Design considerations for increased sedimentation in small wetlands treating agricultural runoff

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Abstract Some suggestions to increase the sedimentation of non-point source pollution in small surface flow wetlands are presented. The recommendations are based on results from seven Norwegian constructed wetlands (CWs) after 3–7 years of investigation, and a literature review. The wetlands were located in first and second order streams. Surface areas were 265–900 m², corresponding to 0.03–0.4% of the watershed. Each CW had a volume proportional composite sampler in the inlet and outlet, in addition to sedimentation plates. The mean annual retention of soil particles, organic particles and phosphorus was 45–75%, 43–67% and 20–44%, respectively. Results showed that erosion and transportation processes in arable watersheds influenced the retention. Sedimentation was the most important retention process, and increased with runoff, because the input of larger aggregates increased. Retention of nitrogen did not follow the same pattern, and was only 3–15%. Making CWs shallow (0–0.5 m) can optimize sedimentation. The hydraulic efficiency can be increased by aquatic vegetation, large stones in the inlet, baffles and water-permeable, low dams. Vegetation makes it possible to utilize the positive effect of a short particle settling distance, by hindering resuspension of sediments under storm runoff conditions. As a result, the phosphorus retention in shallow CWs was twice that of deeper ponds.

Keywords Aggregates; hydraulic efficiency and load; nitrogen; phosphorus; sedimentation depth; soil particles

Introduction
Loss of soil particles, nutrients and pesticides from arable land has been of major concern for several years. Best management practice (BMP) on arable fields is the primary way to mitigate loss from watersheds. However, losses occur anyway, and secondary measures like buffer zones, ponds and constructed wetlands (CWs) can be an efficient supplement (Uusi-Kämppä et al., 2000).

This paper is a summary of several years of investigation and construction of small wetlands. The main focus has been to stimulate the sedimentation process. The retention of soil particles is a key factor, since phosphorus and many other pollutants are mainly particle-bound. It is a general agreement that particle sedimentation velocity, runoff and pond or wetland surface area influence the retention performance. This can be expressed in three commonly used models. For laminar flow, steady state conditions and a rectangular pond, the relative retention, E (%), for a particle is (Chen, 1975):

\[ E = 100 \frac{w}{AQ^{-1}} \]  

where \( w \) is the particle settling velocity (m s\(^{-1}\)), \( A \) is the CW surface area (m\(^2\)), and \( Q \) is the runoff from the pond (m\(^3\) s\(^{-1}\)). For fully developed turbulence, the retention is (e.g., Chen, 1975; Haan et al., 1994):

\[ E = 100 \left[ 1 - \exp\left(-wAQ^{-1}\right) \right] \]
where \( \exp \) is the value of \( e \) (2.718...). A model similar to (2) is the first-order area model (Kadlec and Knight, 1996):

\[
C_{\text{out}} = (C_{\text{in}} - C^*) \exp (-kAQ^{-1}) + C^* \tag{3}
\]

where \( C_{\text{in}} \) and \( C_{\text{out}} \) are concentration of pollutants in inlet and outlet (mg L\(^{-1}\)), \( C^* \) is the background 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, because \( E = 100 \left[ 1 - \frac{(C_{\text{out}} - C^*)(C_{\text{in}} - C^*)}{(C_{\text{in}} - C^*)^{-1}} \right] \), and that models [1, 2 and 3] use the inverse hydraulic load \( (AQ^{-1}) \).

For all three models retention is independent of depth, as stated by Hazen in 1904. Retention, however, increases as surface area (\( A \)) and particle sedimentation velocity (\( w \)) increases, and decreases as runoff (\( Q \)) increases. Hence, doubling the pond volume by a doubling of the surface area increases the retention in model (1) twofold, while a doubling of the depth does not affect retention. In the deep pond, the extra detention time is counteracted by a greater particle travel time (Kadlec and Knight, 1996).

Factors in the watershed influence CW-retention significantly (Braskerud et al., 2000). Hence, this paper shows how knowledge about the input of pollutants makes it possible to improve retention through CW localization and design.

**Methods**

CWs under investigation were located in different temperate and cold temperate climatic and arable regions in South Norway. CWs could contain up to 4 different components (Figure 1 and Table 1).

Watershed areas varied from 22 ha in CW-G to 150 ha in CW-A. Annual precipitation varied from 750 mm–1,400 mm in CWs A and G, respectively. Average annual hydraulic load \( (QA^{-1}) \) varied from 0.66 m d\(^{-1}\) (or m\(^3\) m\(^{-2}\) d\(^{-1}\)) in CW-G2 to 3.4 m d\(^{-1}\) in CW-D.

**Water flow measurements**

A V-notch weir was installed in the dam outlet. A logger using a pressure gauge recorded the discharge. The logger controlled a water flow proportional sampling system in the inlet and outlet. In CW-G an additional sampler was situated after the 3rd wetland filter,
providing data from “two” CWs; G1 and G2 (Table 1). On average, 11 sub-samples were collected daily and pumped to a sample container. A 1-litre sample was taken from the sample container, usually in 9- to 12-day intervals. Sampling throughout the entire year was only possible in CWs A, C, F and G1 and 2, which had heating cables to prevent frost in the pump and tubes. Sedimentation plates were placed in the vegetation filter(s). They were made of 25 × 25 × 0.9 cm plastic coated plywood. Sampling was carried out in June.

Analyses
Norwegian standard methods were used for measurement of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN). Dissolved-P was determined on 0.45 µm-filtered samples. Organic particles (org-SS) were measured by loss of ignition of TSS. A Coulter LS 230 laser measured the texture of TSS (Braskerud, submitted-a). For more details on the sampling program, analyses and watersheds, see Braskerud (2000; 2001; submitted-b) and Braskerud et al. (2000).

Results and discussion
Aggregates and sedimentation velocity
Retention of particles can be predicted by using model (2). In Figure 2 the predicted retention of particles with diameter 0.6, 2, 6, 20 and 60 µm is shown as lines. The same was done by Novotny and Chesters (1981). Sedimentation velocity is estimated by Stoke’s Law for water temperature 7°C, and specific gravity of particles 2.65 g cm –3. As an example, Figure 2 shows that the predicted average retention of 2 µm particles, which is the largest clay particle, should have been 17% for the average AQ –1-value 76,000 m2 m–3 s–1. The hydraulic load decreases to the right hand side in the figure. Observed retention of clay particles in composite sample events are points in Figure 2.

The average observed clay retention was 57%, which is more than three times higher than predicted by model (2). Since average A, Q and E are known in every composite sample, model (2) can estimate w. The data in Figure 2 show that the clay particles behaved as fine silt and medium silt with respect to sedimentation velocity. Several investigations show that particles in streams and rivers are transported as flocs or aggregates (e.g., Droppo and Ongley, 1994; Eisma, 1993). Floc and aggregate are often used synonymously, because they may be difficult to distinguish (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.

Suspended solids were probably dominated by aggregates (Braskerud, 2001). Transport in streams most likely leads to a break-up of aggregates. Thus, particle transport should be kept at a minimum, and rather small watersheds are preferable for CWs.

![Figure 2](https://iwaponline.com/wst/article-pdf/45/9/77/425638/77.pdf)
Runoff and sedimentation velocity

According to models (1), (2) and (3), retention of all types of suspended solids decreases with increasing runoff (Q).

However, as Q increased, Braskerud (submitted-a) showed that soil particles and aggregates with higher sedimentation velocities entered the CWs. As a result, the retention often increased with increasing Q. This was also observed for total phosphorus (Braskerud, 2000) and organic particles (Braskerud, submitted-b). For clay particles (Figure 2) and total suspended solids (Figure 3), however, the positive effect of increased Q was not statistically significant. Still the data show that retention does not decrease with increased hydraulic load as expected. Hence the models (1), (2) and (3) incorrectly predict retention, because they do not include the effect of soil erosion processes in the watershed.

Since CWs often have the best retention performance under storm runoff situations, they should be located in the low-order streams, even though Mitsch (1992) showed such CWs were unpredictable. Location beside the streams is unfavorable, since by-pass water will remain untreated. Even though hydraulic loads as high as 26 m d⁻¹ may occur, some particle retention will occur (Braskerud et al., 2000).

Table 2 summarizes some results from 3 to 7 years of investigation. The highest relative retention was found in the CW-G2, which had the highest surface area : watershed area ratio (Table 1), even though CW-A also had high performance for all variables except nitrogen. CW-C demonstrated the lowest particle retention. Smaller aggregates, due to low aggregate stability of the topsoil, are likely to explain the low retention in this CW (Braskerud, submitted-a).

The minimum phosphorus retention was observed in CW-F, as a result of a high content of plant-available P (P-AL) in the topsoil. Hence, only 52% of input TP was particle-bound (84% in the other CWs). As a result, sedimentation had least effect in CW-F. Since sedimentation is the most important retention process in small CWs, the retention of soluble-P is insignificantly affected.

Table 2

<table>
<thead>
<tr>
<th>Retention</th>
<th>k m yr⁻¹</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>%</td>
<td>g m⁻² yr⁻¹</td>
</tr>
<tr>
<td>45–75</td>
<td>16–83 × 10³</td>
<td>339–727</td>
</tr>
<tr>
<td>Org-SS</td>
<td>43–67</td>
<td>6–8 × 10³</td>
</tr>
<tr>
<td>TN</td>
<td>3–15</td>
<td>26–285</td>
</tr>
</tbody>
</table>
A similar effect was seen for nitrogen. The N-retention was dominated by organic-bound nitrogen (Braskerud, submitted-b). Organic-N, however, accounted for only 28% of TN. Hence, nitrogen retention was low. Most of the N-turnover involves microbial processes like nitrification and denitrification (Kadlec and Knight, 1996). These processes need a longer time than was available in the small CWs. Hence, the highest retention of nitrate and dissolved-P was found in the largest CW-G.

The first-order area removal constant (k) usually followed the same pattern as the retention in the individual CWs. The background value (C*) was set to 1.0–2.3 mg L⁻¹ for nitrogen, and 0 for the other variables. Since sedimentation is the most important retention process in small CWs, k is an estimate of the sedimentation velocity (w). Braskerud (submitted-a) estimated median w for coarse clay particles (0.6–2 µm). It was 378 and 173 m yr⁻¹ for CWs A and C, respectively. According to Stoke’s Law w should have been 6–79 m yr⁻¹. Hence, aggregates increase the sedimentation even under storm runoff events. However, aggregates with low stability have lower w.

Soil particle concentration

It is known that sedimentation velocity increases with the concentration of suspended solids (Eisma, 1993). Hence, unpolluted water from e.g. forests, should be by-passed. This keeps runoff intensities lower and the concentration of pollutants higher. Particle concentration often increases in the early phases of a storm event (Figure 4). Sedimentation of this first flush should be easy, since concentrations are high and runoff (Q) low. The higher flow peak, however, will easily disturb retention, unless soil particles have reached the CW-bottom. Hence, CWs should be shallow to allow rapid settling.

Dams

The use of low embankment dams or permeable dams (Figure 5-A) results in short settling distances. An embankment dam is filled with earth and covered with plastic, unless the soil is clayey. A fiber cover is needed between earth and stones, to prevent water from eroding the earth core. The stone coating should include stones large enough to resist destruction by storm water events.

A permeable dam is created if the earth core is replaced with small stones and pebbles. No plastic is used, and a fiber cover is used in the same way as shown in Figure 5-B. The
permeable dams can make the CWs very shallow in low Q-situations. As Q increases, the water table increases, because Q exceeds the hydraulic conductivity in the permeable dam. Permeable dams utilize short settling distances for the first flush particles, and the increasing depth mitigates resuspension of the sediment during the peak runoff situations. In addition, the surface area (A) increases. Unfortunately, particles will reduce the hydraulic conductivity in the permeable dam with time. Moreover, as sections in the dam become clogged, preferential flows are stimulated, and short-circuit flow may be created. Hence, if a stream is particle-rich, a permeable dam should not be the first dam in the CW. One or several parallel V-shaped dam constructions are an alternative.

A special version of the permeable dam is the “footbridge” dam (Figure 5-B and C). Large stones are placed transversely to the water flow, for example on top of a low embankment dam (Figure 5-A). The gap between the stones (Figure 5-C) influences the backwater, or time delay of the water. The “footbridge” is a handy place to cross a CW. In addition, the stones can be used to increase the hydraulic efficiency where needed.

Depth and vegetation
The positive effect of shallow depth was supported in a comparative study of phosphorus retention in ponds and CWs. Phosphorus is mainly attached to particles, hence sedimentation is very important. The ponds were often deeper than 1 metre, and vegetated only on the banks. CWs were the same as presented in this paper, while the ponds were located in Sweden and Finland, with lower specific runoff. Details are outlined in Uusi-Kämppä et al. (2000). Results indicate that depth is important (Figure 6). Phosphorus retention in CWs was twice the retention in ponds, and the difference was statistically significant. Water velocity on the sediment surface increases as depth decreases. Resuspension of the sediment under high runoff situations is the main argument for not building shallow constructions. Resuspension was detected in two situations in CWs:

1. When CWs A, B, C and D had less than 20% vegetation cover, approximately 40% of the sediment was resuspended. However, as vegetation cover increased to approximately 50%, resuspension was insignificant (Braskerud, 2001). As a conclusion, vegetation makes it possible to utilize the positive effect of a short particle settling distance in shallow ponds, since it hinders resuspension. Hence, CW depth should be adjusted to optimal plant growth, e.g. 0.5 m.

2. The overflow zones in CWs have a double function. First, water is oxygenated. Second, under low flow situations soil particle retention increases due to low settling distance. This should be positive for small size particles. However, as runoff increases, sediments are resuspended and lost. As a conclusion, an outlet basin is built after overflow zones to catch resuspended sediment. Overfilled CWs will probably act as overflow zones.

Surface area and hydraulic efficiency
According to model (1), retention increases with increased surface area (A). However, the effective area involved is often less than A. If the hydraulic efficiency is set to 1.0 the whole
area is used equally. Figure 7 shows how the hydraulic efficiency changes for different ponds using a two-dimensional hydraulic model, MIKE-21 (Persson et al., 1999). Persson et al. showed that ponds with a width to length ratio of 1:4 or less need adjustments in the inlet to promote good hydraulic efficiency. Wide dams in the outlet would be able to increase the hydraulic efficiency even more.

The positive effect of baffles was already known to Hazen (1904). Vegetation cover is also positive. Hydraulic efficiency increased from 0.32 to 0.64 if vegetation was used in the pond (Persson et al., 1999). An analysis of the sediment distribution data in the wetland filter in CW-A (Braskerud, 2001), showed that “hydraulic efficiency” was 0.78 and 0.86 for the winter and summer half-years, respectively. Note that dead vegetation stands as a bristle under the ice cover in winter. Some experiments show that vegetation creates short-circuits or preferential flow, due to differences in plant density (e.g., Fennessy et al., 1994). This is also seen in the small CWs under low flow situations. However, under high runoff situations, when the input of pollutants is largest, the preferential flow canals are too small, and more of the CW-width is needed.

Surface area and maintenance
For all parameters under investigation, CW-G2 had the highest relative retention (Table 2). Hence, as the ratio of surface area (A) to watershed area increases, retention increases (Figure 6). Flooding areas is a possible way to utilize shallow depth and large A. For example, side banks made for easy excavation of the sedimentation pond could be constructed for temporary flooding under storm runoff situations. Moreover, using a
permeable dam in the stream could flood suitable areas. Mitsch (1992) also suggested temporary flooding.

Annual average soil loss varied from 580 to 4,760 kg ha\(^{-1}\) for arable land in the F and C watersheds, respectively. Constructors of wetlands should be aware of the possible filling rate. An easy to empty sedimentation basin should always be located in the CW-inlet for coarse silt, sand and pebbles (Figure 1). Figure 8 shows the filling rate of the wetland filters. Originally, water depth was approximately 50 cm in the wetland filter. CW-D is overfilled after 9 years. It is the smallest wetland compared to the watershed area. This example shows that it is often more convenient to construct a large wetland in the first place, because it requires less maintenance. Sediments from CWs in arable watersheds can be re-used as top-soil, unless some sort of industrial pollution has contaminated it. The contents of clay, organic matter and phosphorus are usually the same as, or even exceed, the original topsoil.

Conclusions

Small CWs are capable of retaining soil particles and pollutants attached to these through sedimentation, even though retention models (1), (2) and (3) imply otherwise for clay particles. Retention performance in CWs can be increased if:

- Measures to mitigate aggregate break-up are considered. Keep transport distances from arable fields to CWs short. Hence, the particle sedimentation velocity is kept high. If CWs are located in the streams, sedimentation velocity often increases with runoff due to loss of larger aggregates in the watershed.
- The runoffs that influence the detention time are kept to a minimum. If possible, unpolluted water from, e.g. forests, is by-passed. This keeps runoff intensities lower and the concentration of pollutants higher.
- The CW-surface area is made as large as possible. As a general rule of thumb, Norwegian CWs should be at least 0.1% of the watershed area in arable areas. Hydraulic considerations must be taken into account. Hydraulic efficiency increases by using dams, stones and baffles. Furthermore, the layout serves a multifunctional use if it is aesthetic and is adjusted for a variety of plant and animal life.

CWs perform better than ponds because:

- they are shallow, which gives particles a short settling distance;
- they are vegetated, which mitigates resuspension of sediments.

![Figure 8](https://iwaponline.com/wst/article-pdf/45/9/77/425638/77.pdf)

**Figure 8** Annual mean sedimentation in the wetland filters based on sedimentation plate data in the four CWs.
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References


