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Influence of small constructed wetland on surface water quality

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Introduction

Loss of soil particles, nutrients and pesticides from arable land may harm streams and lakes. Use of constructed wetlands (CW) is often regarded as an efficient and maybe the only applicable measure for reduction of diffuse pollution in streams. The objective of this chapter is to show how small CWs can contribute to cleaner waterways through sedimentation of particles and retention of P, based on a review of research on constructed wetlands in Norway. The research referred here was conducted from 1995–2005, resulting in widely used guidelines for the construction of constructed wetlands under Norwegian conditions. For more details on the sampling programme, analyses and watersheds see Blankenberg et al. 2006; Braskerud 2001a, b; 2002a, c and 2003; Braskerud et al. 2005b. This chapter explain the background for these guidelines, based on research and monitoring of the cleaning effect of several wetlands.

The conditions for agriculture and runoff from agriculture in Norway differ much compared with many other countries in northern Europe. Sloping Norwegian topography results in higher erosion and higher phosphorus losses than in neighbouring countries. In a comparative investigation between the Nordic countries, including the Baltic States, soil losses from Norwegian agricultural watersheds were normally considerably higher (Vagstad et al. 2004). Normal annual soil losses in Norway were 400–1000 kg/ha for agricultural land, while the losses in the other countries were below 200 kg/ha. The annual losses of Phosphorus in Norway were normally 1500–2500 g/ha, but often below 500 g/ha in the other countries. The particles mainly came from surface erosion, which meant that they were rich in Phosphorus. These conditions should make CWs a very efficient measure for P-retention. Small Constructed Wetlands were implemented in the agricultural landscape in Norway to reduce the content of particles and phosphorus in natural streams and lakes. They were normally placed near the agricultural areas, in creeks or outlets of drainage systems in watersheds dominated by agriculture.

The first Constructed Wetlands were made in 1990. From 1994 records have been kept on the establisment of Constructed Wetlands, as subsidies from the Ministry of Agriculture in Norway have been given for their construction. In the years 2001–2010 nearly 100 wetlands were constructed each year. At present, Norwegian agricultural regulatory authorities subsidises wetland construction with approximately 70% of the construction costs. Throughout the last decade 1000 CWs were grant-aided.

Methods

This chapter presents results from several wetlands, each monitored by water proportional composite sampling in the inlets and outlets. Sedimentation traps and sedimentation plates were placed in 6 wetlands to study the distribution and characteristics of the sediment. In addition, the redox potential was monitored in one CW to study whether it influenced the loss of P.

We present also some results on nitrogen retention, even though nitrogen pollution is not regarded as a significant threat to fresh water in Norway. We also have some results on pesticide retention from two wetlands.

Results and disciussion

Normally a large CW-surface area is required to achieve good results. However, the small Norwegian farms and the hilly landscape, makes it impossible to set aside large areas for wetlands. Consequently, small wetlands of approximately 0.1% of the watershed area have been constructed, even though several models (Chen 1975; Haan et al. 1994; Kadlec and Knight 1996) predicted little retention of particles and P due to their small dimensions.

The retention of soil particles is a key factor, since P and many other pollutants are mainly particle bound. It is generally agreed that particle sedimentation velocity, runoff and pond or wetland surface area influence retention performance. This can be expressed in a commonly used model; the first-order area model (Kadlec and Knight 1996):

$$C_{out} = (C_{in} - C^*)\exp(-k\,AQ^{-1}) + C^* \qquad \text{(Model 1)}$$

where:
C_{in} and C_{out} are concentration of pollutants in inlet and outlet ($mg \cdot l^{-1}$). C* is the background value ($mg \cdot l^{-1}$) and k is the removal rate constant ($m \cdot s^{-1}$). Note that the constant k is equal to the settling velocity for retention of suspended soil particles.

The retention is independent of depth, as stated by Hazen in 1904. Retention 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, while a doubling of the depth does not affect retention.

Design of Norwegian wetlands

The investigated CWs were located in different temperate and cold temperate climatic and agricultural regions in Southern Norway. The examined CWs contain up to four different components (Figure 13.1 and Table 13.1). Most studies were conducted in the oldest wetland, type CW-A (Table 13.1).

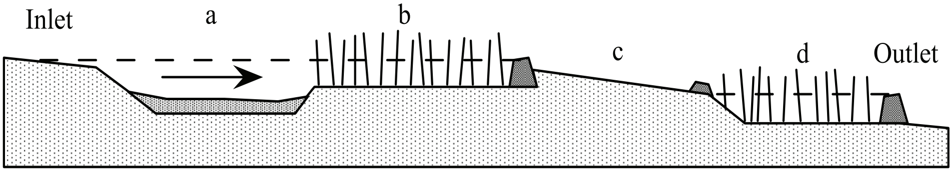

FIGURE 13.1. Components used in Norwegian constructed wetlands: (a) sedimentation pond, (b) vegetation filter, (c) overflow zone covered with vegetation or stones and (d) outlet basin. Often low dams separate CW-components. Depths were originally 1 m in a, 0.5 m in b, 0 m in c and 0.5–0.8 m in d

The CWs were tested in six agricultural watersheds varying in size from 22 ha in CW-G to 150 ha in CW-A. The dominating soil types were silty clay loams in watersheds A-D, silty moraine in F and G, and silty sand in L. Annual precipitation varied from 750 mm to 1400 mm in CWs A and G, respectively. Average annual hydraulic load ($Q \cdot A^{-1}$) varied from $0.66 \cdot m \cdot d^{-1}$ (or $m^3 \cdot m^{-2} \cdot d^{-1}$) in CW-G2 to $3.4\ m \cdot d^{-1}$ in CW-D. A typical Norwegian watershed includes more than 50% forest (Table 13.1).

TABLE 13.1. Characteristics of the constructed wetlands (CWs) and watersheds (wat.)

CW	Year of construction	*A* (m^2)	CW component	*A*/wat. A (%)	Wat. A (km^2)	Agricult. (%)
A	1990	900	a b	0.06	1.48	17
B*	1990	630	a b	0.07	0.86	11
C	1990	345	a b	0.07	0.5	27
D*	1990	263	a b	0.03	0.9	28
F	1994	870	a c b b c b	0.08	1.03	14
G#	1993	840	a b b b c c c b	0.38	0.22	99
L*	2001	1 200	a b:c,b,x–y:b	0.15	0.8	88

* Only water sampling through the summer season. CW components see Figure 13.1.

\# CW-G was monitored half way (G1), and at the outlet (G2). G is G2 if nothing else is stated.

Hydraulic load and soil particle retention

The average observed clay retention was 57% in CW-A, which is more than three times higher than predicted by Model 1. A similar result was observed in CW-C. The data show that the clay particles behaved as fine silt and medium silt with respect to sedimentation velocity (Figure 13.2). Suspended solids were probably dominated by aggregates (Sveistrup et al. 2008). Transport in streams most likely leads to a break-up of aggregates. Therefore, particle transport distance should be minimized, and this can be achieved by incorporating CWs into small watersheds.

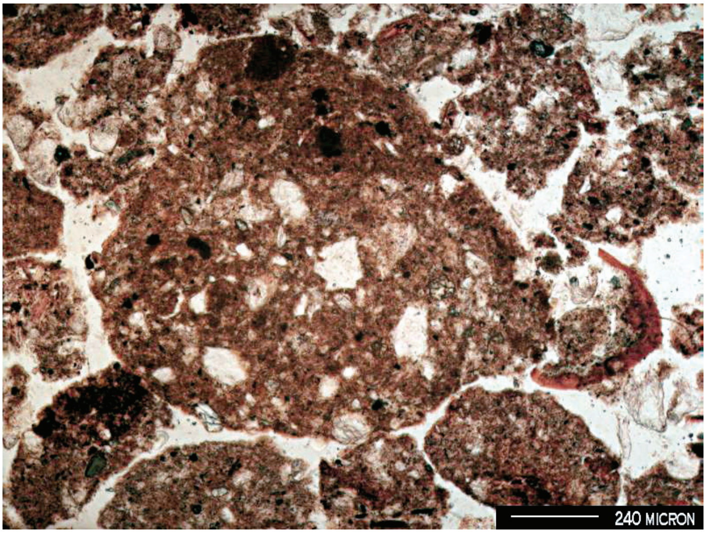

FIGURE 13.2. The high clay retention in small constructed wetlands is the result of clay and fine silt having settled as aggregates. The round shape of the aggregates in the wetlands shows that they have undergone erosion on the way from the agricultural site to the wetland where the sedimentation has taken place (photo: T. Sveistrup)

Hydraulic load and phosphorus retention

According to Model 1, retention of all types of suspended solids decreases with increasing runoff (*Q*). However, as *Q* increased, Braskerud (2003) 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 P (Figure 13.3). For clay particles and total suspended solids, 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 one would expect. Hence Model 1 incorrectly predicts retention, because it does not include the effect of soil erosion processes in the watershed.

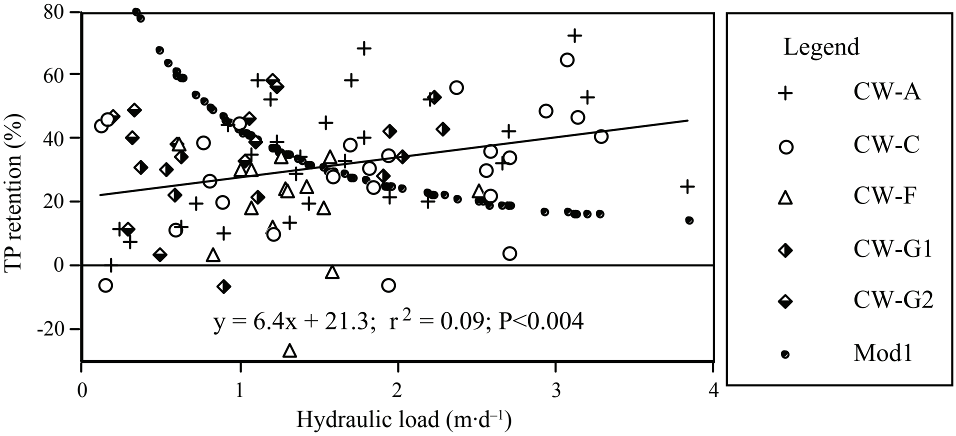

FIGURE 13.3. Observed relationship between P-retention (%) and hydraulic load ($Q \cdot A^{-1}$) for the constructed wetlands (CWs), and according to the first-order area model, (Mod1) with k = 204 and C* = 0. The data is retention per season (three months). Negative retention was net loss of phosphorus from the CWs (after Braskerud 2002a)

Since CWs often have the best retention performance under storm runoff conditions, they should be located in low-order streams, even though Mitsch (1992) reported that such wetlands were somewhat unpredictable. Locations next to streams are not favourable, since by-pass water will remain untreated. Even though hydraulic loads as high as 26 $m \cdot d^{-1}$ may occur, some particle retention will occur (Braskerud et al. 2000).

Table 13.2 summarises the results. The highest relative retention was found in the CW-G2, which had the highest ratio of surface area to watershed area (Table 13.1), even though CW-A also had high performance. Constructed wetland-C demonstrated lowest particle retention. Smaller aggregates, due to low aggregate stability of the topsoil, are likely to explain the low retention in this CW (Braskerud 2003). The minimum P retention was observed in CW-F, as a result of a high content

TABLE 13.2. Annual average hydraulic load (Q/A), and retention of soil particles and phosphorus for four small wetlands

CW	*Q/A* (m/d)	Soil particles		Total phosphorus	
		Relative (%)	Specific ($g/m^2/year$)	Relative (%)	Specific ($g/m^2/year$)
A	1,7	66	83	42	51
C	1,9	45	89	27	58
F	1,8	62	36	21	37
G	0,8	74	22	44	46

of plant available P (P-AL) in the topsoil. Only 52% of input TP was particle bound in contrast to 84% in the other CWs. As a result, sedimentation had the least effect in CW-F.

Phosphorus in the wetland sediment

The average TP content in the sediments was the same in CWs A and C. For wetlands F and G, the P content in the sediments was higher (Figure 13.4). Generally, the P content in wetland sediments was higher than in the surrounding topsoil. In watershed F, however, the variability of the P content in the topsoil was higher than in the topsoil in the other watersheds. In addition, the arable fields are more scattered and the P-rich topsoil may not contribute significant to the wetland sediment. As a result, it is not possible to exclude F from the general trend mentioned earlier.

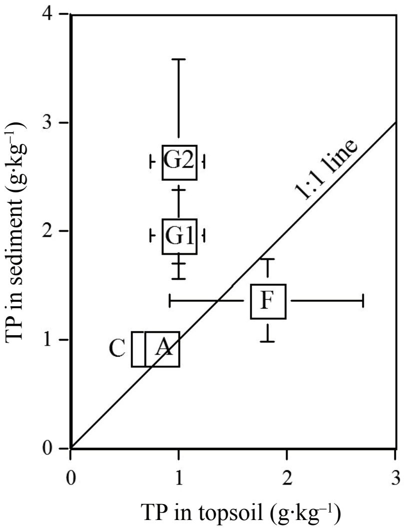

FIGURE 13.4. Relationship between total phosphorus (TP) content in the topsoil and in wetland sediments of CWs A, C, F, G1, and G2 (±std. dev.). The 1:1 line indicates equal TP content in soil and sediment (Braskerud 2002a)

Even though the P contents in the wetland sediments were high, P contents on suspended solids in the stream were even higher (median from 0.11 to 0.64% of TSS, Braskerud, 2002a). Hence, the most P rich fraction was not retained, probably because soil particles or aggregates were too small for sedimentation.

Redox potential and phosphorus retention

In general particle bound P typically settled in the small wetlands studied. The sorption behaviour of P is, however, redox-sensitive, and bound P may be remobilized in periods with low redox potential. The redox potential in the outlet water of CW-A was measured throughout a monitoring period of 3.5 years (Braskerud et al. 2005b). Values were always positive and often high (median 550 mV) indicating aerobic conditions. Runoff and redox potential data for 2001 are shown in Figure 13.5. High hydraulic loads (average 2.3 m·d^{-1}) supplied the wetland with sufficient water to keep the surface water aerobic. The redox-potential in sediment without vegetation was measured occasionally with a similar electrode. It was always negative (below –200 mV) suggesting anaerobic conditions. When redox potential is below approximately 100 mV, Fe(III) is reduced to Fe(II), and iron bound P is released.

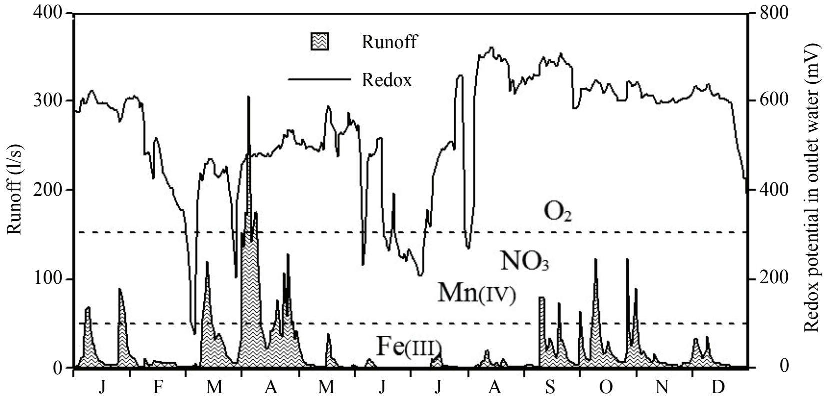

FIGURE 13.5. Daily observations of runoff and redox potential in CW-A throughout 2001. The dominating electron acceptor at a given redox potential is shown

Due to the high redox potential in water, retention of P was significant, and periods with P loss from the CW, were rare. Loss was observed during less than 19% of the total period of time. Six out of 68 episodes had a net loss of TP. The net loss was less than 5% of the specific retention. The relative loss decreased as the redox potential increased. Penn et al. (2000) has shown that an oxidized micro layer exists in the upper lake sediment under well-mixed conditions in the spring and fall. This layer partly inhibits the release of sediment bound P. The redox electrode used was too large to detect the mm-thin layer. Even though the redox potential was relatively high, the oxidised micro-layer may be reduced in periods with low runoff, which may result in P release.

Soluble P-retention in mineral filter

Much of the P is particle bound. In summer with low water flow, the concentration of dissolved P is higher, in addition CW sediments can leak phosphorus during low flow situations (Figure 13.5). A filter of *Leca Filtralite P* (0,5–4 mm) was added close to the outlet of a wetland similar to CWs A-D (Table 13.1). The filter was dimensioned for low-flow situations only (0.2 $l \cdot s^{-1}$). The water stays in the filter for 20 hours. For higher runoff situations runoff goes through a bypass. Preliminary results showed a 50–80% reduction of phosphorus (input 0.03–0.3 mg $P \cdot l^{-1}$). A similar study was done in CW-L (Figure 13.6) (Braskerud 2005a), with a filter of Fe-rich, coarse sand. The retention of soluble P was 55% (input 0.3 mg·P l^{-1}). The mineral filter did not perform well for nitrogen and pesticide retention.

Mineral filters should be located at the end of the wetlands to prevent clogging of soil particles.

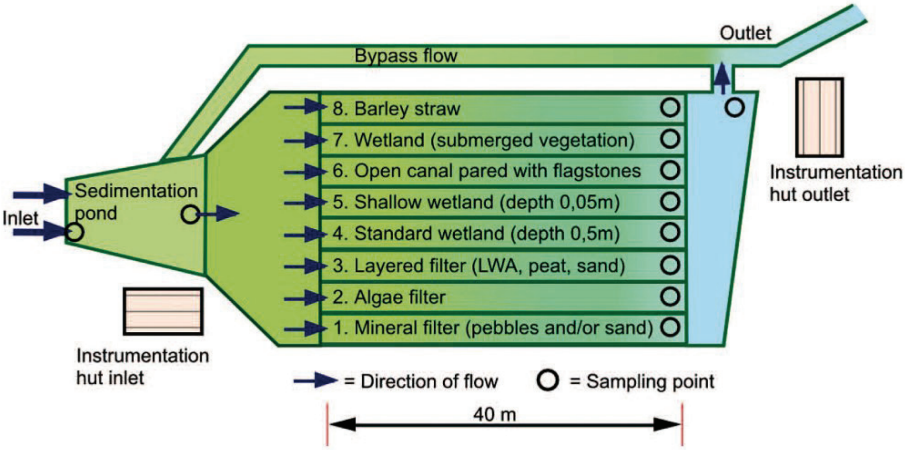

FIGURE 13.6. The constructed wetland L (Lierdammen), consists of eight different types of CW-filters

Wetland depth and vegetation

Phosphorus is usually attached to particles, so the sedimentation process is very important. The positive effect of shallow wetland depths was supported in a comparative study of P retention in ponds and CWs (Uusi-Kämppä et al. 2000) (Figure 13.7). These ponds, located in Sweden and Finland, were often deeper than 1 meter, and vegetated only on wetland banks. The CWs were similar to those presented in this report.

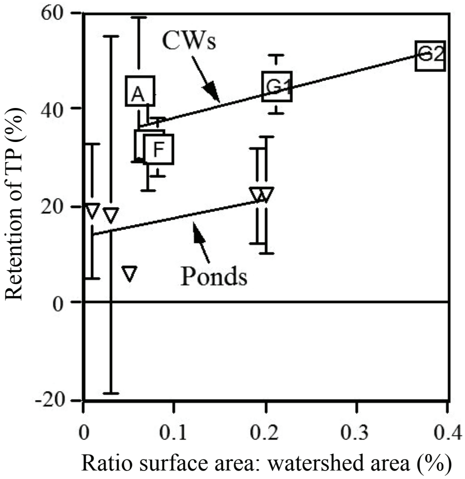

FIGURE 13.7. Retention of total phosphorus (±std dev.) in CWs and ponds (Modified from Uusi-Kämppä et al. 2000)

Phosphorus retention in CWs was twice that of ponds. Resuspension of sediment under high runoff conditions is the main reason for not building shallow CWs. Resuspension was detected in two situations in the studied CWs:

(i) 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 2001a). As a conclusion, vegetation makes it possible to utilize the positive effect of a short particle settling distance in shallow ponds, since it prevents resuspension. Thus, CW depth should be adjusted to optimal plant growth, e.g. 0.5 m or less.

(ii) The overflow zones in CWs have a double function. Firstly, water is oxygenated. Secondly, soil particle retention increases due to low settling distance under low flow conditions. This should be positive for small size particles. However, as runoff increases, sediments are resuspended and lost. Based on observations, an outlet basin built after overflow zones can provide a means of recapturing resuspended sediment. Overfilled CWs will probably act as overflow zones.

In addition, macrophytes increased the hydraulic efficiency by reducing short-circuit or preferential flow under storm runoff situations (Braskerud 2001a).

Nitrogen retention

Constructed wetlands (CWs) in Norway are often too small to achieve high relative N-retention. Figure 13.8 shows how the TN-retention increases as the ratio of CW surface area/watershed area increases. Often the Norwegian wetlands cover only 0.1% of the watershed area.

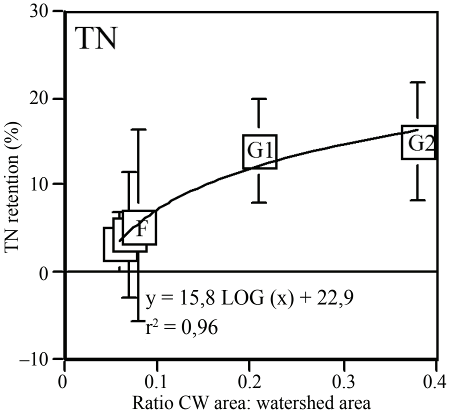

FIGURE 13.8. The nitrogen retention increases as the CW surface area increases in wetlands A, C, F and G1&2 (Braskerud 2005a)

In wetland L (Figure 13.6) we have tried to improve the N-retention by using 8 different types of filters. Filter 4 is like the average Norwegian vegetation filter, and serves as our reference. The average total-N retention through the experimental wetland was 17% for the period of May – September in 2003, but only 2% in the same period in 2004. Lower retention in 2004 was probably caused by higher hydraulic load that year. The organic filters, like barley straw, performed better than the mineral filters and the standard CW. The barley straw filter (L8, in Figure 13.6) had the highest TN-retention performance both in 2003 and 2004 (48% and 13%, respectively) (Blankenberg et al. 2007b). However, the organic filter decreases the redox potential in the water. As a result, this filter had no net phosphorus retention (Braskerud 2005a).

Nitrate is the dominating N-fraction leaving the Norwegian agricultural watersheds, followed by organic-N and ammonia. Settling of organic N is the most important retention factor in the small wetlands. Long term study of CWs A-G showed a decline in nitrogen retention as the wetlands aged, presumably because trapped organic nitrogen was converted to inorganic forms that were exported from the wetlands (Braskerud 2002c).

Pesticide retention

Where pesticides are used, loss of pesticides to the environment is likely (Braskerud 2005a). Small constructed wetlands (CWs) in first and second order streams can reduce the loss of pesticides, since water purification processes are stimulated.

Pesticides were applied on arable soil on the watersheds in the wetlands G and L. Pesticides were found in the wetlands, with the highest concentrations measured immediately after spraying. At the most 13 pesticides were applied.

For CW-G, retention varied from 25 to 67% in the first summer season (Table 13.3). In the second year we observed both positive and negative retention. Losses

TABLE 13.3. Measured input of pesticides and retention in CWs G2 and L through May-September (Blankenberg et al. 2006)

Pesticide	G (2000)		G (2001)		L (2003)	
	Input (g)	Ret. (%)	Input (g)	Ret. (%)	Input (g)	Ret. (%)
Propachlor	60.0	67	3.5	14	10.8	47
Metribuzin†	28.2	40	0.2	19	1.9	3
Linuron	22.9	30	7.2	3	16.1	19
Metamitron	124.4	58	2.8	7	4.1	11
Metalaxyl	140.9	41	6.5	–11#	3.8	3
Propiconazole‡	11.0	25	13.2	13		
Fenpropimorph‡	4.9	36	5.1	10	1.0	15

†Metribuzin was applied only in one year (2000) in CW-G.

‡Propiconazole and fenpropimorph were added twice per season in CW-G.

#Metalaxyl was one of three compounds with residues in the soil. It may have been washed out from the previous years application. Metalaxyl has a very long half life in soil, and high water solubility.

were often connected to low pesticide concentrations in the stream. The retention generally increased with the size of the wetland, e.g. doubling the wetland surface area increased the average retention by 21% – units in the first year and 9% units in the second year. Chemical properties of the pesticides could explain some of the behaviour in the watershed and in the wetland (Haarstad and Braskerud 2005).

The pesticide retention in the CW-L was 3–47% in 2003 and 19–56% in 2004. The flagstone filter (L6, Figure 13.6) and the barley straw filter (L8) performed well compared to our reference (L4). Natural UV-light had a possible effect on the shallow polluted water passing the flagstone, while low redox potential and organic matter may be important for the barley straw filter. The other filters were more unpredictable (Blankenberg et al., 2006; Braskerud 2005a). The flag stones and the barley straw filter did not perform well for phosphorus retention.

Surface area and maintenance

For all parameters under investigation, CW-G had the highest relative retention (Table 13.2). Hence, as the ratio of surface area (*A*) to watershed area (wat. A) increased, retention increased (Figure 13.6). Conversely, the specific retention in the wetland will decrease. There exists an optimal wetland size; it will however depend on factors in the watershed and the vulnerability of the receiving water (Braskerud et al. 2005c).

Figure 13.9 shows the filling rate of four CWs studied. Originally, water depth was approximately 50 cm in wetland systems. CW-D was filled in after 9 years of operation due to the accumulation of sediments. It is the CW with the lowest surface area to watershed area ratio (Table 13.1). The content of clay, organic matter and P are usually the same as or even larger than the original topsoil (Figure 13.4; Braskerud 2002a and

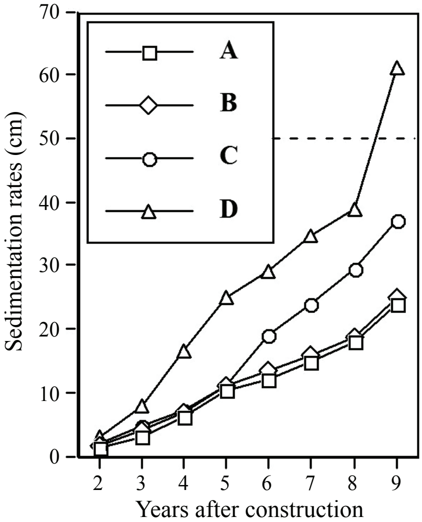

FIGURE 13.9. Cumulative sedimentation in constructed wetlands. Sedimentation was measured using sedimentation plates (Braskerud 2002b)

2003). Often the wetland sediments reflect the topsoil of the watersheds and consist of fine, stable aggregates. Excavated sediments from filled-to-capacity CWs will probably be well suited in soil mixtures and for replacement in the agricultural fields, unless it has been contaminated by industrial pollutants or agricultural diseases (Sveistrup et al 2008).

Annual average soil loss varied from 580 to 4760 kg·ha–1 for arable land in the F and C watersheds, respectively. Due to these excessive losses of soil from arable land the use of a sedimentation basin before wetland treatment of incoming waters is advisable (Figure 13.1).

Using wetlands for lake protection

Lake Akersvannet (Norway) is eutrophic. According to estimates, the annual phosphorus (P) load has to be reduced by approximately 475 kg to attain good environmental status. In 11 streams entering the lake, wetlands have been constructed. After 5–7 years the amount of sediment collected was measured and the P content analysed as a way to evaluate the retention performance (Braskerud 2005a).

The 11 wetlands retained a total of 314 kg P, which are about two-thirds of the annual P load reduction goal. However, the individual variation in retention performance was large: One wetland took care of 59% of the total P retention alone, while the next best wetland stopped 17%. Three wetlands performed less than 1% of the total P retention each. Poor P load reduction from the latter three watersheds was the main reason for lower overall P-retention.

Construction of wetlands may mitigate the phosphorus load to a lake. In this case additional measures are also needed. The P-loss from some watersheds may justify building large wetlands. However, it is not cost effective to build wetlands in watersheds with low P-losses. For increased biological diversity and scenery, however, the priority may be different.

General conclusions

Due to the low ratio of surface area to watershed area in Norwegian CWs, the hydraulic loading rate is rather high. As a result, retention models typically predict low retention of fine particles and P, which is often associated with clay particles. Norwegian trials document that CWs are capable of retaining clay sized particles through sedimentation. The main factors affecting sedimentation are:

- Runoff, because erosion and transportation processes in the watershed are able to deliver large sized particles to the CWs,
- Aggregates, because the clay particle settling velocity is improved. This influences the retention of pollutants attached to clays.

As a result, factors in the watershed are more important for the wetland retention performance than the wetland design itself.

Constructed wetland design needs to incorporate several components for successful retention. Important factors include:

1. Shallow depth,
    a. stimulates sedimentation and improves plant growth,
    b. increases the oxygenation of water.
2. Vegetation,
    a. increases hydraulic efficiency under storm flows and mitigates resuspension of sediments,
    b. makes an environmental and microbiologically active area in the wetland for retention and decomposition of pollutants.
3. Constructed wetland surface area, as retention increases with increases in wetland surface area.
4. Organic and mineral filters, for retention of soluble pollutants. Note that high hydraulic loads may overload filters, sediments may clog them, and a filter solution for one pollutant may have an opposite function on other pollutants.

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