The use of design elements in wetlands

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Abstract In literature on wetland design it is often recommended to use design elements to improve the hydraulic performance, which is linked to the pollutant removal efficiency. To investigate the effect these elements have on the hydraulic performance, a case study was carried out on two wetlands located in southern Sweden. The two main questions of the study were how the performance differs between the two wetlands and how it is affected by the use of deep zones and islands. Field measurements and computer simulations were carried out to obtain residence time distributions (RTD) and flow patterns. As analytical parameters, normalized peak time and effective volume ratio were used to interpret the results. The conclusion is that islands and deep zones as design elements can improve the hydraulic performance, but also that it is important to use them wisely. In one of the wetlands, the bad location of several islands led to severe short-circuiting and large areas of dead zones.

Keywords CFD; design; hydraulic; pond; tracer; wetland

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Introduction

The hydraulic regime has, according to basic water quality modeling, e.g. the $k-C^*$ model, a major impact on the water quality improvement in wetlands and ponds. Poor hydraulic performance reduces both the detention time and the effective volume and area, resulting in lower removal efficiency (Persson and Wittgren 2003). It is also relatively well known that the hydraulic regime is determined by wetland design as regards inlet and outlet location, vegetation, shape and topography (Kadlec and Knight 1996; Persson 2000). Literature on pond and wetland design therefore often recommends the use of design elements. Some refers to work by Knight *et al.* (1994) who recommended deep zones placed perpendicular to the flow. This is done to improve the distribution of the incoming water, thereby improving the performance. Also the use of islands to distribute incoming water is recommended (Persson 2000).

The Magle Wetland Park in southern Sweden was constructed in 1995 and covers 30 ha. It receives water from the Hässleholm sewage treatment plant and is used for removing both nitrogen and phosphorus, and as a recreation area mostly for bird watching. When designing the Magle wetlands, the constructing engineer placed deep zones perpendicular to the flow pathway to improve the distribution of the water. Islands and banks were constructed as deposits of soil that arrived from the excavation. An additional objective in constructing the islands was to create resting and nesting sites for birds. In the plans, the islands were located along the flow, to avoid dead zones. After studying the plans and speaking with the constructor, it is clear that the design was based on hydraulic considerations. However, the constructor's plan was not always followed.

The aim of this study was to analyze the effect that design elements, such as islands and deep zones, have on hydraulic performance. Two wetlands within the Magle Wetland Park were chosen as cases and two questions were raised: how does the performance differ between the two wetlands, and how does the use of deep zones and islands affect the performance? The results add to the growing understanding of wetland hydraulics and the relation between hydraulic performance and the use of design elements.

Magle Wetland Park

The Magle Wetland Park (latitude 56°N, longitude 14°W) covers 30 ha, of which 20 ha are water surface and 10 ha dry land (Figure 1). It is divided into several smaller wetlands and receives about 4.4 million m^3 treated wastewater each year. Water flows through a common inlet to wetland A and is distributed to four parallel wetlands B–E. The outflow is collected in an outlet canal and discharged to a small stream, Maglebäcken. The detention time for the whole system is assumed to be around 7 days (Hässleholms kommun 2000).

Wetlands B and D were chosen for this study. The islands in wetland B, according to the plan, had a design similar to that in wetland D. But during the excavation the layout became very different, which makes these two interesting to compare (Figure 2). They have a length-to-width ratio of about 2.5:1, a surface area of around 3–4 ha and a discharge of 2000–3000 m^3/d (Table 1). The mean depth was 1.1 m in B and 0.74 m in D. Each wetland is subdivided into three basins, separated by a series of small islands. The water depth in B was 0.60–0.75 m in the first basin and in the following basins 1.00–1.20 m. The deep zones are around 2 m deep and placed close to the wetland inlets and outlets, and in the upstream part of the second and third basins. Wetland D has a bottom level around 0.60–0.70 m and deep zones around 1.30–2.10 m placed as in wetland B. In many locations the vegetation density was rather sparse and the wetlands had large open areas, especially during the winter.

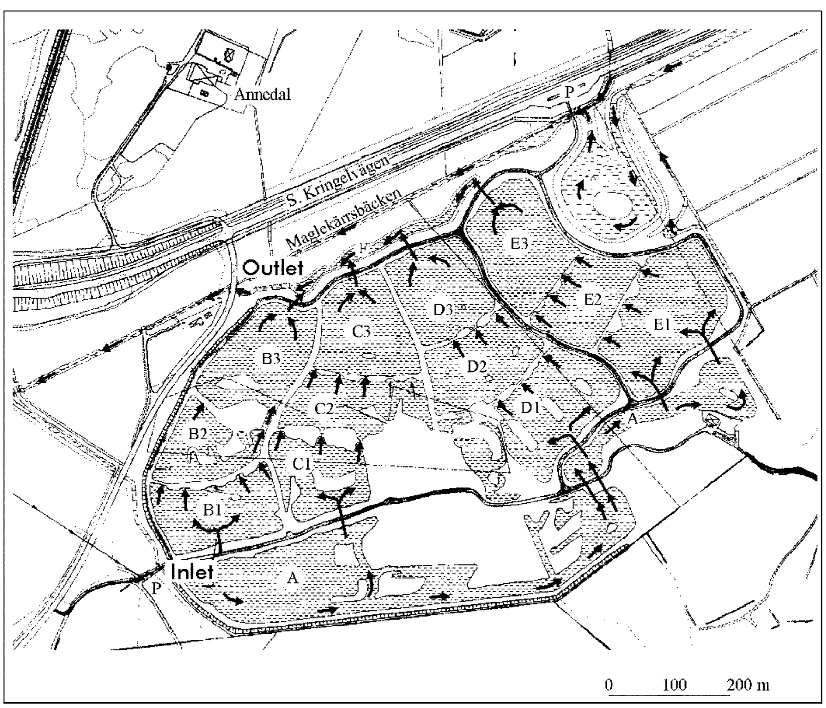

Figure 1 Magle Wetland Park. Wetlands B and D are investigated in this study. The arrows are assumed flow directions, drawn by personnel from the Hässleholm municipality. It is noteworthy that the representation of wetland B does not correspond with the existing wetland (see Figure 2)

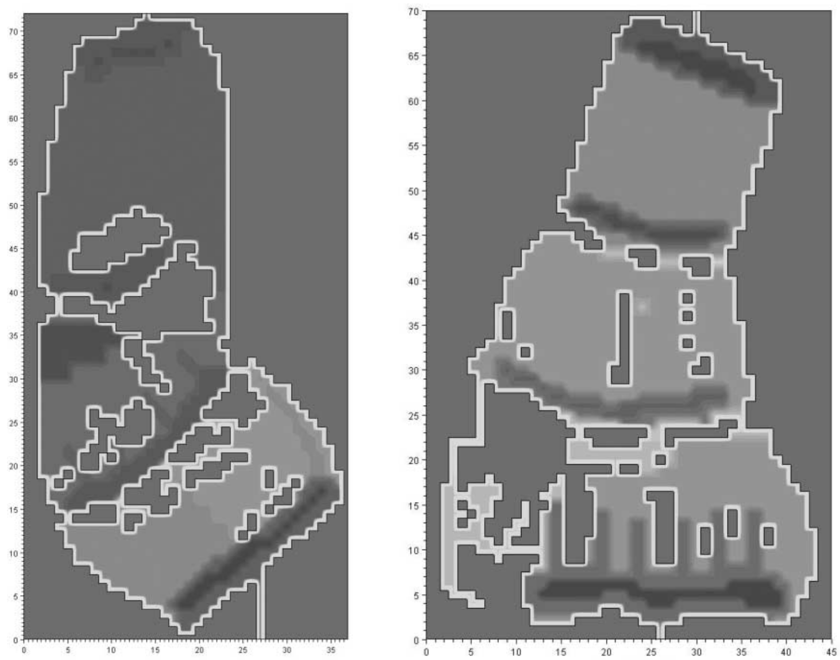

Figure 2 Layout and topography of wetlands B and D. The scales are in m/unit

Tracer tests

Hydraulic performance in wetlands and ponds is analyzed by studying flow patterns or residence time distributions obtained from tracer tests. In this study both methods were used to analyze the design elements. One tracer test was carried out during the summer and winter periods in each of the two wetlands, resulting in four residence time distribution (RTD) functions. Water velocities were not measured. However, flow patterns were generated in the computer simulations, giving a general description of the flow pattern, i.e. unsteady water discharge and wind was not added to the simulation model. A limited change in discharge does not alter the direction, but does affect the magnitude over time. Wind, though, can essentially change the flow pattern and dispersion. Flow patterns were therefore used in interpreting the results originating from the tracer tests.

For an impulse input of tracer into a steadily flowing system, the RTD function $f(t)$ is

$$f(t) = \frac{QC(t)}{\int_0^\infty QC(t)\mathrm{d}t} = \frac{C(t)}{\int_0^\infty C(t)\mathrm{d}t} \tag{1}$$

where $C(t)$ is the exit tracer concentration and Q is the water flow rate. The time when the maximum value of the function occurs is the peak time, t_p. The mean detention time, t_{mean},

Table 1 Hydrological data on wetlands B and D

	Wetland B	Wetland D
Surface area (m^2)	33 700	39 900
Volume (summer) (m^3)	37 200	27 700
Volume (winter) (m^3)	36 500	31 700
Discharge (summer) mean value (l/s)	24	32
Discharge (winter) mean value (l/s)	20	32

which is the average time that a tracer particle spends in the water system, is defined as the centroid of the RTD:

$$t_{\mathrm{mean}} = \int_0^\infty t f(t) \mathrm{d}t. \tag{2}$$

An estimation of the active portion of the wetland volume, and in principle also of the wetland area, is given by the effective volume ratio, e. Thackston *et al.* (1987) define it as

$$e = \frac{t_{\mathrm{mean}}}{t_{\mathrm{n}}} = \frac{V_{\mathrm{effective}}}{V_{\mathrm{total}}} \tag{3}$$

where V_{total} is the total volume of the water system and $V_{\mathrm{effective}}$ is the total volume minus the dead volume (i.e. the volume of water that has no interaction with the water flowing through the system). The nominal detention time, t_{n}, is equal to the total volume divided by the flow and is always larger than t_{mean}.

By studying a large number of shallow ponds around 60–600 000 m^3, Thackston *et al.* (1987) could develop an equation which determines the effective volume ratio, based on length, L, and width, W:

$$e = 0.84\lfloor 1 - \mathrm{e}^{(-0.59L/W)} \rfloor \tag{4}$$

Sometimes variation or skewness of the distribution function is calculated, to further characterize the wetland's hydraulics. This is not included here since hydraulic performance of the treatment wetlands is often analyzed in terms of normalized peak time and effective volume ratio, as these parameters are firmly linked to pollutant removal efficiency (Persson and Wittgren 2003). However, the value of peak time is linked to dispersion, in the sense that functions with a small peak time often contain a large dispersion. Other work on how to measure hydraulic performance can be found in Thackston *et al.* (1987) and Persson *et al.* (1999).

In this study, lithium chloride (6% solution by mass) was used as a tracer and added instantaneously at the inlet. Samples were taken at the outlet with an automatic sampler. The sampling frequency was one sample per 6 h during the first 9 days and one per 8 h for the following 6 days. During the summer experiment, 9 kg LiCl (1.48 kg Li) were added, and during the winter experiment 11.5 kg (1.89 kg Li). In both experiments the added tracer was in the form of a 6% solution. The sampling periods in wetland B were 8–22 July and 10–25 November 1999 and in wetland D they were 21 June–5 July 1999 and 10–25 November 1999.

To compare the tracer results, each tail of the tracer curve was cut in the same manner. In this study the tail was cut when 95% of the tracer had left the wetland. In the cases where an approximation of the tail was needed, results from CFD simulations were used.

The inflow data, obtained from an electromagnetic flow detector located at the outlet from the sewage treatment plant, give the diurnal mean value. The water flows from the plant into wetland A (Figure 1). Next it flows into four parallel wetlands B–E through rectangular weirs. The level of each weir regulates the distribution to these wetlands and the distribution rate was determined by manual measurement of the water levels in each weir. The flows to wetlands B and D were then calculated by using this distribution rate.

Evapotranspiration was assumed negligible due to high humidity, low wind conditions and air temperatures. Other measured data were the water level in the wetlands (every second day) and daily values of precipitation, which were received from a rain gauge managed by the personnel of the treatment plant. Infiltration was assumed to be negligible.

Mapping the depths of each wetland was done by hand from a small boat, since the plan did not correspond with reality. Air photos were taken to locate vegetation areas, but above all to obtain a better image of the layout, since the plan was not accurately followed when the wetlands were constructed.

Altered topography

In literature on design (Knight and Iverson 1990; Knight *et al.* 1994; Kadlec and Knight 1996, p. 618) deep zones placed perpendicular to the flow are recommended. The hydraulic function of a zone is to provide a low resistance path, distributing the water across the wetland. A problem is, however, that no scientific investigation has been found that convincingly supports the hypothesis that deep zones actually increase the hydraulic performance in wetlands.

To investigate the effects of the topography (i.e. islands and deep zones), computer simulations were performed for the winter period for both wetlands B and D. In these cases all islands and deep zones were removed and the bottom was flattened. In case B, the general depth was reduced to 0.92 m instead of the existing mean depth of 1.1 m. This was done to have the same volume since the area increased when all the islands were removed. When case D was flattened the area increased from 39 900 to 40 800 m^2 and the mean depth was set to 1.06 m.

In numerous studies, Computational Fluid Dynamics (CFD) models have been used to analyze the flow in small lakes, ponds and wetlands (Barrett 1996; Adamsson *et al.* 1999; Pettersson 1999). The commercial software Mike 21 (DHI 1996) was used to investigate the hydraulics. It simulates two-dimensional flows in one-layer fluids, assuming that the water mass is vertically homogeneous. This vertically integrated model (also called 2.5D) is intermediate between 2D and 3D, since it considers varying topography. If there are no 3D effects, as in vertically stratified flow or in basins with steep slopes, it can therefore be assumed to represent well the hydraulic conditions. The advantage of a 2.5D model compared to a 3D one is that it is less time-consuming, with respect to both grid generation and simulation time, especially when simulating unsteady flow (Persson, 1999).

In wetlands B and D, the Manning coefficient was set to 0.067 $s/m^{1/3}$, except for areas with reeds or twigs, which were given the coefficient 0.11 $s/m^{1/3}$, and very shallow areas, which were given the coefficient 1 $s/m^{1/3}$. In the cases with flattened topography Manning's coefficient was set to 0.067 $s/m^{1/3}$. The grid space was $5 \times 5\,m^2$. Turbulence was calculated from Smagorinsky's concept, assuming it to be a function of constant *C*s, grid space and the integrated velocity gradients in the *x* and *y* directions. Dispersion was calculated as a function of velocity and water depth.

Results

The nominal detention times during the summer and winter experiments were slightly higher in winter due to changes in water depths and discharge. Also, wetland B had a considerably larger nominal detention time than wetland D due to a larger water volume. When simulations were done on the cases with flat bottom surfaces, the nominal detention time was held constant in case B but was increased in case D.

The peak time was normalized to make it possible to compare the cases, since the tracer tests were carried out during different flow and water-depth conditions. The results showed great consistency between field measurements and calibrated CFD simulations. However, the results differed considerably between the summer and winter cases. In wetland B the value increased in the winter experiment, while it decreased in wetland D. It is also clear that wetland B had an overall much shorter normalized peak time than wetland D, showing that the water package with maximum concentration leaves the system much earlier.

Studying the effective volume ratios, which are based on the mean detention time, the results showed that the simulated data were relatively close to the measured data and the ratio from the summer experiment corresponded quite well with the winter experiment in wetland D. However, differences between summer and winter were larger for wetland B, which had an effective volume ratio as low as 0.46 in summer. Neither could the simulation for the summer period fit the measured data. In this context it is worth noting that the mean detention times are well below the nominal detention times, which are often used to size wetlands.

In both cases it is also apparent that the existing wetlands had a better hydraulic performance than the modeled cases with a flat bottom surface. When comparing the results of model simulations with varied topography and with a flat bottom surface, the current topography resulted in 24% and 21% higher normalized peak times for B and D, respectively (Table 2). However, the same comparison for effective volume ratio showed only a respective 9% and 0% improvement.

Differences between the cases: a discussion

Studying the results it is clear that wetland D has a better hydraulic performance than B. Since both of them have the same set of deep zones, the main difference consists of the location of the islands. Therefore it can be concluded that the location of islands is the most likely explanation for why wetland D performs better than B. This is also confirmed by the general flow pattern in Figure 3, showing large dead zones in wetland B. This difference, however, is even larger during summer. One explanation for this may be that vegetation (also submerged) enhanced short-circuiting. Further, it is possible that there was stratification due to temperature. The facts that wetland B has a larger mean depth, if not by much, and that there was a quite small lag time support the hypothesis of short-circuiting.

The second question put forward in the study was whether the use of deep zones and islands affects the hydraulic performance. The answer must be that the design elements did partly improve the hydraulic performance. This analysis focused on comparing the simulated data, since there were no measured values on the flattened wetlands. The focus was also on the winter simulations, since that was the period chosen for the simulation.

Studying the locations of islands in wetland D (Figure 3) it seems that they do not lead to areas of dead zones. Therefore the deep zones are the major difference between the existing case and the case with flattened bottom. The results then show that these zones increase the peak time but did not affect the effective volume ratio. The latter is, of course, not what had been expected, especially since (a) the flow pattern clearly shows that the water is better distributed at the inlet, (b) wetland D according to Thackston's equation Eq. (4) should have

Table 2 Results of tracer study and simulations during summer and winter tracer test in wetlands B and D of Magle Wetland Park in 1999. Nominal detention time t_n, peak time t_p, normalized peak time t_p/t_n, mean detention time t_{mean} and effective volume ratio e are shown. The simulation results of the wetlands with flattened topography are also shown

Tracer study		t_n (h)	t_p (h)	t_p/t_n (−)	t_{mean} (h)	e (−)
B − summer	Field measurements	430	136	0.32	197	0.46
	CFD simulations		146	0.34	271	0.63
B − winter	Field measurements	507	180	0.36	325	0.64
	CFD simulations		194	0.38	343	0.68
D − summer	Field measurements	240	160	0.67	218	0.91
	CFD simulations		163	0.68	218	0.82
D − winter	Field measurements	275	156	0.57	237	0.86
	CFD simulations		156	0.57	208	0.76
B − winter flat	CFD simulations	507	146	0.29	295	0.58
D − winter flat	CFD simulations	375	170	0.45	284	0.76

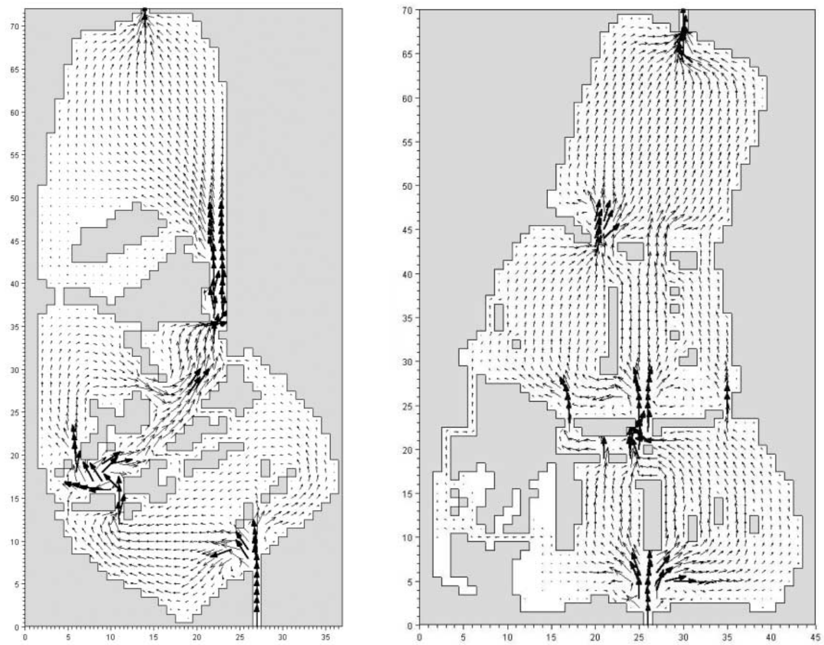

Figure 3 Flow patterns with mean water velocities in the existing wetlands B and D, showing the effects of deep zones and islands. The scales are in 5 m/unit

an effective volume ratio of about 64% and not 76% and (c) the flattened cases of wetland D and wetland B should have similar values. An explanation might, in this case, be the errors of, for example, the hydrological data (discussed below) or that there was something wrong with the simulation process. But if the simulation is correct, another explanation could be that deep zones perpendicular to the flow, in larger wetlands (in this case 3 ha) and with large areas of open water, do not significantly affect the effective volume ratio. Due to uncertainties and the lack of additional tracer tests, it is not possible to draw any profound conclusion, but it is not unlikely that deep zones are more effective in wetlands with dense vegetation and less effective in cases such as wetland D.

In wetland B the locations of the islands have (in contrast to D) a negative impact on the performance, since they create a short-circuiting in the mid-section and a large dead zone in the last section (Figure 3). But the results show that the total effect of the design elements, in spite of the islands, improves the hydraulic performance. The existing wetland is therefore slightly better than the case with no islands and deep zones. However, if the tracer result from the summer period is included, the design elements reduce the performance.

There was a relatively good correspondence between field measurements and CFD simulations. But for wetland B during summer, the simulated value of the mean detention time differed dramatically from the measured one, while there was a good correspondence between the peak times. One explanation for this is that vegetation was not sufficiently represented in the model, enhancing short-circuiting. If so, this additional vegetation should have been added as an increased bottom resistance. Further, it is possible that there was stratification due to temperature, which the model did not take into consideration.

The mass balances of the tracer tests were good with one exception. Accumulated mass per added tracer during the summer experiment was 91% and 84% in B and D, respectively. In the winter experiment the recovery was 60% in B and 79% in D. A likely explanation for a 60% recovery is that the lithium chloride was not added carefully enough, with the result that some of the salt was not dissolved.

Conclusion

A comparison of the two wetlands shows that incorrectly located islands decrease the hydraulic performance, as regards the normalized peak time and effective volume ratio. Further, it can be concluded that deep zones improve the performance by increasing the peak time. But for the two wetlands studied it could not be verified that deep zones significantly increase the effective volume ratio.

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