Performance of constructed wetland for highway runoff treatment

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Abstract Highways have a long-term impact on the environment, therefore a sustainable approach to their design is vital. In the spring of 2001 a pilot constructed wetland (CW) system was set up at a section of the northeast-southwest motorway in Slovenia. It was designed for a critical flow of 11.75 l/s for 0.75 ha of catchment area. It consisted of a sedimentation basin covering an area of 36 m² and a CW of 85 m². The CW was filled with sand media and planted with reeds. Performance efficiency of the system was evaluated from summer to autumn 2001. Some of the physical and chemical parameters monitored varied noticeably. Removal efficiency was 69% for suspended solids, 97% for settleable solids, 51% for COD, 11% for BOD₅ and 80% for Fe. Heavy metals such as Cu, Zn, Cd, Ni and Pb were below limited level at the inflow with reduction efficiency in the system of over 90%. Concentrations of N and P showed a limited level of nutrients for biological processes. Results of the study suggest that CW could be an alternative for highway runoff treatment. Further long-term investigations are needed to provide more data on their proper design.

Keywords Constructed wetland; highway runoff; metals

Introduction Efficient environmental protection is a vital part of design features and maintenance of highways. The volume and mode of pollutant accumulation depend on road surface type, traffic density, carriage-way maintenance, seasonal characteristics, and roadside land use. Consequently, the quantity of runoff and concentrations of pollutants tend to be highly variable since they are also affected by the volume, frequency, intensity, kind of precipitation and the effect of the first wash (Hvited-Jacobson and Yousef, 1991). Pollution originating from motorway runoff is well known, but its treatment is a demanding task, particularly due to fluctuations in hydraulic and pollutant loads. Therefore the requirement for highway surface runoff treatment was paralleled by the concept of using a biological system with a great species diversity, which could compensate for both hydraulic and pollution fluctuations (Munger et al., 1995). These efforts resulted in the concept of creating constructed wetlands (CW) (Kadlec and Knight, 1996). The use of CW technology is now well established for treatment of discharges of sewage, landfill sites, industrial wastewaters, and of agricultural runoff (Bulc et al., 1997; Platzer, 2000; Husband et al., 2000). Some examples of the application of CW have also been recorded for the treatment of highway runoff (Bavor et al., 2001; Pontier et al., 2001a; Shutes et al., 2001). Part of CW technology, which is recognised to play an important role, is the efficiency of a sedimentation basin for the protection of reed beds against the inlet of heavier sediments in order to prevent the clogging up of the system. The system must ensure slow wastewater flow and necessary retention time for optimal removal efficiency. CW technology must provide efficient physical filtering, adsorption and sedimentation, efficient biochemical decomposition of wastewaters, and uptake of substances by plant tissues. To achieve a high level of runoff treatment efficiency of CW, it is essential that the system be designed with regard to hydraulic and pollutant loadings.
Methods

**Constructed wetland – process design**

A section of Slovenia’s northeast-southwest motorway was selected as a study site. An existing retention basin with principal characteristics shown in Table 1 was reconstructed into a constructed wetland (CW) in combination with a sedimentation basin equipped with an oil, a grease and a silt trap (Figure 1). Retention and sedimentation functions of the existing retention basin were supplemented with a runoff treatment function in order to increase the protection of the aquatic environment, groundwater in particular, because the selected motorway section runs in an area covered with Quaternary sediments of clay and gravel at the recipient site. Due to a thin impermeable layer, groundwater could come into direct contact with the runoff.

To determine CW dimensions, highway runoff management guidelines and data on characteristic maximum pollutant loadings generated from highway runoff in Slovenia were used (Kogovsek, 1995; Rismal et al., 1995; Pintar et al., 1998). To calculate a particular critical flow ($Q_{\text{crit}}$), a rainfall event of 15 l/(s.ha) was selected. For a non-reduced catchment area of 0.751 hectares and an inflow of 1.5 l/(s.km), $Q_{\text{crit}}$ was calculated to be 11.75 l/s. The permissible surface hydraulic loading was 10 m/h. This means that for the selected $2 \times Q_{\text{crit}}$, which was approximately 24 l/s, a sedimentation basin 8.64 m$^2$ in size was required. Functionally, the sedimentation basin was designed that both sand and silt of the inflow were to be retained by sedimentation, while lighter insoluble liquids, such as mineral oils and petroleum products, were to be retained by floating. Part of the retention basin 85 m$^2$ in size was reconstructed into the CW so that it was filled with sand media to a depth of 1.1 m and planted with *Phragmites australis*. A heavier rainfall gets discharged before it reaches the sedimentation basin, draining off into the existent recipient. Later on the circular flow could be changed so that it would be recycled to the CW. A water mirror was the sole open water surface of the sedimentation basin. To prevent infestations of insects, a thin layer of mineral oils or of petroleum products was allowed to collect on the surface. Before the inflow into the CW, a double stockade filled with gravel was set up as a silt trap.

### Table 1 Principal features of the retention basin

<table>
<thead>
<tr>
<th>$Q$ ($m^3/s$)</th>
<th>$F$ (ha)</th>
<th>$l$ (m)</th>
<th>$P_{\text{si}}$</th>
<th>$Q_{15}$ (l/(s.ha))</th>
<th>$Q_{\text{crit}}$ (l/(s.ha))</th>
<th>$V_2$ (m$^3$)</th>
<th>sum$V$ (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.09</td>
<td>0.751</td>
<td>306</td>
<td>0.777</td>
<td>156</td>
<td>15</td>
<td>114.4</td>
<td>139.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$F_{\text{red}}$ (ha)</th>
<th>$V$ (m$^3$)</th>
<th>$h_2$ (m)</th>
<th>$Q_{\text{max}}$ (m$^3$/s)</th>
<th>$Q_{\text{om}}$ (m$^3$/s)</th>
<th>$T$ (min)</th>
<th>$t_c$ (min)</th>
<th>$A$ (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.584</td>
<td>20</td>
<td>2.5</td>
<td>0.001</td>
<td>0.0007</td>
<td>131.2</td>
<td>7.9</td>
<td>297.5</td>
</tr>
</tbody>
</table>

Legend:

- $Q$ – average low flow; $F$ – catchment area; $l$ – length of motorway section; $P_{\text{si}}$ – discharge coefficient; $Q_{15}$ – 15-minute rainfall event; $Q_{\text{krit}}$ – critical rainfall; $V_2$ – usable storage of retention basin; sum$V$ – required usable storage; $F_{\text{red}}$ – reduced catchment area; $V$ – pollution volume (mineral oils); $h_2$ – retention basin depth; $Q_{\text{max}}$ – maximum permissible discharge from retention basin with regard to permitted recipient loading; $Q_{\text{om}}$ – $2/3Q_{\text{max}}$ – permissible flow through throttle; $T$ – duration of design rainfall; $t_c$ – time of discharge concentration; $A$ – required minimum size of retention basin
Monitoring
In the period from summer to autumn 2001 five rainfall events were sampled, approx. at monthly intervals. Performance efficiency of the system as a whole was evaluated with regard to the difference of chemical water composition at the inflow and outflow. We assumed that the mass balance calculation due to inaccuracy of the discharge measurements, especially during heavy rainfall could be misleading. The average values present the concentrations of five sampling events. Sampling was carried out manually at the inflow into the sedimentation basin and at the outlet sump after the CW. Inflow samples were collected at 15-minute intervals within one hour from the start of the rainfall and cumulated into one sample. Outflow samples were collected over a 24-hour period from the start of the rainfall. The flow was measured volumetrically each time of sampling. At sampling sites temperature, pH, dissolved oxygen and conductivity were measured with a WTW MultiLine F/Set. Samples were analysed for suspended and settleable solids, COD, BOD₅, copper, zinc, cadmium, nickel, lead, iron, chromium, vanadium, cobalt, total phosphorus, nitrate, Kjeldahl nitrogen (KN), mineral oils, and AOX in an authorised laboratory according to Standard Methods (1998). The results were evaluated according to Slovenian permission standards stated in the Decree on the Emission of Substances and Heat in the Drainage of Wastewater from Pollution Sources, Official Gazette of the Republic of Slovenia (OG RS 35/96) for daily traffic of 5,000 vehicles (Tables 2, 3).

Results and discussion
Dissolved oxygen content
Average inflow concentration of dissolved oxygen was 10.6 mg/l, decreasing to 2.8 mg/l at the outflow due to decomposition processes. Inflow values ranged from 6.4 to 18.1 mg/l and outflow values from 0.5 to 5.7 mg/l. Close to the outflow site, sedimentation of organic matter had a delayed impact on the increase of oxygen requirement in the sediment and hence on the decrease of concentrations of dissolved oxygen in the water column. Organic deposits accumulate in the sediment either due to direct input of particles from the runoff or due to decomposition and sedimentation of debris and biomass of primary producers. In addition, nutrients carried by the motorway runoff enhanced the growth of algae, which settled then at the bottom, causing a rise in the demand for oxygen in the sedimentation basin. In the CW decomposition of autochthonous material took place, since particulate allochthonous loadings declined due to filtering through the silt trap.

Temperature
Inflow temperatures ranged from 12.6 to 19.5°C, with an average of 14.9°C. The average outflow temperature was 16.3°C, with the range of temperature from 14.5 to 19.3°C. Heat loss was observed in the sedimentation basin and not in the CW. Low temperatures can have a considerable effect on water quality, as a result of a decrease in decomposition. Maehlum (1998) even reports about a higher CW efficiency for BOD₅ in winter. On the other hand a possible lower CW efficiency could occur at the time of low temperatures due to increased biofilm thickness and hence lower diffusion of dissolved oxygen to microorganisms. A lower efficiency level in winter months could be attributed to a decrease in the number of bacteria active in the rhizosphere. Owing to an increase in the decomposition of plant tissues in summer months and higher oxygen solubility in winter, the effect of temperature is, as a rule, difficult to notice, which was also reported by Maehlum (1998). The actual temperature effect on the efficiency of the reconstructed
retention basin could be determined by monitoring conducted over a longer period during different seasons.

Specific electrical conductivity
Average specific electrical conductivity (SEP) was 471 µS/cm at the inflow and 434 µS/cm at the outflow. Thus it was practically unaltered. SEP monitoring is an essential condition for monitoring the diluting process of motorway runoff due to rainfall or runoff concentrations after a drought and for measuring retention time in the CW. Due to subsequent measures, such as substratum addition, SEP monitoring had not showed any significant differences yet. A significant decrease in SEP concentration in the outflow was found only in August. Further monitoring could be used to determine retention time in the CW at different hydraulic loadings.

pH
The average pH value of the inflow and outflow was 7.8 and 8.3 respectively. Inflow values ranged from 7.7 to 7.9 and outflow values from 7.9 to 9.2. The buffer property of the CW is, according to Kadlec and Knight (1996), primarily a result of the reduction of ferri-ion if the system is overflowed. The inflow pH value decreased only at the initial stage of the system, where an intensive decomposition of organic matter occurs or oxidation of hydrocarbons to fatty acids takes place so that pH ranged from 7.1 to 7.2. The pH of wastewater started increasing when the water reached the point where oxygen requirement is lower. Probably neutralisation of fatty acids occurred, along with the formation of salts, and the conversion of fatty acids into CO₂. As a result, outflow pH values were within the range of base values, which may have favoured metal precipitation of inorganic compounds.

Suspended and settleable solids
Inflow values of suspended solids under consideration were slightly increased. They ranged from 22 to 74 ml/l. Inflow concentrations were close to exceeding the Slovenian permitted limit (Table 2). Outflow values ranged from 7 to 13 mg/l. Removal efficiencies fluctuated from 57% to 82%, with an average of 69% (Figure 2). Concentrations of settleable solids averaged 0.5 mg/l at the inflow and 0.03 mg/l at the outflow. Inflow concentrations exceeded occasionally permissible levels for drainage into a watercourse, ranging from 0.1 to 1.1 mg/l. Fluctuations in outflow concentrations were paralleled by inflow concentrations, with values from 0 mg/l to 0.1 mg/l. The removal efficiency was 97%. Accumulation of solid particles depends on average daily traffic. Data indicated that fractions of heavy metals and other pollutants depend on solid particles and that concentrations are, in general, higher on smaller particles (10 µm). The size of solid particles is, as a rule, smaller than 100 µm. On average, it is 30 µm. Because of substantial uptake of nutrients and heavy metals by small solid particles (< 10 µm), their removal causes problems in the case of a short sedimentation period (Hvited-Jacobson and Yousef, 1991). In view of results of the present study, it may be presumed that sedimentation of particles in the sedimentation basin and filtration in the silt trap of the CW were efficient for the treatment of motorway runoff. However, further long-term monitoring is needed to substantiate the actual sedimentation efficiency.

COD, BOD₅
Inflow values of COD ranged from 15 to 58 mg/l, and inflow values of BOD₅ ranged from 2 to 5 mg/l (Table 2). Inflow values of both parameters did not exceed the permitted concentration limit (OG RS 35/96). Outflow values of COD ranged from 8 to 11 mg/l, while those of BOD₅ ranged from 2 to 5 mg/l. Outflow BOD₅ values attained the residual level.
Removal efficiency of COD ranged from 27 to 86% and of BOD$_5$ from 0 to 33% (Figure 2). Owing to distinct fluctuations and occasional low inflow values, the average removal efficiency for COD was 51% and for BOD$_5$ 11%. Surface et al. (1993) have found that filter beds attain a higher level of efficiency in reducing BOD$_5$ concentrations if planted with wetland plants. Therefore increased removal efficiency is expected for both parameters in the future. Nevertheless, the ratio between COD and BOD$_5$ indicated the biologically inert nature of motorway runoff (Pontier et al., 2001a), therefore high efficiency for BOD$_5$ reduction could not be expected. It is known that decomposition takes place at a slower rate if temperatures are lower, which in turn decreases the consumption of BOD$_5$. Anyway, physical processes such as sedimentation, which is not affected by temperature, provide additional removal treatment of BOD$_5$. Therefore, in the future, essential differences in the functioning of the system are not expected to occur for similar initial concentrations in different seasons.

**KN, nitrite, nitrate**

Inflow KN values ranged from 0.9 to 22 mg/l (Table 2). At the outflow, the values ranged from 0 to 0.5 mg/l. The average removal efficiency was 89% (Figure 2). Inflow nitrite values were low, ranging from 0.003 to 0.4 mg/l. Outflow concentrations ranged from 0.016 to 0.05 mg/l. Nitrate concentrations were occasionally found increased at the outflow. Inflow concentrations ranged from 0.4 to 1.8 mg/l. Outflow concentrations were normally low, ranging from below detection level to 0.6 mg/l. The average removal efficiency for nitrite was 19% and for nitrate 76%. Inorganic plant nutrients in the motorway runoff, particularly nitrogen and phosphorus, originate mainly from atmospheric deposits and the application of fertilisers on roadside land. Nitrogen concentration in the motorway runoff is, on average, 4.1 mg/l (Hvited-Jacobson and Yousef, 1991). Results of analyses show that only KN concentrations were high, while nitrite concentrations were below the permitted limit for discharge (OG RS 35/96). Nevertheless, these concentrations may enhance, in the long run, eutrophication in slowly flowing watercourses. Recipient loadings of motorway runoff are relatively low in comparison with nutrients originating from other sources (Hvited-Jacobson and Yousef, 1991). Nitrification depends on oxygen, the content of

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Susp. s.</th>
<th>Sett. s.</th>
<th>COD</th>
<th>BOD$_5$</th>
<th>KN</th>
<th>N-NO$_2$</th>
<th>N-NO$_3$</th>
<th>P$_{tot}$</th>
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<td><strong>Inflow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>22–74</td>
<td>0.1–1.1</td>
<td>15–58</td>
<td>2–5</td>
<td>0.9–22</td>
<td>0.003–0.4</td>
<td>0.4–1.8</td>
<td>0.1–0.7</td>
</tr>
<tr>
<td>Mean</td>
<td>42</td>
<td>0.5</td>
<td>29</td>
<td>3.3</td>
<td>1.5</td>
<td>0.13</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Outflow</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>7–13</td>
<td>0–0.1</td>
<td>8–11</td>
<td>2–5</td>
<td>0–0.5</td>
<td>0.016–0.05</td>
<td>&lt;0.3–0.6</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td>Mean</td>
<td>11</td>
<td>0.03</td>
<td>9</td>
<td>3</td>
<td>0.25</td>
<td>0.006</td>
<td>0.23</td>
<td>0.1</td>
</tr>
</tbody>
</table>

OG RS 80 0.5 120 25 – 1.0 5.0 2.0

**Figure 2** Removal efficiency of the monitored parameters
which was sufficient in the CW for nitrification, which was also proved by the rise in nitrate concentrations in August. Nitrification also depends on increased concentrations of a number of poisonous substances, particularly cyanide, phenol, aniline, Ag, Hg, Ni, Cr, Cu, and Zn (Bitton, 1994). Concentrations of these substances were not found to increase in the CW and so their presence did not have a distinctly adverse effect on nitrification.

**Phosphorus**

Inflow concentrations of phosphorus determined in the CW were in agreement with our expectations. On the whole they were low (Table 2). Inflow concentrations ranged from 0.1 to 0.7 mg/l, while outflow concentrations ranged from below 0.1 to 0.3 mg/l. Average removal efficiency was 79%, which was indicated by a decrease in phosphorus concentrations of the wastewater passage through the system (Figure 2). Concentrations of phosphorus, which is generally present as orthophosphate, are usually very low in motorway runoff. Consequently, phosphorus is often a limiting factor in treatment processes. In addition, uptake by wetland plants also occurs, although at this stage of investigation, however, the role of plants could not be evaluated as yet.

**Copper, zinc, cadmium, nickel, lead, iron**

Inflow values of copper ranged from 0.08 to 0.38 mg/l (Table 3). Outflow concentrations were on average 0.005 mg/l. Thus the average removal efficiency was as high as 94% (Figure 2). Inflow concentrations of zinc ranged from 0.2 to 1.1 mg/l. Outflow concentrations were on average 0.003 mg/l. The average removal efficiency was as high as 98%. Inflow concentrations of cadmium ranged from 0.01 to 0.07 mg/l. Outflow concentrations were below 0.01 mg/l. The assumed average removal efficiency was as high as 99%. Inflow concentrations of nickel ranged from 0.02 to 0.3 mg/l. Outflow concentrations were on average 0.01 mg/l. The average removal efficiency was as high as 98%. Inflow concentrations of lead ranged from 0.04 to 0.4 mg/l. Outflow concentrations were below 0.01 mg/l. The assumed average removal efficiency was as high as 99%. Inflow concentrations of iron ranged from 0.8 to 4.5 mg/l. Outflow concentrations ranged from 0.1 to 0.7 mg/l. Removal efficiency ranged from 63 to 95%, with an average of 80%. Inflow concentrations of iron exceeded the permitted limit for drainage into a watercourse (OG RS 35/96), while inflow concentrations of lead were close to the permitted limit. Outflow concentrations of all metals were below the permissible level. Increased concentrations of trace metals, despite their lower inflow concentrations, may give rise, in the long run, to changes in species composition of organisms and in the primary and secondary production, and, in some cases, they may cause sudden kills of aquatic organisms. It is an important finding by Hvited-Jacobson and Yousef (1991) that 50% of metals studied are leached in the first quarter of a storm event, 25% in the second quarter and the remaining 25% in the third and last quarters. Therefore the retention basin was designed that it was intended to catch the first most polluted wash of the rainfall. Cd, Ni and Cu are present with 75% in dissolved fractions, while Fe and Pb prevail with 80% in the particulate fraction. Zn is equally represented in dissolved and particulate fractions. The quantity of heavy metals and the form in which they occur in wastewater depend to a great extent on physical and chemical features of individual elements. Thus Pb is mainly found in insoluble particles (88%) in inorganic form (Hvited-Jacobson and Yousef, 1991). Therefore the sediment analysis will be included in the future monitoring of the system. Significantly higher concentrations of heavy metals occur in melted snow in roadside areas. In the melted snow several biologically available forms of metals are to be found at higher concentrations than in other kinds of runoff. Consequently, it would be essential to investigate them under early spring conditions.
Mineral oils, polycyclic aromatic hydrocarbons

Inflow concentrations of mineral oils varied, as a rule, from 0.004 mg/l to 0.1 mg/l, that was far below the permitted limit for drainage into a watercourse (10 mg/l). The concentrations of all polycyclic aromatic hydrocarbons were at the inflow less than 0.05 mg/l. Therefore they were not monitored at the outflow.

Conclusion

The results shown in this paper demonstrate that it is necessary to have an amount of good quality data over a long term to provide useful information for the design of a runoff treatment system. Nevertheless, the results proved that the CW for runoff treatment, combined with the sedimentation basin, could be designed to meet effluent standards, that it is not always true for conventional retention basins constructed in Slovenia (Kogovsek, 1995; Pintar et al., 1998). The system showed efficient removal of suspended and settleable solids, and metals. As also proved by Pontier et al. (2001a, b), the dominant treatment mechanism within the system seemed to be sedimentation of solids in the sedimentation basin and in the CW. As most metals are associated with solids it is obvious that the systems could be efficient in removal, especially with pH base values that favoured metal precipitation. Nevertheless, road runoff obviously poses a number of environmental problems due primarily to the extreme variability in quality and the heterogeneity of its composition. Therefore further investigations with automatic samplers and a gauging station for discharge and rainfall should give more data on proper design, media, surface area, hydraulic loading and climate especially for reduction of heavy metals. The final objective of the future research will be to offer design criteria for highway runoff of daily traffic of 5,000 vehicles, derived from our experiences, and linked with the common standards in the literature.

Acknowledgements

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References


Table 3 Average concentrations of monitored metals in the inflow and outflow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cu (mg/l)</th>
<th>Zn (mg/l)</th>
<th>Cd (mg/l)</th>
<th>Ni (mg/l)</th>
<th>Pb (mg/l)</th>
<th>Fe (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow</td>
<td>0.23</td>
<td>0.5</td>
<td>0.03</td>
<td>0.13</td>
<td>0.17</td>
<td>2.4</td>
</tr>
<tr>
<td>Outflow</td>
<td>0.005</td>
<td>0.003</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>OG RS</td>
<td>0.5</td>
<td>2.0</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>


