SEDIMENT BEHAVIOUR WITHIN A FLOOD CONTROL AREA WITH A CONTROLLED REDUCED TIDE – PILOT PROJECT LIPPENBROEK

PROCESSUS SEDIMENTOLOGIQUES DANS UN ZONE DE CONTROLE D'INONDATIONS ET DE MAREE REDUITE CONTROLEE – PROJET PILOTE LIPPENBROEK

Patrik Peeters, Stijn Claeys, Stef Michielsen, Jan De Schutter
Flanders Hydraulics Research, Flemish Government, Berchemlei 115, Antwerp 2140, Belgium
patrik.peeters@mow.vlaanderen.be

Stijn Temmerman, Patrick Meire, Wouter Vandenbruwaene, Tom Maris,
Universiteit Antwerpen, Department of Biology, Universiteitsplein 1, Antwerp 2610, Belgium
wouter.vandenbruwaene@ua.ac.be

Margaret Chen, Stanislas Wartel
Vrije Universiteit Brussel, Hydrology and Hydraulic Engineering, Pleinlaan 2, Brussels 1050, Belgium
margaret.chen@vub.ac.be

KEY WORDS

Schelde-estuary, Actualised Sigmaplan, combining safety with estuarine restoration, sedimentation heights

ABSTRACT

Pilot project Lippenbroek is a flood control area (FCA) with a controlled reduced tide (CRT). This paper presents results from ongoing multidisciplinary hydromorphological research on the experimental site. Characteristics, distribution and composition of the sediments are of primary importance to understand the hydrodynamic and the physical, biological, geochemical processes of the system. The characteristics of sediment natural compositions were examined and compared to those in the main channel of the Schelde. Combining water flows and sediment fluxes measured at the entrance and exit sluices allow estimating the sediment entrapment within the CRT-area. Volumes of sediment which retain within Lippenbroek can be converted into sedimentation height using in-situ measured sediment densities. In addition, the spatial distribution of the sedimentation is monitored on multiple sedimentation plots, which in turn allow estimating the rate of sedimentation. Relationships between inundation characteristics and sedimentation rates are investigated.

RESUME

Le Projet pilote Lippenbroek est une zone de contrôle d'inondation (FCA) caractérisée d'une réduction contrôlée de la marée (CRT). Ce document présente les résultats de la recherche multidisciplinaire hydromorphologique en cours sur un site expérimental. Les caractéristiques, la distribution et la composition des sédiments sont d'une importance primordiale pour comprendre les phénomènes hydrodynamique ainsi que les caractéristiques physiques, biologiques et les processus géochimiques du système. Les caractéristiques physiques des compositions sédimentologiques ont été examinées et comparées à celles du chenal principal de l'Escaut. La combinaison des flux d'eau et des sédiments, mesurés à l'entrée et la sortie de Lippenbroek, permet d'estimer les dépôts retenus dans la zone CRT. Les volumes des dépôts retenus dans le périmètre de Lippenbroek peuvent être convertis en hauteur de sédimentation au moyen de densités mesurées sur le site. En outre, la distribution spatiale de la sédimentation est contrôlée sur plusieurs parcelles de mesure, qui à leur tour permettent l'estimation des taux de sédimentation. Les relations entre ces taux et les caractéristiques d'inondation sont à l' étude.

1. INTRODUCTION

1.1 Actualised Sigmaplan

Due to changing physical circumstances and new insights in water management, recently an actualisation of the Sigmaplan (safety plan of the tidal river Schelde) was elaborated. The so-called Actualised Sigmaplan aims for satisfying safety and ecological needs along the river Schelde in a sustainable way. Therefore different restoration techniques are elaborated which combine safety with estuarine restoration, eg. dike strengthening together with more space for the river, flood control areas (FCA) with or without a controlled reduced tide (CRT), non-tidal wetlands, … (W&Z, 2005). Figure 1 shows the overall setting of the Actualised Sigmaplan and gives an overview of the set of measures contained within.

Figure 1. General overview of the Actualised Sigmaplan.

1.2 Pilot project Lippenbroek

Pilot project Lippenbroek is a flood control area (FCA, 8.2 ha, ring dike at +8.35 m AD) with a controlled reduced tide (CRT) (Cox *et al*, 2006; Maris *et al*, 2007). During storm surges (on average once a year) the FCA is filled via a lowered levee (at +6.80 m AD). In addition, a well designed sluice system allows limited semi-diurnal water exchange between this FCA and the estuary. Twice a day tidal water flows in at high tide through 3 inlet sluices (1.0m x 1.9m) with high sill levels (at +4.70, +5.00 & +5.30 m AD) and flows out at every low tide through an outlet sluice with low sill level. A tide gate (1.8m x 1.8m with sill at +1.50 m AD) is attached to the lower outlet structure. Goal is to obtain inundation characteristics similar to natural tidal marshes (Figure 2).

In 2006 Lippenbroek started functioning as freshwater intertidal habitat. Two years of intensive monitoring on a pilot site demonstrate the potentials of this approach (Maris *et al*, 2008). Former cropland is evolving towards an estuarine ecosystem. The vegetation cover shows a succession from pioneer generalist to typical estuarine and wetland species, driven by the installed tidal variation. The same evolution, colonisation by typical estuarine and wetland species, is also observed for zoobenthos, fish and birds. In addition, a pronounced springtide/neap tide variation is realised and sedimentation-erosion patterns comparable to natural marshes are observed.

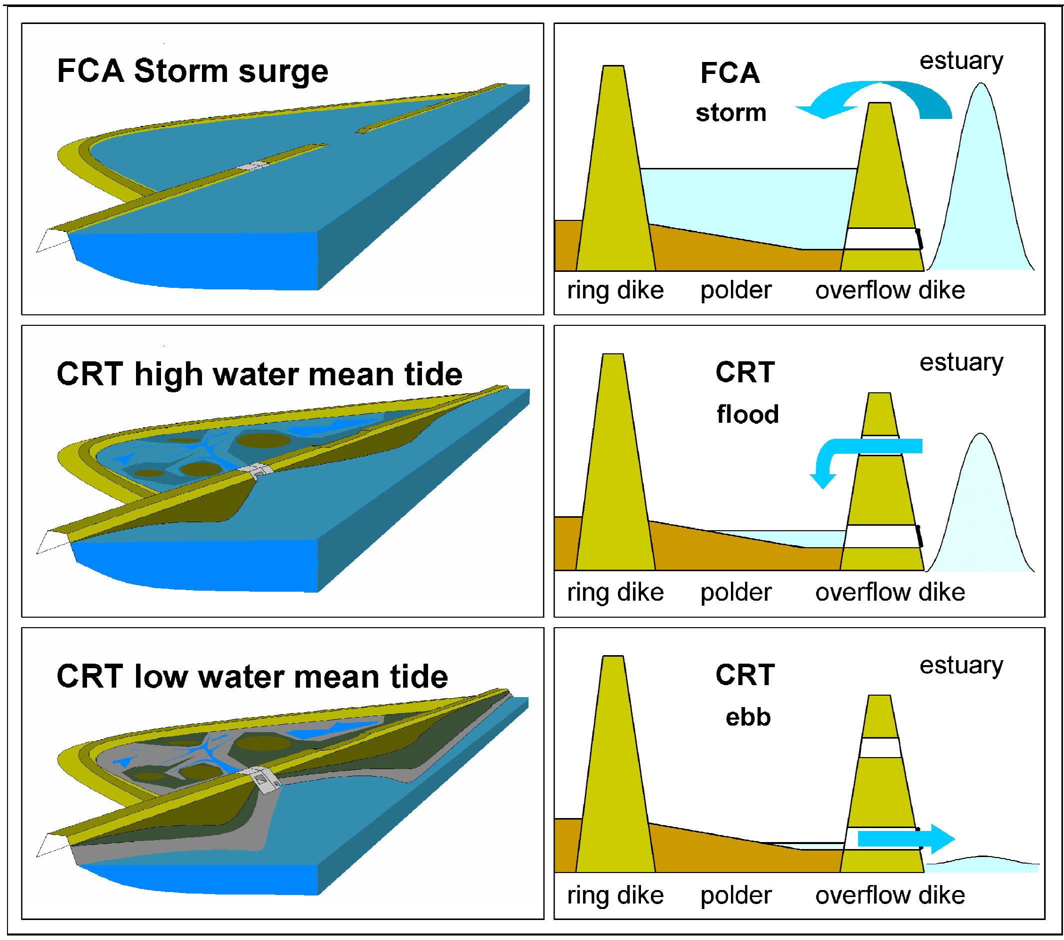


Figure 2. Overview of the CRT-principle.

2. WATER AND SEDIMENT BALANCE

2.1 Discharge measurements

From May 2006 onward, water levels and flow velocities at the inlet and outlet sluices of Lippenbroek are monitored continuously on a 2 to 5-minute time interval. At distinguished moments, discharge measurements were executed using portable measurement devices. Comparing continuous time series with measured discharges made it possible to establish good relationships between the continuously measured data and the actual (in case of water levels) and average values (in case of flow velocities).

Based on head-discharge measurements at the inlet sluices, it was found that the inflowing discharges (Q_{in}) could be obtained using the standard discharge equation for a sharp-crested weir (Bos, 1989):

$$Q_{in} = C_e \frac{2}{3}\sqrt{2g}\, b\, h_{Schelde}{}^{1.5}, \qquad (1)$$

where b is the breadth at bottom of control section, $h_{Schelde}$ represents the upstream head over crest and the effective discharge coefficient C_e equals 0.602 + 0.075 h_{up}/p with p the height of crest above approach channel bed (Figure 3). From literature, it is believed that Equation (1) will provide field measurement accuracy in the order of 5%.

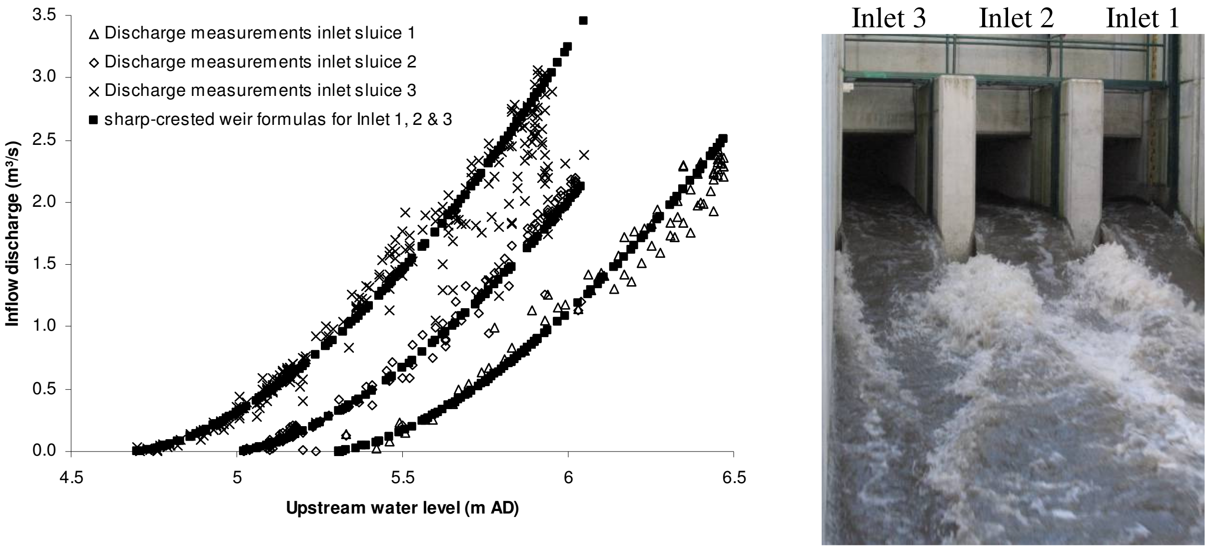


Figure 3. left: Head-discharge relations for inlet 1, 2 & 3, right: downstream view of the 3 inlet sluices.

Validated flow discharges through the outlet structure are obtained using validated water levels and flow velocities. In addition, for non-confined flow, outflow discharges could be predicted fairly well using the discharge equation for a broad-crested weir according to Bos (1989):

$$Q_{out} = C_d \frac{2}{3}\sqrt{\frac{2}{3}g}\, b\, h_{LPB}^{\ 1.5}, \tag{2}$$

giving a discharge coefficient (C_d) equal to 0.95 and with h_{LPB}, the upstream head over crest . Due to tidal movement of the Schelde, the outlet sluice is regularly operating under submerged (drowned) flow conditions. For drowned flow conditions, the broad-crested weir formula is modified as follows (Claeys *et al*, 2009):

$$\text{for } \frac{h_{Schelde}}{h_{LPB}} \geq m : Q_{out} = C_d \frac{2}{3}\sqrt{\frac{2}{3}g}\, b\, h_{LPB} \left[\frac{h_{LPB} - h_{Schelde}}{1 - m}\right]^{0.5}, \tag{3}$$

Besides the use of downstream water levels ($h_{Schelde}$), the use of a 'modular limit' (m) is proposed to correct for the influence of drowned flow conditions. Based on the discharge measurements, the modular limit was chosen 0.7. At this time, the accuracy of Equations (2) an d (3) is roughly estimated to be 10%. This accuracy estimation does not include errors associated with head measurement, which in turn will be much greater under submerged flow conditions.

Often good agreement is found between validated and predicted discharges at the outlet (Figure 4). Negative flow discharges at the outlet, due to leakage of the tide gate, are estimated based on the difference between upstream and downstream water levels. In case solid flow velocity measurements are lacking, it is suggested to use the fitted discharge relations. However, the occurrence of orifice flow through the outlet together with the presence of a tide gate and a trash rack (causing partially jamming of the outlet by debris), can be responsible for altering the head-discharge relation at the outlet which cannot be accounted for by discharge equations. Therefore predicted outflows should be used with caution.

Overflow during storm surges, ie. when the water level of the Schelde exceeds the (lowered) overflow dike (Photo 1), is estimated using the following discharge equation based on physical experiments (Lamoen, 1937) and literature (Bos, 1989; Laforce, 1990):

$$Q_{overflow} = C_d \frac{2}{3\sqrt{3}}\sqrt{2g}\ \ l\ \ h_{Schelde}^{\ 1.5} = 1.36\ \ l\ \ h_{Schelde}^{\ 1.5}, \tag{4}$$

where l is the length of the overflow dike (~50 m) and C_d equals 0.80.

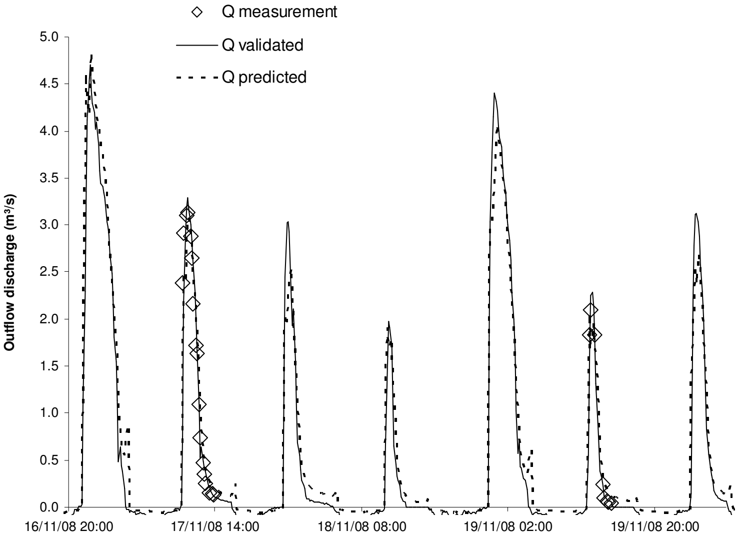


Figure 4. left: Validated versus predicted outflows, right: ADCP-discharge measurements at the outlet.

Photo 1. Lowered overflow dike of Lippenbroek in action.

2.2 Sediment flux measurements

During each in- and outflow, a tidal sediment sample is taken by a cooled autosampler at resp. the in- and outlet of Lippenbroek (Photo 2, left). The suspended solid concentrations (SSC) of each tidal sample is determined in the laboratory. The suspended matter of the samples consists of a mineral and a, sometimes pronounced, organic fraction (Photo 2, right). Moreover, at distinguished moments of in- and outflow, detailed sediment samples are obtained and, since March 2008, turbidities at the inlet and outlet sluices of Lippenbroek are monitored continuously on a 5-minute time interval. Combining tidal and detailed samples together with continuous time series of turbidity should allow to estimated SSC at the in- and outlet.

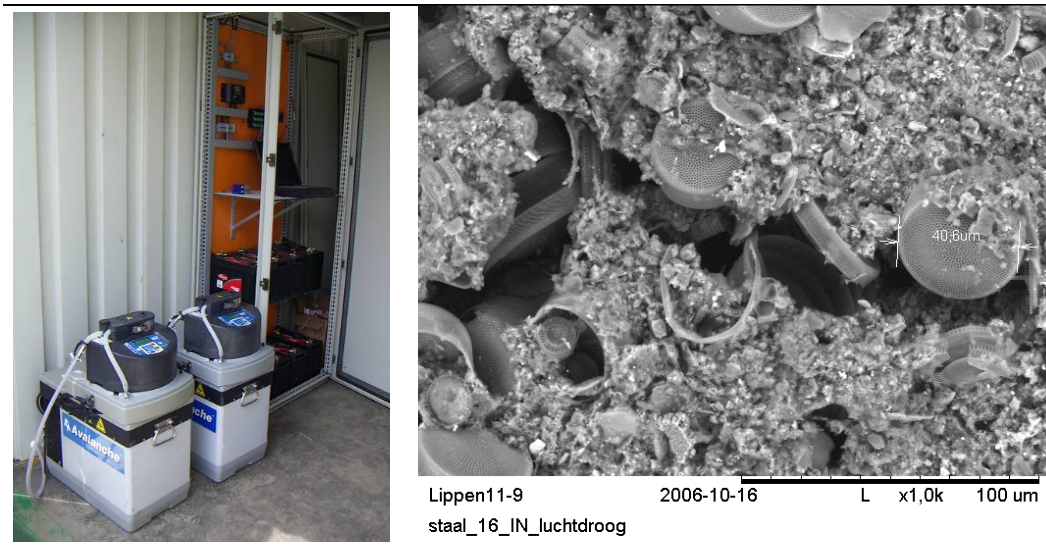


Photo 2. left: Autosamplers for tidal sediment sampling, right: Microscopic view of diatoms within a sediment sample

For the entrance a fairly good relation could be found between the inflow discharge (m³/s) and the SSC (mg/l) for the tidal sediment samples at the inflow (Figure 5). In addition, Figure 6 shows the relation between the SSC (mg/l) of detailed sediment samples and the continuously measured turbidities (NTU). Hence, sediment concentrations at the entrance can be obtained based on the tidal samples, from continuously measured flow discharges (Figure 7) and/or by converting continuously measured turbidities.

Unfortunately, no relation could be established for predicting the SSC at the outlet, nor based on the outflowing discharge and velocity, time-interval between in- and outflow (stagnant phase), etc. Some However, some relation was found between the SSC (mg/l) of detailed sediment samples and the continuously measured turbidities (NTU) at te outlet (Figure 8). Some statistical characteristics of the sediment samples are shown in Table 1.

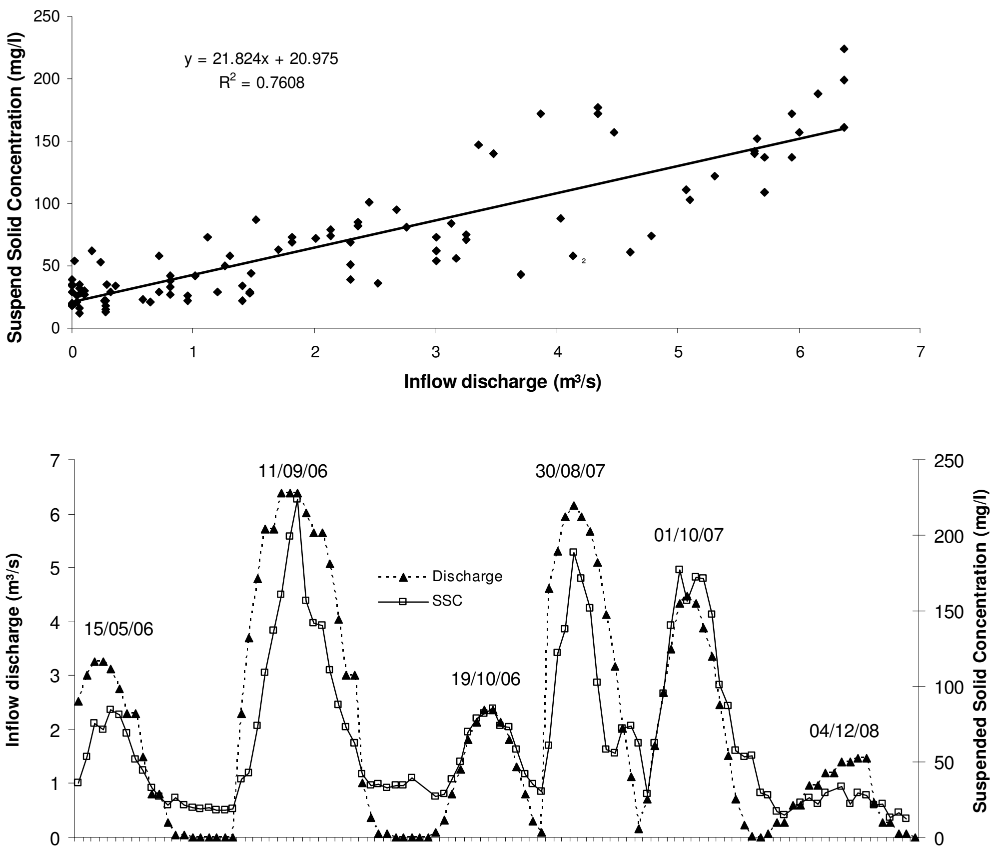


Figure 5. Relation between inflow discharge and accompanying suspended solid concentration

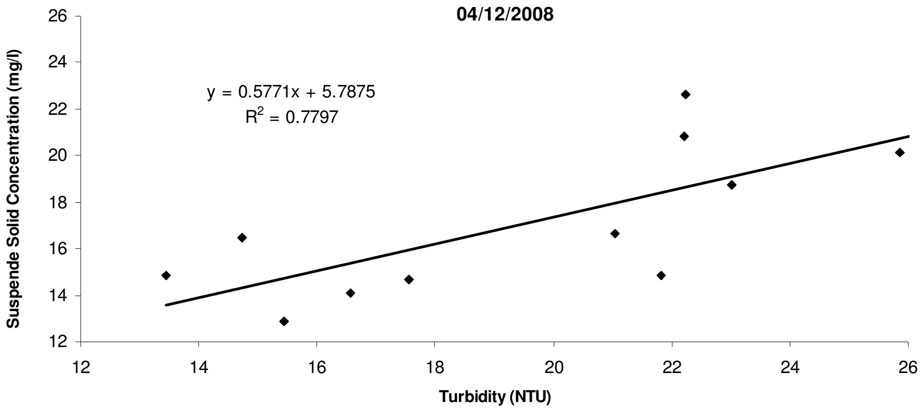
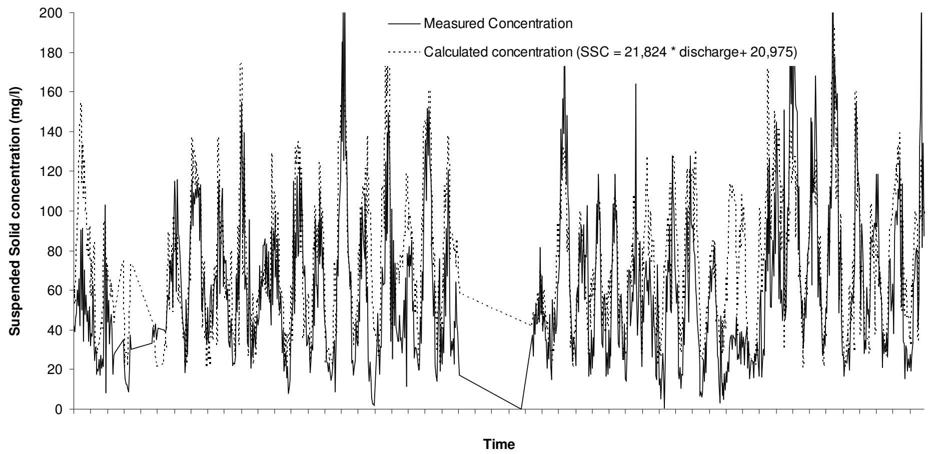


Figure 6. Relation between SSC of detailed sediment samples (mg/l) and continuously measured turbities (NTU) for the inlet



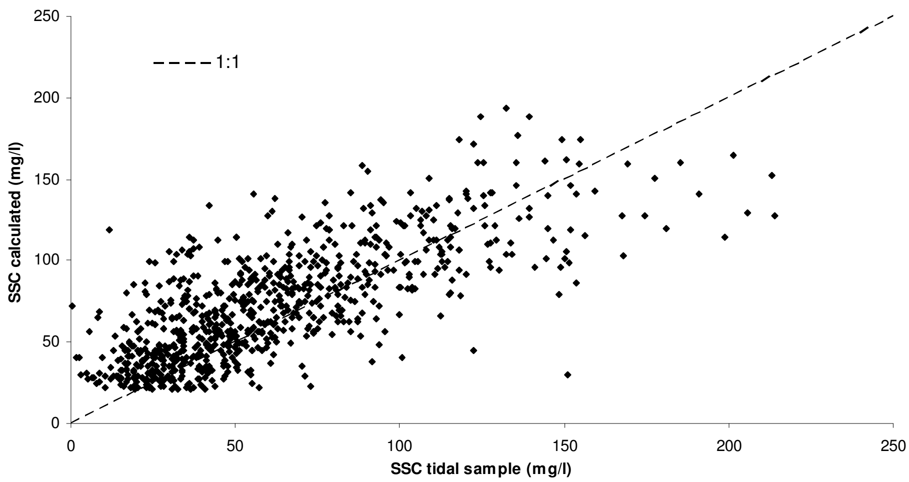


Figure 7. Relation between measured suspended solids concentration of longterm tidal sampling (mg/l) and calculated concentration out of inflow discharge (mg/l)

Table 1. Statistical characteristics of sediment samples

SSC (mg/l)	Tidal samples	Detailed samples	NTU-samples	Average
Mean	43	35	31	36
Median	40	34	30	35
- 1 Sigma	18	20	8	15
+ 1 Sigma	63	47	52	54
90% confidence interval	18 - 63	20 - 47	8 - 52	15 - 54

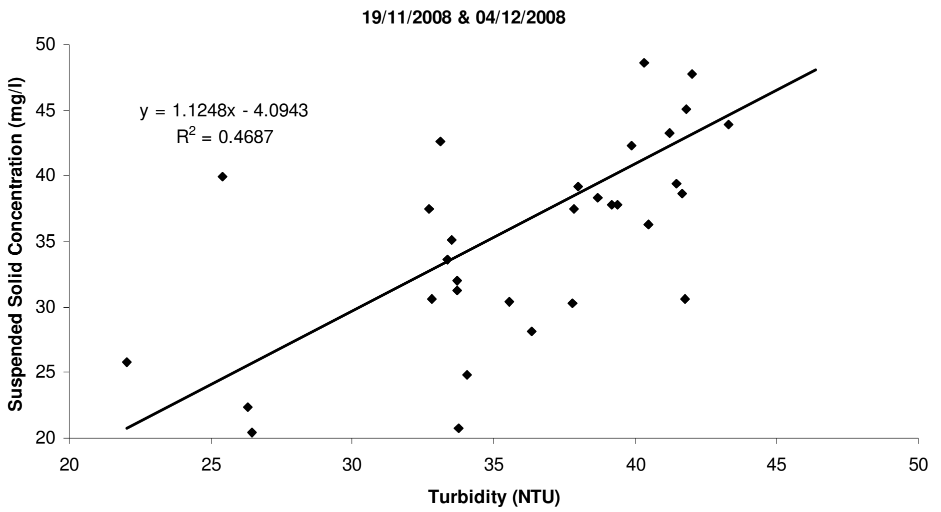


Figure 8. Relation between SSC of detailed sediment samples (mg/l) and continuously measured turbidity (NTU) for the outlet

2.2 Water and sediment balance

For those tides where solid measurements during in- and outflow are available, validated flow discharges were analysed. From Table 2, a strong neap tide/spring tide variation is noticed. One can also see that, on average, only for neap tide situations peak discharges are at in- and outflow are of the same magnitude.
For almost 90 % of all considered tides, total incoming and outgoing volumes do not exceed 40.000 m³.

Table 2. Water- and sedimentbalance for Lippenbroek (period 2006 – 2008)

Inflow	Peak discharge (m³/s)	Duration (hr:min)	Volumes (m³)	SSC at peak flow (mg/l)
Mean tide	3.5	2:25	18.000	97
Neap tide	1.0	1:55	5.000	43
Spring tide	5.4	2:45	28.000	139
Leakage (inflow through tide gate)	Mean discharge (m³/s)	Duration (hr:min)	Volumes (m³)	SSC (mg/l)
	0.5	6:40	1.000	15 - 54
Outflow	Peak discharge (m³/s)	Duration (hr:min)	Volumes (m³)	SSC (mg/l)
Mean tide	2.5	5:30	19.000	15 - 54
Neap tide	1.1	4:50	7.000	15 - 54
Spring tide	3.3	5.45	29.000	15 - 54

On a long term basis, the ratio ‘outflowing to incoming volumes’ is equal to 1. However, a wide range of this ratio (from 0.7 to 1.3) is noticed due to neap tide/spring tide variations, seasonal and wind effects, measurement accuracy etc. On average, for neap tides the ratio is larger then 1 where for spring tides it approaches unity. Finally, Table 3 summarises yearly amounts of sediment entering and leaving CRT Lippenbroek.

Table 3. Sediment entrapment in Lippenbroek

10^3 kg/year	Incoming sediment	Outflowing sediment		Remaining sediment	Sediment entrapment (%)
2006	1300	Mean outflow	330	970	75
	1300	- Sigma	80	1220	94
	1300	+ Sigma	570	730	56
	1300	Mean outflow (2006-2008)	380	920	71
2007	1550	Mean outflow	390	1160	75
	1550	- Sigma	100	1450	94
	1550	+ Sigma	680	870	56
	1550	Mean outflow (2006-2008)	450	1100	71
2008	1300	Mean outflow	470	830	64
	1300	- Sigma	120	1180	91
	1300	+ Sigma	820	480	37
	1300	Mean oufflow (2006-2008)	550	750	58

3. SEDIMENT CHARACTERISTICS

3.1 Comparison of sediment characteristics in the Lippenbroek and in the Schelde main channel

Characteristics, distribution and composition of the sediments are of primary importance to understand the hydrodynamic and the physical, biological, geochemical processes of the system. The characteristics of sediment compositions were examined and compared to those in the Schelde main channel. The suspended sediments were sampled in the Schelde river up- and downstream of the Lippenbroek area, in front of the inlet of the Lippenbroek, in the in- and outlet gates, and also during in- and outflow through the main creek. The bulk sample was treated with diluted peroxide to remove organic substances and with diluted hydrochloride to remove carbonate particles. The remaining sample was then wet sieved on a 76 µm sieve. The coarse fraction was dry sieved using ASTM standard sieves on a ¼ phi interval and the fine fraction was analysed with a Sedigraph using the same size interval.

A summary of the average values of suspended sediment physical compositions is given in Table 4. Analytical results indicated coarser sediments in the FCA compared with the Schelde as expressed by the first percentile values, in particular, higher sand content occurred near the in- and outlet gates of the sluices. Moreover, coarser sediments occurred during inflow around (220 - 240 micrometers) than during outflow (around 180 micrometers).

Table 4. Suspended sediment physical compositions (FP = first percentile which represents the size of the coarsest particles transported in suspension).

Location	FP µm	median µm	sand % (>63µm)	clay % (<2µm)
Upper estuary	128	2	6	54
Middle estuary	116	3	5	44
Schelde-Lippenbroek surface	167	2	6	58
Schelde-Lippenbroek bottom	137	3	8	50
Inlet gate	223	7	14	40
Outlet gate	181	5	13	61
Creek inflow	241	2	7	52
Creek outflow	184	2	6	51

3.2 Comparing suspended solid concentrations in the Schelde, near the entrance of and within the Lippenbroek

The characteristics of sediment compositions in and out of the FCA-Lippenbroek reinforces the need to better understand the evolution and variability of suspended solid concentration (SSC) in function of the flow strength in the FCA and in the Schelde. In general, the SSC near the surface in the FCA followed the evolution of flow velocity during the inflow period (flood), and settled fast with the decreasing flow strength. Comparing to the in flowing situation, the out flowing current was relatively weak, and also was not strong enough to erode the bottom sediments. Overall the SSC were initially much lower than the SSC near the surface in the river Schelde. However, once the inflowing velocity reached maximum in the FCA, then both the SSC in the FCA and in the Schelde showed very close values and both decreased rapidly with the weakening of the flow throughout the out flowing period.

The aboved measured pattern is illustrated in the following example of a tidal measurement carried out on October 10, 2007 (Figure 9). It is worth noting that the measured increase in SSC during the outflow may result from erosion of freshly deposited sediment on the marsh. This can also explain the higher SSC near the surface (180 g m^{-3}) than near the bottom (160 g m^{-3}). SSC and water velocity were also measured in front of the inlet sluice in the river Schelde during the inflow period (Figure 10). It can be noticed that at the moment that the inflow started the SSC was very high (exceeding 400 g m^{-3}) and decreased rapidly with the decreasing flow velocity. However, after the slack of ebb tide, though the flow velocity increased, the SSC remained low (around 50 g m^{-3}).

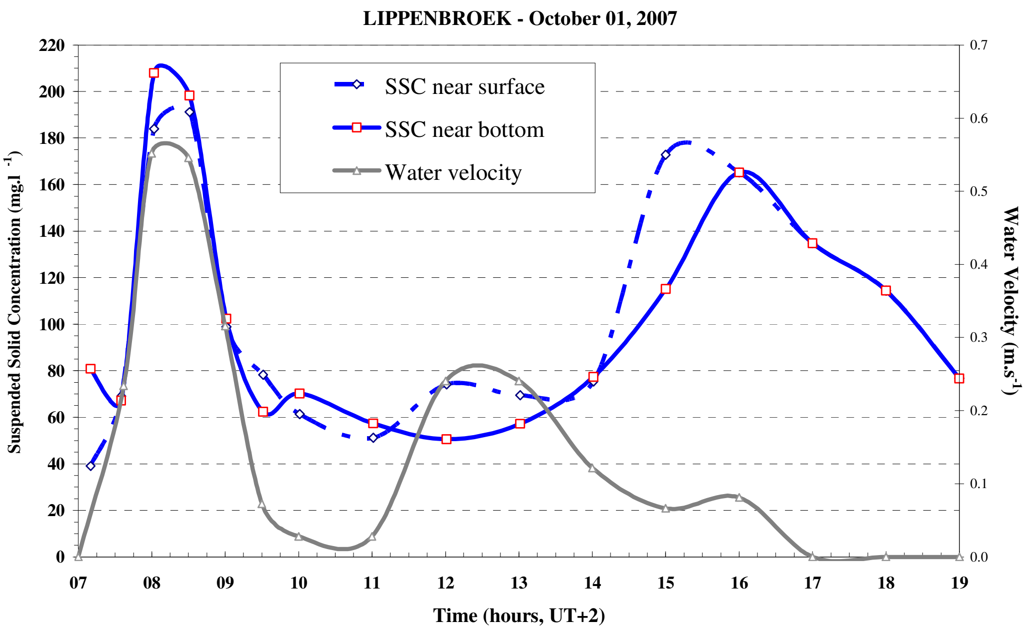


Figure 9. Water velocity and SSC at the bridge 1 in the Lippenbroek**.**

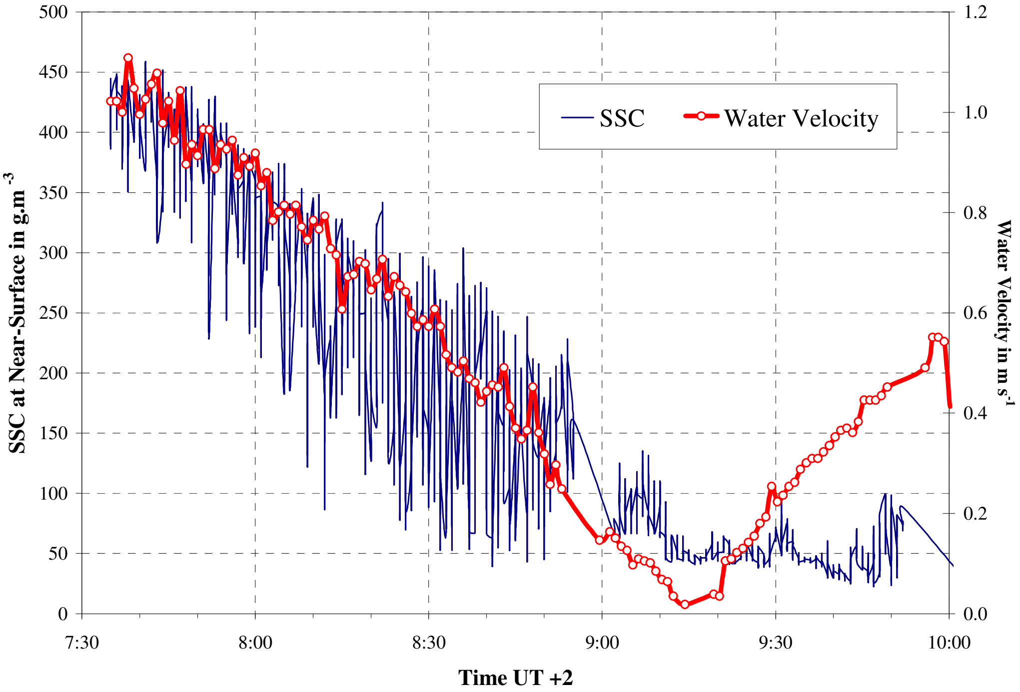


Figure 10. Suspended solid concentration and water velocity in the near surface water of the river Schelde in front of the inlet of the Lippenbroek during the inflow period.

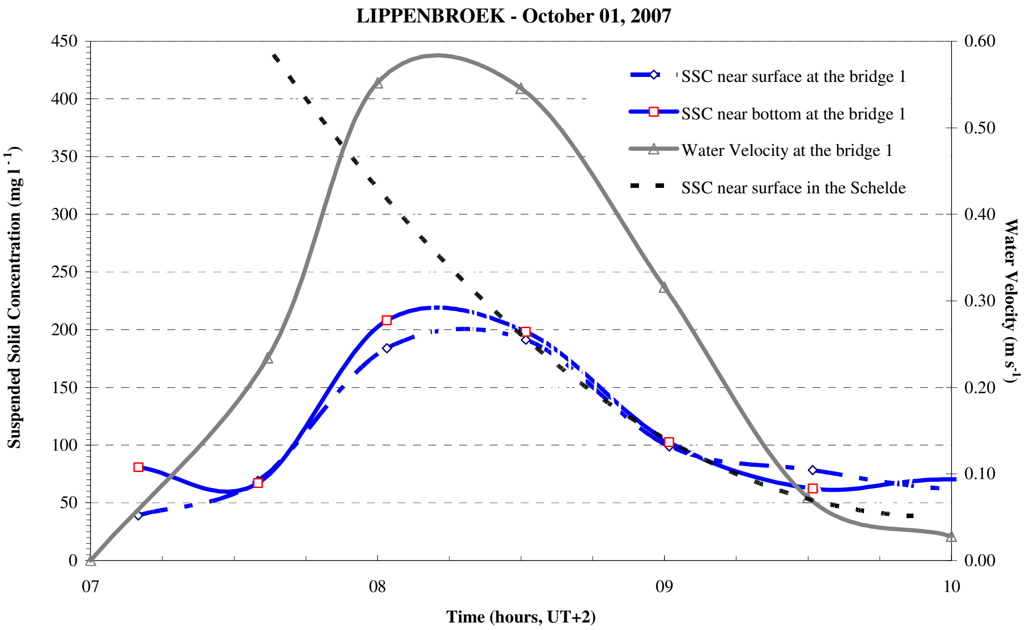


Figure 11. Comparison of SSC in the river Schelde and in the Lippenbroek**.**

It is clearly shown on Figure 11 that the SSC values at the surface and at the bottom near the bridge were initially much lower than the SSC near the surface in the river Schelde. However, the SSC near the bridge increases with the inflowing flow velocity reaching maximum and having very close value to the SSC in the river Schelde. After the peak period, both SSC and flow velocity decreases rapidly. The rapid decrease of SSC with decreasing flow velocity suggest a rapid sedimentation in the main creek.

Full-tide measurements in the Schelde, facing the inlet gate of the FCA, and at a fixed position inside the FCA showed that the SSC deceases rapidly after entering the FCA. This suggests either fast deposition of SSC or significant dilution of SSC near the inlet gate of the FCA.

4. SEDIMENTATION AND EROSION PATTERNS

4.1 Spatial distribution of sedimentation

Elevation changes in the Lippenbroek CRT were measured with so-called Surface Elvation Tables (SET), a technique that was developed by the US Geological Survey (e.g. Cahoon *et al*, 2002). A SET consists of a vertical stainless steel rod which is put into the ground untill a stable layer is reached. The upper part of the rod is about 0.5 m above the marsh surface. This rod is used than as a fixed reference point from which accurate soil elevation measurements are performed. This is done by attaching a horizontal aluminium beam to the vertical rod. The beam is put in a perfectly horizontal position by use of a levelling system. Nine vertical pins, which fit into the horizontal beam, are lowered then to the soil surface, so that the distance between the horizontal beam and the soil surface is measured with an accuracy of 1 mm. This procedure is repeated for four different directions, resulting in 36 measurements for each SET site. After two months the procedure is repeated so that the same 36 points are measured. In that way the elevation change, which is the combined effect of sedimentation, erosion and autocompaction, is measured.

Thirteen SETs have been installed, 10 in the Lippenbroek CRT and 3 in the adjacent natural tidal marsh. The stainless steel rods where pushed into the ground up to 10 to 15 m below the soil surface, into a stable sand layer. All SETs were installed before tidal action was introduced in the Lippenbroek in March 2006. From then on SET measurements are carried out every two months (Photo 3).

Figure 12 shows that the elevation change (in cm/year) strongly varies between the 10 sites within the Lippenbroek, from alsmost no elevation change to about 13 cm/year of sediment accretion. This spatial variation in elevation change is explained by the variability in soil surface elevation, which results in spatial variations in tidal inundation frequency. The elevation change in the natural marsh is considerably lower than in the Lippenbroek CRT, which is caused by the lower inundation frequency in the natural marsh (Figure 12). The relationship between elevation change and inundation frequency is however comparable for the natural marsh and the CRT. The two locations in the CRT with an inundation frequency of 100% (Figure 12) are permanent pools, to which few or no sediments are supplied during tidal inundation. Therefore elevation changes are very small on these two locations.

Photo 3. Carrying out SET measurements

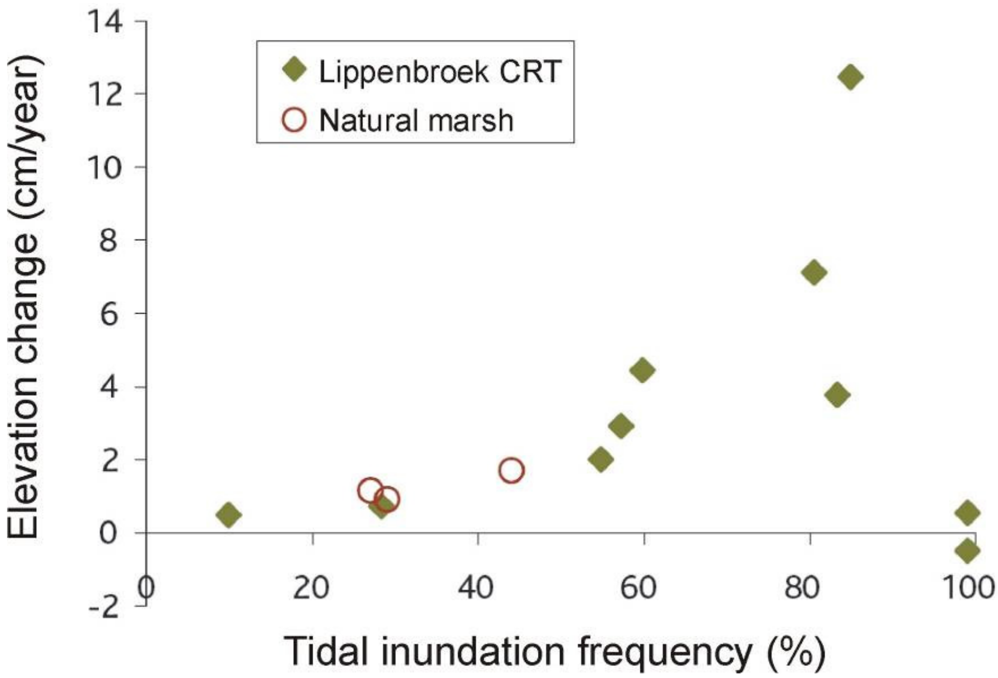


Figure 12. Elevation change (cm/year) as a function of tidal inundation frequency (%) for 10 locations in the Lippenbroek CRT, compared to 3 locations in the adjacent natural tidal marsh.

4.2 Estimation of sedimentation heights

The change in elevation of the Lippenbroek sediment surface is measured at 10 locations using surface elevation tables. Based on the measurements of May 2009 an average increase of 2.9 cm/year was calculated. However, a more exact value can be derived by using the elevation relationship (Figure 13) and a Digital Elevation Model (DEM) of the former Lippenbroek polder surface. For most pixels in the DEM (lowest and highest pixels are excluded) the increase in elevation was calculated, resulting in a weighted average increase of 2.4 cm/year for the entire Lippenbroek. It should be noted that the calculations based on the surface elevation tables only apply on marsh surface dynamics and do not include channel dynamics.

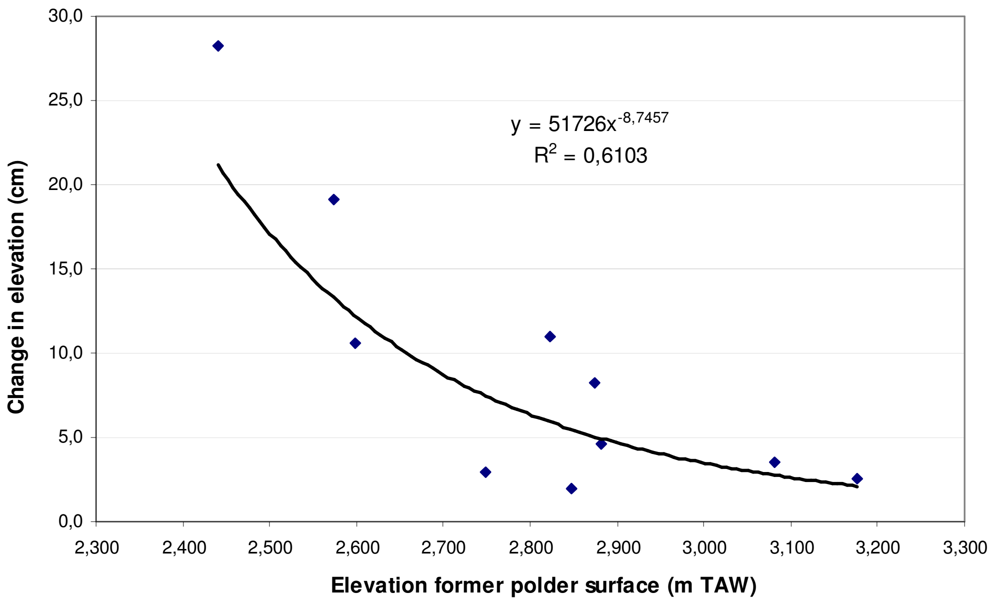


Figure 13. Relationship between the initial elevation and the increase in elevation, based on the 10 surface elevation table measurements in May 2009.

In addition, using in-situ measured sediment densities, entrapped sediment volumes from Table 3 can be converted into sedimentation heights. Therefore, undisturbed sediment profiles have been analysed for density. The sludge column in Lippenbroek has been divided into three density ranges: 1.26 10³ kg /m³ (top sludge); 1.28 10³ kg/m³ (middle); 1.35 10³ kg /m³ (hard bottom). Out of these wet density levels; a mean mineral density of 2.4 10³ kg /m³ and an assumed water saturation of the pores equal to 100%; the volume of the entrapped sediment can be calculated following Verruijt & van Baars (2007). The pore volume (n) of the entrapped sediment can be calculated with:

$$n = \frac{(\rho_k - \rho_n)}{(\rho_k - \rho_w * S_r)}, \tag{5}$$

where ρ_k is the density of the solids, ρ_n stands for the wet density of the sludge (measured by Gamma ray-densitometer), ρ_w is the density of the water in the pores and S_r the saturation level of pores (set equal to '1'or 100%). Out of the pore volume, the dry density of the sludge (ρ_d) is calculated with:

$$\rho_d = (1 - n) * \rho_k, \tag{6}$$

Finally, from the dry density, the volume of the wet sludge (V_g) can be found with:

$$V_g = M_{dry} / \rho_d, \tag{7}$$

where M_{dry} stands for the mass of the dry sediment (measured mass of entrapped sediment). Taking an overall area of 8.2 ha into consideration, preliminary estimations of the height of the entrapped sediment in Lippenbroek are shown in Table 7.

Table 7. Yearly sedimentation heights in Lippenbroek using in-situ measured sediment densities

cm	Series of tidal samples	$[\text{mean}]_{out}$	$[-\text{Sigma}]_{out}$	$[+\text{Sigma}]_{out}$
2006	2.2	2.4	3.0	1.8
2007	2.7	2.8	3.5	2.1
2008	1.8	2.0	2.9	1.2

CONCLUSIONS

In 2006 Lippenbroek started functioning as a FCA with CRT and has been studied and monitored since. Special interest goes to the (amount of) sediment entering the system each tide and partially remaining entrapped within Lippenbroek. Discharge measurements together with sediment sampling in the Schelde, at the entrance and outlet sluices as well as within Lippenbroek itself are carried out. In addition, at several locations, detailed elevation measurements are carried out.

After 3 years of intensive monitoring it is found that the suspended solid concentrations (SSC) entering Lippenbroek are related to amount of the sediment in the Schelde, but clearly smaller in absolute quantities. However, on average, 70% of all the sediment entering Lippenbroek, remains within the CRT and settles down. Following two different kinds of monitoring techniques, yearly sedimentations heights ranging between 2 and 3 cm are found.

It should be stressed that in order to obtain a well functioning freshwater intertidal habitat, settlement of sediment is a necessity and therefore wanted. However, it is believed that yearly sedimentation heights will diminish after years of functioning (e.g. due to consolidation and subsidence). More over, when the amount of sedimentation becomes to high in terms of safety, appropriate action will be taken.

ACKNOWLEDGEMENTS

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