Determining the short-term sediment budget in a tidal freshwater wetland: a case study in the Kleine Noordwaard, the Netherlands.

Master Thesis Earth Surface and Water

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Preface

'Water is the driving force of all nature'
L. da Vinci

The many aspects of Earth Sciences have intrigued me throughout the 5 years of my study. Even though geology and sedimentology still fascinate me, I decided to specialize myself in the direction of physical geography. The present day processes and theories have a direct influence on research and management measures of the present day water problems and challenges, which we face every day. I hope that the knowledge I gained throughout the masters courses and the research I have done for this thesis, will contribute to future knowledge and understanding of the dynamics of wetland systems. As the quote above already states, water drives so many systems on earth and is an important topic of research in my eyes. For the future, I hope I will contribute more in research and projects about water systems and spread the knowledge to different countries.

For the research in this thesis I would like to thank my main supervisors Marcel and Eveline. We have done fieldwork and gained new information about several topics of interest. It was interesting to brainstorm together about new techniques and formulas to use for different calculations. It helped me to improve my research and writing skills and to always think critically about your results and conclusions, something that will stay difficult but that one will learn with more and longer experience.

Wouter and Nanda, even though we had different topics to investigate in the Biesbosch, we gathered data together, helped each other with lab work sometimes and shared thoughts about the sedimentation processes in our little research area. Even though our methods did not work out that well in the field, we could laugh about it and then try to think about other methods which could work after all.

Last of all, my study friends Rinse, Peter, Florian, Renee and Lars. We were working on the GIS rooms for hours and days, modelling, writing, complaining but most of all supporting each other in times of distress. It was nice to write a thesis at the same time as you guys.

Abstract

Due to the predicted rise in sea level, it is quite possible that river deltas in low-lying areas will start to drown. When the rate of sea level rise exceeds sediment accretion in a wetland, loss of delta land is inevitable. The Netherlands has many wetlands and the Biesbosch in the south-western part of the Netherlands is one of the best known examples. The area investigated in this thesis is called the Kleine Noordwaard. In this area, a recently inundated tidal freshwater wetland provides an ideal opportunity for investigating the sediment budget of such a wetland. This can give information on the survival chances of such a wetland.

The main focus in this thesis is to gain information on the short term sediment budget in the Kleine Noordwaard. In order to answer this question, stream velocities and suspended sediment concentrations were measured. Using the suspended sediment measurements, maps of suspended sediment concentration were made. From the stream velocities, discharges were calculated which in turn were used for flux calculations. These flux values were used for sediment budget calculation in order to answer the main research question. Fall velocities were computed as well and used for the calculation of the trapping efficiency of the Kleine Noordwaard.

Temporal differences in suspended sediment concentrations were seen on the maps which were made, the flux calculations and meteorological data. It has been found that the research area was a source of sediment during low river discharges and strong SSW winds. The area acted as a sink of sediment during high river discharges and low SSW winds and during average river discharges and strong NE winds.

The mean median settling velocity of the suspended sediment was 0.04 mm/sec. The trapping values that were calculated using two different formulas varied between 51% and 71%. In contrast to the positive trapping efficiency of the Kleine Noordwaard, the calculated accretion rate of the area shows a smaller value (0.014 mm/yr) than the rate of sea level rise (1.6 mm/yr). This means that even though the trapping efficiency is generally positive, the wetland's accretion rate is insufficient to keep up with present sea level rise, let alone any possible future enhanced sea level rise.

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1. Introduction

In this first chapter, a general description of Tidal Freshwater Wetlands (TFWs) will be given. The importance of these areas and the existing literature that is available on this subject will be briefly discussed. Furthermore, this section will provide the aim and outline of this thesis, as well as the structure of the remaining chapters.

1.1 Drowning delta's

The Netherlands is a delta country, embracing the well-studied Rhine-Meuse delta and its many tributaries. These rivers provide opportunities but also some difficulties. In the past, much (wetland) area has been reclaimed. At the same time, upstream sediment delivery and river flooding frequency were reduced, causing delta sediment starvation. Furthermore, local subsidence takes place due to compaction of the underlying delta sediments. All these factors may become problematic and may result in drowning and loss of delta land. A reduction of sediment supply to the delta in combination with future enhanced sea level rise emphasizes the importance of this problem for the next century. A solution for this possible threat is the reintroduction of sediment to the delta which may prevent drowning of the delta and loss of delta land with the upcoming rising sea level and future increase in peak river discharges.

One of the important delta ecosystems prone to potential future drowning are tidal freshwater wetlands (TFWs). In the next section an introduction to TFW's will be given along with the importance of these ecosystems.

1.2 Tidal freshwater wetlands (TFWs) and their importance

Tidal wetlands occur in the upstream reaches of many temperate estuaries. The definition of a wetland defined by the RAMSAR convention is as follows:

" Wetlands are areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh or brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres. "

In tidal freshwater wetlands, the river discharge is sufficient to prevent saline water intrusion, but the tidal influence still exist in these regions. Therefore within estuaries, TFWs are limited to the part of the estuary where there is tidal action but little or no salinity (Baldwin et al., 2009). *Figure 1* shows the different zones of an estuary as well as the tidal movements in it. The presence of TFWs are controlled by several factors other factors as well, such as (Barendregt et al., 2006):

- Shape of the river mouth. The river mouth should encompass estuarine conditions creating a tidal flow of saline water into the river, propagating upstream (creating the tidal component in the wetlands).
- Presence of substantial amount of lowland area. TFWs are associated with rivers in coastal plains regions with relatively flat topography and enough lowland area to create a relatively large tidal area in the river system.
- Constant freshwater discharge from the river. This is needed for sustaining the tidal freshwater area throughout the entire year.
- Tidal impact dominates the river mouth in such a way that the fresh water flow will be influenced by saline or brackish water before reaching the sea.
- Conditions that promote sedimentation (further discussed in 1.3.2)

As the name suggests, TFWs have a tidal signal but it is rather small (often less than 0.3 m). In most cases flooding of a TFW is rather periodic due to the effect of upstream runoff and wind effects instead of a clear diurnal signal of tidal flooding. This is significantly different from (salt water) tidal marshes where tides often fluctuate several meters, twice a day (*Baldwin et al., 2009*). In TFWs, typically there is a short period of intense incoming tide and a longer period of ebbing tide (*Barendregt et al., 2006*).

The elevation of the substrate of a TFW relative to mean high tide affects the frequency and duration of flooding at any location in the wetland. Strong currents and turbidity are often present in the tidal creeks, thereby preventing vascular plants from being established. Dynamic sand banks and mud flats are surfacing just above low tide level in the tidal creeks. Vascular plants like reed become more common closer to the high-tide level. Some aquatic plants are present in the more isolated shallow pools (*Barendregt et al., 2006*).
The presence of vegetation is often thought to affect sediment dynamics (*Harter and Mitsch, 2003*), where vegetation creates a spatial variability in sediment deposition (*Fennessy et al., 1994*). The presence of vegetation is believed to enhance sedimentation, though not all studies agree on this hypothesis (*Darke and Megonigal, 2003*, *Fennessy et al., 1994*). *Darke and Megonigal* (2003) suggest that vegetation determines deposition rates, but only when river suspended sediments (which feed the wetland) are not limited, which is not always the case. Therefore, a direct link between sediment deposition and the presence of vegetation is not yet fully understood.

TFW's are special because of high plant productivity and a net effect of high development of organic soils. Often high rates of sedimentation occur in TFW compared with the more saline tidal wetlands. The intensive sedimentation rates creates clayey soils, which are rich in nutrients and organic matter. Due to high primary productivity (nutrient rich) and the habitat provided by the different plant species, diverse communities of terrestrial and aquatic animals exist (*Barendregt et al., 2006*). The consequence of high sediment deposition rates and lack of salinity stress results in high productivity, typically high rates of decomposition, and higher rates of nutrient uptake during the growing season in freshwater tidal wetlands relative to non-wetland ecosystems (*Baldwin et al., 2009*). Even though TFW are located in culturally important areas, they have not been studied as frequently or intensively as brackish and saline wetlands that occur near the coast (*Barendregt et al., 2006*).

In many countries, such as the Netherlands, wetland areas were reclaimed for multiple uses such as housing, industry and, most of all, agricultural purposes. Previous land reclamation resulted in only a limited area being available for ecosystem restoration. Some ecological conditions can be restored by wetland restoration, especially ecological conditions in the river due to the influence of the tidal flow. The Biesbosch region used to have large areas of tidal freshwater wetlands. Not only ecological reasons are an important reason for wetland restoration but also a solution for the problem of excessive river discharges, sea level rise and heavier and more frequent storms due to climatic change. More wetland area will acts as water bypasses and water retention areas, which is a safer solution than further heightening of the dikes, which will ultimately result in more risk. When dikes are raised, height difference between the water levels during storm and the adjacent polders will become larger. Then, during cases of a dike breach, the damage effects will be more severe (*Barendregt et al., 2006*). All the facts mentioned above press the importance to sustain TFW's under future climate change, temperature change, sea level rise etc. (*Baldwin et al., 2009*). In order to prevent disastrous water problems in the future and to restore nature in the rivers and their wetlands, the Netherlands has started the 'Room for the River' project (RfR). This project will be described in the next chapter.

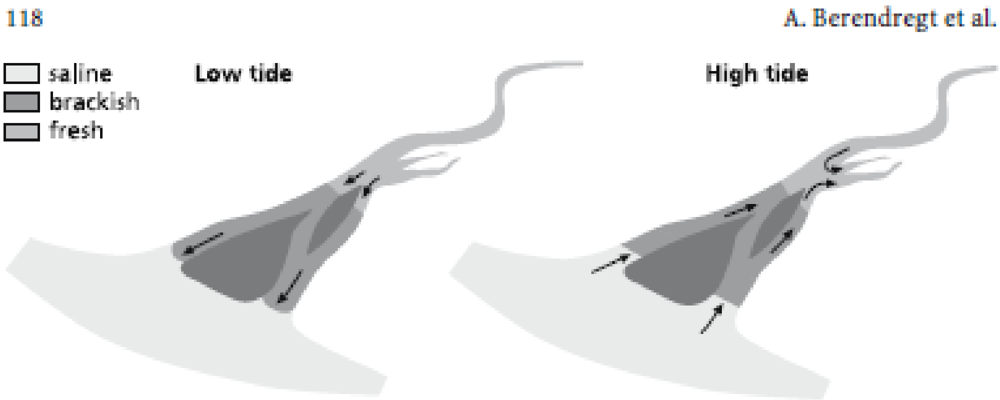


Figure 1: Three zones in an estuary (saline, brackish and fresh) with flow direction at low and high tide. Source: Barendregt et al. 2006

1.3 Sediment budget and sedimentation processes in TFW's

1.3.1 Sediment budget

Sediment budgets are often calculated for entire river deltas, but also for single wetland areas. Sediment budgets provides information; they form the base of frameworks which give more insight in sediment mobilization, deposition, transport, storage and the sediment output in a wetland area. Moreover, sediment budgets can be used for wetland management strategies. For these strategies, the sediment budget gives information about the nature and the location of the main sediment source but also about the wetland sediment sinks and areas of sediment storage. These areas can then be controlled and maintained or further investigated, for example sediment-associated contaminants and nutrients. When knowing the sediment budget and processes inside a wetland area, the potential impact of upstream control measures controlling the sediment input can be evaluated, thereby assessing the impact it will have on the downstream wetlands (*Walling et al., 2002*).

River systems transport sediment from the source (erosional areas) to the sink (depositional areas), such as lowland floodplains and estuaries. A potential depositional areas in the downstream riverine area is the presence of wetlands, which may lead to sedimentation but also to the redistribution of sediment transported by the river. The depositional areas present between the source and the sink will reduce the total sediment load of the river, thereby influencing the sediment budget of the river system which feeds the wetland areas on its way (*Wright and Schoellhamer, 2004*). Not all sediment which enters the river at its source will reach the river mouth and often gets trapped in estuaries and deltas, coastal wetland sediment trapping is one of the major sediment depositional areas. Delta, coastal wetland and marshlands are an ultimate sink for river sediments thereby reducing the total sediment load from the river and having a major role in the overall sediment budget of the river system (*Phillips and Slattery, 2006*). Due to overbank deposition of fine sediments (explained later on) and the processes mentioned above, the (suspended) sediment load transported by the river flowing through a wetland area will be reduced (*Walling and Owens, 2003*).

Tidal freshwater wetland ecosystems are therefore effective sediment traps and generally retain more suspended sediment than they export, thereby causing a reduction of total sediment in the feeding river (*Fennessy et al., 1994*). However, this overbank deposition is frequently low (*Walling and Owens, 2003*). Wetland areas mostly do not act as a permanent sink but they often act as a temporary sink or even as critical buffers, which also have possible effect on storage of polluted sediments (*Pasternack, 1998*). To sum up, wetlands act as a major sink along the river's course to the sea. Therefore, freshwater tidal wetlands tend to decrease to overall sediment budget of the river which flows through wetland area.

1.3.2 Wetland sedimentation processes

Overbank sedimentation is a factor concerning tidal freshwater wetland sediment budgets, which has already been investigated extensively . Overbank sedimentation on river floodplains can result in a significant reduction of the suspended sediment load transported by a river. This means that in the wetland area, overbank sedimentation is an important factor and will act as a sink, or loss in the sediment budget (*Walling and Owens, 2003*).

Furthermore, overbank sedimentation may play an important role regarding sediment which can be associated with contaminant storage and the corresponding sediment fluxes in the catchment. Overbank sedimentation is especially important during flood events because it is a major factor for floodplain construction and development (*Walling and Owens, 2003*). The overbank flows are often consisting of high concentrations of fine-grained suspended sediment. The fine-grained sediment are transported from the channel to the floodplain by convective and diffusive mechanisms and on smaller scale this is also the case in the wetland areas. Sediment dispersion is suppressed in the areas of shallow, slow moving flows and the more elevated parts of a wetland (*Nicholas and Walling, 1998*).

Spatial patterns of overbank deposition in tidal freshwater wetlands are strongly dependent upon small scale topographic features, such as drainage ditches (still present in the Kleine Noordwaard after de-poldering), bank breaches and depressions. These features determine local floodplain inundation sequences and velocity vectors (*Nicholas and Walling, 1998*). This causes spatial and temporal variability in sediment deposition patterns. Sediment flux measurements provide insight in tidal to fortnightly marsh sedimentation processes, especially in these complex systems where sedimentation is spatially and temporally variable (*Nicholas and Walling, 1998, Harter and Mitsch, 2003, Neuabauer et al., 2002, Ganju et al, 2005, Fennessy et al., 1994, Walling et al., 2002, Pasternack and Brush, 1998*). Other factors that have been suggested in controlling sediment deposition rates embrace flood depth and duration, elevation, river suspended sediment load, proximity to source, surficial floodwater velocity, presence of vegetation and surficial floodwater suspended sediment load (*Darke and Megonigal, 2003*) but also flooding frequency (*Neubauer et al., 2002*). In the wetland itself, the greatest sedimentation often occurs near the inlet of the wetland (where the river comes in). The sedimentation rates decrease with distance from the sediment source. However, this may not be the case in every wetland as suggested in the study of *Harter and Mitsch, (2003*). Therefore, sediment deposition rates are generally controlled by combinations of hydrological, geomorphological and biotic factors as well as the importance of summer floods. The summer floods are important because of the high flood-induced sediment loads and the general abundance of sediment-trapping vegetation (*Darke and Megonigal, 2003*).

Fennessy et al (1994), found that the open water areas have the highest sedimentation. Furthermore, the deeper open water areas generally are more favorable to sediment deposition and accumulation than the shallower open water areas. These shallower open water areas are more prone to the influences of wind driven and biological disturbances and resuspension of the sediments.

1.3.3 Wetland sustainability

The import-export of suspended sediment does not only play a large role in the total sediment budget of a wetland but also contributes to the formation and, most of all, the maintenance of tidal wetlands. A decrease in sediment supply can hamper the amount of accretion, which is necessary for wetland survival. Considering the future enhanced sea level rise, the fluxes of material going in and out of tidal freshwater wetlands may greatly control their sustainability (*Ganju et al., 2005*). If vertical sediment accretion gets outpaced by sea level rise, wetland loss will be the result. At places where lateral wetland migration is not possible, salt water will intrude further upstream, thereby causing a shift in plant community. In the end, the once freshwater tidal wetlands will change into saltwater tidal wetlands (*Darke and Megonigal, 2003*). This means that the stability of tidal freshwater wetlands depends on the net balance between in and output of material to the system. This balance, if positive, allows the system to grow vertically as sea level increases. Research indicates that in most of the tidal freshwater wetlands the vertical deposition in the systems was sufficient to balance the effect of subsidence and sea level rise (e.g. *Neubauer et al., 2002, Neubauer, 2008, Neubauer et al, 2009*). Another influence on the sediment budget within a wetland is the presence of biotic factors, such as bentic fish species. These are known for causing sediment resuspension, thereby also maintaining increased levels of water turbidity in the wetland (fish such as carps). But also other animals can cause sediment resuspension or bioturbation in the sediments (such as muskrats) (*Harter and Mitsch, 2003*). This means that wetland fauna also significantly influences the patterns of sediment deposition. As a result, both geomorphological features and biotic factors are important for sedimentation processes in a wetland and therefore on wetland sustainability as well.

1.4 Aim and outline

1.4.1 Problem definition

The information in the above sections reflect the importance of TFW's and the problem of drowning deltas. A future problem is the survival chance of these wetlands in case of enhanced sea level rise. In other words, the question is whether the sedimentation in the TFW's will be sufficiently large enough in order to keep up with sea level rise and prevent wetland drowning. It was clear that there were only few limited studies on the behaviour of TFW's, making it a very interesting subject to study. Since each wetland has its own specific sedimentation processes, determining the sediment budget is a common method to study wetland survival in the future. The results of such a study can be used for more insight in the behavior of a (site specific) TFW, the associated sediment fluxes and sedimentation pattern in the area and the potential survival changes under enhanced sea level rise.

The main aim of this thesis is to investigate the present day, short term sediment budget in the Kleine Noordwaard area. With more insight in the (short and long term) sediment budget of this newly created TWF, the sedimentation processes, including the spatial and temporal deposition patterns, will give information about sustainability of the wetland. Given the information gained from this study, future management plans could be adapted in order to sustain substantial wetland elevation. This way, it is possible to compensate at an early stage for enhanced sea level rise, higher peak river discharges and increased tidal range in the area. It is also possible to use the results of this study in other parts of the Netherlands and to even use and extend it to other tidal freshwater wetlands all over the world.

The following subquestions will be investigated in order to answer the main research question:

- *What are the in- and outgoing fluxes in the wetland?*
- *How much sedimentation does occur within the enlarged deposition areas during the field period?*
- *What is the distribution of (suspended) sediment concentration throughout the wetland area?*
- *What is the spatial distribution of sediment concentrations in the wetland and which locations are most important for sedimentation?*

- *What are the settling characteristics of the suspended sediment in the wetland?*

1.4.2 Outline

In order to answer the research question of this thesis, fieldwork was conducted. More information about the research area will be given in Chapter 2. The variables measured in the field comprise of suspended sediment concentrations (SSC) throughout the area, in situ settling characteristics of the sediment in the water column, discharge measurements and visual observations. The methods of the above described parameters will be described in Chapter 3. The discharge and SSC variables were necessary to calculate flux values and sediment budgets, from which the results will be described in Chapter 4. Statistical values of the used calculations and the implications on the results themselves (flux calculation) will be described and discussed (Chapter 5). Last of all, Chapter 6 will summarize the most important results.

By using this approach to determine the short term sediment budget in this TFW of the Biesbosch, hopefully some insight can be gained about sediment and sedimentation pathways in this newly restored TFW's and the possible dynamics under different conditions.

2.0 Study area

2.1 Site description

The study area is located in the Brabantsche Biesbosch, The Netherlands. This part of the Netherlands is generally known as the downstream riverine area of the Rhine-Meuse delta. The Biesbosch is one of the few tidally influenced freshwater areas in Europe and known for its many small rivers, water basins, willow forests and erratic creeks.

In this thesis, a small part of the Biesbosch will be investigated. The study area is called the 'Kleine Noordwaard' located near the city of Werkendam, between the river Boven Merwede and the river Amer (*Figure 2*). The Kleine Noordwaard is a former polder, but due to measures of the Room for the River (RfR) project, it is currently being depoldered again, thereby restoring the area to its former wetland state. Water and sediment have been reintroduced since 2009. The area mainly receives sediment from the Nieuwe Merwede River, a downstream distributary of the Rhine River. The northern boundary of the study area is taken at bridge Banddijk (BrBan) and the southern boundary is located near the sealed off part of the area (a ball line to prevent boats to enter the area) near Polder Maltha (OpMal). A history of the Biesbosch and explanation about the RfR project are given in the next paragraph.

Figure 2: Location of the study area. Source map: Esri

2.2 History of the Biesbosch

The Biesbosch emerged after a storm surge in 1421 A.D. which caused dike-bursts in poorly maintained dikes. During the 1421 storm surge (also known as the St Elisabeth's flood), 300 km^2 of embanked land was inundated and a large inland sea was created. After the St Elisabeth's flood, the area was given up. In the centuries after the storm surge, the area silted up from the northeast (sediment from the river Merwede) as an inland delta. The rate of silting slowed down when the delta front reached the old channel belt of the Meuse (around 1700). By then, the delta front had prograded more than 10 kilometres, filling most of the north-eastern part of the Biesbosch to mean sea level. The higher parts of the silted delta land were embanked for agricultural use. Dikes were built around 1880, closing of the connections to the river Nieuwe Merwede. At the southern part of the Biesbosch area, connections remained to the Amer-Meuse and Hollands Diep estuary. In 1970, the Haringvliet-sluices were put into operation (as part of the Deltaworks program, protecting the southwest of the Netherlands against inundations). The closing of the Haringvliet resulted in a significant reduction of tidal influence in the Biesbosch area (from 1.9 m fluctuation to 0.3 m). This reduction of tidal influence in the tidal freshwater wetland of the Biesbosch resulted in a reduction of sediment supply. The result was erosion of natural banks as smaller creeks silted up, drying of marshland area and an accelerated soil subsidence all over the area (*De Boois, 1982, Kleinhans et al., 2010*). After some years the area was more or less in equilibrium again. In 2008 it was decided to depolder the Kleine Noordwaard area as a measure to prevent flooding of cities in case of high river discharges. This is conducted as a part of the Room for the River project. A description of this project and the depoldering of the Noordwaard area will be given below.

2.3 Room for the River project

2.3.1 Project description

The Room for the River project was initiated to implement spatial security measures which will accommodate water and thereby increase the spatial quality of the landscape, nature and culture (Schut et al., 2010). The project has three general objectives:

- The branches of the river Rhine should be able to cope with discharges of 16.000 m^3 per second without flooding (by 2015)
- Improving the overall environmental quality of the river region
- The area available for the rivers has decreased throughout the past centuries. Therefore, the extra room for the river created during the project should remain permanently available for the river to cope with higher discharges in the future.

There are nine different types of measures which will provide the rivers with more room (*Figure 4*)

- Lowering of floodplains. The lowering (excavation) of (a part of) the floodplain increases the room for the river during high waters
- Deepening the summer bed. The deepened river will provide more room for the river
- Water storage. This measure will be made in the Volkerak-Zoommeer lake. In a case of a closed storm surge barrier in combination with high river discharges to the sea, the lake will provide a temporary water storage area.
- Dike relocation. Relocating the dikes, thereby increasing the width of the floodplain, provides more room for the river

- Lowering the groynes. During high waters, the groynes can form obstructions for the river flow. Therefore, lowering the groynes will increase the flow rate of the river at high water levels.
- High water channel. During high discharges, a part of the main river discharge can be diverted via a separate route. The high water channel will be a embanked area.
- **Depoldering**. The dike on the river side of a polder will be relocated more landwards. The polder will be depoldered and during high water levels of the river, the depoldered area can be flooded.
- Removing obstacles. By removing obstacles (as is the case with groynes, but can also account for bridges), the flow rate of the water in the river will be increased.
- Strengthening dikes. At places where the creation of more room for the river will not be possible, the dikes will be reinforced.

(Brochure room for the river, 2012)

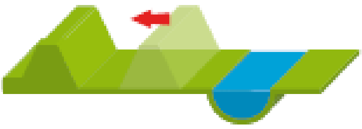
2.3.2 Depoldering of the Noordwaard (RfR)

As already explained in the previous subparagraph, one of the measures in the room for the river project is depoldering. This measure was also implemented in the Kleine Noordwaard.

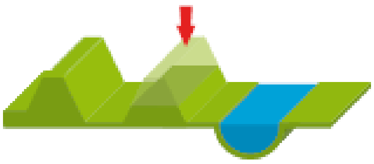
Depoldering plans were made for the Noordwaard, the Biesbosch. A part of the Noordwaard has already been depolderd, the Kleine Noordwaard, and will be the focus in this research (*Figure 3*). The goals of depoldering the Noordwaard were to create a freshwater area with open water, reed- and rush fields, swamp forests and open areas. At the same time, the area should be able to contribute to the water storage and discharge capacity of the major rivers. In other words: the newly created wetland should be able to function as a water retention area and being able to contribute to the lowering of river water level during potential high discharges in the future in a safe way. The lowering of the river water levels should be enough in order to prevent the lower lying cities and villages from drowning during such conditions (every 100 or 1000 years). During 'normal' conditions the area will also contribute to the spatial quality of the rivers embracing the Noordwaard *(Brochure room for the river, 2012)*. The area now comprises of several channels, an island, flats and banks covered with reeds and trees. Some old features are still present as well, such as old ditches and brick foundations of houses.

Figure 3: Research area before and after depoldering. Source maps: IPO luchtfoto's

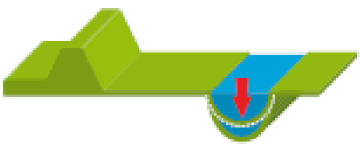
Lowering floodplains
Lowering/excavating part of the floodplain increases room for the river in high water situations.



Dyke relocation
Relocating a dyke inland widens the floodplain and increases room for the river.

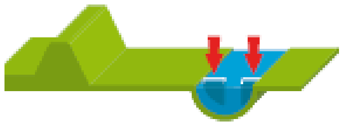


Depoldering
The dyke on the riverside of a polder is lowered and relocated inland. This creates space for excess flows in extreme high water situations.

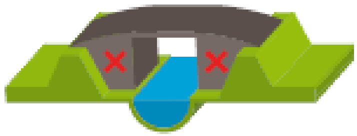


Deepening summer bed
Excavating/deepening the surface of the riverbed creates more room for the river.

Dyke reinforcement
Dykes are reinforced at given locations where river widening is not feasible.



Lowering groynes
Groynes stabilise the location of the river and ensure its correct depth. However, in a high water situation, groynes may obstruct the flow to the river. Lowering groynes speeds up the rate of flow.



Removing obstacles
If feasible, removing or modifying obstacles in the riverbed will increase the rate of flow.

Water storage
The Volkerak-Zoommeer provides temporary water storage in extreme situations where the storm surge barrier is closed and there are high river discharges to the sea.

High water channel
A high water channel is a dyke area branching off from the main river to discharge some of the water via a separate route.

Figure 4: The different measures in the RfR project. In the research area depoldering has been implemented. Source: brochure room for the river, 2012

2.4 *Field observations in the research area*

Small scale topographic features such as old foundations of farms and drainage ditches from the former polder topography were noted in the field. When the area was drained with water, the ditches were not filled up but left the way they were before the depoldering. The drainage ditches were not directly noted in the topography and seem to have the same height as the flats in the area. However when stepping accidently in one of the old drainage ditches you will immediately sink to the bottom of the old ditch. The ditches are therefore filled up with the soft silty material from the flats which was most probably transported in the old drainage ditches during conditions when wind and waves transport the silty sediment or at least brings it into suspension.

A clear sedimentation pattern was visible in the northern part of the research area. It seems that all the sediment which gets eroded in the channels of the Spiering polder (north of bridge Banddijk) is deposited almost immediately when entering the area near the bridge. Sedimentation was noted at the northern part of the island. During earlier field campaigns, a wooden pole was placed on the most northern part of the island. During the field campaign of this thesis, it was noted that the wooden pole was not on the very top of the island anymore but sedimentation had taken place. This means that the island was building out towards the north.

Almost all the margins of the island showed erosional edges. However, only at the south-eastern edge of the island, degradation of the erosional ridges was actually visible (*Figure 5*). These small erosional edges were most probably caused by wind and wave effects. At some places on the island, vegetation clearly protected the edges from further erosion. The edges of the island at the sides of the vegetation were further degraded than at the edges themselves. The total erosion of the island was calculated as $31m^3$ of sediment, whereas the calculated deposition of sediment in the channels was calculated as $59532m^3$ of sediment between 2009 and 2014. This means that the contribution of sediment in the area caused by erosion is rather low (only 0.05% of the channel sedimentation) and not of considerable effect in the supply of sediment in the wetland area.

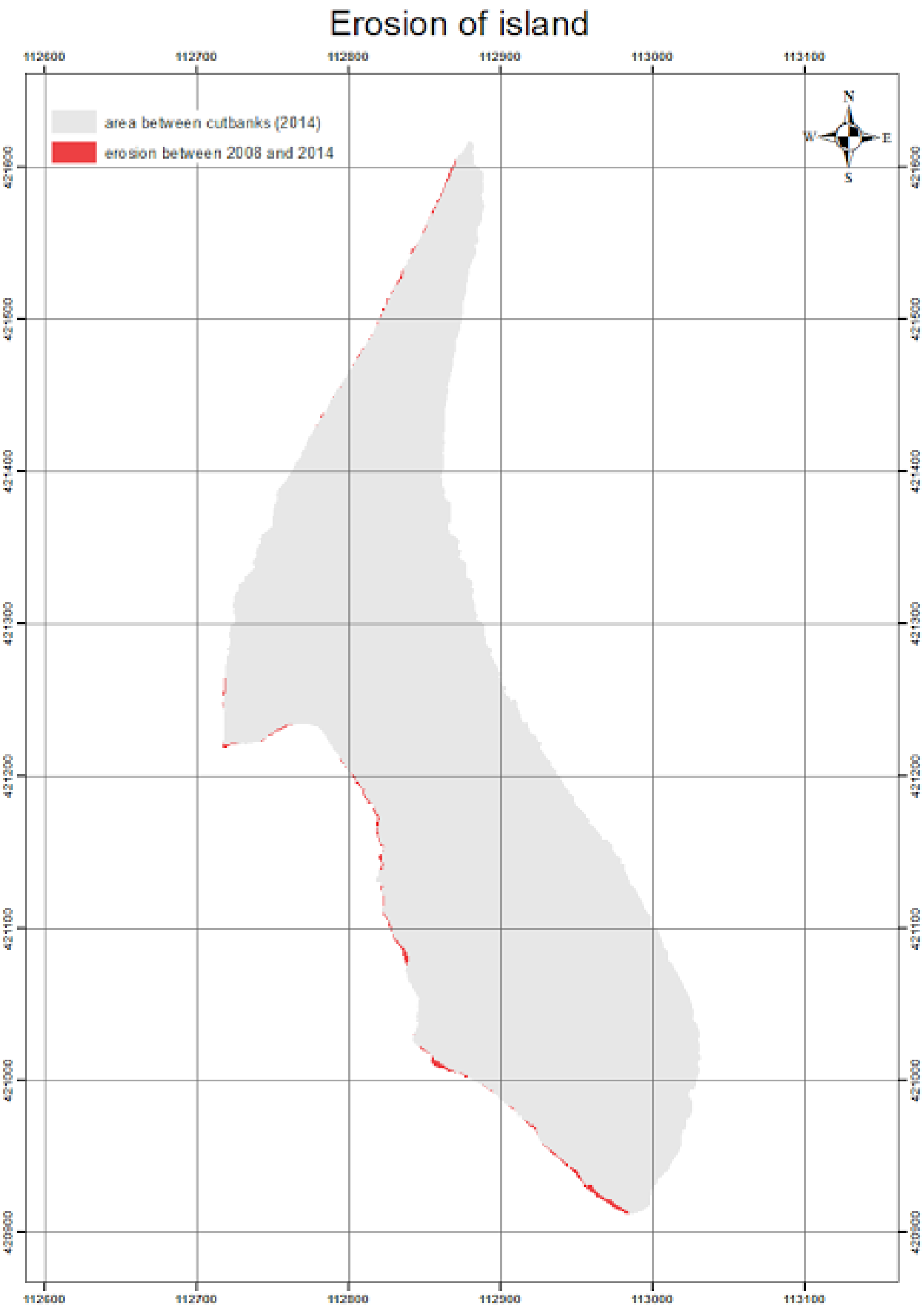


Figure 5: Erosion of the island since 2008. Source: E.C van der Deijl

3.0 Method

3.1 Measured variables

3.1.1 Pole construction

In the research area, four measuring poles were installed at different locations from which two were used in this thesis. These two locations are situated near the in- and outlet of the research area. The inlet is situated in the north, bordered by the nieuwe merwede. The pole is located just southward of Bridge Banddijk (BrBan), where the water enters the area. The pole near the outlet is located in the South, near the inlet of polder Maltha (OpMal) (*Figure 6*).

Mounted on the poles are the following instruments:

- A H-ADCP (horizontal acoustic Doppler current profiler) device which measure flow velocities over a certain part of the cross section of the channel).
- A STM (Seapoint Turbidity Meter) to collect values of suspended sediment concentration
- A diver to measure water level

Figure 6: Locations of the four different measuring poles. A: BrBan, B: OpMal. Source:Esri

3.1.2 Flow velocity

Flow velocities were measured at the locations of the poles using the H-ADCP devices. Data from the fixed poles at the in- and outlet of the area were used (BrBan and OpMal) for further calculations. The H-ADCP devices measure in a certain direction and at a fixed height at an interval of 10 minutes (for a schematic view see *Figure 7*). The H-ADCP has in total nine cells of a predefined width (defined in the device's manual). For each cell, the velocity was therefore measured at a fixed location and height above the bottom.

The H-ADCP uses sound (the Doppler effect) to measure the water current. The device transmits pings of a constant frequency into the water. When these sound waves travel through the water, they ricochet off suspended particles in the (moving) water thereby getting reflected back towards the instrument. Particles which are moving away from the instrument will result in a slightly lowered return frequency whereas particles which are moving towards the instrument will sent back a slightly higher frequency. The difference between the frequency which the instrument has sent out and the frequency which is being send back to the instrument is called the Doppler shift. Using this Doppler shift, the speed of the particle (and the water around it) can be calculated. Because sound waves take longer to come back with increasing distance from the instrument, it is possible for the profiler to measure current speeds at many different distances from the instrument with each series of pings (using the time passed) (http://www.whoi.edu/instruments/viewInstrument.do?id=819).

A V-ADCP (vertical acoustic Doppler current profiler) was used during the field campaign as well. This device uses the same principle as described above, however, instead of horizontally positioned cells, the V-ADCP measures in a the vertical direction. This V-ADCP was mounted on a boat and discharges were measured by the device during several transect measurements.

The flow velocities collected from the ADCP's were used for further discharge calculations, which will be described below.

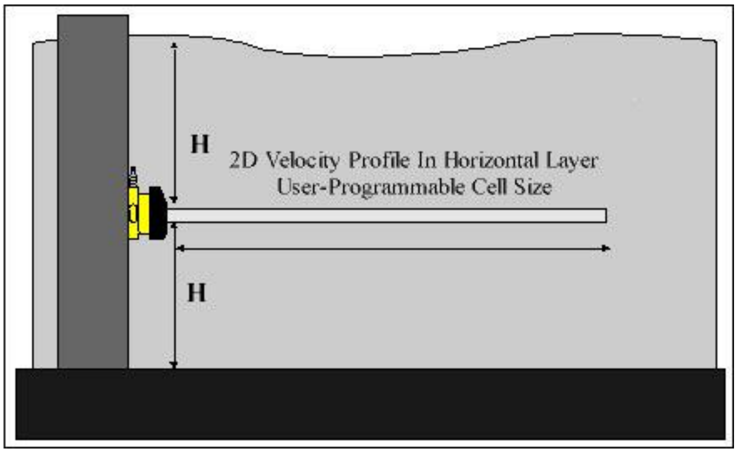


*Figure 7: Schematic view of the H-ADCP. Source: **www.whoi.edu***

3.1.3 Suspended Sediment Concentrations (SSC)

SSC values were measured using a STM device. Suspended particles in the water scatter light and this scattered light is detected by the STM device. The device then generates an output voltage which is proportional to the suspended sediment concentration (after calibration of the STM device) present in the water column at the specific time of the measurement. Each STM device in the field needed to be calibrated separately (STM user manual 2013).

The STM which was mounted at the boat for SSC measurements throughout the research area was calibrated in the lab with water samples from the field. This was done using the following property of the device.

The sensing volume of the STM is confined to a small space near the sensor which will reduce the interference from reflections from large objects outside the sensing volume (STM user manual 2013). Therefore, calibration could easily be done with a simple construction in the lab with the water samples from the field. This construction consisted of the STM mounted on a small stand. The STM device was allowed to move vertically. Beneath the stand, beakers with the samples from the field were placed. In the beakers a magnetic stick was planted and the beaker was put on top of a device caused the magnet to spin around. This way, the suspended sediment in the water column was prevented to settle out. Finally, the STM device was lowered in the beaker and output values were registered by a computer.

The STM values measured on the fixed poles in the field at both measurement locations were calibrated using water samples collected by a ISCO automatic water sampler. An automatic water sampler was placed on a small raft during selected periods of time. On average 24 samples were taken with a sample interval of 6 hours. The sample interval was chosen in such a way that samples were taken during different stages of the tide, thereby increasing the change for scatter in SSC values which will improve the calibration of the STM. The water samples from the sampler were then filtered and weighed in the lab. Using the weight of the samples combined with the corresponding voltage values from the STM device at the time the water samples were taken, a calibration curve could be fitted through the data points. This was done for both STM devices at the in- and outlet of the research area (BrBan and OpMal).

3.1.4 Meteorological data

Discharge data from Tiel were obtained for the field period from Rijkswaterstaat (part of the Dutch ministry of infrastructure and environment). Tiel is the closest measuring station upstream the river Merwede; north-east of the research area. Wind direction and magnitude were used from the measuring station at Herwijnen, these meteorological data were gained from the KNMI (Dutch royal weather institute). Tidal conditions were collected from from www.live.waterbase.nl

Meteorological data were collected for the time span of the field period. The average discharge at Tiel during the field period was 1570 m3/sec. Average discharges have also been calculated for the different STM rounds and they are shown in the table below (Table 1). Wind direction and magnitude are also given as well as tidal information.

Table 1: Meteorological data from the field days with STM data

	Measurement period	Average wind speed	Wind direction	River discharge (Tiel)	Tidal conditions
15-Jul	09:33-14:03	2.4 m/s	SW	1761.4 m3/sec	HW
16-Jul	16:05-16:55	0.9 m/s	SW	1803 m3/sec	towards LW
24-Jul	14:30-16:37	3.4 m/s	NE	1574.6 m3/s	LW-HW
7-Oct	9:46-11:33	5.1 m/s	SSW	1081.9 m3/s	HW
	15:08-16:30	5.1 m/s	SSW	1072.7 m3/s	LW
8-Oct	09:07-11:30	4.7 m/s	S	1065.6 m3/s	HW
22-Oct	09:51-14:20	4.9 m/s	NNE	1495.8 m3/s	HW-LW
	14:26-16:39	4.9 m/s	NNE	1490.1 m3/s	LW

3.2 Data processing

3.2.1 Discharge calculations from the ADCP data

In order to obtain a discharge from the velocities measured by the H-ADCP, the VPM (velocity profile method) was used. This method uses the general knowledge of the vertical velocity profile, which illustrates the variation of flow velocity over the vertical distance from the bed of a channel (*Figure 8*).

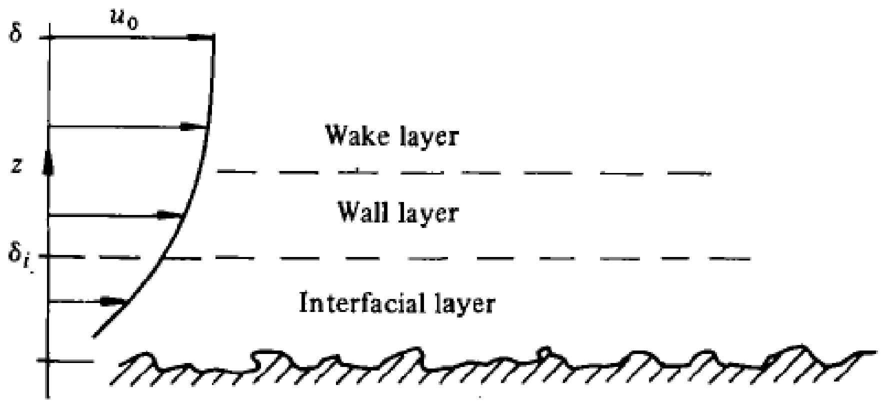


Figure 8: Vertical velocity profile. Source: Jackson 1981

Recognizing the validation of the vertical velocity profile, this principle was used for the discharge calculation. Assuming that the flow velocity near the bottom(Z_0) is zero and using the velocity measured by the H-ADCP (at a known height Z), vertical velocity profiles could be generated for each cell (*Eq. 1*). Relative distances above the bottom were used as well as for the heights (Z_0 and Z). Depths were measured from a digital height map from the area (2012); it should be noted that it is likely that the bathymetry of the area has changed from 2012 up to now.

$$u = u^*/k*ln(z/Z_0) \qquad Eq.(1)$$

Using the logarithmic profile and integrating the formula over the water depth, an average flow velocity was calculated for each measuring cell of the H-ADCP. Multiplying the average velocity per cell with the cell width, the discharge per cell was calculated. Combining the discharges of all the cells, the total discharge for the reach of the H-ADCP was calculated. This was done for both the two H-ADCP poles used in this thesis. The discharges were generated automatically in a Matlab script and some manual calculations were done with Excel. The used formula are given below (*Eq.3 – Eq.7*).

$f = a*\ln(x)+b$	*Eq.(2):*	Logarithmic formula of the vertical velocity profile
$\int \ln(x) = x*\ln(x)-x + C$	*Eq.(3):*	Integration of vertical velocity profile over depth
$\int f(x)dx = a*(x*\ln(x)-x)+ (b*x)$	*Eq.(4):*	Integration of vertical velocity profile
$q = \int f(x)dx*\text{cell width}$	*Eq.(5):*	Discharge per cell
$Q = \sum q(\text{all})$	*Eq.(6):*	Total discharge measured by H-ADCP

The H-ADCP only measures a specific part of the channel (The device has nine measurement cells, with a blanking distance of two meters (distance between instrument and the first cell) and a cell size of two meters. This means that the H-ADCP only measures flow velocities in a cross-shore reach of 18 meters wide of the channel, whereas the channel cross section is much larger than that. Therefore, the discharge for the whole channel had to be interpolated. In order to make this interpolation, transects were measured using the V-ADCP device mounted on a frame on a boat.

These transects were made in the same direction in which the H-ADCP on the poles were measuring. During the collection of the transects, the boat speed was kept to a minimum in order to gain the best results as possible for the conditions (water velocities and wind conditions). On average, six transects were sailed to make an average discharge for the transect location. This was performed several times during different days and conditions for the locations BrBan and OpMal. Since data collection at the fixed locations are constantly recording, a relation between the H-ADCP discharges and the V-ADCP discharges could then be computed.

Since the time span was known over which the V-ADCP data was collected, the average H-ADCP value for those exact times could be used as well. Plotting the V-ADCP and the H-ADCP data against each other, a calibration between the two could be gained. This was done for both fixed poles in the field (BrBan and OpMal). A fixed intercept of zero was used. The estimated regression equations for both locations could then be used for the discharge calculations at the locations of BrBan and OpMal.

Over time, the water balance between the in- and outlet of the area should be balanced; meaning that as much water enters the area as it will leave again. When the initial water balance was calculated it was noticed that the value deviated from the theoretical value of zero. This was most probably caused by the error in the calibration of the H-ADCP data according to the V-ADCP data, which differ for both locations. In order to close the water balance, a correction factor had to be applied. A multiplicative factor was chosen and the value was determined by manually trial and error of the value.

3.2.2 Calculation of sediment fluxes

In the previous steps the discharge and the SSC values were calculated. These steps were necessary for the flux calculation and were calculated simply from these two details by multiplying the discharge with the SSC values (Eq. 7). This formula assumes that the SSC values are more or less constant over depth and width of the channels near the locations of the fixed poles.

$$\text{Flux(kg/sec)} = \text{Q(m}^3\text{/sec)*SSC(g/L)} \qquad \textit{Eq.(7)}$$

As described in the discharge method, an error is present in the discharge calculation. Since the values of the calculated discharge were further used in the flux calculations, an uncertainty analysis was performed in order to have more insight in the standard error of the flux calculation. The statistical analysis used for calculating the error in multiplying with numbers that already have an error is described in Eq. 8 (wisfaq.nl).

$$\mathrm{s}^2(\mathrm{flux}) = ((\mathrm{s}^2(\mathrm{Q}) + \overline{\mathrm{Q}}^2) * (\mathrm{s}^2(\mathrm{SSC}) + \overline{\mathrm{SSC}}^2) - (\overline{\mathrm{Q}}^2 * \overline{\mathrm{SSC}}^2) \qquad \textit{Eq.(8)}$$

The variances of the discharge and the SSC values were obtained from the linear regression lines from the discharge calculation (relation of the H-ADCP and the V-ADCP) and from the calibration curves of the STM on the poles.

The ‘average’ values of discharge and SSC are all single data points, so a variance was calculated for each data point (every ten minutes). The standard error of the flux calculation was then computed by squaring the variance obtained from the flux. An average standard error for the flux value was calculated for the times of STM data collection from the boat .

3.2.3 Settling velocity

The in situ fall velocity was based on the method developed by Cornelisse et al.(1996) and included the usage of 30 cm diameter PVC settling tubes. Five PVC columns were used in the field campaign (*Figure 9*). A tap point was fixed at a level of 25 cm from the top (each column identically structured). In the field, the PVC settling columns were filled with water as soon as possible after each other; thereby placing them at the same location and depth. The columns were transported horizontally to a suitable location for the experiment to run. Before starting the experiment, the tubes were rolled over carefully, to make sure the sediment is totally in suspension and uniformly distributed across the column. The tubes were placed in an upright position within an hour of sampling and the experiment was started. Water samples of 250 mL were taken at logarithmic time increments. The begin and end time of the tapping were noted. On average the tapping of the water samples took about 30 seconds.

After the experiments, the water samples were filtered using 0.45 µm pore size membrane filters, dried in the oven during the night at 70° Celcius and weighed. Using the dry weight of the samples, a fall velocity distribution was made. This was done for 2 locations (near the in- and outlet of the area), at different moments of the tide.

Figure 9: PVC fall tube and experiment setting in the field

3.2.4 Trapping efficiency

Using the settling velocity, an educated guess of the total sediment trapping in the area could be made using two different approaches (eq. 9):

$$\text{Fluxout/fluxin} = \exp^{-(\omega * A/Q).} \qquad \textit{Eq. (9)}$$

The left hand side of the equation uses the measured fluxes and will result in the 'measured' trapping efficiency during the field period. The right hand side of the equation uses the median fall velocity measured in the research area, with ω being the fall velocity, A is the area (on average $2.3e^6$ m^2). The average discharge (Q) is taken (71.75 m^3/sec). Using these two equations, the theoretical maximum trapping efficiency could be calculated and could be compared to the measured trapping efficiency measured during the field period.

4. Results

4.1 Flow velocities from H-ADCP

The water velocities measured using the H-ADCP over time are shown in *Figure 10* and *Figure 11*. The relation between the average water velocity measured by the H-ADCP and the water level was significant at $\alpha = 0.05$ with p-values of 0.6 and 0.7 for BrBan and OpMal respectively.

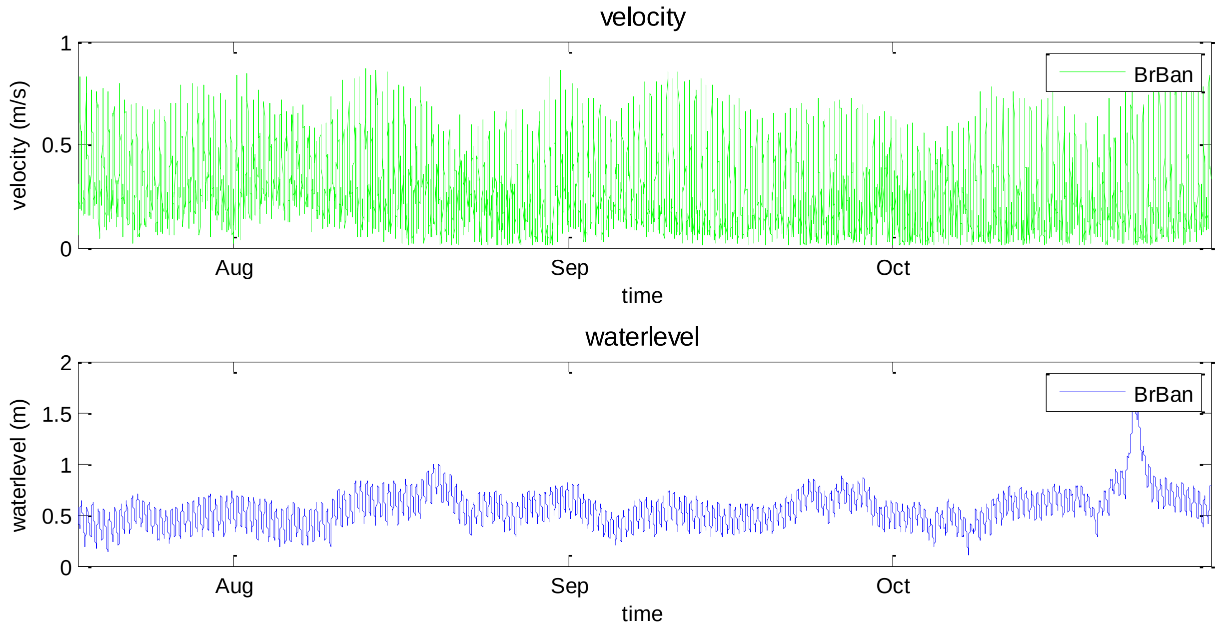


Figure 10: Velocity and water level at BrBan

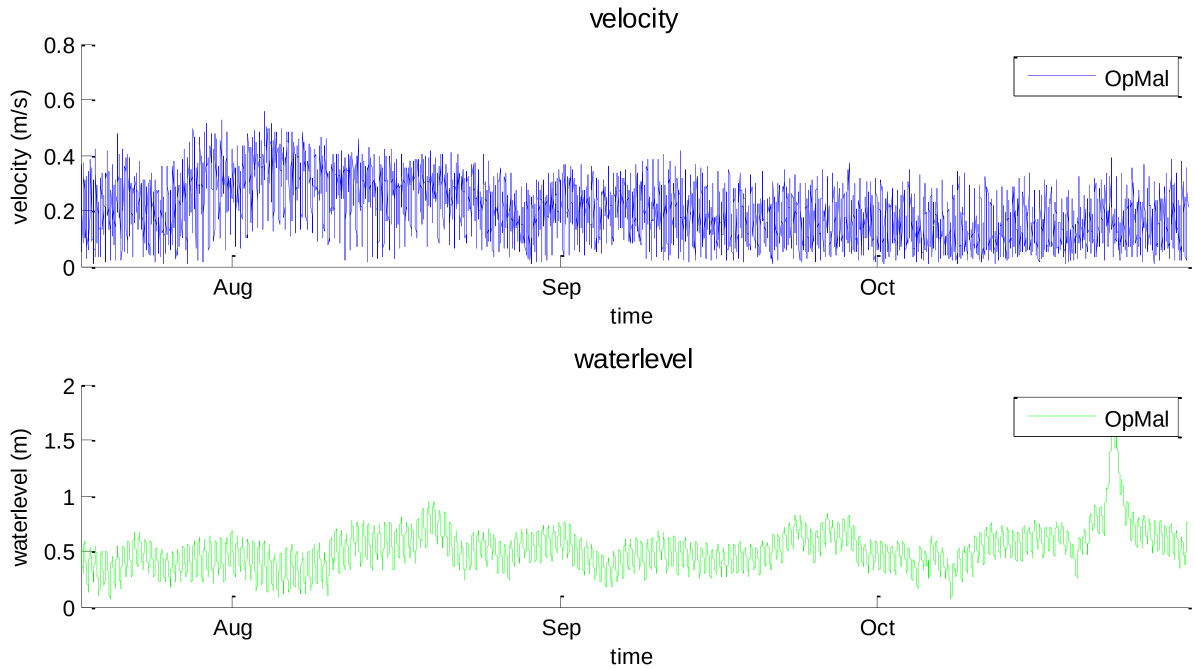


Figure 11: Velocity and water level at OpMal

4.2 Discharge

The results of the regression analysis of the measured H-ADCP discharges against the V-ADCP discharges are shown in Appendix I. By using a fixed intercept of zero, the quadrate of the correlation coefficient (R^2) was rather low. An approximation for the standard error of the regression of location BrBan was 11.4 m^3/sec and for OpMal is 8.57 m^3/sec. This error should be mentioned since further calculations were performed using this discharge calculation but will be further discussed in section 4.4. The correction factor applied to discharge values in order to close the water balance resulted in a multiplicative factor of 1.2. The number for alpha was specified such that the difference of the in- and outgoing discharges resulted in a closed water balance.

The result for the in- and outgoing discharges are visualised in *Figure 12*. In general the discharges calculated from BrBan are higher than the discharges at OpMal.

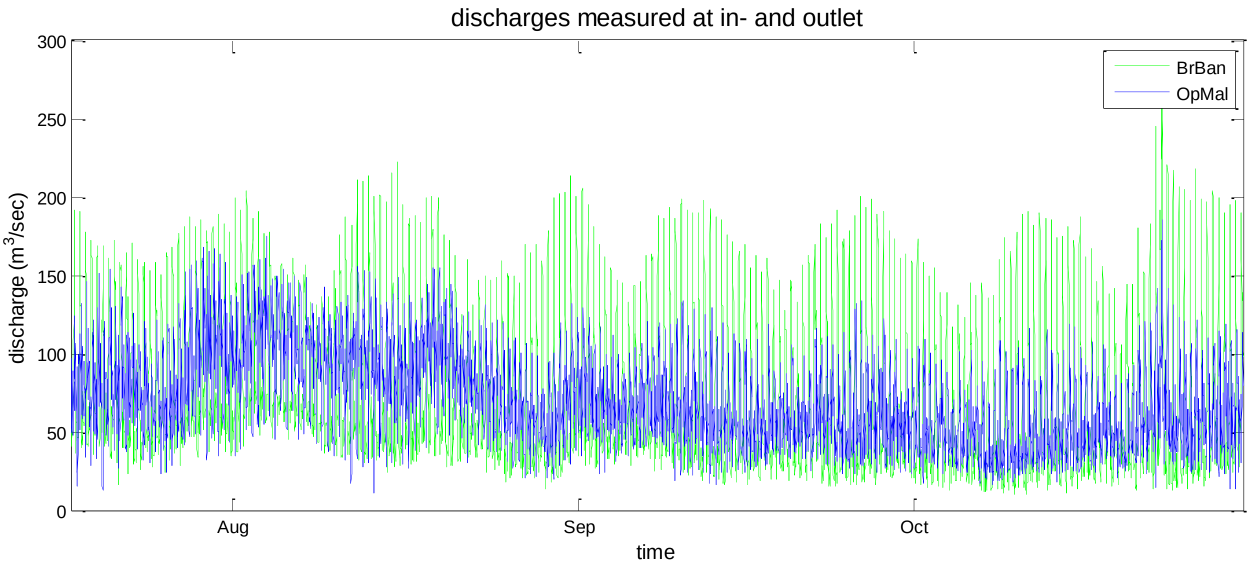


Figure 12: Discharge from BrBan and OpMal

4.3 Suspended Sediment Concentrations (SSC)

4.3.1 SSC patterns from the fixed poles

The results of the calibration of the SSC values out of the STM data are given in Appendix I. The error in the SSC calibration was found to be 0.033 g and 0.0375 g for BrBan and Opmal respectively and the correlation value (R^2) was 0.9 and 0.78 for both locations respectively.

The SSC patterns calculated for the entire field period are shown in *Figure 13.* It is immediately apparent that SSC values near the inlet were nearly always larger compared to the SSC values near the outlet of the area.

When zooming in on a random location in the graph (*Figure 14*), a relation between water level and SSC values seem visible. The SSC values show a pattern which more or less follows the trend of the water level where high SSC values seem to coincide during periods of high water levels. However, the correlation between water level and SSC values is not significant (p values of $3.5e^{-10}$ and $1.3e^{-22}$ for BrBan and OpMal respectively).

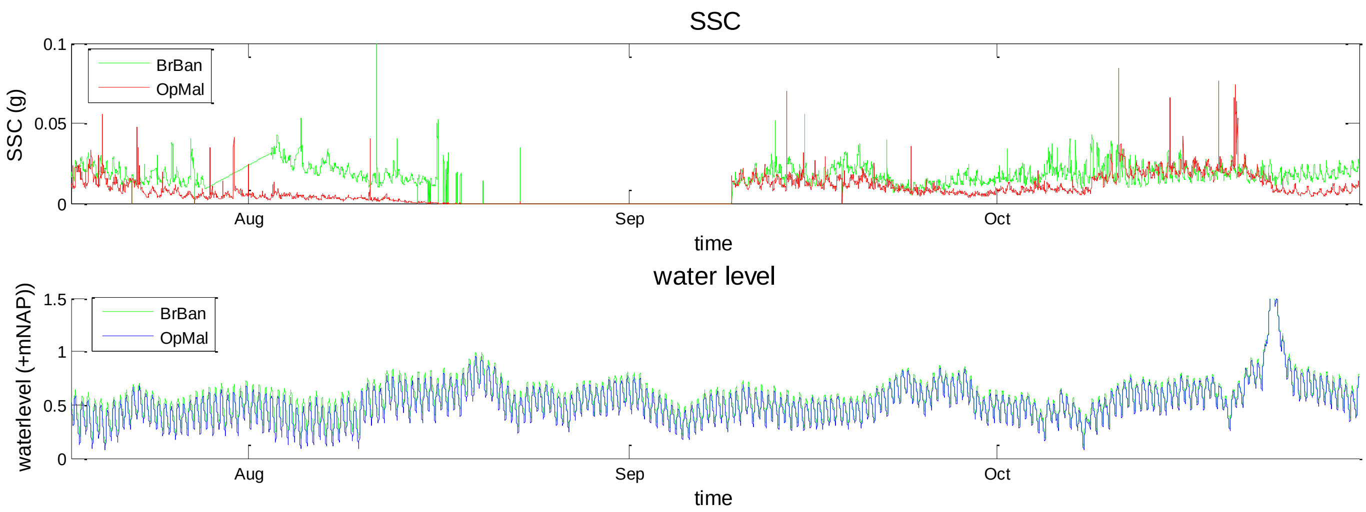


Figure 13: SSC values and waterlevel

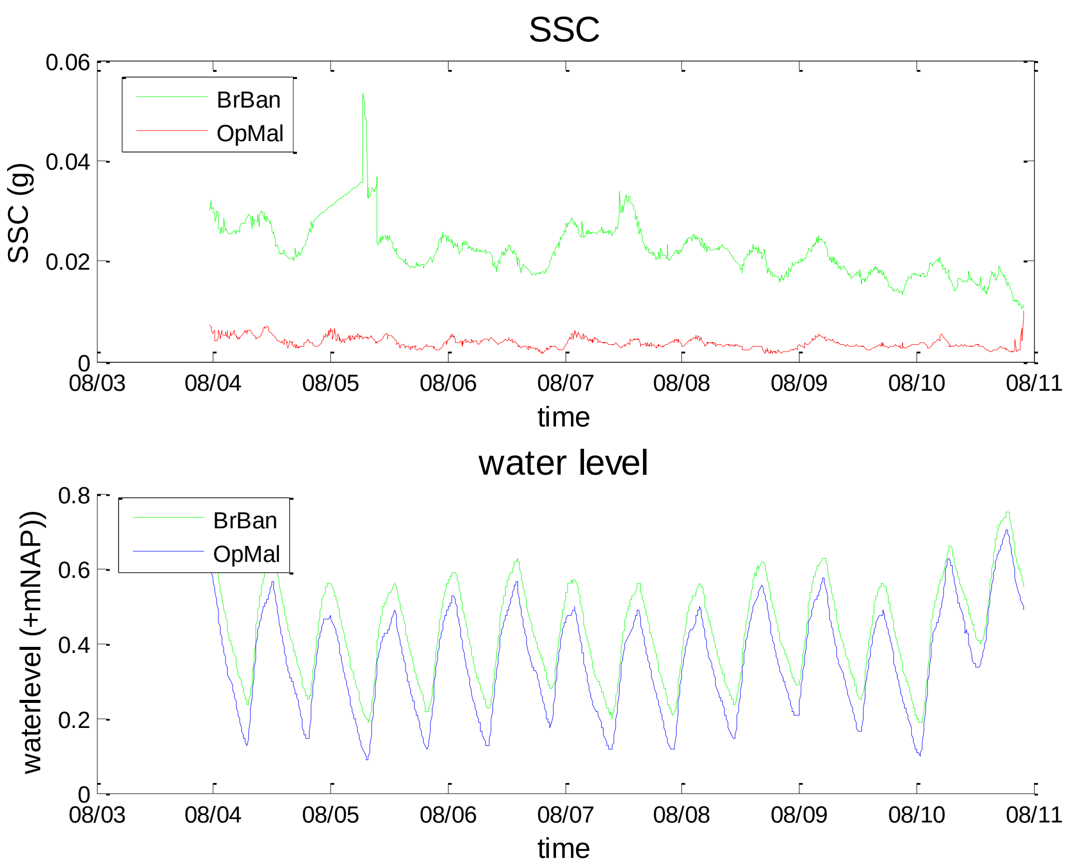


Figure 14: Zoomed in part of SSC values and water level

4.3.2 Spatial variation in SSC values

Visual interpretations of spatial variation in SSC values collected with the STM mounted on the boat from the different field days are described below. The maps described can be found in Appendix II.

15 July 2014

From the map it was noted that SSC values were higher near the outlet of the area than at the inlet. Also, the eastern branch of the island shows higher SSC values compared to the western branch. An overall increase in sediment concentration was noted from the north of the wetland towards the southern part. In *Figure 15Figure* the north-south distribution is visualized in a plot. It can be seen that the round of 15 July shows some higher peaks in SSC values towards the North but the general trend of higher SSC values in the south compared towards the North is slightly visible. The east-west distribution is shown in *Figure 16.* Not a clear distribution pattern is recognized as it was in the STM maps.

16 July 2014

The STM trajectory sailed by the boat did not cover the entire area between the in- and outlet. Still, the values in the north were somewhat lower than in the south of the map. As in the map of 15 July, SSC values were higher in the eastern branch of the island compared to the western branch, though less pronounced.

24 July 2014

The pattern of higher SSC values on the eastern side of the island recognized in the maps of 15 and 16 July were not recognized in the map of 24 July. At first, the western branch of the island shows (from north to south) an increase in SSC values, then a peak, followed by a decrease in SSC values around the middle of the island. Looking at the outlet of the area, the SSC values have decreased compared to the inlet and northern the part of the area. However, this was not clearly visible in *Figure 15*.

7 October 2014

First round

From the map, it was noted that near the outlet of the wetland, the SSC values were somewhat higher than near the inlet of the wetland. Going from the inlet to the eastern branch, there was an increase in SSC values at the eastern side of the central island.

The SSC values remain higher from the eastern side of the island towards the south until the area is reached which houses more (stable) vegetation (trees and reeds cover the banks). Despite this, SSC values were still higher at the outlet of the wetland compared to the inlet. Throughout the entire western branch the SSC values were somewhat consistent until the confluence point. From the confluence point towards the outlet, the SSC concentrations stay more or less continuous up to the outlet of the area.

Second round

The SSC values during the second round were slightly different from those during the first round. SSC values near the inlet were higher than during the first round. From the map it was not directly clear whether values were higher near the in- or outlet or if they were more or less in balance. It was still noted that the eastern branch of the island has higher SSC values compared to the western branch, however, values were decreasing again near the confluence point following the channel towards the outlet. Highest values were found in the middle of the research area.

8 October 2014

The map of 8 October follows more or less the same trend as the maps of 7 October. It was not directly clear whether values at the in- and outlet were higher or more or less the same. Slightly higher values were noted again in the eastern branch of the island. Other peaks in SSC values were not noted in this map and the values stay more or less consistent from the North going to the South except for the higher SSC values on the North of the island.

22 October 2014

It was directly noted that the SSC pattern with high values at the eastern side of the island was not as pronounced as during other days (for example 15 July and 7 October). It was not directly clear whether higher values were present at the in- or outlet of the area. Some higher values were noted during the swinging pattern, these places of higher values were not as pronounced as during the other rounds of the day. For both maps somewhat higher SSC values were present at the eastern part of the island until the confluence point, where values were more stable again towards the outlet. Highest SSC values were again noted in the most eastern branches of the area, until the confluence point near bridge Maltha.

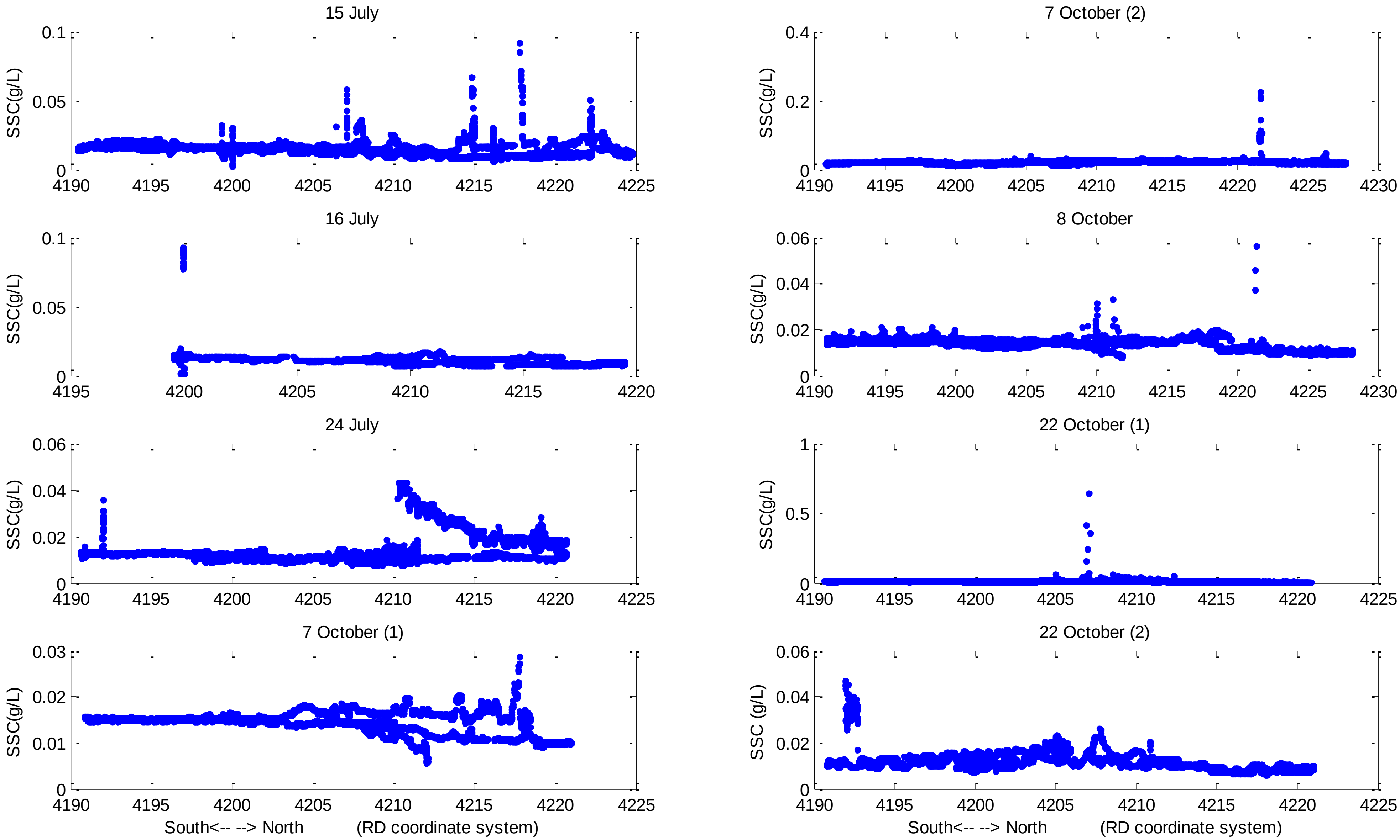


Figure 15: North-South distribution of SSC values

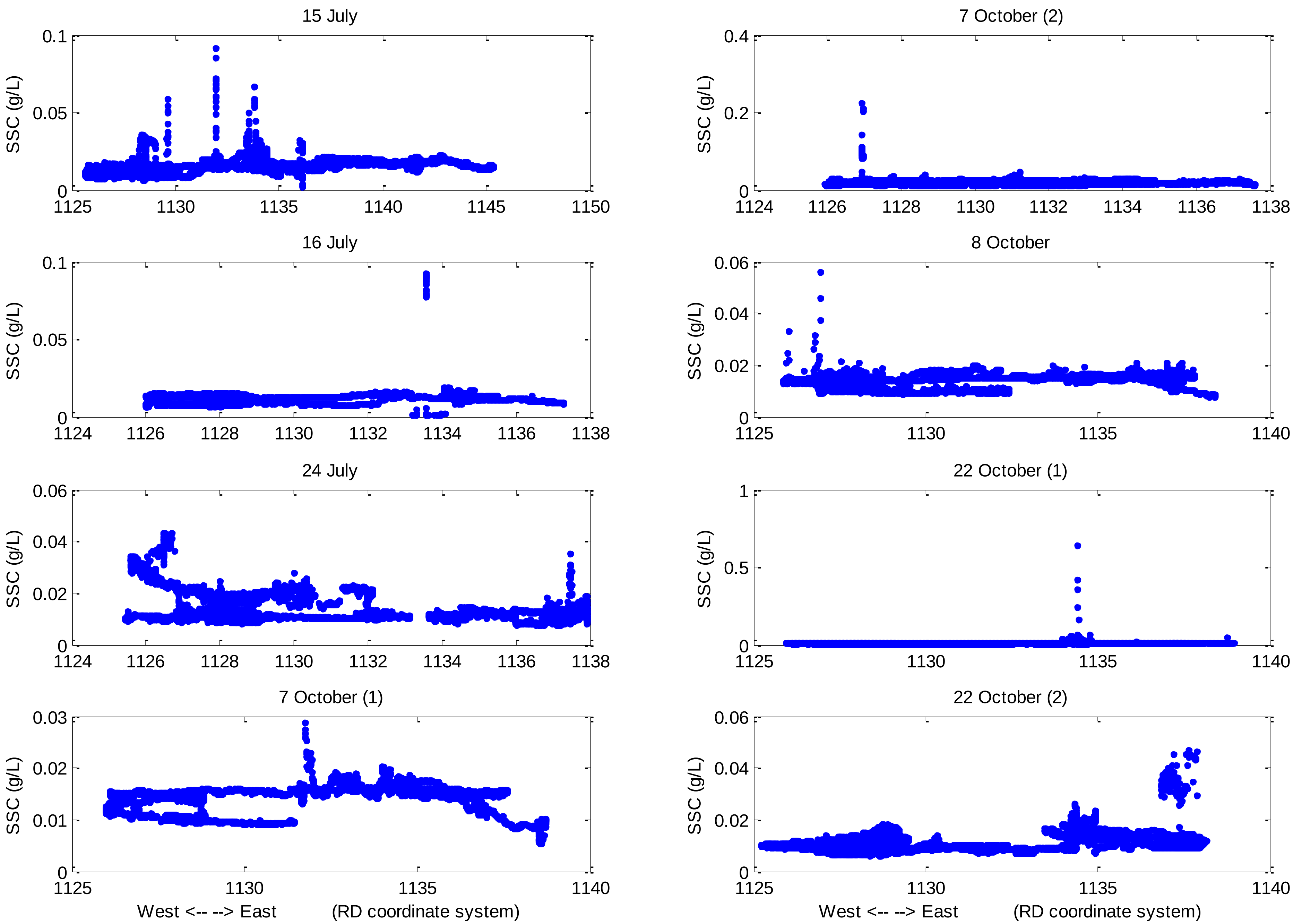


Figure 16: East-West distribution of SSC values

4.4 Sediment flux

Figure 17 visualizes the in- and outgoing fluxes for the entire field period. The average incoming flux over the entire field period was 1.4 g/sec and the outgoing flux was on average 0.5 kg/sec. Both visually and the numbers show that the in going fluxes were consistently higher than the outgoing fluxes.

The average flux values combined with the standard errors for the different STM rounds are given in Table 2. From this table it was noted that the standard error for the incoming fluxes were consistently higher than for the outgoing fluxes. The errors are between 21% and 76% of the mean values. The highest error values range between 75 and 200 % of the calculated flux and the lowest between the 1 and 20 % of the calculated flux values. However, even considering the different standard errors in the flux calculation, the ingoing fluxes generally remain higher than the outgoing fluxes.

Figure 18 shows the water level and the flux values. When zooming in on a random part of the plot (*Figure 19*), visually there seems to be a relationship between water level and flux values. A hysteresis was noted in the values for BrBan. The peak in flux values is earlier than the peak in water level. This means that just before high water, the highest SSC values were present at the inlet of the area. This is in contrast with the data from OpMal, where the peaks in fluxes coincide with the peaks in water level. Why this hysteresis exist at the inlet of the area and not at the outlet of the area was not clear. Even though a trend seems visible between water level and flux values, the correlation was not significant; p-values of $5.0e^{-7}$ and $1.4e^{-70}$ for BrBan and OpMal respectively.

Table 2: Average fluxes

	Measurement period	Sediment flux IN		Sediment flux OUT	
15 July	09:33-14:03	0.027 kg/s		0.057g/sec	
16 July	16:05-16:55	0.76 kg/s	± 0.21	0.69 kg/sec	± 0.18
24 July	14:30-16:37	1.29 kg/s	± 0.25	0.28 kg/sec	± 0.11
07 October	9:46-11:33	0.36 kg/s	± 0.19	0.23 kg/s	± 0.18
	15:08-16:30	4.45 kg/s	± 0.44	0.1 kg/s	± 0.24
08 October	09:07-11:30	0.40 kg/s	± 0.21	0.77 kg/s	± 0.16
22 October	09:51-14:20	0.51 kg/s	± 0.19	0.53 kg/s	± 0.17
	14:26-16:39	1.29 kg/s	± 0.30	0.55 kg/s	± 0.21

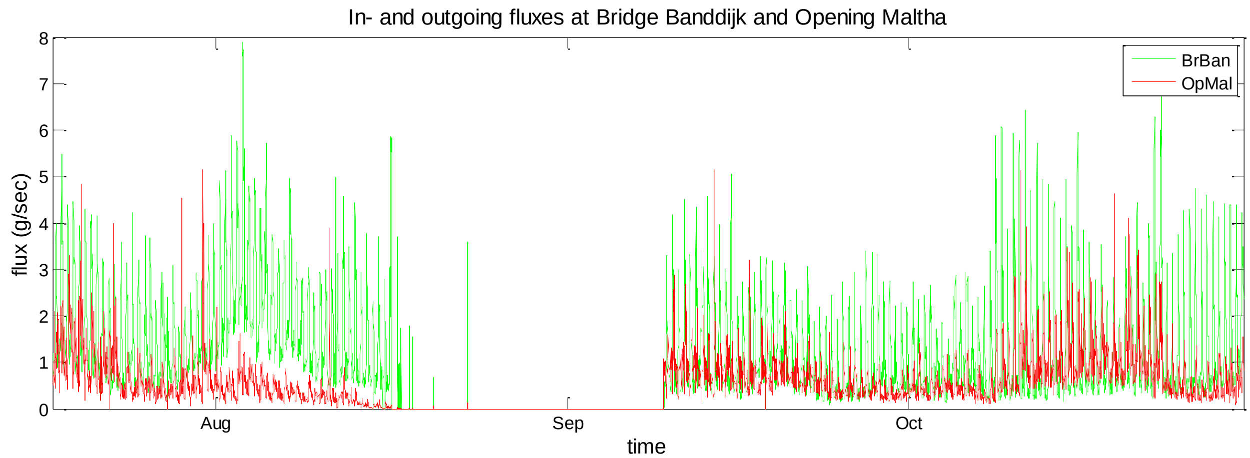


Figure 17: Flux values from the in- and outlet

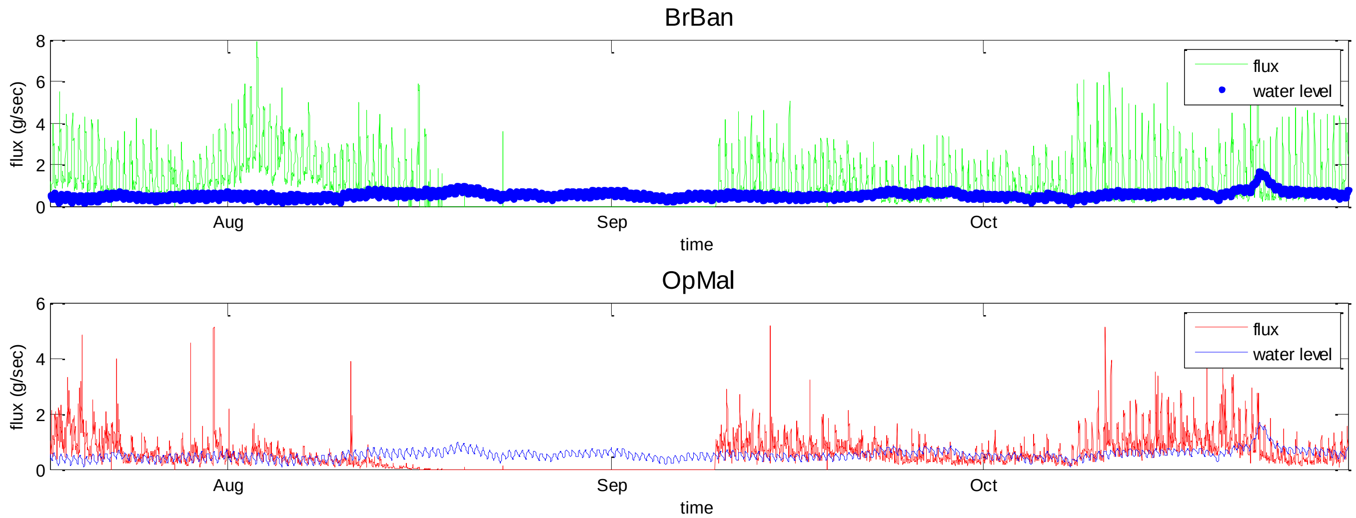


Figure 18: Flux values and water level

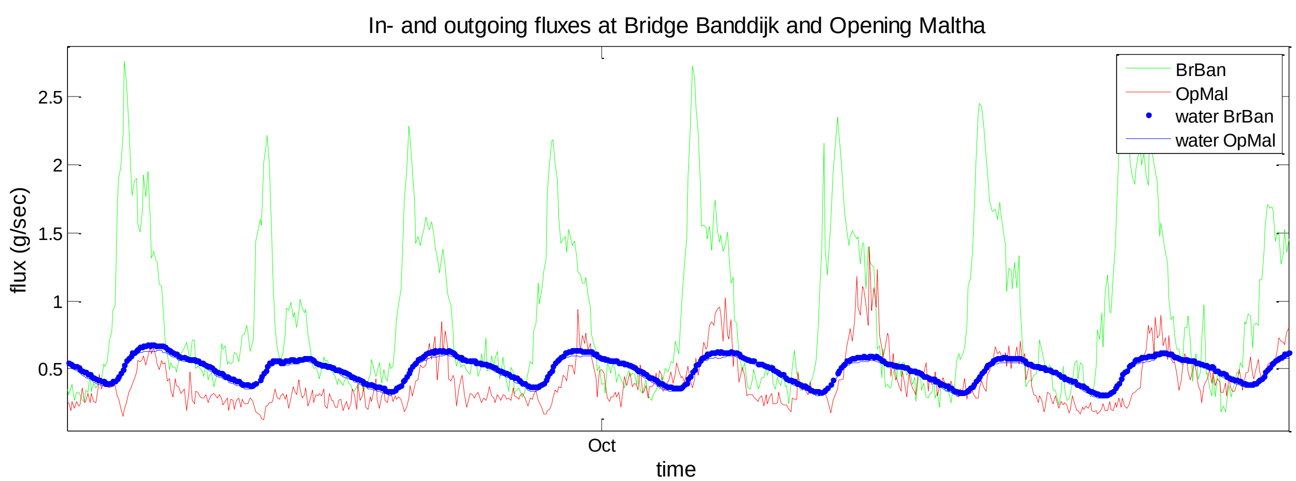


Figure 19: Flux values and water level, zoomed in

4.5 Settling velocity

Fall velocity distributions and mean median fall velocities for all experiments are given in Appendix III. In general, the sediment concentration decreases exponentially during the measurements. This is also visualised in *Figure 20* with the only exception of the experiment of 10 September. The median settling velocity was rather consistent between the different measurement locations and also over the different tidal periods. The mean median settling velocity was about 0.04 mm s-1, calculated from the seven different experiments.

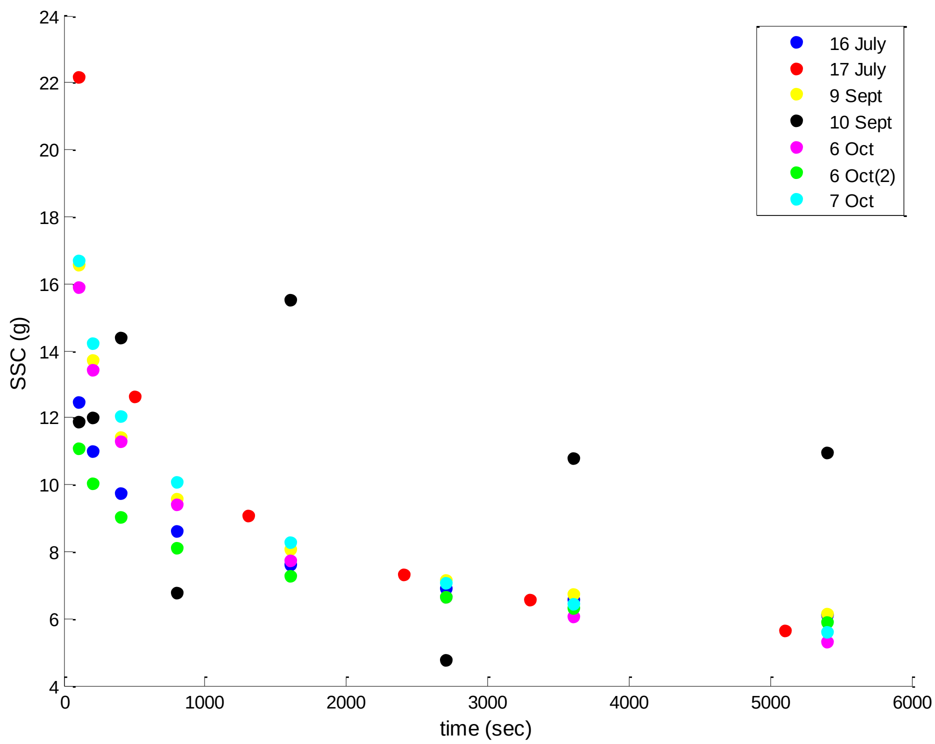


Figure 20: Suspended sediment concentration through time for the seven different experiments

4.6 Trapping efficiency

There is a difference between the measured trapping efficiency and the trapping efficiency calculated with the median fall velocity. The value calculated with the measured fluxes showed that 51% of all sediment which entered the area should have been trapped inside the wetland. The second method based on fall velocities give an even higher value: 71%, this would be the theoretical maximum trapping efficiency of the research area. This means that 71% of the total amount of sediment which the area theoretically could trap was actually being deposited inside the wetland. These values will be further discussed in Chapter 5 with respect to the used variables in both methods.

5. Discussion

5.1 Settling Velocities

The median sediment settling velocity in the Kleine Noordwaard was calculated to be 0.04 mm/s. *Ganju et al. (2005)* estimated fall velocities between 0.01 and 0.10 mm/s in the Sacramento river. Settling velocities measured in the Rhine ranged between 0.01 and 2 mm/s with increasing particle size from 3.5 to 395 µm (*Thonon et al., 2005*). These values are in line with the fall velocity found in this research.

Settling velocities reported by *Cornelisse et al. (1996),* on which the perspex fall tubes were based in this thesis, had performed their experiment in the Elbe river. The median fall velocity of their experiment was 0.26 mm/s with average silt particles smaller than 53 µm. Fall velocities between 1.5-15 mm/s were measured in the floodplains of the River Culm in Devon, the UK (*Walling et al., 1989*). In the muddy suspension of the York River estuary fall velocities measured by an ADV were averaged 0.46 mm/s, with particle sizes larger than 30 µm (*Catwright et al., 2013*). Smaller fall velocities were found near the water surface (0.05 mm/s). So called Owen tube results from the same research gave fall velocities between 0.01-0.06 mm/s. Other methods using LISST (laser in situ scattering and transmissometry) and ADV (acoustic Doppler velocimeter) methods showed values between 0.15-1 mm/s. Fall velocities reported from a salt water tidal marsh in South Carolina ranged between 0.07-0.1 mm/s (*Voulgaris and Meyers, 2004*), using ADV and LISST as well. These last measurements are more in line with the fall velocities found in this research.

As can be noted from the above described fall velocities, a range in values exists with, in general, larger grain sizes and associated settling velocities near the main river channel and deeper in the water column. The water samples of the fall velocity experiments performed in this thesis were collected near the water surface (+- 30 cm below water surface). This might explain the difference with the higher fall velocity values in other studies, apart from the possible larger grain sizes or potential flocculation compared to those found in the Kleine Noordwaard. However, in general, the fall velocities measured in this research are in line with values found in other studies.

5.2 Sediment budget

5.2.1 Accretion rate

The accretion rate in the Kleine Noordwaard was estimated at 0.014 mm/yr based on a net import of 49057 kg/yr (calculated from flux values), a bulk density of 1150 kg/m^3 (*Gillens et al., 2006*) and an estimated depositional area of 3144240 m^2.

There is no general agreement on the accretion rates of wetlands among different studies. Two wetlands in the Mattaponi river, USA, (Walkerton and Gleason) were investigated and accretion rates were found to be 12 and 27 mm/yr respectively. These values integrated the sediment deposition as well as autochthonous aboveground organic matter production and erosion (*Darke and Megonigal, 2003*). In contrast to the relatively high accretion values described above, accretion rates of 0.2 mm/yr were found at the Brown Islands, USA (*Ganju et al., 2005*).

All the discussed studies mention the spatial and temporal variability in the accretion rates and this is clearly visible in the various accretion rates mentioned above. The difference in accretion rates is also described in the research of *Orson et al., 1990*. Rates of sediment accumulations were determined for the Delaware River tidal freshwater marsh. In the years before 1940, sediment accretion rates were estimated to be 0.4 mm/yr. Shortly after introduction of the tide in the area, accretion rates increased slightly up to 1.2 mm/yr. Between 1940 and 1988 the accretion rates ranged between 10.4 and 13.8

mm/yr. During years with increased storm activity the accretion rate was 16.7 mm/yr. After 1966, storm activity decreased which reflected in an accretion rate of 9.7 mm/yr (*Orson et al., 1990*).

Sediment accretion rates have been calculated for a freshwater tidal wetland in the USA as well. This wetland, the Sweet Hal marsh, has a microtidal range of 70-90 cm (slightly higher than in the Kleine Noordwaard). Accretion rates were calculated to be 10.6 – 64.7 mm/yr, reflecting spatial and temporal differences within the wetland. The highest rates were found near the tidal creeks on the elevated parts immediately adjacent to the creek and decreased into the marsh interior. This spatial difference in accretion rates reflects the fact that within the same marsh, processes controlling sediment deposition and erosion can vary between different topographical features such as more protected creek banks and for example exposed high energy riverbank sites (*Neubauer et al., 2002*).

Spatial differences in the Kleine Noordwaard were noticed during the field period. For example, former polder features such as drainage ditches and foundations of old farms (loose bricks) are still present. The former drainage ditches appear to be important sites for sedimentation of silty material. The fact that small scale topographic features such as bank breaches and drainage ditches could be the cause for spatial and temporal variability in sedimentation patterns is pressed above and is mentioned by *Nicholas and Walling (1998)* as well. Their results coincides with the observations from the field in this research. The drainage ditches were filled with silty material which most likely came from the flats. The silt from the flats was most likely transported in the old drainage ditches during conditions when wind and waves transported the sediment towards the drainage ditches or at least brought it into suspension from which another processes transported the sediment in the ditches. No visible erosion or sedimentation patterns were noted yet around the loose bricks and old foundations in the area.

Darke and Megonigal (2003) suggest that vegetation determines deposition rates, but only when river suspended sediments (which feed the wetland) are not limited. In the research area, the input of river suspended sediments was not limited (in general positive trapping efficiencies (see *Table 3*). On the flats, it was noted during silt thickness measurements that places with small aquatic vegetation characterised a relatively thicker layer of silt compared to the areas without the small aquatic vegetation. However, it is not yet clear whether the small aquatic vegetation does indeed result in higher silt sedimentation rates. In the tubes, it was noted that the root system of the small plants mixed the sand/mud and silt very well. It is therefore possible that the silt layer looked thicker (in combination with the abundance of algae near the vegetation) than it is in reality. The exact effect of the aquatic vegetation on sedimentation on the flats or islands is therefore still not clear yet.

Another example for spatial difference in suspended sediment concentrations is a marsh surface in the North Inlet, USA. It was noted that overall, sediment concentrations were higher near the creek bed than measured on the marsh surfaces (*Voulgaris and Meyers, 2004*). It should be mentioned however, that the creek has influence of salt water rather than the fresh water wetland described in this thesis and therefore can behave differently from a freshwater tidal marsh.

From the studies described above, the accretion rate calculated in this thesis is reasonable, but low compared to other wetland areas. Spatial differences in accretion rate are not studied in detail yet for this area, as well for a longer time span of data availability in order to optimize the sediment accretion rate for the Kleine Noordwaard.

5.2.2 Trapping Efficiency

In Chapter 4, trapping efficiencies of 51% for the left hand equitation (eq. 8) and 71% for the right hand equation were calculated. These values seem rather high and will therefore be discussed and explained in more detail in this section.

Looking at the variables on the right hand side of the formula, some aspects can be further discussed. The in situ fall velocity, measured from the experiments with the PVC tubes in the field, does not take into account the movement of water. Since the fall velocity used in the formula is the value calculated from the in situ fall velocity experiment, movement of water is not included, meaning that the fall velocity could differ from the fall velocity in a moving water column. Assuming that the in situ fall velocity is not the same as the flow velocity in flowing water, the value would be lower than the calculated 0.04 mm/s. This would mean that the output of the trapping formula would be lower as well.

The average discharge during the field period was used in the formula. However, the discharge varies over time (tidal cycle). When taking two random tidal cycles from the data set and calculating the trapping for each data point, the average value of fluxout/fluxin were 71.7% and 72%. Therefore it seems that the discharge does not vary that much over a tidal cycle in order to influence the resulting value of the trapping efficiency.

The exact value of the area can make a difference as well. Different calculations were performed including and excluding the Maltha polder and including and excluding the dry land. Performing the calculations using the average discharge described earlier, the computed trapping efficiencies for the four scenarios ranged between 65% for the dry area without Maltha polder up to 79% for the wet area including polder Maltha. Using the average value resulted in a trapping value of 71% of all the sediment which enters the area.

The left hand side of the equation used the calculated flux values from the field period in order to calculate the trapping efficiency. The calculated errors in the flux calculations ranged between 21% and 76% of the original values. Therefore, the flux values should be interpreted with criticism. The highest error values ranged between 75 and 200 % of the calculated flux and the lowest between the 1 and 20 % of the calculated flux values.

The uncertainties and variables on the right hand side of the equation and the error in the flux calculations used on the left hand side of the equation could explain the different values for both methods. However, in both cases the sediment budget remained positive, taking the different scenarios into account. This generally results in a wetland where sedimentation dominates erosion.

The error in the flux calculation is noticeable and the results are therefore not perfect. Nevertheless, these results can be used to make an educated guess of sedimentation patterns and fluxes in further discussion and conclusions. Retention rates were examined in a one-hectare experimental wetland (the Olentagy River Wetland Research Park). Retention rates for two different wetlands were 40.7% and 43.1% per year (Harter and Mitsch, 2003). Compared to the values calculated in the experimental wetland, the retention rate in the Kleine Noordwaard seems rather high. However, especially the left hand side of the equation, is only based on the field data, and not over data of an entire year. In order to optimize both flux calculations and trapping efficiencies, more data would be recommend, which will be discussed later on.

5.2.3 Temporal variability

Using the STM data from the boat, maps visualizing SSC values were made. These maps, in combination with flux calculations and meteorological information, were used to gain information about the area acting as a source or a sink of sediment. Several scenarios were recognized for the conditions ‘source’ and ‘sink’ which will be described below. An overview of all the collected and measured data is given in *Table 3*. For all the maps mentioned below see Appendix II.

Source: Low river discharge and strong SW winds

The conditions of relatively low river discharges and a relatively strong south-western wind generally resulted in the area being a source of sediment. The maps of 15 July, 7 and 8 October coincide with these conditions. According to the flux values from *Table 3*, the area would acts as a sink of sediment on 7 October, which does not coincide with the visual interpretation of the map. Standard errors in the flux calculations on this day are between 54 and 76 % of the original calculated values, which is rather large. Therefore the visual observations of this day are used for further interpretation.

As described in the results, in some of the maps higher SSC values at the eastern side of the island were noted compared to the western side of the island. The wind conditions during these observations were dominantly directed from the southwest. The (strong) southwestern winds created conditions which were ideal for local sediment to be brought in suspension. During high tide or relatively high river discharges, the flats which were normally dry were now submerged (if only a couple of centimeters). If more area is (somewhat) submerged, the wind will have a longer fetch than during lower water levels. In combination with (strong) SW winds, water ripples are created. The longer the fetch, the higher the water ripples can get. The turbulence in the water created by the small water ripples causes the sediment to come in suspension. This process was seen clearly at the eastern part of the island. This effect seemed to be of less influence on the western side of the island, where SSC values stayed more or less constant, wind fetch is smaller and some more (stable) vegetation was present on the banks.

To summarize, during southwestern wind conditions, most of the sediment went into suspension due to wind effects. Relatively high SSC values were seen at the eastern side of the island, but this was not noted when approaching the outlet. Most likely, the sediment which was brought into suspension at the eastern side of the island was locally reworked. Even though part of the suspended sediment was most likely locally generated and reworked in the area itself, still a part of the incoming sediment would be deposited. This would make the area for these specific conditions a source of sediment.

Sink: High river discharge and low SW winds

From *Table 3* it can be seen that the days with the conditions of relatively high river discharges (above 1570 m3/sec) and relatively low wind speeds (<2 m/s) had relatively high ingoing fluxes and lower outgoing fluxes. This indicates that the area acts as a sink for sediment. The day that represents these conditions is 16 July 2014. Even though some higher SSC values were observed at the eastern side of the island, it was not as pronounced as during the above described conditions of relatively strong southwestern winds. Since this STM round was not entirely finished until the outlet of the area, the flux calculations were consulted to obtain a decisive answer whether the area was a source or sink of sediment. Looking at the standard error in the flux calculations, these were lower than for the conditions described above (between 25 and 28% of the original flux values).

Sink: Average river discharge and strong NE wind

Days with high discharges and relatively strong north-eastern winds showed high incoming fluxes and lower values for the outgoing fluxes. The days with these conditions were 24 July 2014 and 22 October 2014. The pattern of higher SSC values at the eastern side of the island was not noted in the map of 24 July and just slightly on the maps of 22 October. This strengthens the explanation given above; southwestern winds caused higher SSC values at the eastern side of the island. It seemed that during north-eastern winds, the water was pushed more towards the western branch. In some of the maps (for example 24 July), higher SSC values were noted in the western branch of the island. Visual interpretation of the map showed that higher SSC values were present in the northern part of the area, but these values decreased following the channel towards the outlet. Therefore can be assumed that most of the sediment was deposited in the northern part of the area.

With the calculated standard error in the flux calculations, it is possible that the days which were noted to be a source of sediment according to visual interpretation of the STM maps (for example 7 October) were indeed a source of sediment whereas the ADCP data showed it to be a sink of sediment. It is also possible, that an equilibrium state of sediment exists; an equal amount of sediment is entering and leaving the wetland. From the numbers calculated in this study this state was not recognized.

Baldwin et al. (2009) explained that the flooding of a TFW is rather periodic due to wind effects and upstream runoff instead of a clear tidally influenced diurnal signal. This coincides with the observations from the field, where wind effects could be seen in the maps made from the STM data and the observations that were made during high river discharges. During high river discharges, the water level during ebb was already higher than during a 'normal' high tide. In these cases, the change in water level was less noticeable and significantly different compared to the changes in water level during the average river discharges.

During south-western winds, higher SSC values were observed at the eastern part of the island. However, these high values did not proceed to the outlet. This suggest that during these conditions, local sediment was brought in suspension. Although most of the sediment brought in suspension would be locally reworked, a relatively small part of the stirred sediment could flow to the outlet, making the wetland a temporary sink of sediment. This is in agreement with patterns noted by *Pasternack (199*8), who stated that wetland areas most often act as temporary sink of sediment and polluted materials.

As already described earlier, in several SSC maps it was noted that higher values occured in the northern part of the area, but those values did not prodeed until the outlet. Visual observations showed that the northern part of the island was growing. Not all the sedimentation will take place directly near the inlet of the area, but instead the sediment deposition will be controlled by combinations of factors such as the hydrological, geomorphological and the biotic factors. *Harter and Mitsch (2003)* stated that the greatest sedimentation occurs near the inlet of the wetland and that sedimentation rates decrease with distance from the sediment source. This is in agreement with the results from this study. Possible reasons for the sediment to settle near the inlet of the area are settling properties of the suspended sediments but also the effect of the presence of deeper water and vegetation.

Contradictory statements have been found on these two sediment enhancement factors; *Harter and Mitch (2003)* has found that wetlands with a large proportion of deep water areas enhances sedimentation instead of the ponds with lots of vegetation. Thereby, the deep water areas would protect the sediment from wind-induced resuspension. This is in contradiction with *Darke and Megonigal (2003)* who state that vegetation is the most important factor for sedimentation. As already described earlier, vegetation in the research area seemed to contribute to sedimentation of silt materials. Since most of the silt thickness measurements were performed on the flats, it is not known how the deeper water parts of the wetland influences sedimentation and if this contributed to the decrease in suspended sediment concentrations from the inlet to the outlet.

Darke and Megonigal (2003) also mention the importance of summer floods, since they often bring in high (flood-induced) sediments and the presence of abundant sediment trapping vegetation. This was not seen directly from the results, but the vegetation seems indeed to be of importance. As was already mentioned above, the importance of vegetation was noted during the silt thickness measurements. Vegetation present on the island seemed to protect the island against erosion as well.

5.3 Wetland sustainability

The above mentioned and discussed results will have some effects on the sediment balance and the wetland's sustainability. *Table 3* shows a general positive trapping efficiency, meaning that most of the time the area acted as a sink for sediment. In general, when the trapping efficiency and total trapping of a wetland is positive, the sedimentation rates as it is with present day conditions will lengthen the effective lifetime of the wetland. In other words, the trapping efficiency in the Kleine Noordwaard should theoretically be sufficient enough to keep up with possible future enhanced sea level rise. This statement gets pressed by *Ganju et al (2005),* who stated that hampering the amount of sediment accretion by a decrease in sediment supply can impede wetland survival. The stability of a TFW depends on the balance between in and outgoing material in the system. If this balance is positive, the system will grow vertically even as sea level increases (*Neubauer et al., 2002, Neubauer, 2008, Neubauer et al, 2009).*

In newly created wetlands, it is also important to consider the development of other ecosystem processes when predicting future sediment dynamics. For instance, as the vegetation community develops in newly created wetland systems, the sediment dynamics are likely to be affected (*Harter and Mitsch, 2003*). The Kleine Noordwaard is a relatively young and newly created ecosystem and most probably has not yet reached its equilibrium state. Some vegetation is still in development and other previous vegetation (such as tree lines) are still in the degradation process. During previous years the channels have changed as well, especially near the inlet of the wetland where the channel has deepened at some locations and swallowed in other places. Is should be mentioned that the sedimentation rates calculated in this research therefore might not represent the depositions rates for a longer time span. This does not only count for the Biesbosch wetland but is applicable for other wetlands on earth as well. Systems can change (going to new equilibrium stadia) and this is in close relation to other boundary conditions such as river discharge, upstream sediment input, vegetation changes and more. However when upstream river discharge and sediment supply will not change substantially and only sea level rise changes significantly, the likely wetland survival can be calculated from the accretion rates in the wetland.

Sea level rise is measured in Amsterdam since the beginning of 1700. Since 1850, the sea level rise amounts 1,6 mm/year (*Beets and van der Spek, 2000*). The calculated accretion rate for this region is substantially smaller (0.014 mm/yr) than the rate of sea-level rise. This would mean that even though the trapping efficiency calculated for the Kleine Noordwaard is generally positive, if current conditions continue the same in the future, the area will not be capable of surviving any possible future enhanced sea level rise. Let alone the current rate of sea level rise.

If present sedimentation processes and the main deposition areas in the wetland themselves are known, future management plans can be made in attempt to maintain the wetlands if necessary. This is in agreement with the statement of *Walling et al. (2002)* who states that the sediment budget provides information about the nature and the location of the main sediment source but also about the wetland sediment sinks and areas of sediment storage. With the knowledge about the sediment budget and processes inside a wetland area, the potential impact of upstream control measures controlling the sediment input can be evaluated. Using this, it is possible to assess the impact it will have on the downstream wetlands. This is applicable for wetlands all over the world; if enough information is present about sedimentation processes and the up- and downstream boundary conditions, estimations about wetland sustainability can be made. For example, the accretion rate in the Kleine Noordwaard is substantially smaller than the rate of sea level rise. If it is decided that the Kleine Noordwaard should still exist in the future, it could be decided that measures should be applied in the area, such as sediment feeding. More information about spatial and temporal differences within the area than make it possible to specify the measurements which would have the best effect on the sustainability of the wetland.

5.4 Future research

As mentioned above, future management plans can be made if sedimentation processes and the spatial and temporal patterns of sediment are known in a wetland area. From the results it was evident that the wetland acts as a sink of sediment for the gross of time. For future research it would be interesting to focus more on the spatial and temporal distribution of (suspended) sediment. *Nicholas and Walling (1998)* mention for example that areas of shallow, slow moving flows and the more elevated parts of a wetland suppress sediment dispersion. The convective, dispersive and diffusive mechanisms are not directly noted in the field and in the results. It is also interesting to have a closer look at the effect of vegetation, geomorphologic features and the influence of the old drainage ditches, old foundations and other irregularities in the area. These features may have a significant influence on sedimentation patterns. As discussed above as well, the influence of vegetation or deep water on sedimentation in a wetland differs in various wetlands as well. It would be useful for future management plans to gain more knowledge about these processes and the spatial distribution of the sediment in the research area. This way, we can hopefully increase our understanding of other wetlands all over the world.

Since the accretion rate was found to be lower than the rise in sea level, spatial and temporal differences in the accretion rate in the area are of importance for future management plans as well. Literature suggested that there is a spatial (and possible temporal) difference in accretion rates, for example between channels and flats. In this thesis a general accretion rate has been calculated for the entire area. If more specific, spatial specific numbers are known, in combination with more detailed sedimentation processes for the Kleine Noordwaard, this can contribute in any possible future sustainability measures.

In some cases, the flux values from *Table 3* did not give a conclusive answer whether the area was a source or sink of sediment compared to the visual interpretation of the STM maps. This was particularly important when it was not clear from the STM maps whether the area was a source or sink of sediment. When this was not clear from the maps, the flux calculations were consulted. However, the flux calculations were sometimes characterised by large errors, meaning that those values did not give a conclusive answer as well. It also possible that an equilibrium state of the area exist, meaning that the same amount of sediment enters the area as it leaves again. It would be interesting if in the future more STM rounds will be realized in combination with better flux calculations. This way, it would be possible to investigate if there indeed is some kind of stable state situation, whilst it would also be possible to improve the scenarios recognized and described earlier. In order to improve the flux calculation, the main variable of concern was the discharge. The error of the calibration of the STM was minimum, whereas the error in the discharge calibration was concerning. In order to improve the discharge calculation, more V-ADCP discharge data should be collected. In particular a better scatter in values (low discharges as well as higher discharges) would improve the relation and thereby the discharge and flux calculation as well.

If more information (especially a longer time span) is available for discharge and SSC values, a more complete educated guess can be made about flux values, the accretion rate of the Kleine Noordwaard as well as the trapping efficiency. More detailed information about spatial and temporal variability of this freshwater tidal wetland will increase reliability on the potential survival of the wetland and any possible future management measures.

Table 3: Overview of all measured data

	15 July	16 July	24 July	07 October		08 October	22 October	
Time cruised	09:33-14:03	16:05-16:55	14:30-16:37	9:46-11:33	15:08-16:30	09:07-11:30	09:51-14:20	14:26-16:39
Average wind speed	2.4 m/s	0.9 m/s	3.4 m/s	5.1 m/s	5.1 m/s	4.7 m/s	4.9 m/s	4.9 m/s
Wind direction	SW	SW	NE	SSW	SSW	S	NNE	NNE
River discharge (Tiel)	1761 m^3/sec	1803 m^3/sec	1574.6 m^3/s	1081.9 m^3/s	1072.7 m^3/s	1065.6 m^3/s	1495.8 m^3/s	1490.1 m^3/s
Sediment flux IN	0.027 kg/sec	0.76 kg/sec ± 0.21	1.29 kg/sec ± 0.25	0.36 kg/s ± 0.19	4.45 kg/s ± 0.44	0.40 kg/s ± 0.21	0.51 kg/s ± 0.19	1.29 kg/s ± 0.30
Sediment flux OUT	0.057 kg/sec	0.69 kg/sec ± 0.18	0.28 kg/sec ± 0.11	0.23 kg/s ± 0.18	0.1 kg/s ± 0.24	0.77 kg/s ± 0.16	0.53 kg/s ± 0.17	0.55 kg/s ± 0.21
Tidal conditions	HW	LW	LW-HW	HW	LW	HW	HW-LW	LW
source/sink (flux)	source	sink	sink	sink	sink	source	source	sink
Source/Sink (maps)	source	sink	sink	source	source	source	sink	sink
Trapping efficiency		9.21%	78.29%	36.11%	97.75%	-92.5%	-3.92%	57.36%

6. Conclusions

The aim of this thesis was to gain insight in the short term sediment budget in the tidal freshwater wetland the Kleine Noordwaard, situated in the downstream riverine area of the Netherlands. This was investigated by doing fieldwork in the research area and gathering information of stream velocities and suspended sediment concentrations. Statistical adaptations have been conducted and discharge, flux calculations and fall velocities were computed. Using this information, maps, figures and tables were made from which the following conclusions could be drawn.

It was found that during the field period, the ingoing fluxes were in general larger than the outgoing fluxes. Values of in- and outgoing fluxes ranged between 0.1 and 1.29 kg/sec and varied over time and between different conditions.

The suspended sediment concentrations are more or less consistent over depth but spatial variations in SSC values were noted from the STM maps. Settling characteristics of the suspended sediment were consistent for different locations as well over different moments of the tide. The mean median settling velocity was 0.04 mm/sec.

Trapping values ranged between 0.49 and 0.29 using two different methods, meaning that between 51% and 71% of all the incoming sediment has been deposited during the fieldwork period. The accretion rate for the Kleine Noordwaard was calculated to be 0.014 mm/yr.

During the fieldwork period three different scenarios for suspended sediment distribution have been noted. These conclusions are drawn from the different flux values, discharges, SSC values and meteorological data and are summed up in the table below.

Source/Sink	Conditions
Source	Relatively low river discharge and relatively strong SSW wind
Sink	Relatively high river discharge and low SSW wind Average river discharge and strong NE wind

A clear pattern was observed during (strong) SW winds: high SSC values were present at the eastern side of the island compared to other places in the area. These higher SSC values did not proceeded towards the outlet and are most likely caused by local re-suspension and reworking of the sediment. During weaker wind speeds and other wind directions this pattern was less or even not visible at all.

Sedimentation was seen at the northern part of the island; the sandbank in front of the island was growing towards the north. Other clear depositional areas have not been noted directly in the field. Locations on the flats with aquatic vegetation seemed to promote the deposition of silt compared to locations without aquatic vegetation.

To sum up, the Kleine Noordwaard has a positive trapping value and acts as a sink of sediment. The conditions during which the area acted as a sink of sediment were during high river discharges and low SSW winds and during average river discharges and strong NE winds. The conditions during which the wetland acted as a source was during low river discharges and strong SSW winds. The mean median in situ settling velocity was 0.04 mm/sec. A minimum of 51% of all the incoming sediment was deposited in the wetland. However, the accretion rate of 0.014 mm/yr is not sufficient to keep up with present sea level rise of 1.6 mm/yr. Therefore the Kleine Noordwaard, under present day conditions, will not survive any future (enhanced) sea level rise.

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Brochures, proposals, manuals and sites:

Brochure ontpoldering Noordwaard op hoofdlijn

STW proposal – Delta engineering: drowning or emerging

STM user's manual 07/2013

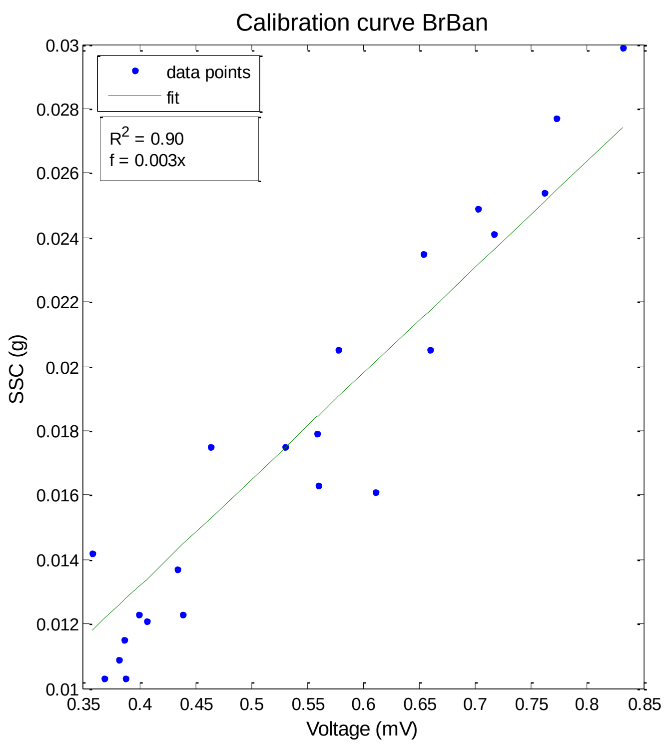
http://www.wisfaq.nl/show3archive.asp?id=15989&j=2003

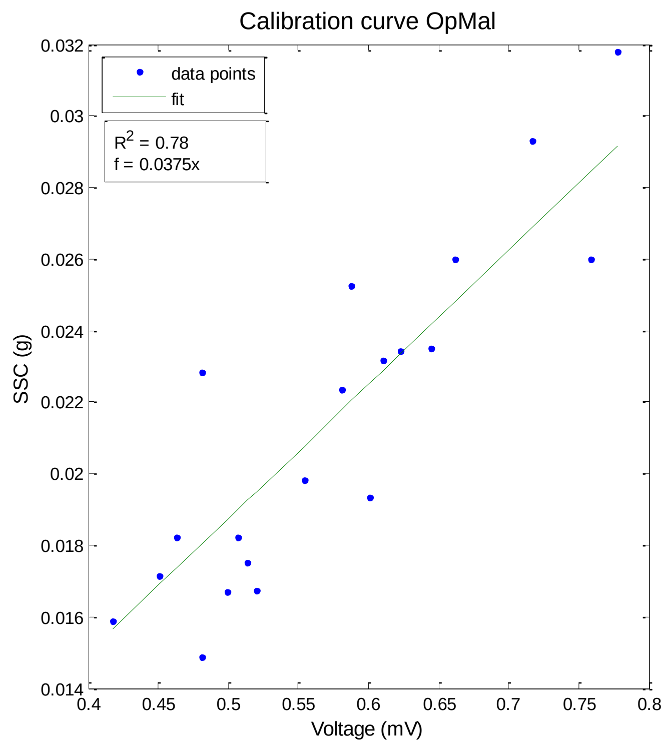
Appendix I Instrument calibration

In this appendix the calibration of the STM instrument will be described as well as the discharge calibration (H-ADCP and V-ADCP data).

STM calibration

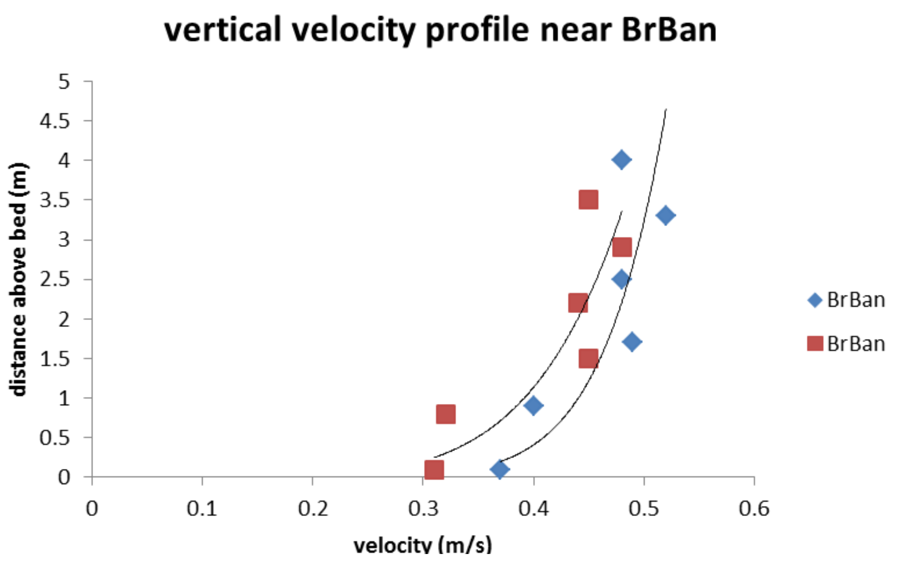
The calibration curves for the inlet (BrBan) and the outlet (OpMal) are given below. Root mean square errors were 0.90 and 0.78 and the slopes 0.033 and 0.0375 resp. The calibration curve was used in order to gain SSC values from the STM data from the poles for further flux calculations.



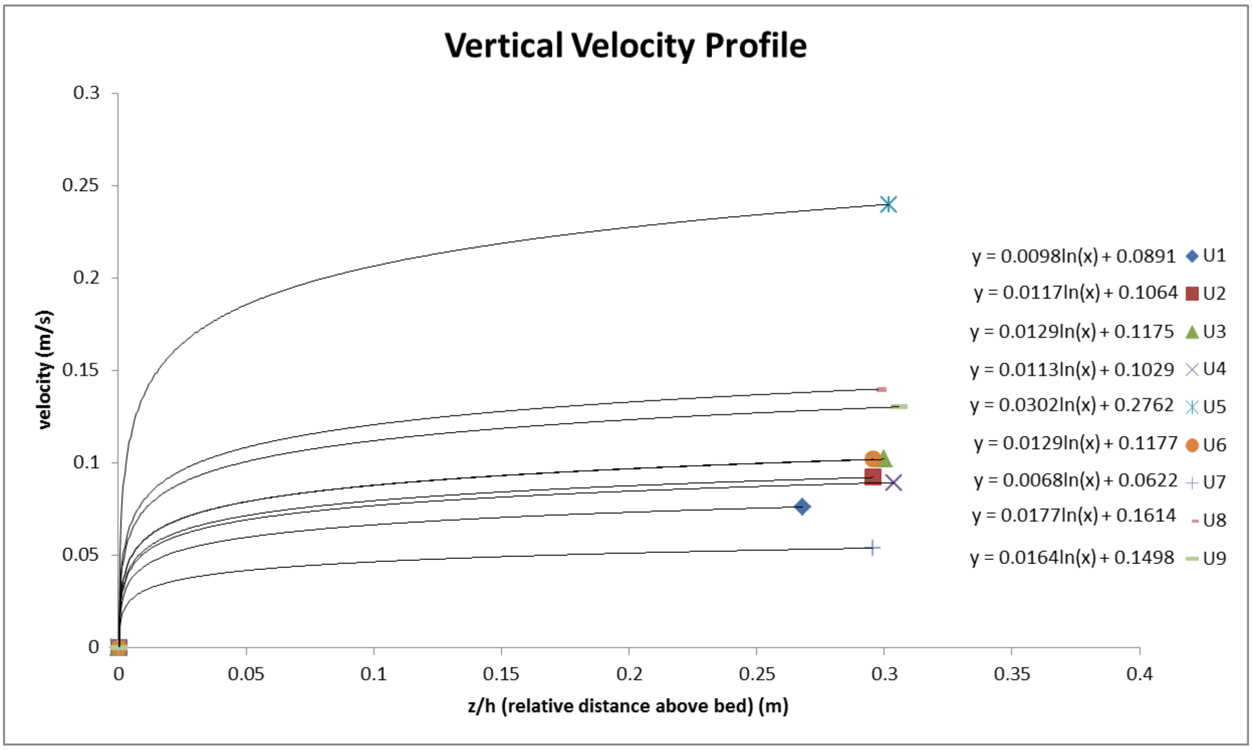


Discharge calibration

Point measurements with a Sensa were done for validation of the vertical velocity profile. The result is given in the figure below.



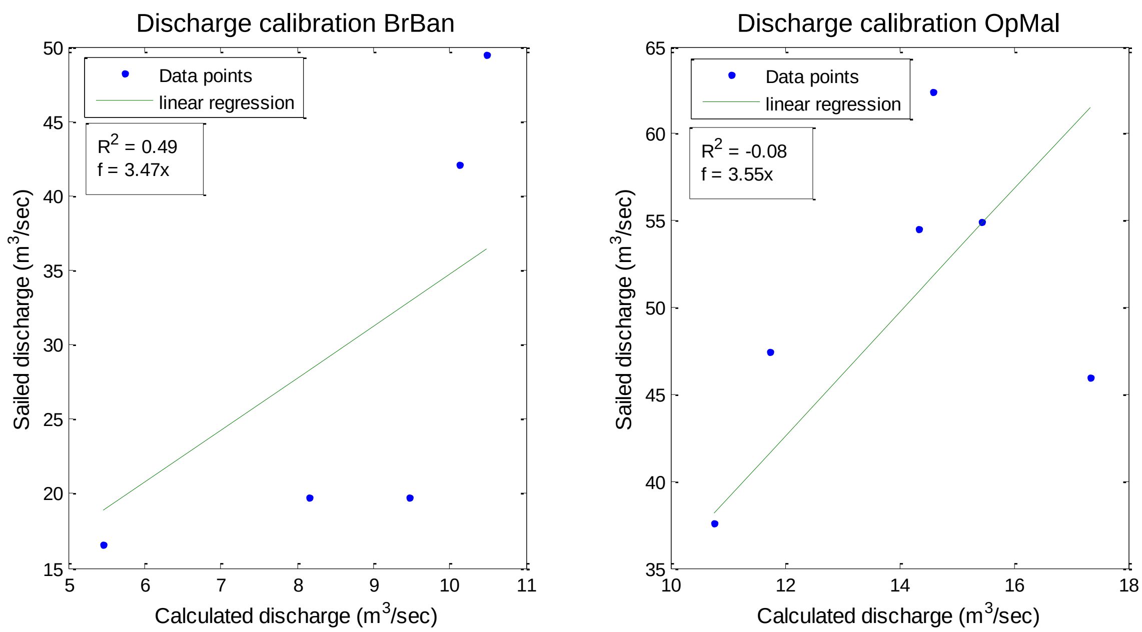
The velocity measurements from the H-ADCP were used for discharge calculations. In the figure below, an example of the measured vertical velocity profiles are given. This was done for all the data points available. After interpolating the vertical velocity profiles over the depth, the nine cells were added together for the discharge of the whole reach of the H-ADCP.



A1 1: Vertical velocity profiles at BrBan

In order to obtain the discharge over the whole channel instead of just the H-ADCP measuring reach, the H-ADCP data were plotted against the V-ADCP data. A linear regression was fitted through the points in order to make a relation between the V-ADCP and H-ADCP discharges. A fixed intercept of zero was chosen for both locations in order to get the best relation for both location, since a H-ADCP discharge of zero should always result in a V-ADCP discharge of zero as well.

Using this fixed intercept the quadrat of the correlation coefficient (R^2) was rather low . An approximation for the standard error of the regression of location BrBan was 11.4 m^3/sec and for OpMal was 8.57 m^3/sec.



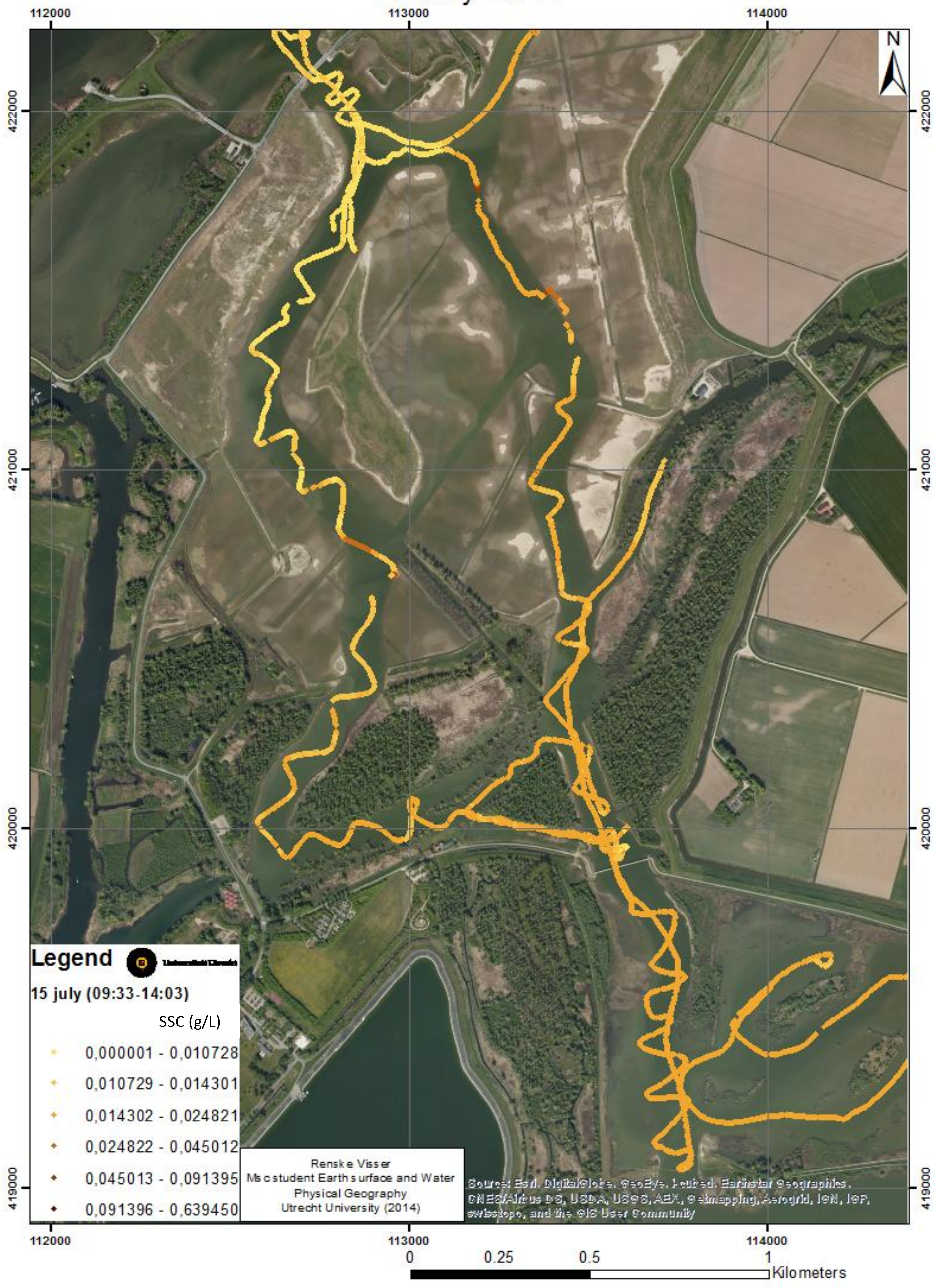
A1 2: Discharge calibration curves of BrBan and OpMal

Appendix II STM Maps

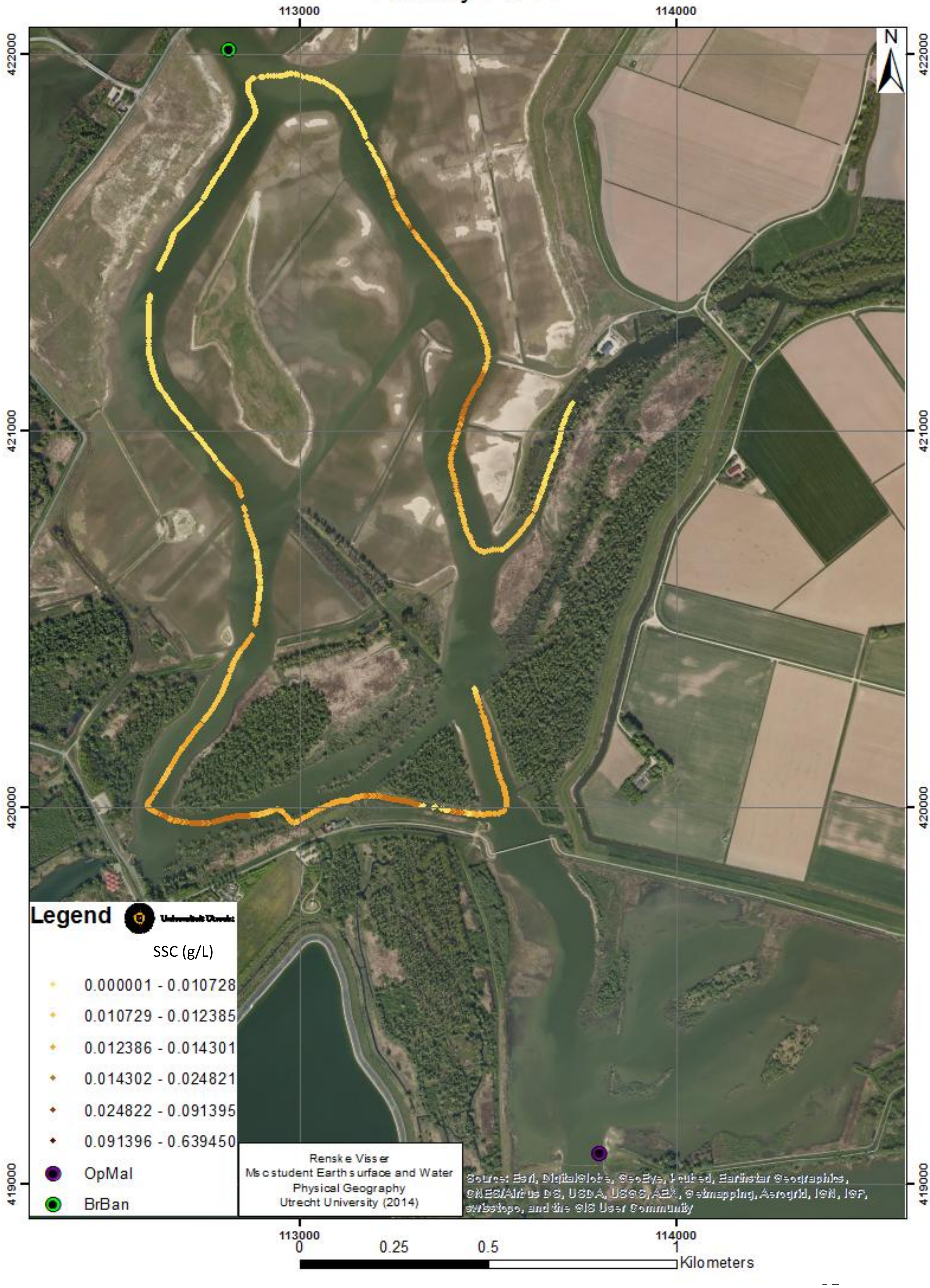
In this appendix, the STM maps of the various days of data collection are displayed in the following order:

15 July 2014
16 July 2014
24 July 2014
7 October 2014 (2 maps)
8 October 2014
22 October 2014 (2 maps)

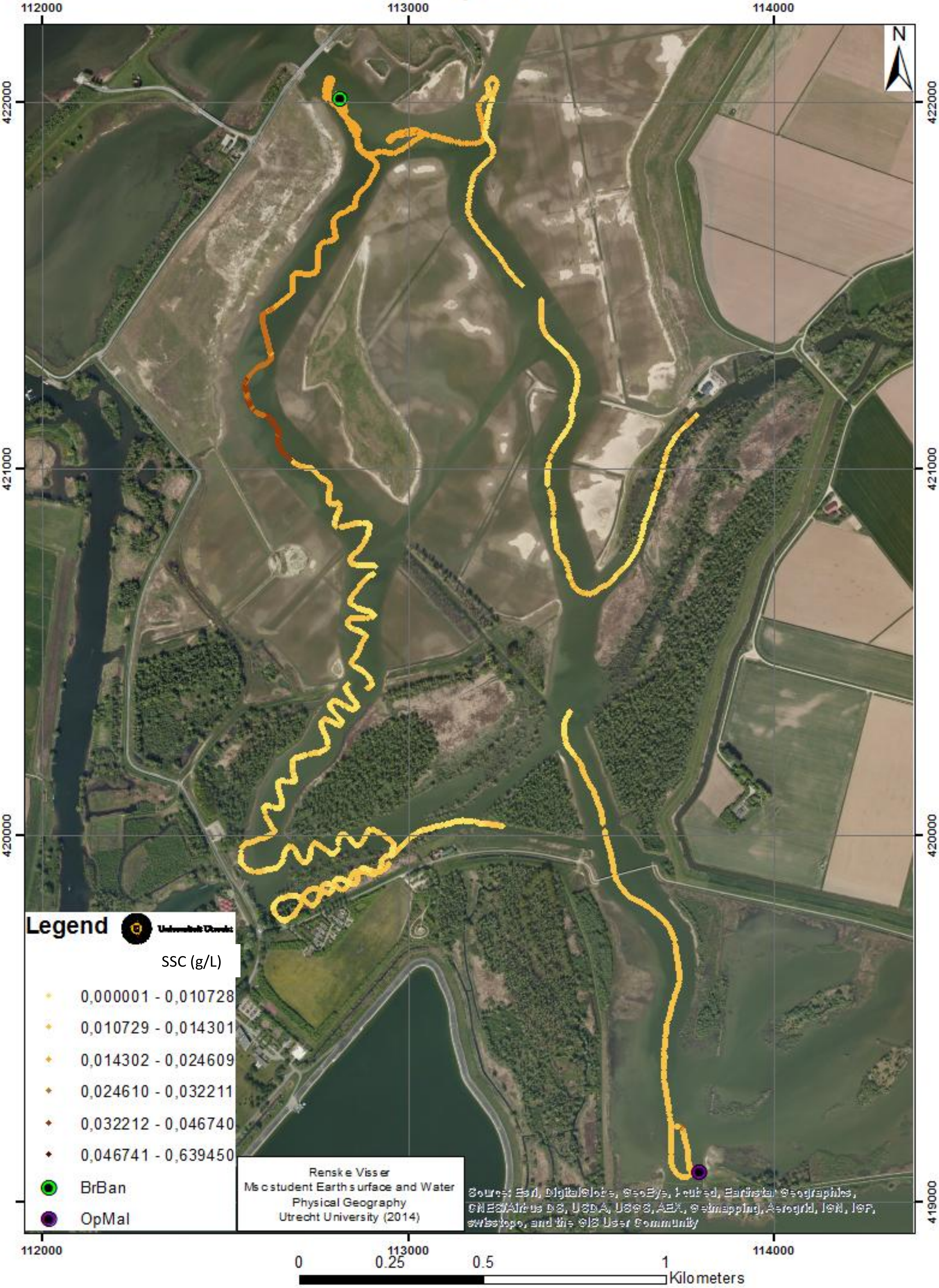
15 July 2014


112000
113000
114000
422000
421000
420000
419000
N
Legend
15 july (09:33-14:03)
SSC (g/L)
0,000001 - 0,010728
0,010729 - 0,014301
0,014302 - 0,024821
0,024822 - 0,045012
0,045013 - 0,091395
0,091396 - 0,639450
Renske Visser
Msc student Earth surface and Water
Physical Geography
Utrecht University (2014)
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
0
0.25
0.5
1
Kilometers

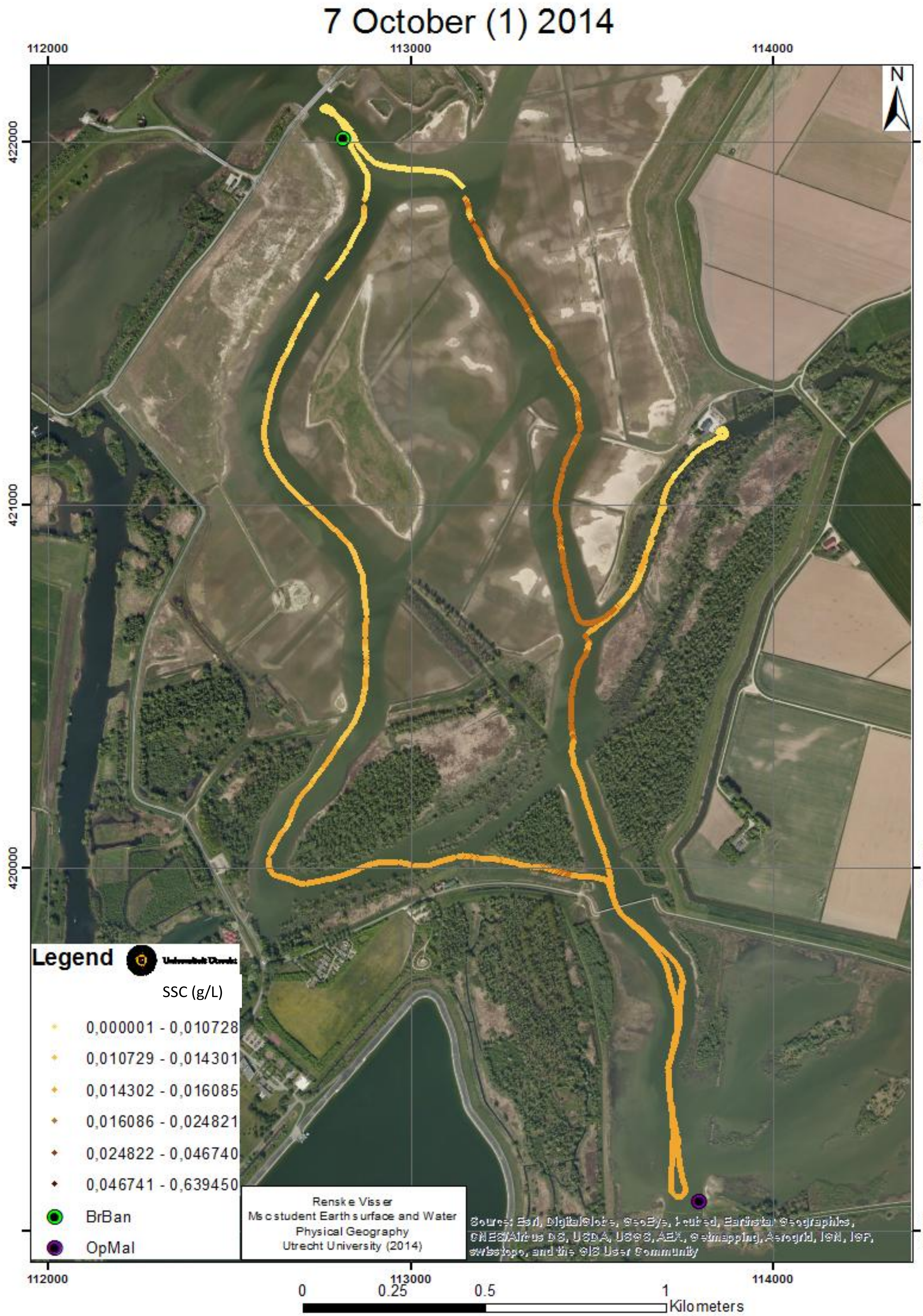
16 July 2014


113000
114000
422000
421000
420000
419000
N
Legend
SSC (g/L)
0.000001 - 0.010728
0.010729 - 0.012385
0.012386 - 0.014301
0.014302 - 0.024821
0.024822 - 0.091395
0.091396 - 0.639450
OpMal
BrBan
Renske Visser
Msc student Earth surface and Water
Physical Geography
Utrecht University (2014)
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
0
0.25
0.5
1
Kilometers

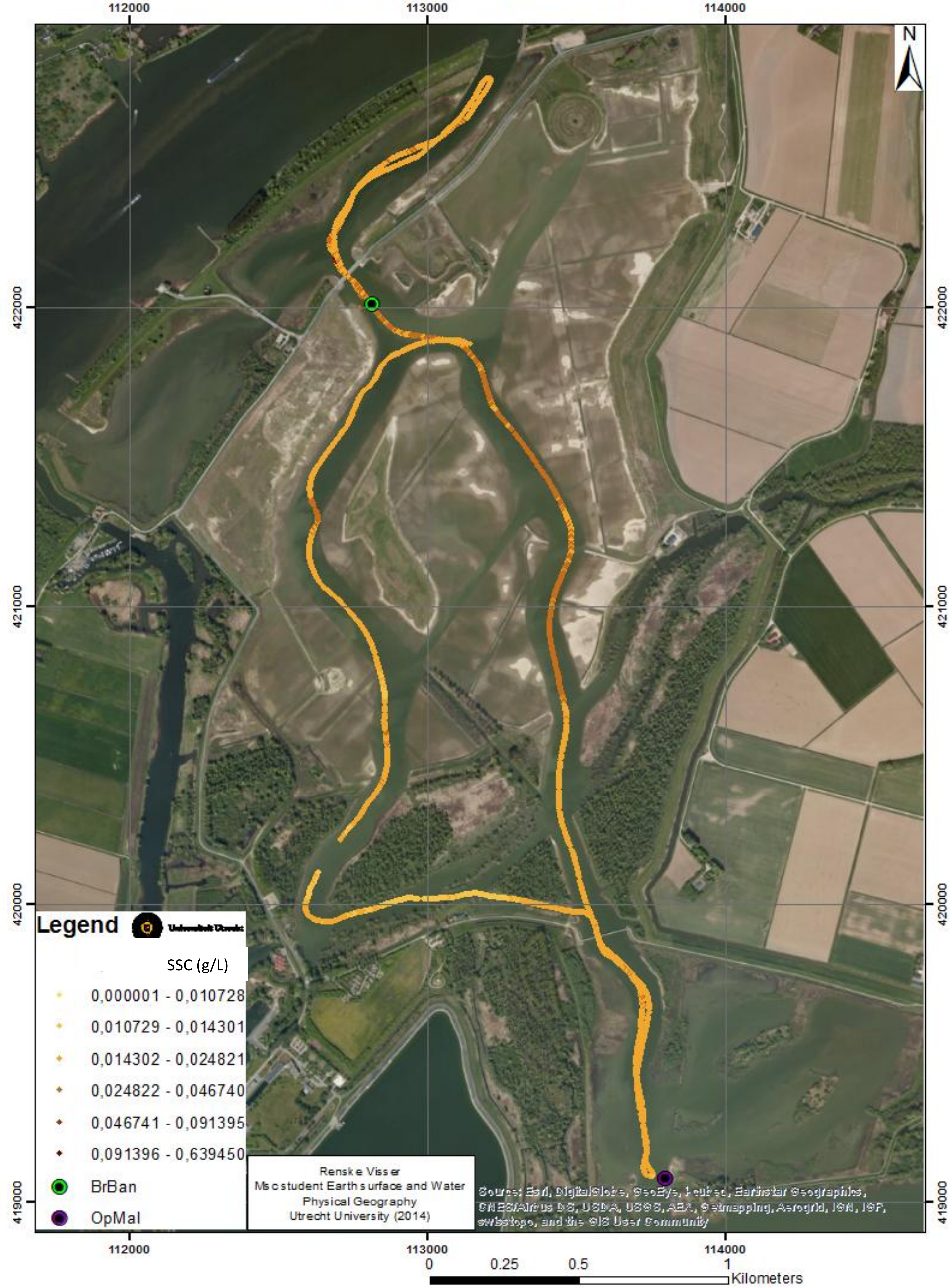
24 July 2014

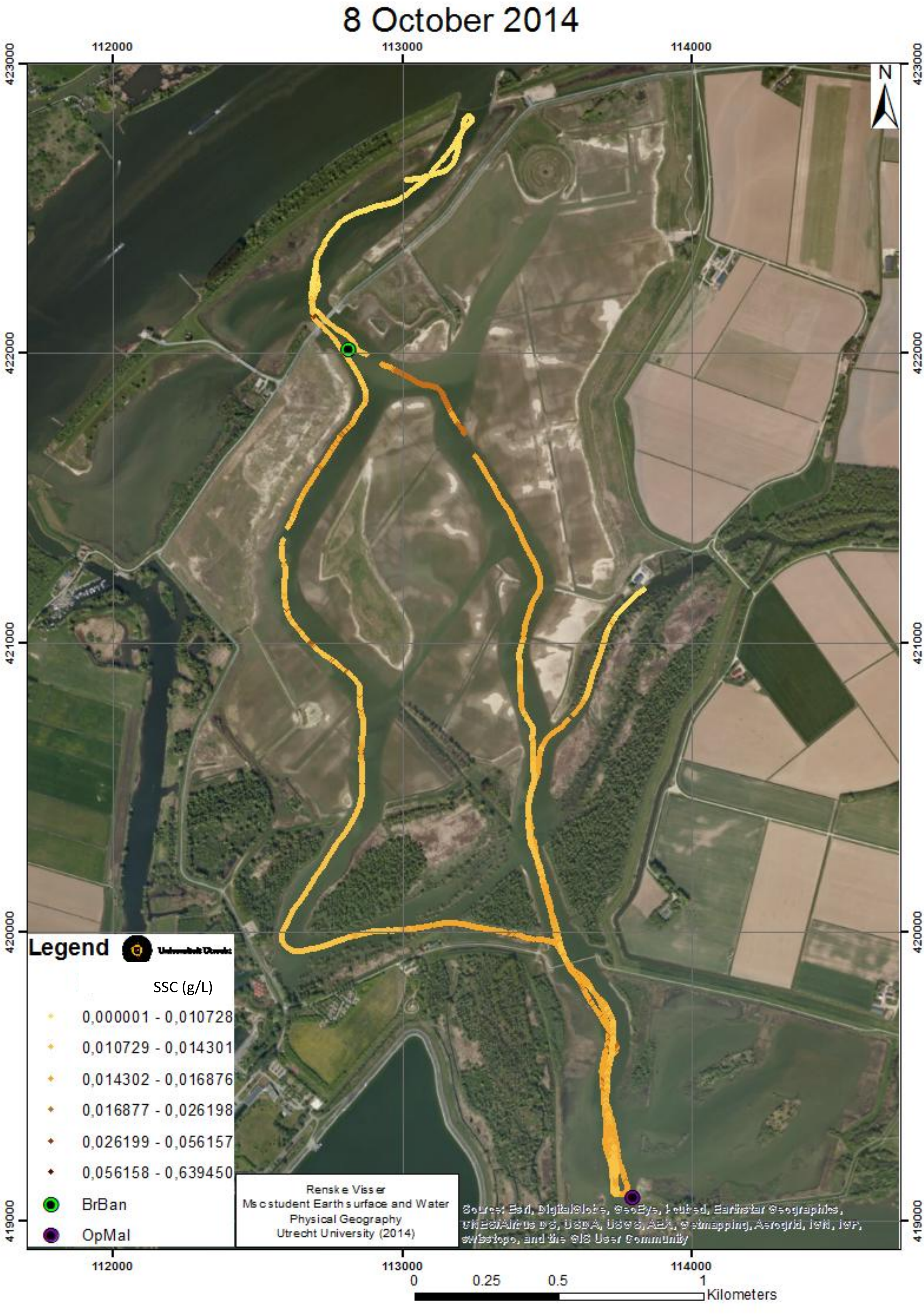


112000
113000
114000
422000
421000
420000
419000
N
Legend
SSC (g/L)
0,000001 - 0,010728
0,010729 - 0,014301
0,014302 - 0,024609
0,024610 - 0,032211
0,032212 - 0,046740
0,046741 - 0,639450
BrBan
OpMal
Renske Visser
Msc student Earth surface and Water
Physical Geography
Utrecht University (2014)
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
0
0.25
0.5
1
Kilometers


7 October (1) 2014
112000
113000
114000
422000
421000
420000
419000
N
Legend
SSC (g/L)
0,000001 - 0,010728
0,010729 - 0,014301
0,014302 - 0,016085
0,016086 - 0,024821
0,024822 - 0,046740
0,046741 - 0,639450
BrBan
OpMal
Renske Visser
Msc student Earth surface and Water
Physical Geography
Utrecht University (2014)
0
0.25
0.5
1
Kilometers

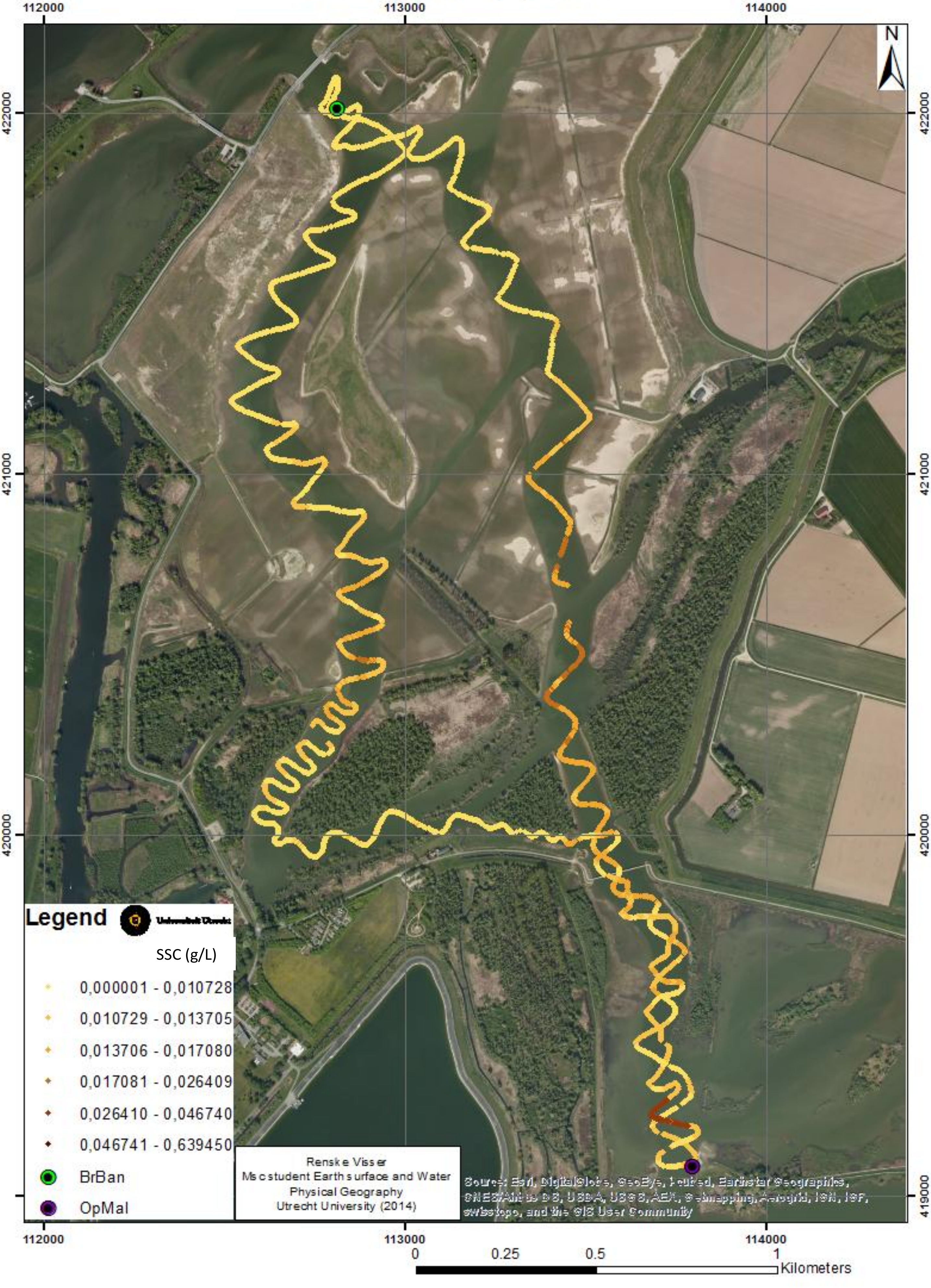
7 October (2) 2014



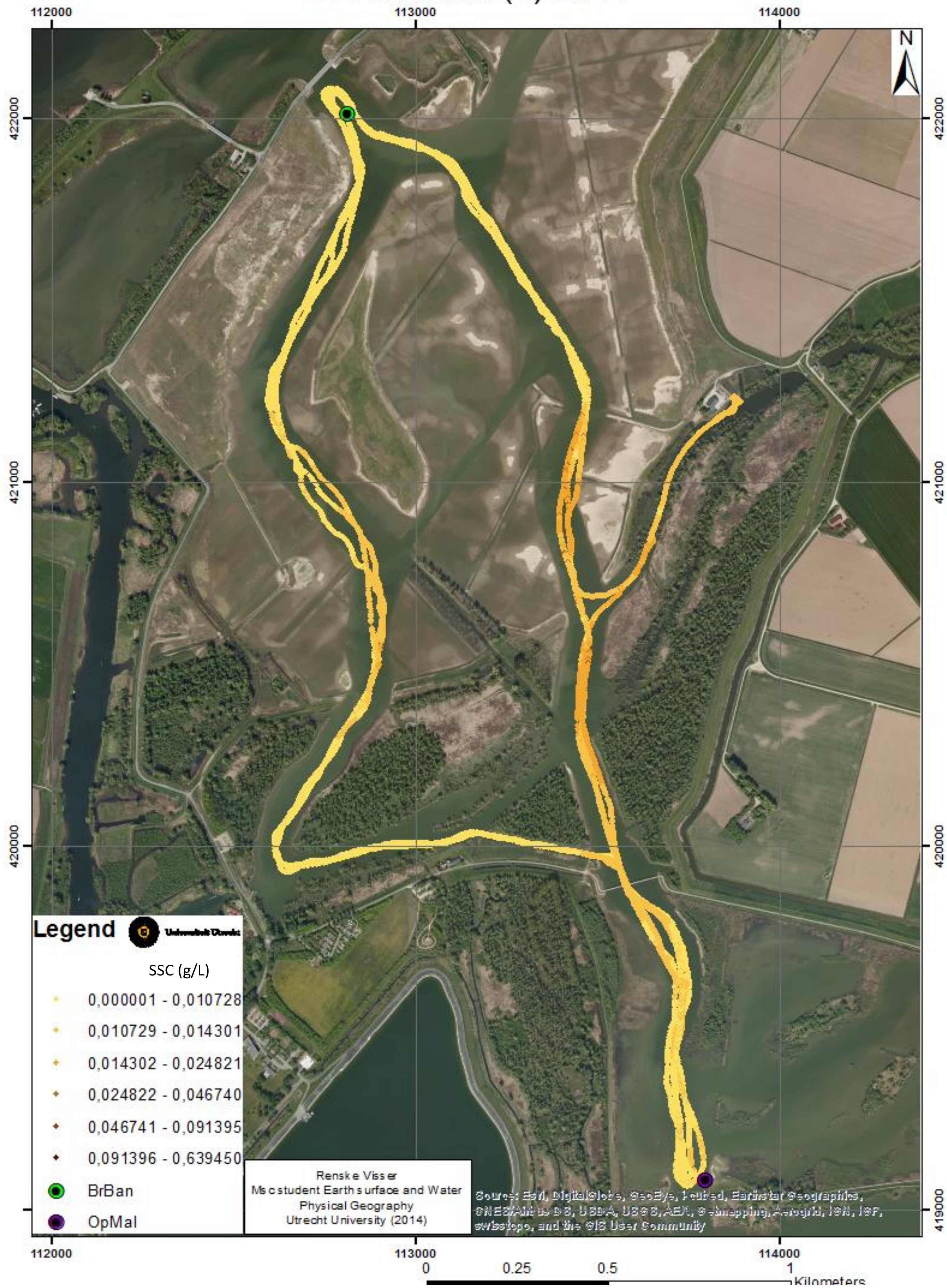


8 October 2014
112000
113000
114000
423000
422000
421000
420000
419000
N
Legend
SSC (g/L)
0,000001 - 0,010728
0,010729 - 0,014301
0,014302 - 0,016876
0,016877 - 0,026198
0,026199 - 0,056157
0,056158 - 0,639450
BrBan
OpMal
Renske Visser
Msc student Earth surface and Water
Physical Geography
Utrecht University (2014)
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community
0
0.25
0.5
1
Kilometers

22 October (1) 2014



22 October (2) 2014



Appendix III   Fall velocity distributions

In this appendix the fall velocity distributions for the different experiments are shown, as well as the median fall velocity for each experiment.