series A)

Erosion rate versus bottom shear stress (series B)
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
A2: Development total eroded mass

Please note that the scaling of the y-axis is different for every graph.
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer

Development total eroded mass (series E)

Development total eroded mass (series F)
A3: Erosionrate

Please note that the scaling of the y-axis is different for every graph.
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
Appendix B: Input parameters erosion experiment

The shear stresses are created by a specific combination of a certain rotational speed of the disk and flow velocity induced by the pump. In addition, the shear stress that is produced is depended on temperature. The manual of the U-GEMS microcosm provides us with calibration equations to calculate the required parameters to produce a certain shear stress.

The calibration equations for the U-GEMS microcosm are expressed in shear velocity. Shear velocity is related to shear stress according the following formula: \( u_s = \sqrt{\frac{\tau}{\rho}} \)

The calibration equations belonging to the U-GEMS microcosm are the following, (De Lucas Pardo 2011):

\[
\begin{align*}
Q &= -28.31u_{s15}^2 + 170.2u_{s15} - 23.85 \\
u_{s15} &= -0.00001n^2 + 0.011n + 0.0956
\end{align*}
\]

Where \( u_{s15} \) is the shear velocity [Pa] for a temperature of 15º, \( n \) is the disk rotation per minute [RPM] and \( Q \) is the pumping rate [ml/min]. As appears from the formula, the produced shear velocity is dependent on temperature. The following equation is used to account for the temperature effect:

\[
u_{sT} = u_{s15} \left(1 + 0.006(T - 15)\right)
\]

Where \( u_{sT} \) [Pa] represents the shear velocity at temperature \( T \) [º].

Furthermore, de Lucas Pardo (2011) determined calibration equations for the pump and rotational disk. The pumping rate input is a percentage. The following calibration equation relates this to the discharge

\[
PR_{ml/min} = 786.56 \frac{PR_{\%}}{100} + 48.35 \quad \text{where } PR_{ml/min} \text{ is the pumping rate in ml/min and } PR_{\%} \text{ the pumping rate in %}.
\]

The disk rotation per minute [RPM] is related to the input voltage [V]. The following calibration equation is used:

\[
\begin{array}{l}
\text{Table B-1 presents the input parameters for an erosion experiment with a water temperature of 9º.}
\end{array}
\]

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The effect of Bioturbation on the Erodibility of Fine Sediments in Lake Markermeer
Appendix C: Experimental procedure: improvements & remarks

This appendix will describe the problems encountered during the experiment and the improvements made to solve them. In some cases we did not find a totally satisfying solution, therefore some remarks are made to be aware of those weak points.

C.1 Calibration of the Oslim

We observed quite some variation in the output results when calibrating the Oslim. The calibration procedure resulted in a linear calibration equation with a certain offset and a certain slope, as described in paragraph 4.4.1. Both parameters varied for every calibration that was performed. This paragraph describes how we deal with this inaccuracy.

First it is important to be aware that the Oslim instrument is intended for long-term erosion experiments. The instrument actually becomes stable after 24 hours. This is because the inside of the instrument and the tubes get polluted with sediments. First equilibrium should be reached between sediments that get attached and detached from the inside surface. As in our experiments the duration is only nine minutes, there is by far not enough time to reach this equilibrium. This could affect the accuracy of our measurements. Moreover it could be an explanation for the high variability of the calibration parameters.

Some improvements were made. Sometimes concentrations of 0 g/l and 0.1 g/l gave the same output. This indicated that Markermeer water was already polluted with suspended sediments. Therefore it was decided to use filtered Markermeer water, with a membrane filter of 45µm. Then we used a magnetic stirrer to make sure the sediments that were added were all in suspension. Then we performed a total series of calibration, to see if we could discover a trend. We observed that the offset is changing more gradually than the slope. It seems that the offset increases after an erosion experiment with high erosion and decreases again for experiments with normal erosion. Therefore we decided to measure the offset prior to every experiment. The slope is changing a lot, but no clear pattern is discovered. We decided to use an averaged value for the slope parameter.
The calibration procedure was executed regularly during the rest of the experiments. Figure C-1 reveals that the scatter for the slope-parameter remains quite big, the values range from 3.5 to 5.7. By taking an averaged value we neglect this variety. Especially when we look at the last results of January, it remains questionable if this accurate. Possibly the response of the instrument to suspended sediment concentrations is varying due to the fact that it is not stable yet. Moreover the results are quite sensitive to the calibration equation. A change of the slope from 3.5 to 5 results in an increase of the total eroded mass of more than 40%.

For this study the method used was considered sufficient. Especially because we studied the relative change in erosion and the quantities are not that important. However further study is recommended.

C.2 Experimental setup

At the beginning of the experiments we experienced air bubbles coming up from the soil sample. Due to these air bubbles the soil sample got disturbed and a lot of extra erosion occurred during the experiment.

The first improvement was the diameter of the microcosm tube. The inner diameter of the big tubes from the field campaign was ca. 93 mm. The inner diameter of the microcosm tube was ca. 94.5 mm. This means that the soil sample was smaller than the microcosm. With the consequence that air could get stuck inside the microcosm. Therefore a smaller tube with a diameter of ca. 92 mm was used insted. The extruding piston and the erosion head required some changes to fit again on this smaller tube. The diameter of the extruding piston was made smaller. A thicker O-ring was put into the erosion head, to create a watertight connection again.

After those adjustments, a new unexpected event occurred: the total soil sample rises during the experiment. This must be a consequence of a low pressure inside the microcosm and leakage of air through the bottom. Probably the O-ring that was closing off the bottom of the microcosm wasn’t working properly. Some adaptions were made and a new tool was constructed to screw the extruding piston really tight. After those adjustments the soil sample stayed in place. Only this time the air bubbles came up again during the experiment. Then the only thing left to change was the pressure inside the microcosm. We discovered that the low pressure in the microcosm was caused by the position of the output bucket. The output bucket was based on a lower level than the microcosm.
Driven by gravity, water from the microcosm flew through the tube to the output bucket, resulting in an under pressure in the microcosm. As soon as the output bucket was put on a higher level than the microcosm no air bubbles were observed anymore.

C.3 Erosion experiment at the start

The erosion experiment performed at the start showed unexpected high erosion rates. Also because the top layer of the sample was disturbed by the experimental procedure. The erosion experiment at the start was executed on the black anoxic mud layer. Therefore first the oxidized layer was cut off with a knife, causing remolding of the sample. After that water was pumped on top of the sample. Although minimal velocity was used, resuspension of small sediment particles was observed.

The goal of the erosion experiment at the start was to represent the erodibility of the soil sample without the influence of bioturbation. The fine sediment particles that were easily resuspended due to the working method should not be included. For that reason two erosion experiments were performed at the start. The first experiment is meant to remove loose fine sediment particles and remolded soil. The second experiment is expected to represent the erodibility of the soil sample. Figure C-2 shows a comparison between the first and second experiment. Indeed the erosion rate is much lower for the second erosion experiment. We have to note that is difficult to define the difference between erosion due to the working method and ‘real’ erosion. However we believe that the large variation between the different results for the first experiment is consequence of the experimental procedure. The erosion rates for the 2nd experiment are rather constant, in the order of 0-0.3 g/m²/s. Therefore it is assumed that these results are a better representative of the erodibility of the soil sample.

![Erosion rate of bioturbated Markermeer mud (series A)](image)

Figure C-2 - Erosion rate at the start, comparison between 1st and 2nd experiment (Series A)
Appendix D: Shear stress

This appendix will describe the method used to calculate the shear stresses induced by waves and currents.

The following formulas are used, (Van Rijn 2011):

Shear stress induced by currents: \( \tau_c = \frac{1}{8} \rho f_c (U_c)^2 \) with \( f_c = 0.242 \left( \log \left( \frac{12h}{k_a} \right) \right)^{-2} \)

Shear stress induced by waves (time-averaged): \( \tau_w = \frac{1}{4} f_w \left( \dot{U}_s \right)^2 = \frac{1}{4} f_w \left( \frac{\pi H}{T \sinh(kh)} \right)^2 \)

Friction factor (hydraulic rough regime): \( f_w = e^{-6+5.2 \left( \frac{\dot{A}_s}{k_s} \right)^{0.19}} \) with \( f_{w,\text{max}} = 0.3 \) for \( \frac{\dot{A}_s}{k_s} \leq 1.57 \)

With \( \dot{A}_s = \frac{H}{2 \sinh (kh)} \)

The following parameters are used. Water velocity is based on measurements of Vijverberg (2010). Median grain size is based on measurements of De Lucas Pardo (2011).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) Water density</td>
<td>1000</td>
<td>[kg/m(^3)]</td>
</tr>
<tr>
<td>( U_{c} ) Flow velocity</td>
<td>0.2</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( h ) Water depth</td>
<td>3.5</td>
<td>[m]</td>
</tr>
<tr>
<td>( k_a ) Apparent roughness</td>
<td>2.5(*k_s)</td>
<td>[m]</td>
</tr>
<tr>
<td>( k_s ) Bed roughness</td>
<td>10(*D_{90})</td>
<td>[m]</td>
</tr>
<tr>
<td>( D_{90} ) Grain size (upper limit)</td>
<td>100(*10^{-6})</td>
<td>[m]</td>
</tr>
<tr>
<td>( H_s ) Significant wave height</td>
<td>Varying for different wind speed</td>
<td>[m]</td>
</tr>
<tr>
<td>( T ) Wave period</td>
<td>Varying for different wind speed</td>
<td>[s]</td>
</tr>
<tr>
<td>( k ) Wave number</td>
<td>Varying for different wind speed</td>
<td>[m(^{-1})]</td>
</tr>
<tr>
<td>( U_{10} ) Wind velocity at an altitude of 10 meter</td>
<td>Varying</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( F ) Fetch (average)</td>
<td>27</td>
<td>[km]</td>
</tr>
</tbody>
</table>

Table D-1 – Parameters hydraulic conditions Markermeer

Wave height is based on measurements that reveal a linear relation with wind speed, see the figure below:

\[ H_s = 0.056 \* U_{10} - 0.0086 \]
According to the Bretschneider formula, wave height is a function of windspeed, water depth and fetch. The water depth is more or less constant around the lake. The fetch is also more or less constant for the middle of the lake. This explains the relationship found from measured data. Most probably scatter is caused by the variation of the fetch.

**Figure D-1 - Relation wave height wind speed for the middle of Lake Markermeer (FL42), (De Lucas Pardo 2011)**

For the wave period, no measured data was available. Therefore, the wave period is calculated with Bretschneider:

\[
\tilde{T} = 7.54 \tanh \left(0.833 \tilde{d}^{0.375}\right) \tanh \left(\frac{0.77 \tilde{F}^{0.25}}{\tanh \left(0.833 \tilde{d}^{0.375}\right)}\right)
\]

With:

\[
\tilde{T} = \frac{gT}{U_{10}^2}, \quad \tilde{d} = \frac{gd}{U_{10}^2} \quad \text{and} \quad \tilde{F} = \frac{gF}{U_{10}^2}
\]

The wave number, k, is determined from the dispersion equation:

\[
\frac{1}{k} = \frac{gT^2}{(2\pi)^2} \tanh \left(kh\right)
\]
This results in the following shear stresses.

<table>
<thead>
<tr>
<th>Wind force</th>
<th>BFt</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
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<tbody>
<tr>
<td>Wind speed</td>
<td>U10</td>
<td>m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of days that wind speed is exceeded</td>
<td></td>
<td>280</td>
<td>148</td>
<td>59</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Significant wave height</td>
<td>H_s</td>
<td>m</td>
<td>0.33</td>
<td>0.55</td>
<td>0.66</td>
<td>0.83</td>
</tr>
<tr>
<td>Significant wave period</td>
<td>T</td>
<td>s</td>
<td>2.44</td>
<td>3.1</td>
<td>3.36</td>
<td>3.69</td>
</tr>
<tr>
<td>Significant wave length</td>
<td>L</td>
<td>m</td>
<td>9.14</td>
<td>13.81</td>
<td>15.63</td>
<td>17.90</td>
</tr>
<tr>
<td>Orbital velocity near the bottom</td>
<td>U_δ</td>
<td>m/s</td>
<td>0.077</td>
<td>0.237</td>
<td>0.321</td>
<td>0.452</td>
</tr>
<tr>
<td>Shear stress induced by waves</td>
<td>τ_w</td>
<td>Pa</td>
<td>0.095</td>
<td>0.421</td>
<td>0.650</td>
<td>1.067</td>
</tr>
<tr>
<td>Shear stress induced by current</td>
<td>τ_c</td>
<td>Pa</td>
<td>0.067</td>
<td>0.067</td>
<td>0.067</td>
<td>0.067</td>
</tr>
<tr>
<td>Shear stress induced by both</td>
<td>τ_{w,c}</td>
<td>Pa</td>
<td>0.116</td>
<td>0.426</td>
<td>0.654</td>
<td>1.072</td>
</tr>
<tr>
<td>currents and waves</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table D-2 – Shear stresses in Lake Markermeer