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Aggregates explain the high clay retention of small constructed wetlands: a micromorphological study

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Earlier studies have shown that small constructed wetlands are more efficient as sedimentation basins for eroded soil material than expected from calculations based on detention time. It has been suggested that this is caused by sedimentation of aggregates. The present microscopic study of thin sections made from undisturbed samples of wetland sediments confirmed that the fine silt and clay fractions are present in aggregated form. Aggregates from the wetland sediments had the same mineralogical composition as those from the corresponding arable land, but were more rounded, indicating erosion during transport. To prevent breakdown of aggregates, wetlands should therefore be constructed as close to the source of erosion as possible. A correct prediction of particle retention in constructed wetlands has to take into account the presence of aggregates. Textural analysis methods, which require clay dispersion pre-treatment, are not suitable for the calculation of the retention of fine silt and clay.

Introduction

Erosion by water occurs in all catchments and soil particles are transported through tile drains or as surface runoff to waterways. (e.g., Øygarden *et al*. 1997, Bechmann and Våje 2001). The marine silt loam and clay loam soils are rather vulnerable to water erosion because they normally occur in sloping areas intersected by ravines. Due to their large specific surface area, clay particles have a high affinity for phosphorus and pesticides (Spark and Swift 2002, Gburek *et al*. 2005). High amounts of clay and organic matter, and thus pollutants, are lost through erosion from catchments with agricultural production. As a result, eutrophication due to phosphorus enrichment stimulates algae growth in lakes and rivers (Krogstad and Løvstad 1989, Uusitalo *et al*. 2003), while aquatic life is harmed by accumulation of pesticide residues (Ludvigsen and Lode 2002) and the visible depth (i.e., *Secchi* depth) is reduced.

In Norway, small wetlands are often constructed downstream to reduce losses of particles, nutrients and pesticides and to prevent the pollutants' negative effects on stream and lake water quality. They need to be small due to the rugged Norwegian landscape. According to Eq. 1 (e.g., Haan *et al*. 1994), small wetlands with high hydraulic loading rates (QA^{-1}) or with low detention time would not efficiently retain clay particles:

$$E = 100[1 - \exp(-wAQ^{-1})]. \quad (1)$$

Here E = relative retention of particles (%), w = sedimentation velocity (m s^{-1}), A = surface area (m^2), and Q = discharge from the pond (m^3 s^{-1}). Trap efficiency thus increases with surface area and decreases with discharge. Hence, as the hydraulic load (QA^{-1}) increases, trap efficiency decreases.

Equation 1 is based on theoretical work performed for laminar flow by Hazen (1904), and includes turbulent water. Kadlec and Knight (1996) presented the first order area model for estimation of the retention of particles and nutrients in treatment wetlands as follows:

$$C_{out} = (C_{in} - C^*)\exp(-kAQ^{-1}) + C^*. \quad (2)$$

Here C_{in} and C_{out} are concentrations of pollutants (mg l^{-1}) in the inlet and outlet, respectively, C^* is the background concentration value (mg l^{-1}), and k is the removal rate constant (m s^{-1}). Note that the constant k is equal to w for retention of suspended soil particles. Hence, Eqs. 1 and 2 are the same model for particle retention (Braskerud 2002a).

Braskerud (2003) studied two small constructed wetlands and found that the clay retention was much higher (Table 1) than predicted by Eq. 1. He explained the large clay retention by increased settling velocity due to clay particles being transported and settling as aggregates. Aggregates consist of primary soil particles that cohere to each other more strongly than to other surrounding particles (Soil Science Society of America 1997). The words aggregate and floc are often used as synonyms, because it may be difficult to distinguish these entities (Droppo and Stone 1994). However, their origin is different: aggregates are formed as a result of processes in the soil, while flocs are formed in the watercourse. Soil material can be lost either as aggregates or isolated particles (e.g., Armstrong and Stein 1996, Stone and Walling 1996), and is transported as aggregates or flocs in the streams (Droppo and Ongley 1994).

The main objective of the present study was to verify, with the aid of micromorphological techniques, that the clay and silt particles retained in the wetland sediments were aggregated, as hypothesised by Braskerud (2003). Do aggregates survive the transport in storm flooded streams? If they do this could explain why small constructed wetlands perform better than predicted from Eqs. 1 and 2. Since clay particles have enormous specific surface area and ability to sorb nutrients and pollutants, this knowledge will moreover provide valuable information for planners of environmental measures to mitigate loss of diffuse pollutants from arable fields. Micromorphological techniques that are based on the observation of thin sections made from undisturbed soils (or sediments) with a petro-

Table 1. Particle retention (%) in the constructed wetlands Berg and Kinn. *E* predicted by Eq. 1 and observed values ± SD (after Braskerud 2003).

Particle diameter	Berg		Kinn	
	E predicted*	*E* observed**	*E* predicted*	*E* observed**
< 0.6 µm	< 2	47 ± 21	< 1	19 ± 32
0.6–2 µm	2–17	62 ± 15	1–10	25 ± 26
2–6 µm	17–82	67 ± 11	10–63	31 ± 27
6–20 µm	82–100	82 ± 12	63–100	47 ± 26
20–60 µm	100	94 ± 21	100	69 ± 30
60–2000 µm	100	99 ± 11	100	89 ± 24

* predicted by Eq. 1.
** observed values ± SD (after Braskerud 2003).

graphic microscope (Stoops 2003) are often used in soil science to study the arrangement of soil particles and their mineralogy.

Materials and methods

The three wetlands selected for the study were all situated in southeast Norway, east of the Oslo fjord, with a distance of about 50 km between the sites. They were chosen because their behaviour is well documented in former studies (e.g., Braskerud *et al*. 2005). The Berg and Kinn wetlands were constructed in 1990 and the Skuterud wetland in 2000. They were all constructed by expanding the stream banks. Selected catchment and wetland characteristics are given in Table 2. All sites are located in areas with marine sediments where plains are intersected by ravines. The dominant soils are Gleysols and Cambisols (IUSS Working Group WRB 2006) with silt loam, clay loam or silty clay textures. At Skuterud, some moraine ridges with sandy texture also occur inside the catchment area. The agricultural fields at Kinn were artificially levelled in 1969–1975 by scraping material from the shoulder and summit and depositing it at the foot of the slope. This levelling resulted in the decrease of the organic matter content of the topsoil (Table 2). The soil at Berg had higher organic matter content (Table 2), which is probably related to its use in crop rotation with grassland and cereals while at the other sites the fields were used almost exclusively for cereals. The catchment at Skuterud was previously described in detail by Deelstra *et al*. (2005) and the Berg and Kinn areas by Braskerud (2001a).

The climate is continental at all sites, with about 5 months of frost per year. The mean annual air temperature is around 5 °C. January is the coldest month, with –5 to –6 °C and normally frozen topsoil. The mean annual precipitation ranges from 700 to 800 mm. Cereal production dominates in all cultivated areas, but some small areas are used for grass production for cows and horses.

Constructed wetlands are located in the stream at the outlet of the catchments. They consist of a sedimentation basin about 1-m deep and a wetland filter that is 0.5-m deep (Fig. 1). The length is approximately 250 m, 100 m and 65 m for Skuterud, Berg and Kinn, respectively. The ratio of wetland surface area to catchment area is smaller than 0.1% at all sites (Table 2). As a result, the hydraulic load is very high (Table 2) and the detention time short, less than 6 hours for the average annual runoff. Vegetation cover in the wetlands was approximately 50% in Skuterud, and more the 90% in Berg and Kinn. When wetlands are covered with more than 50% vegetation, resuspension of sediment in the small Norwegian wetlands is negligible (Braskerud 2001b).

At each site undisturbed soil samples were collected from the upper 10 cm of the sediments in the wetlands, under the water surface and from the upper 10 cm of the corresponding agricultural soil. The wetlands were sampled at different distances from the inlet and the agricultural soils were sampled upstream from the wetlands at different landscape positions, as shown in Table 3. Sampling was done in the summer of 2003 for Skuterud and in the summer of 2004 for Berg and Kinn in slightly moist soils. The sampling boxes measured 90 × 60 × 40 mm and consisted of an aluminium frame and two lids. The samples were collected by introducing the frame horizontally into a vertical section of the

Table 2. Selected catchment and wetland characteristics (compiled from Braskerud 2003).

	Catchment				Wetland		
Site	AreaCA (km^2)	Soil texture	Organic matter (loss on ignition %)	Cultivated (% of watershed)	Area A (m^2)	A/CA (%)	Hydraulic load QA^{-1} (m^3 m^{-2} yr^{-1})
Skuterud	4.5	Silty clay loam	3–6	61	2300	0.05	920
Berg	1.5	Silty clay	5–10	17	900	0.06	620
Kinn	0.5	Silty clay loam	3–7	27	350	0.07	680

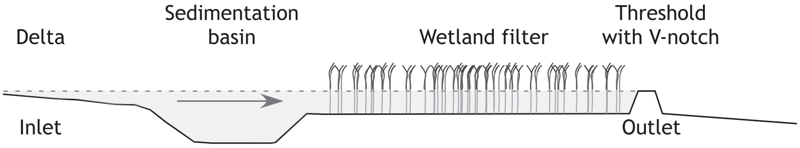

Fig. 1. Different parts of a constructed wetland. Depths were originally 1 m in the sedimentation basin and 0.5 m in the wetland filter (after Braskerud 2003).

soil and thereafter cutting it free before shutting the sampling box with the lids. The procedure is described by Murphy (1986). The sampling procedure was the same at all locations.

Thin sections (0.03 mm thick; 90 × 60 mm) were prepared from the undisturbed samples at the laboratory of Petrology and Mineralogy (Ghent University, Belgium) and studied using a polarising microscope. Observation was carried out in plane polarised light, which permits to clearly distinguish aggregates and coloured components, and in circular polarised light, which is very useful for estimating amounts of transparent minerals because the minerals never not show extinction. The terminology of the guidelines for analysis and description of soil and thin sections by Stoops (2003) was used for the micromorphological descriptions.

The amounts of aggregates and of single mineral grains with diameter larger than 0.02 mm were estimated on the thin sections from the wetland sediments and from the agricultural soils. Smaller units overlap each other in the 0.03 mm thick sections and become therefore difficult to distinguish.

Table 3. Position of the sampling sites in the the wetlands and in the agricultural areas. One ‘x’ for each sample.

Position	Skuterud	Berg	Kinn
Wetland			
Sedimentation basin	x	x	x
Wetland filter, near inlet	x	x	x
Wetland filter, near outlet	x	x	x
Cropland			
Plateau		x	x
Convex slope		x	x
Concave slope	xx	x	x
Plain, near stream	xx		

Results

Wetland sediment samples

The thin sections from all three wetlands were in general very similar. They show a clear grading according to size of the aggregates and mineral particles (Table 4), with decreasing size towards the wetland outlet (Fig. 2). The aggregates were rounded (Fig. 2) and their diameter ranged between more than 2 mm and less than 0.02 mm. Some aggregates were partly deformed. Fine silt and clay particles (finer than 0.006 mm) were only found as an undifferentiated mass inside the aggregates and not as layers.

In the sedimentation basins at all sites, stratification with alternating coarse-grained layers and fine-grained layers was observed (Fig. 3 and Table 4). The coarse-grained layers mainly consisted of Fe and Mn oxide nodules, few coarse single mineral grains (diameter ranging from 0.08 to more than 3 mm), fragments of stratified clay and aggregates of soil material (diameter between 0.2 and more than 2 mm). In the fine-grained layers small aggregates (diameter ranging from 0.04 to 0.6 mm) of soil material dominated. The single mineral grains and the nodules had in general a smaller diameter than the aggregates in the same layer (Fig. 2A–D). The boundaries between the layers were mainly very sharp.

Further down, in the wetland filters, only the aggregates richer in Fe were clearly visible (Fig. 4). Some stratification was observed but not as clear as in the sedimentation basin (Table 4). The size of the mineral grains and of the aggregates gradually decreased (Figs. 2 and 4) from the start to the end of the wetland filter, and the separated mineral grains and the nodules had in general a smaller diameter than the aggregates (Fig. 4A and B). In the samples collected closest to the outlet of the wetlands, the diameter of the aggregates was smaller than 0.1 mm and often smaller than 0.02 mm (Fig. 4C and D).

Agricultural soil samples

The soil thin sections from the agricultural fields were in general very similar at all three sites. All soils had a subangular or subrounded blocky microstrucuture and/or granular microstructure. The aggregates (Fig. 5) were more angular, had a rougher surface and were larger (diameter ranging between more than 5 mm and 0.1 mm) than the aggregates in the corresponding wetlands (Fig. 2A and C), but had similar mineralogical composition. The soil material was very homogeneous and was mainly composed of sand-sized mineral grains and Fe and Mn oxide nodules (Fig. 5B) embedded in the fine fraction. Fragments of a sedimentary layer, with strial b-fabric typical for parallel oriented clay particles were sometimes observed inside the larger aggregates in all sites. Root residues were commonly observed in the interpedal spaces (Fig. 5). Except for a higher amount of Fe and Mn oxide nodules in the plateau soils, no clear differences were found between the samples from different landscape positions.

Table 4. Size distribution (diameter, mm) of aggregates (x) and separate single mineral grains (o) in the different samples of the wetlands. (x and o: few; xx and oo: some; xxx and ooo: many).

	Size classes (mm)								
	> 1	1–0.6	0.6–0.4	0.4–0.2	0.2–0.1	0.1–0.08	0.08–0.06	0.06–0.04	0.04–0.02
Skuterud									
Sedimentation basin:									
Coarse-grained layer	x	xx	xx	x					
	o	o	oo	ooo	oo	o			
Fine-grained layer			x	x	xx	xxx	xxx	xxx	
					o	o	o	oo	
Start of wetland filter				x	x	xx	xx	xx	xx
						o	o	o	oo
Middle of wetland filter						x	xx	xx	x
								o	o
Wetland filter near outlet								x	xx
									oo
Berg									
Sedimentation basin:									
Coarse-grained layer	xx	xx	x	x					
			o	o					
Fine-grained layer				x	xx	xx	x		
					o	oo	oo	oo	o
Start of wetland filter							x	xx	x
								o	oo
Wetland filter near outlet								x	xx
									oo
Kinn									
Sedimentation basin:									
Coarse-grained layer	xx	x	x						
	o	oo	oo	oo	oo	oo			
Fine-grained layer				xx	xxx	x	x	x	
				o	oo	ooo	o	o	o
Start of wetland filter					x	x	xx	xx	x
					o	oo	oo	oo	o
Wetland filter near outlet						x	xx	xx	x
						o	o	oo	oo

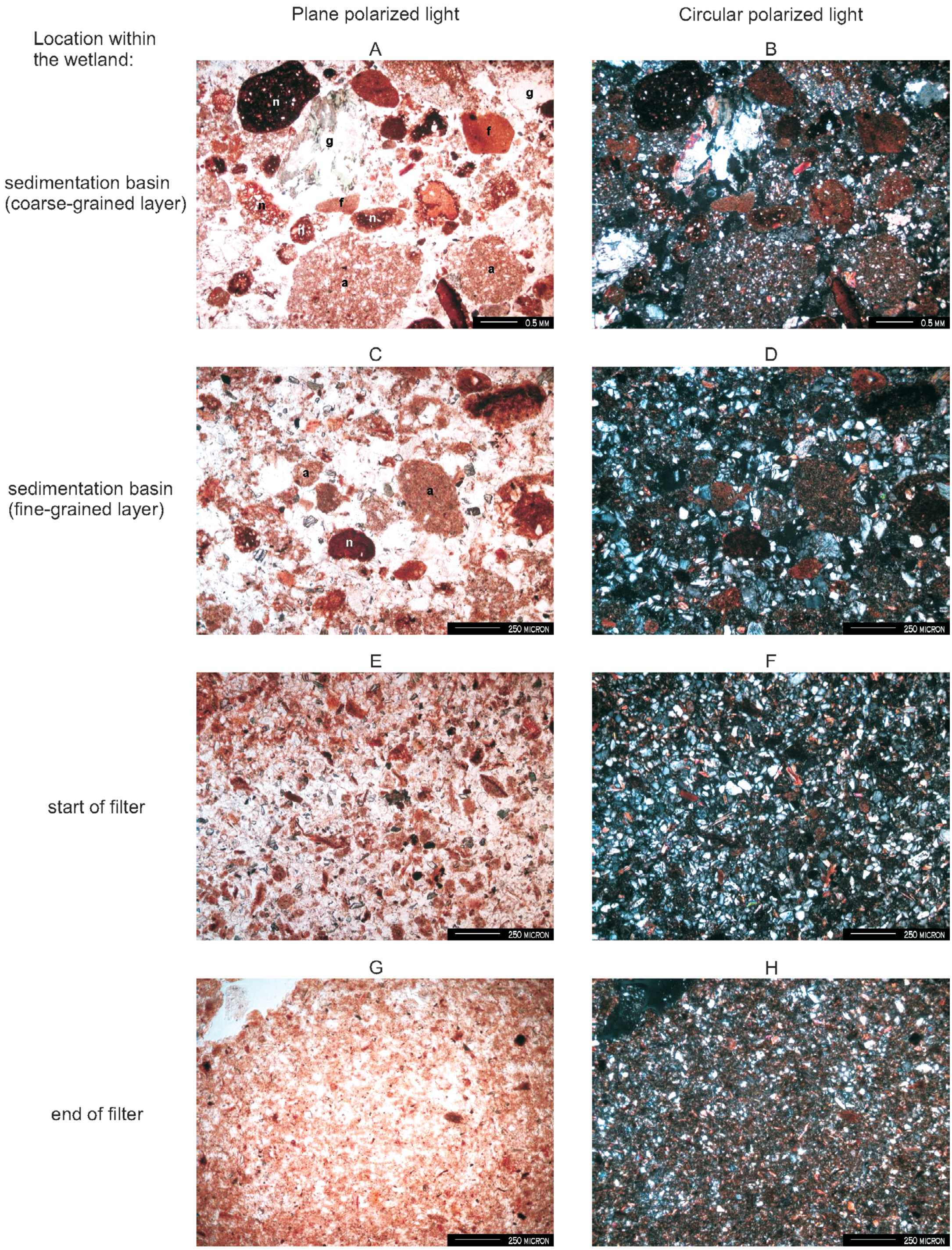

Fig. 2. Thin sections of the Kinn wetland, observed in plane polarised light (PPL) and circular polarized light (CPL), showing aggregates of soil material (a), mineral grains (g), Fe/Mn oxide nodules (n) and fragments of sedimentary layer (f). Note that the size of the different components decreases from the sedimentation basin to the end of the filter (from A/B to G/H) and that the aggregates are often larger than single mineral grains and nodules in the same layer (A & B, C & D).

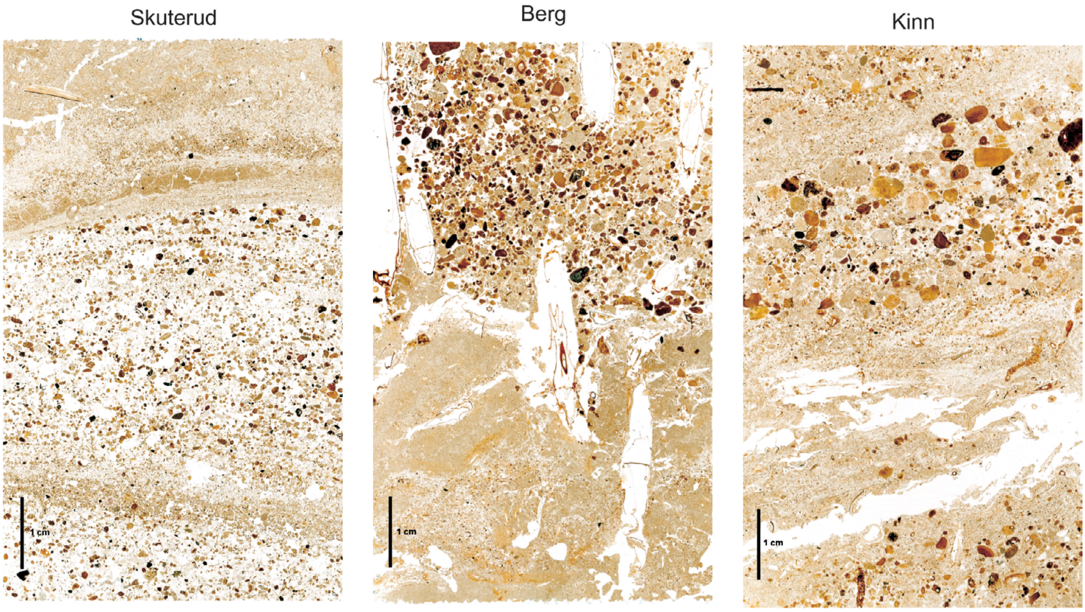

Fig. 3. Thin sections of the sedimentation basin in the three wetlands (scanned in transmitted light) showing the clear stratification of the sediments.

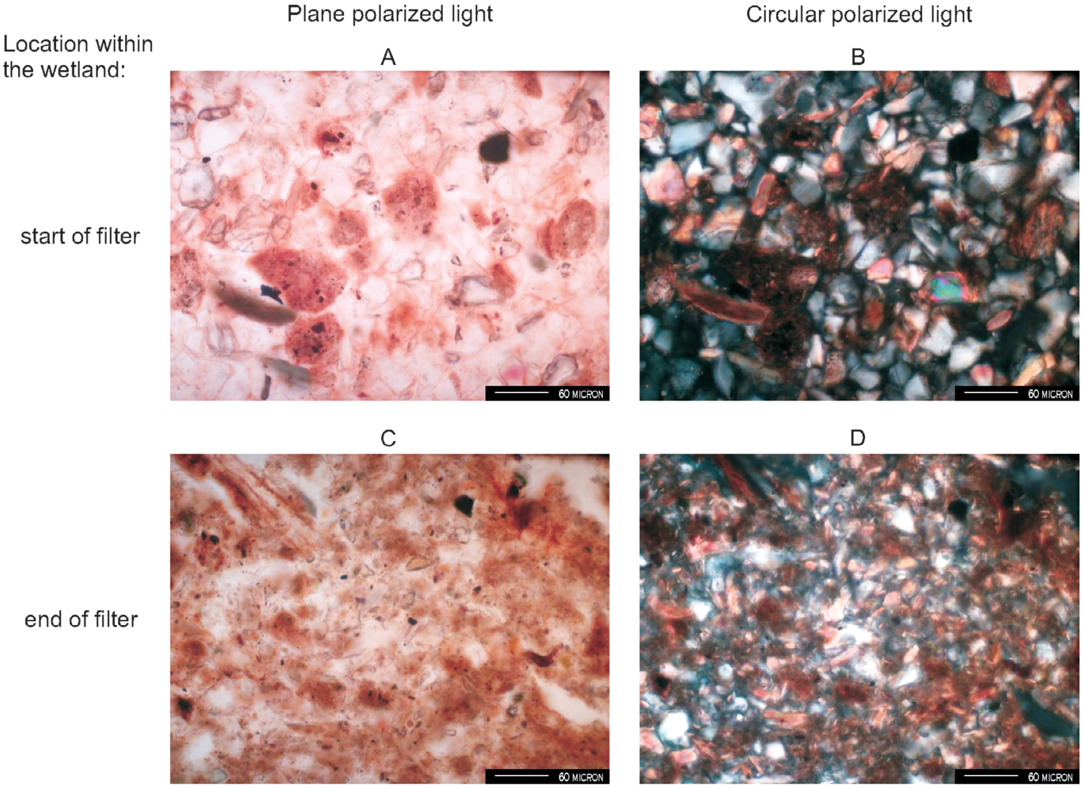

Fig. 4. Panels A–D show detailed views of panels E–H of Fig. 2. Note that the aggregates are larger than the single mineral grains and nodules close to them in the same layer.

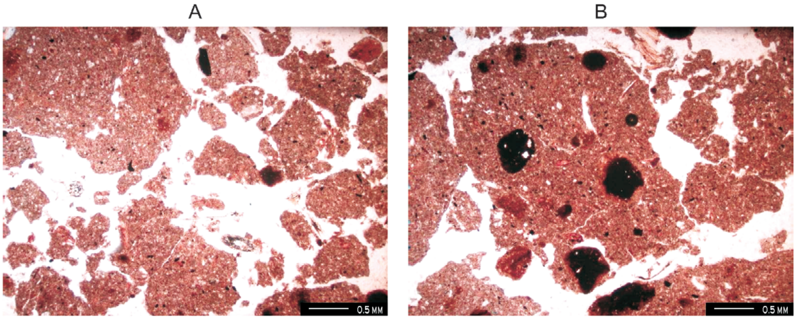

Fig. 5. Thin sections of the arable lands showing the microstructure of the soils: — **A**: subangular aggregates (PPL); — **B**: subangular aggregates containing Fe/Mn oxide nodules (PPL).

Discussion

In the thin sections of the wetland sediments, aggregates with the same composition as the corresponding catchment soil, but more rounded, were observed. This supports Braskerud's (2003) hypothesis that the high clay retention in small constructed wetlands is the result of clay and fine silt having settled as aggregates. However, the round shape of the aggregates in the wetlands shows that they have undergone erosion on the way from the agricultural site to the wetland where the sedimentation has taken place. The wetlands should therefore be constructed as close as possible to the fields to minimise the risk of breakdown of the aggregates in water before settling. The finer part of the eroded material, fine silt and clay, was most probably transported further because no layers with parallel orientated clay and aligned micas, which the sedimentation of such fine particles would create, were apparent in any of the samples studied.

Some aggregates appeared partly deformed, due to the pressure of the load of the aggregates above them and because aggregates become less stable in water saturation conditions. This is also the reason why only the aggregates richer in Fe and thus more stable, were clearly observed in the finer sediments (near the inlet). On the other hand, no layers with horizontal parallel oriented clay (strial b-fabrics) or alignment of elongated particles were apparent, not even in the thin sections near the outlet. These are characteristics typical for unconsolidated sediments (Stoops 2003) and should be present if clay and silt had settled as isolated, non-aggregated particles. Their absence, strengthen the above statement that most of the clay and fine silt present has settled as aggregates and not as isolated particles. Braskerud (2003) used Eq. 1 to determine the average clay particle settling velocity (w), on basis of the trap efficiency values (E) measured on water samples from the inlet and the outlet of wetlands. He concluded that the average clay particles settled as fine silt (2–6 μm) aggregates. However, the clay aggregates observed in the thin sections were actually larger than fine silt.

The observed gradient with decreasing diameter of the aggregates and other particles from the inlet to the outlet of the wetlands is due to the time factor: large particles settle before the small ones. The different sedimentation velocities of aggregates, mineral particles and nodules are due to their different densities. This explains the fact that the aggregates in the wetlands had generally a larger diameter than the single mineral fragments and the nodules of the same layers. Aggregates are less dense than mineral particles because they are porous and have a mineral and organic composition. Due to their heterogeneous composition, the determination of aggregate density is usually very difficult (Gregory 1997). Since single mineral grains have known density and their diameter can be measured using micromorphometric techniques, the occurrence of aggregates and single mineral grains in the same layer could be used to indirectly estimate the density of aggregates.

The size distribution of aggregates was rather similar in all wetlands (Table 4). This agrees with the values of the hydraulic loads, the ratio of wetland area to catchment area and the available settling time, which was also rather similar at all the sites (Table 2). However, the clay retention performance was better at Berg than at Kinn (Table 1). This is probably due to the fact that most of the fields around the Kinn wetland have been levelled and the aggregate stability of levelled soils is usually lower (Lundekvam and Skøien 1998). A large proportion of the fractions resulting from the breakdown of aggregates at Kinn was most probably too small to settle during the available settling time and followed the water out of the wetland.

The first order area Eq. 2 is used worldwide, even though the requirements for its use are often not completely fullfilled (Kadlec 2000). The present study adds a new restriction to the use of Eqs. 1 and 2: the presence of aggregates. As a result, using the results of textural analysis, which require clay dispersion pre-treatment, will not give the right clay retention prediction. Hence, methods for estimation of the actual aggregate settling velocity must be further developed (e.g., Stone and Walling 1996).

The presence of more or less intact aggregates in the wetland sediments can explain the equal or higher P content in the wetland sediments compared to the agricultural topsoil of the Berg and Kinn catchments (Braskerud 2002b). Although DRP (dissolved reactive phosphorus) is commonly regarded as the most crucial P fraction for euthrophication, particulate phosphorus is not without importance. Retention of particulate phosphorus is important because a large proportion of it can be dissolved and induce algal growth (Krogstad and Løvstad 1989, Uusitalo *et al*. 2003). It is also likely that aggregates play an important role for the retention of other pollutants adsorbed to particles, such as pesticides (Itagaki *et al*. 2000, Haarstad and Braskerud 2005) and heavy metals (McBride 1989, Alloway 1995).

The wetland sediments studied consisted mainly of aggregates similar to those found in the agricultural soils. Sediments excavated from filled wetlands would therefore probably be suitable for use in soil mixtures for agricultural land recycling.

Conclusion

The study of thin sections confirmed the presence of aggregates of soil material in wetland sediments. Clay and silt particles had settled as aggregates and not as isolated particles. Therefore results from dispersed textural analysis are not suitable as a basis for calculation of the retention of fine silt and clay in wetlands. Aggregates have higher settling velocity than single clay particles and control of the aggregates would benefit the wetland retention performance. To minimise the risk of breakdown of the aggregates during transport, wetlands should be constructed as close as possible to the fields.

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