Mitigation measures towards morphological alterations of rivers: The receiving water as part of the integrated wastewater system

C. Engelhard*, S. Achleitner, I. Lek and W. Rauch

1 Institute of Environmental Engineering, University of Innsbruck, Technikerstrasse 13, A-6020 Innsbruck, Austria
*Corresponding author, e-mail carolina.engelhard@uibk.ac.at

ABSTRACT
Measures in the rivers, their potential to mitigate morphological alterations caused by overflow events of urban drainage structures and their cost-effectiveness have been investigated. The receiving water is seen as part of the urban wastewater system since integrated management of the system has to consider measures in the receiving water as an option for improvement of the system. In this study the measures were evaluated using the software tool REBEKA. It has been found that increase of combined sewer overflow storage volume is less cost-effective than the investigated in-stream measures. Bed paving with coarse material is an effective and cheap method to reduce erosion problems. Reduction of slope required the smallest relative changes but has to be transferred into applicable methods like ‘increase of meandering’. The effectiveness of the methods for reduction of slope as well as of the measure ‘channel widening’ strongly depends on the dimension of the erosion problem—their applicability is limited for huge impacts. Evaluation of measures in different sub systems of the wastewater system with simulation tools can reveal interesting alternatives. Measures in the receiving water can be cost-effective and enhance the ecological quality which is an important aspect in the implementation of the European Water Framework Directive.

KEYWORDS
Combined sewer overflow; in-stream measures; mitigation of hydraulic impact; modelling

INTRODUCTION
Combined sewer overflows (CSO) or storm sewer outlets can cause erosion in rivers and thus deteriorate its ecological quality. According to the EU Water Framework Directive (2000/60/EC) all surface water bodies have to achieve a ‘good ecological status’; therefore it is important to identify problematic discharge structures and implement measures to enhance the ecological status of a receiving water.
Traditionally erosion problems caused by the urban drainage system have either been solved by measures in the sewer system (e.g. increase of CSO storage capacity) or by transformation of the receiving water into a ‘concrete channel’. This study evaluates the potential of measures in the receiving water (in-stream measures) and compares them with the measure ‘increase of CSO storage volume’. Different in-stream measures to mitigate hydraulic impacts were investigated, covering technical measures as well as restoration measures. Technical measures increase the anthropogenic alteration, they can be divided into bed stabilisation measures (e.g. bed paving) and bank stabilisation measures (e.g. revetments). In contrast restoration measures reconstitute a more natural status of the river.
More than the erosion quantity it is the frequency of erosion events that affects the aquatic biocenosis, where the respective maximum number of erosion events that is acceptable has to be determined for each receiving water depending on its ecological status. Thus the effectiveness of a measure can be expressed as its potential to reduce the number of erosion events. An erosion event can be identified by comparing the actual shear stress with the critical shear stress of the bed (e.g. by using the formula by Meyer-Peter). The required changes to reduce the erosion frequency to an ecological tolerable number of events can be calculated e.g. in terms of CSO storage volume or increase of bed material size with an appropriate simulation tool that includes the urban wastewater system and the receiving water. The study was made with the Swiss software program REBEKA (Rauch et al., 2002). First critical combinations of river and catchment were identified to be used in the further simulations. The influence of rain and catchment size on the number of erosion events was investigated as well as the effect of the limit value (maximum number of erosion events per year) on the effort for impact mitigation. Different measures for mitigation of the hydraulic impact were applied in the simulations: increase of CSO storage volume, reduction of slope, increase of grain size and widening of the river bed. The required relative changes identified for these measures were compared to each other. While increase of grain size and widening of the river bed can applied directly, reduction of slope had to be translated into applicable measures like increase of meandering of the river course. Finally a cost comparison has been made to assess the cost-effectiveness of the in-stream measures compared to the effort for increase CSO storage volume.

**METHODS**

**REBEKA**

REBEKA is a software tool developed to identify the cause-effect relationship between measures in the drainage system and impacts on the receiving water. The programme is specifically designed for being a tool for surface waters with short hydraulic retention time and for small, alpine and pre alpine streams (details see Rauch et al. (2000)). For determination of an erosion event the empirical model of Meyer-Peter is used. The frequency of the events is calculated based on a long time series of precipitation. REBEKA assumes an adverse hydraulic impact is given when the combined sewer overflow result in frequency of the bed load transport events having lasting effects on the aquatic ecosystem. The result of the frequency analysis is compared against the maximum number of impact events acceptable from an environmental point of view. Overall the number of erosion events per year the exceedance of which has an adverse effect vary between 0.5 and 10 (Frutiger et al., 2000) depending on the stream.

In REBEKA the critical flow ($Q_{crit}$) is determined, which is the discharge of incipient motion of the bed material. However, for a better understanding of impact (overflow) dynamics from the CSO, results are presented in terms of the specific critical overflow ($Q_{cr}$). This critical overflow is simply derived as the difference of the critical flow in the river and the upstream base flow $Q_0$ ($Q_{cr} = Q_{cr} - Q_0$). Using the specific critical overflow, comparison can be made for CSO events/ frequency exclusively, independent from river characteristics.

In the simulations different river- catchment combinations were tested. Therefore five different rivers and five different urban catchments were simulated using 10 years rain series from Innsbruck and Brussels. The changes that are necessary to reduce the number of erosion events were identified by varying the respective parameters (slope, grain size, bed width or CSO storage volume) until the acceptable value was achieved. Further the relative changes for
the different measures were compared. Relative change is defined as the ratio between the parameter value that is required by the measure to achieve the goal and the parameter value of the base system. For example when the bed slope is initially 5 % (I_{old}) and 4 % (I_{new}) is required for compliance, the relative change is the absolute value of \(1 - I_{new}/I_{old}\) = \(|1 - 4/5| = 0.2\).

RESULTS AND DISCUSSION

Influence of the characteristics of the river, the catchment and the rain

Figure 1. Influence of rain characteristics (left) and catchment size (right) on the number of erosion events (n_{e}) and the specific critical overflow (Q_{cr,c}).

Figure 1 (left) shows that the rain characteristics have a significant impact on the number of erosion events per year. Even if only the rain data differed in the simulations, the impact caused by the rain from Innsbruck was more severe. Both the annual mean rain volume in Innsbruck is significantly higher and the rain intensity is about two times the one of Brussels. Therefore an evaluation of the hydraulic impact needs to take the regional rain characteristics into account.

Figure 2. Influence of the number of erosion events (n_{e}) that is acceptable per year on the mitigation measures.

Only when catchments of considerable size discharge via a CSO into a small river, problems with the frequency of erosion events occur. With increasing size of the catchment the impact on the receiving water must clearly increase. Further the resilience of the receiving water influences the erosion frequency: the smaller the additional discharge that can be tolerated the higher is the erosion frequency. This can be seen in the example shown in figure 1 (right)
where below a specific critical discharge of 0.5 m$^3$/s the number of erosion events increased enormously.

Figure 2 outlines the relative increase of the relative changes for mitigation measures deriving from different maximal acceptable numbers of erosion events. Logically, the less erosion events can be tolerated by the river the higher are the required relative changes. The relative changes for bed material and bed slope are increasing less than those for channel widening and CSO storage increase, indicating that for cases with higher requirement of mitigation the first two measures might be more effective.

**Figure 3.** Reduction of erosion frequency by increase of CSO storage (left) and comparison of mitigation by increase of CSO storage with different in-stream measures (right).

A measure often used to mitigate impacts due to overflows is the increase of CSO storage capacities. This measure is only of limited effectiveness for mitigation of hydraulic impacts (see figure 3 (left)). Reduction of erosion events is fairly limited by increasing CSO storage volume, especially for large critical overflows. Reason is that the total volume delivered to the CSO exceeds the CSO storage volume by far, thus the basin is filled up rapidly. Even if the basin is increased, it is still rapidly brimmed and the majority of stormwater (including peak flows) is diverted to the river. The characteristics of rain that influence the generation of CSO are not only the annual depth but also its intensity (De Toffol and Rauch, in press). With the rain data from Innsbruck (alpine region with higher annual depth and maximum events) the effectiveness of CSO storage increase was even less (CD4WC Deliverable 4.1, 2005).

In figure 3 (right) the relative changes are compared for different measures (expressed by parameters) that are necessary (according to the simulations) to reduce the number of erosion events to an acceptable number. Three in-stream changes (increase of the bed material’s size, reduction of bed slope and widening of the river bed) are compared with a change in the sewer system (increase of CSO storage volume). The in-stream changes are more effective than the increase of CSO storage. Of the three in-stream changes the reduction of slope required the smallest modifications while the effort for widening of the river bed was significantly higher.

There are various factors that make it impossible to evaluate the accurate cost-effectiveness of the different measures. One factor is the length of the affected stretch in which erosion takes
place because of the CSO discharge. The peak originating from the CSO is dispersed while flowing downstream. As soon as the peak is mitigated such that the discharge is below the critical discharge, no erosion occurs in the downstream section. The problem is that the mitigation of the peaks depends on various factors (like cross section, water depth or roughness) so that it can not be easily predicted. On the other hand it is necessary to define the length of the affected stretch as the in-stream measures have to cover the whole endangered area. In the following comparison of measures the length of the affected stretch has been supposed to be 1000 times the width of the river’s water surface according to an Austrian guideline (OEWAV, 2003).

Another problem is the implementation of the measures. There are no simple relations that allow calculating the height of an obstacle (e.g. bed sill, weir) that is equivalent to a required reduction of bed slope. Therefore it was not possible to include these measures for slope reduction in the comparison.

**Figure 4.** Changes of bed slope and the respective effort necessary to realise these changes in form of channel widening.

REBEKA computes the reduction of slope that is necessary to reduce the hydraulic impact. The reduction of slope can be achieved with the measure increase of meander. Thereby the length of the stretch is increased (due to meanders) so much that the resulting slope is decreased to the value calculated with REBEKA.

In the example shown in figure 4 the affected stretch of the river is 2453 m long with a slope of 5 ‰ resulting in an altitude difference of 1.27 m. The river is assumed to be absolutely straight. To mitigate the effect of the 40 ha catchment the slope of the resulting stretch after applying the measure ‘increase of meandering’ must have a slope of 4.3 ‰. Thus the river stretch has to be increased to have a length of 2957 m (∆L = 16 %); resulting in a slightly braided new river stretch.

Figure 4 (right) shows the relative changes of slope compared to the thereof resulting relative changes in length of the river stretch by increase of meander. The relative changes of reduction of slope and increase of meander are in the same range for the 40 ha and for the 60ha catchment. But for the 100 ha catchment the relative changes of slope are still low while the relative changes for the increase of meander, resulting from implementing the slope reduction, increases dramatically. This example reveals that the relative changes of slope shown in figure 3 (left) do not necessarily represent the relative changes, the implementation
Mitigation measures towards morphological alterations of rivers: The receiving water as part of the integrated wastewater system

of the slope reduction in the form of suitable measures (e.g. increase of meandering, bed sill or weir) will imply.

The results show that none of the measures can be reasonably implemented to mitigate the effect of a 100 ha catchment on a small river of a width about 2 m. To reduce the slope by increase of meander the stretch length would have to be doubled so that a straight river afterwards would be meandering; to reduce the impact by widening the river bed would have to be widened from 2 m to more than 10 m and the CSO storage volume would have to be increased to 60 mm. In such a case other solutions should be found, e.g. relocation of the overflow into a larger receiving water.

Cost comparison – an example

Table 1. Example of costs for different measures, data from Germany.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Unit</th>
<th>Min</th>
<th>Range</th>
<th>Max</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Costs for bed paving</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock filling (layer thickness 20-30cm)</td>
<td>Euro/m²</td>
<td>17.5</td>
<td>35</td>
<td></td>
<td>(Grünebaum et al., 2002; Lange and Lecher, 1993)</td>
</tr>
<tr>
<td>Plaster on gravel bed</td>
<td>Euro/m²</td>
<td>36</td>
<td>92</td>
<td></td>
<td>(Lange and Lecher, 1993)</td>
</tr>
<tr>
<td>2. Costs for increase of meander</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remodeling of river bed</td>
<td>Euro/m</td>
<td>65</td>
<td>225</td>
<td>750</td>
<td>(Interwies et al., 2003)</td>
</tr>
<tr>
<td>3. Costs for widening of the channel bed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel widening</td>
<td>Euro/m</td>
<td>65</td>
<td>200</td>
<td>600</td>
<td>(Interwies et al., 2003)</td>
</tr>
<tr>
<td>4. Costs for increase of CSO storage volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSO volume 3500m³</td>
<td>Euro/m³</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>(CD4WC Deliverable 2.2, 2005)</td>
</tr>
<tr>
<td>CSO volume 600m³</td>
<td>Euro/m³</td>
<td>716</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

For one of the scenarios used earlier a comparison of costs for selected measures has been made. In this example a catchment with an impervious area of 40 ha and 4800 PE discharged via a CSO of 600 m³ (equals 1.5 mm storage volume) to a small river. The river had a discharge Q₃₄₇ (discharge that is exceeded on 347 days a year) of 0.4 m³/s, sediment grain size d₉₀ of 0.035 m, a slope of 5 ‰ and a bed width of 2 m.

The number of erosion events due to CSO discharge was calculated as 11 events per year in the base system. The maximum acceptable number of erosion events was fixed arbitrarily to four events/ year. Then the changes necessary to reduce the number of erosion events were determined. Four different alternatives were tested, first the increase of grain size, second the decrease of slope, third the increase of CSO storage volume and fourth the widening of the river bed (see figure 3 (right)). For the changes that were necessary to achieve the goal of four erosion events per year the costs for the different measures were calculated. The length of the stretch that is influenced by the CSO discharge was assumed to have the length 1000*width of the river water surface.

For the first variant the bed material was covered with gravel or plaster, the resulting costs were calculated to be between 90,000 and 470,000 €. The second variant to decrease the bed slope from 5% to 4% was achieved by remodelling the river course so that the length of the stretch and the meandering increased. Therefore it was assumed that the river was artificially straight, the resulting stretch after applying of the mitigation measure was braided which is usually a more natural status for a river course. The costs for this remodelling of the river bed were determined to be between 600,000 and 1,100,000 €. The third variant was calculated to compare the measures in the river with a measure in the sewer system. To decrease the
number of erosion events to the required number of four, the storage volume of the CSO had to be extended from 600m$^3$ to 3500m$^3$. The costs for the construction for a CSO with a volume of 3500m$^3$ are about 2,000,000 €, about 1,300,000 € more than the costs for a CSO of 600m$^3$. The fourth variant was to decrease the number of erosion events by widening of the river channel. It was necessary to enlarge the width from two to three meters, the costs resulting from this measure for the influenced stretch are between 500,000 and 800,000 €.

![Cost comparison for different measures.](https://iwaponline.com/wpt/article-pdf/1/1/wpt2006013/383473/13.pdf)

**Figure 5.** Cost comparison for different measures.

The comparison of costs for the different measures in this example shows that here an in-stream measure to mitigate the hydraulic impact is cheaper than extension of the CSO storage capacity. The variants two (increase of meandering) and four (widening of the river bed) have furthermore the advantage that they can restore the river to a more natural status and thus can improve its ecological status. This example focused only on the hydraulic impact, so before applying such a measure the effect of pollution caused by the CSO would have to be investigated, too.

**CONCLUSIONS**

Morphological impacts (adverse erosive events) onto the receiving water were investigated for different sets of rivers, catchments and rain series. The numerical study has been done using the software tool REBEKA. The relation of sizes of rivers and catchments connected proved to determine the degree of the impact. Only catchments with considerable size connected to small rivers lead to erosion problems.

Different measures - in-stream and in the urban catchment – were tested to improve the situation. The alternative increase of CSO storage volume was found to be an inappropriate solution as it resulted in unrealistic high volumes, while in-stream measures have potential for mitigation of hydraulic impacts. Besides the different technical measures for bed and bank stabilisation also restoring measures can improve the resistance against erosion, on the one hand by increasing the resilience of the aquatic biocoenosis but also by reduction of slope (e.g. by restoring of meandering river course) or by widening of the artificially narrowed channel. Still, field test for applying restoration measures are missing, but would be necessary to validate their effectiveness. If the catchment size exceeds a certain level no reasonable effort yields an ecological tolerable solution, neither by in-stream measures nor by increase of CSO storage volume. In these cases other solutions have to be found, e. g. redirecting of the discharge into a larger receiving water.

A comparison of costs revealed that in-stream measures can be cost-effective. An extensive evaluation could not be made in the frame of this study due to the complexity of flow.
Mitigation measures towards morphological alterations of rivers: The receiving water as part of the integrated wastewater system

dynamics. Flow peak damping in a river depends on a variety of factors (e.g. roughness of the bed, water depth, cross section) and therefore the length of the stretch that is affected by the peak discharge from the CSO cannot be easily determined. But without this knowledge accurate planning and design of most of the in-stream measures is impossible. Even more difficult is the assessment of effects of structures like bed ramps or weirs as it requires detailed numerical simulations or model experiments.

This study demonstrated the potential of in-stream measures for mitigation of hydraulic impacts by CSO and that costs can be saved by applying simulation tools and testing different measures in the different sub systems of the urban wastewater system (here the receiving water) instead of simply deciding to go for the classical measure (e.g. increase of CSO storage).

ACKNOWLEDGEMENT
The authors gratefully acknowledge the financial support of the EU project CD4WC (EVK1-2001-00286). [http://www.cd4wc.org]

REFERENCES
Rauch W., Krejci V. and Gujer W. (2000). REBEKA - ein Simulationsprogramm zur Abschätzung der Beeinträchtigung der Fließgewässer durch Abwassereinleitungen aus der Siedlungsentwässerung bei Regenwetter (REBEKA - a simulation tool for assessing the impact on running waters by sewage discharges from urban drainage at wet weather conditions). Schriftenreihe der EAWAG, 16, EAWAG (Swiss Federal Institute of Aquatic Science and Technology), Zuerich, Switzerland.