# Effect of retrofitting a saturated zone on the performance of biofiltration for heavy metal removal - preliminary results of a laboratory study

## Traitement des eaux de ruissellement par biofiltration : influence d'une zone saturée sur l'absorption des métaux lourds - présentation des premiers résultats

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## RÉSUMÉ

Le biofiltre végétalisé est un procédé biologique d'assainissement des eaux pluviales de plus en plus utilisé de nos jours pour ses qualités de traitement et son caractère écologique. Des études existantes ont permis de mettre en évidence une amélioration du rendement épuratoire de l'azote en termes d'efficacité et de fiabilité lorsque la base du biofiltre est saturée en eau. De plus, il a été montré qu'une telle zone saturée augmente la rétention des métaux lourds, notamment le cuivre. La plupart des biofiltres existants ne comportent pas de zone saturée mais peuvent facilement être réaménagés par un simple rehaussement de la sortie. Ce projet a pour but d'approfondir les conséquences d'une zone saturée en fond de biofiltre vis à vis du traitement des métaux lourds. L'étude, menée en laboratoire à l'aide de colonnes biofiltrantes, a permis de mettre en évidence une légère augmentation du rendement épuratoire des métaux lourds. La zone saturée augmente la rétention du zinc, mais son effet est variable pour le cuivre. Donc si le traitement des métaux lourds est le principal objectif, l'aménagement d'une zone saturée en fond de biofiltre n'est pas nécessaire. En revanche, celles-ci permettent de protéger le biofiltre contre de longues périodes sèches tout en augmentant la capacité de traitement de l'azote et sans compromettre celui des métaux lourds.

## ABSTRACT

Stormwater biofilters are a stormwater treatment technology which has been becoming increasingly popular. Recently it has been shown that a submerged zone in the filter media improves the magnitude and consistency of nitrogen treatment. Furthermore, the submerged zone has even been shown to be beneficial for retention of heavy metals, particularly Cu. However, most existing biofilters do not include a saturated zone. Since it is relatively simple to retrofit a submerged zone by elevating the outflow, the effect of such a retrofitting on metal removal was investigated in this laboratory study using biofilter columns. It has been shown that a retrofitted submerged zone has a statistically significant but practically small effect on metal removal: Zn removal is slightly enhanced while the effect on Cu removal is inconsistent. Thus, retrofitting of a submerged zone is not recommended if metals are the main target pollutants. But if a submerged zone would have other benefits (e.g. for nitrogen removal or to protect the system from prolonged drying periods) it can be retrofitted without compromising metal removal.

## KEYWORDS

Stormwater, biofilter, heavy metal removal, submerged zone, water sensitive urban design

# 1 INTRODUCTION

Stormwater has been identified as one major reason for degradation of urban waterways (Walsh et al., 2005) due to high peak flows and runoff volumes as well as a high contaminant loads. Key pollutants in stormwater are heavy metals (mainly Cd, Cu, Pb and Zn), nutrients and PAHs (Eriksson et al., 2007). In recent years, the focus in urban drainage has shifted increasingly from mainly considering runoff volumes and their rapid discharge to incorporating water quality issues (Dietz, 2007). Concepts including this more holistic view of urban drainage are given such names as. Water Sensitive Urban Design (WSUD) and Low Impact Development (LID).

Stormwater biofiltration (or bioretention) has been shown to be a promising technology within WSUD for both stormwater retention and water quality treatment (Davis et al., 2001; Muthanna et al., 2008). A biofilter consists of one or more vegetated filter media layers with a typical total depth of 700 to 900 mm. The filter is placed in a depression to provide stormwater storage above it. The filter media is often underlain by a drainage layer with an embedded drainage pipe which discharges the treated water to a receiving water or the conventional stormwater sewer system. Alternatively the treated water can be infiltrated into the surrounding soil (Melbourne Water, 2005). Due to their variable size, biofilters can even be retrofitted into an existing development.

Water quality treatment in stormwater biofilters is commonly effective and reliable. TSS, heavy metal and phosphorus removal is very efficient and the removal rates often exceed 90% (Blecken et al., 2007; Davis et al., 2006; Davis et al., 2003). However, nitrogen removal has commonly been less efficient. While aerobic nitrification (generating nitrate-N) occurs in the usually well drained filter media, anaerobic denitrification is often lacking. Thus, in several studies nitrate-N leaching has been shown which reduced the total nitrogen removal (Blecken et al., 2007; Bratieres et al., 2008; Davis et al., 2006; Hsieh et al., 2007; Passeport et al., 2009).

In order to enhance nitrogen removal, recently a submerged (partly anoxic) zone with an embedded carbon source has been introduced into the filter media in order to enhance nitrate-N removal due to enhanced denitrification. Using this feature, total nitrogen removal could be enhanced significantly (Dietz et al., 2006; Kim et al., 2003; Zinger et al., 2007). Since the primary aim of this submerged zone was to improve nitrogen treatment, studies about a submerged zone in biofilters have mainly been focusing only on nitrogen. However, one has to take care that elevating the nitrogen removal does not deteriorate effective metal removal. The limited research about the effect of a submerged zone on metal removal so far has however not indicated any conflicts between metal removal and a submerged zone with embedded carbon source (Blecken et al., 2009a). It has been shown, rather, that a submerged zone improves metal removal especially after prolonged drying periods, by providing a more stable moisture regime (Blecken et al., 2009b).

Due to its advantages, biofilters have been becoming increasingly popular in urban drainage during the last years. However, in most existing biofilters the submerged zone is not implemented since it has been developed only recently and has not been recommended in current technical design guidelines (e.g. (Melbourne Water, 2005; U.S. EPA, 2004). Despite this, if nitrogen treatment is primarily targeted and/or if prolonged dry periods are expected, one possible strategy is to retrofit a submerged zone into existing biofilters.

It has been shown that retrofitting a submerged zone into conventional biofilters without that feature could enhance nitrogen removal significantly (unpublished results of this study). However, no study so far has investigated the effect of a retrofitted submerged zone on metal removal. It is of particular interest to ascertain whether the introduction of a submerged zone (in this case without a carbon source) will diminish the high metal removal achieved in standard biofilter designs or if it will enhance metal removal as well, as has been shown in purpose-built systems previously (2009a).

The aim of this study is thus to investigate the effect of retrofitting a submerged zone on the metal removal in stormwater biofilters.

# 2 METHODS

## 2.1 Experimental set-up and procedure

In this study biofilter columns with the following configuration were used (Figure 1):

| | |
|---|---|
| • Inner diameter | 375 mm |
| • Height | 1300 mm, made up of 900 mm PVC stormwater pipe and 400 mm transparent plexiglass (allowing ponding of water without shading the plants) |
| • Filter | 700 mm sandy loam |
| • Drainage | 100 mm transition and drainage layer with an embedded drainage pipe connected to the outflow port |

Three groups of five replicate biofilter columns each were utilised which were planted with *Carex appressa* (Tall sedge), *Dianella revoluta* (Blueberry lily) and *Microleana stipoides* (Weeping Grass), resp.

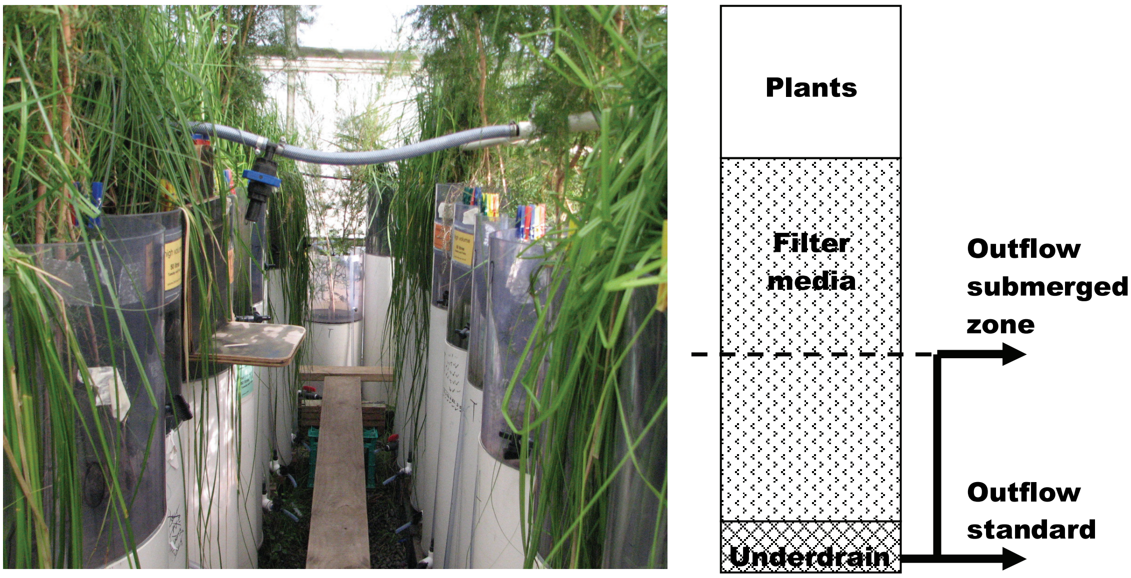

Figure 1: Biofilter columns in greenhouse.

The columns were dosed twice weekly with 50 L (*Carex* and *Microleana*) or 25 L (*Dianella*) stormwater per event. In order to assure constant stormwater quality over the run-time, semi artificial stormwater was used. It was prepared by adding stormwater pond sediment and chemicals to dechlorinated tap water (using sodium thiosulfate) in the required amount to achieve target pollutant concentrations (based on Duncan, 1999). The stormwater characteristics are presented in Table 1. Stormwater preparation and volume calculation are described in detail in Blecken et al. (2009a).

After about one year in operation a permanently water saturated submerged zone was retrofitted to all columns by elevating the outflow port by 450 mm. I.e. all 15 columns were tested as standard biofilters for one year and then the submerged zone was added to all of them. The saturated zone was subject to some drying in-between the storm events, i.e. no water was added to maintain a stable water table in the filter media.

The columns were placed in a greenhouse in Melbourne, Victoria, Australia, to ensure that they did not receive rainfall inflow. Open mesh on the sides maintained that the columns were exposed to local Melbourne climate conditions.

| Pollutant | Mean stormwater concentration ± standard deviation | Chemicals used for topping up of existing sediment concentrations as required |
|---|---|---|
| Total susp. solids (TSS) | 179 mg/L ± 71 | stormwater pond sediment (≤300µm) |
| Copper (Cu) | 67.5 µg/L ± 32.8 | copper sulphate ($CuSO_4$) |
| Lead (Pb) | 154.5 µg/L ± 50.5 | lead nitrate ($PbNO_3$) |
| Zinc (Zn) | 450.3 µg/L ± 136.0 | zinc chloride (ZnCl) |

Table 1 Stormwater characteristics

## 2.2 Sampling procedure and analyses

Before retrofitting the submerged zone, six samplings (in the following labelled A to F) were conducted over the run time of nine month. Two months after retrofitting the submerged zone, three samples (labelled G to I) were taken over a period of three months. At each sampling, one 1 L composite outflow sample from each column was taken made of five sub- samples which were distributed evenly over the whole outflow event. Additionally, the inflow was controlled using two composite inflow samples per event. The samples were taken in one litre PE bottles and analysed for metals by a NATA-accredited laboratory using standard methods (APHA/AWWA/WPCF, 1998). The instrument detection limits were 0.3 µg / L for Cu, 0.6 µg / L for Pb and 0,5 µg / L for Zn.

## 2.3 Data analysis

Average metal outflow concentrations were compared to Swedish water quality guidelines (Swedish EPA, 2000). Detailed analyses were then conducted for the removal rate. Metal removal was calculated as follows: removal (%) = (1 - out / in) x 100. To give an indication of the data variability over the run-time, the metal removal of the biofilter groups was plotted for each sampling event using box plots.

To detect a metal removal difference between the biofilter groups before retrofitting (samplings A to F) a one-way ANOVA was used (response: metal removal, factor: group).

To detect possible effects of the retrofitting of the submerged zone, for each group the outflow concentrations of the four events before and after retrofitting were compared using 2-sample t-tests. The first two events of the run-time were not regarded in order to eliminate the possibly misleading effect of the varying removal in the beginning of the experiment (see Figure 2, especially Cu removal). The mean difference was calculated as mean removal before retrofitting – mean removal after retrofitting. Thus, a positive value indicates worse removal after retrofitting while a negative difference indicates an enhanced removal after retrofitting.

For all statistical analyses, significance was accepted at an α-level of 0.05

## 3 RESULTS

The inflow Cu and Pb concentrations were relatively constant over the experimental run time while the Zn concentrations varied more. Outflow quality was enhanced significantly: Mean Cu outflow concentrations were 4.9 µg/L, Pb 2.6 µg/L and Zn 5.4 µg/L. These outflow concentrations meet most often class 2 or 3 (2: **slight risk of biological effect, 3: effects may occur)** of Swedish water quality guidelines (Swedish EPA, 2000) while the stormwater inflow always lays far above the threshold for class 5 (very high concentration / growing rsik of biological effects). Thus, all standard biofilters (i.e. before retrofitting the submerged zone) provided very high levels of heavy metal removal (Figure 2, samplings A to F). Pb and Zn stormwater concentrations were commonly reduced by more than 95 %. Cu removal was less effective at the first two samplings (around 70 to 80 %) but reached subsequently about the same excellent removal as Pb and Zn. There was no significant difference between the three biofilter groups at the events A to F (One-way ANOVA: Cu, Pb and Zn removal vs. Group, α = 0.05, $R^2$(adj.) = 0.000).

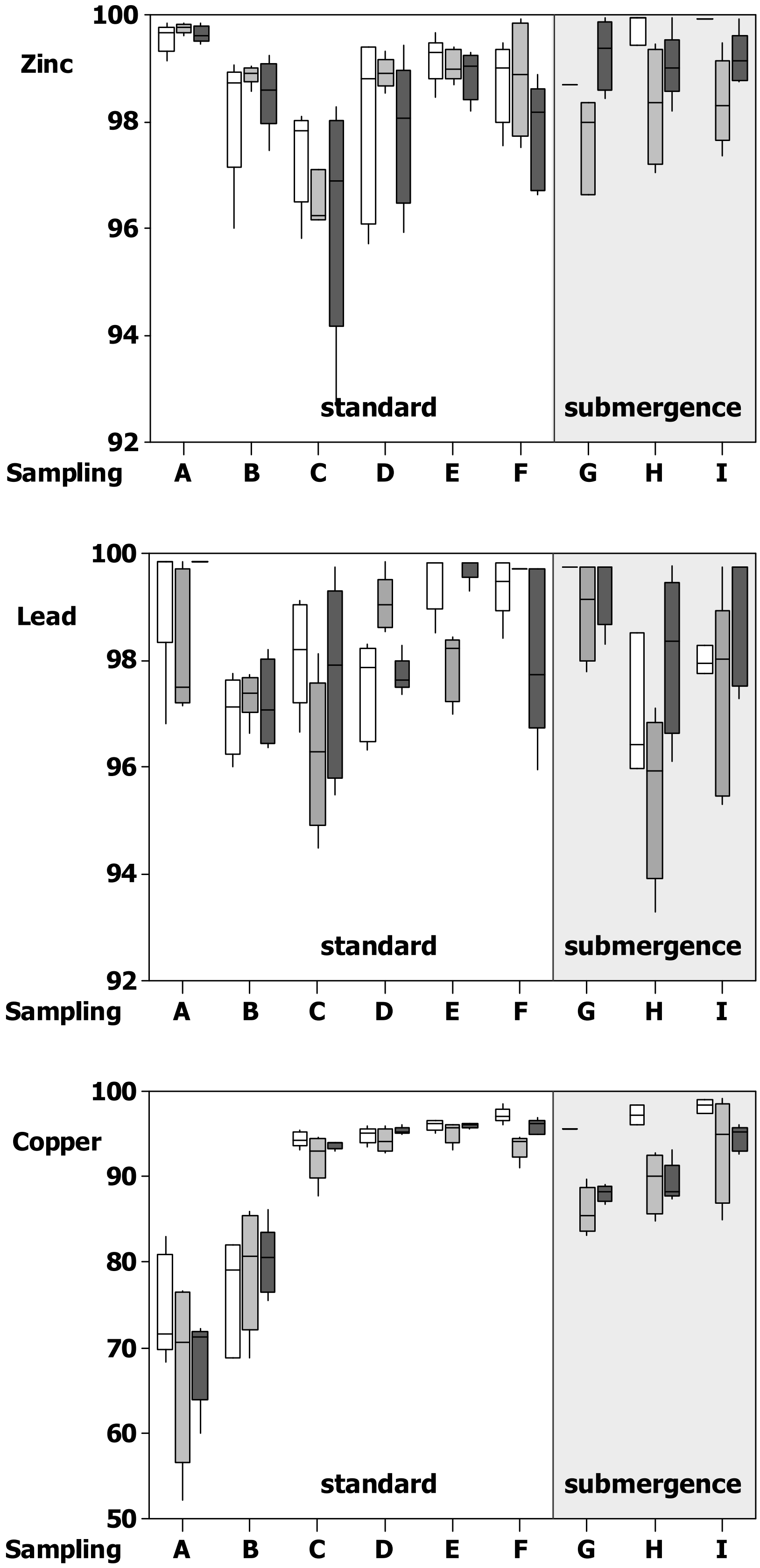

Figure 2: Box plot of Cu, Pb and Zn removal in % by biofilters with *Carex* (white boxes), Dianella (light grey boxes) and *Microleana* (dark grey boxes) at the samplings before (A to F, white background) and after retrofitting (G to I, shaded background) of the submerged zone.

Retrofitting of the submerged zone influenced Cu and Zn removal slightly while Pb removal remained unaffected at its high level in all groups. The effect of retrofitting the submerged zone on metal removal is presented in Table 2. Doing the same analyses for outflow concentrations gives about the same results.

Zn removal in the *Carex* and the *Microleana* groups was enhanced by around 1.5 %. For the *Dianella* groups no difference was detected. Cu removal was enhanced in the Carex group by 1.9 % while it was about 4 % worse in the other two groups.

| Sample | | Two sample t-test | |
|---|---|---|---|
| | | p-value | estimate for difference (%) |
| Cu removal (%) | *Carex* | 0.007 | – 1.9 % |
| | *Dianella* | 0.018 | + 4.2 % |
| | *Microleana* | 0.000 | + 4.4 % |
| Pb removal (%) | *Carex* | 0.170 | |
| | *Dianella* | 0.166 | |
| | *Microleana* | 0.281 | |
| Zn removal (%) | *Carex* | 0.000 | – 1.4 % |
| | *Dianella* | 0.352 | |
| | *Microleana* | 0.001 | – 1.5 % |

Table 2: Results of the two sample t-test comparing metal removal before and after retrofitting a submerged zone into the two biofilter groups. Negative difference indicates better removal after retrofitting and positive difference worse removal after retrofitting of the submerged zone.

## 4 DISCUSSION

The excellent metal removal in standard stormwater biofilters has commonly been shown in a number of both field and laboratory studies (e.g. (Davis et al., 2001; Dietz, 2007; Fletcher et al., 2007; Lau et al., 2000).

Given the complex processes influencing metal removal in biofilters it is difficult to identify the mechanisms behind the effect of the submerged zone based on the existing data and given the very small detected difference compared to the total variation of the data (Figure 2).

A submerged zone in a stormwater biofilter reduces drying of the filter media by providing a constant pool of water which may be drawn up into the media via capillary and evaporative actions and thus provides a more stabile moisture regime. It has been shown that a submerged zone provides at least partially anoxic conditions (Zinger et al., 2007) under which metal sorption of sediments is higher than under oxic conditions (Bradl, 2004). Oxidation of (previously anoxic) sediment is estimated to be the most efficient way to mobilise metals into the environment (Förstner et al., 1989). By introducing a submerged zone into biofilters, oxidation between the storm events of the filter media is prevented (or at least minimised). Thus, less oxidation of the filter media might be one reason for the slight increase of some metal treatment after retrofitting. However, given the only small effect of the submerged zone and the regular dosing of the filters without prolonged drying (and thus oxidation), it is difficult to estimate the effect of drying and oxidation on the results. It has however been shown that drying exceeding three to four weeks has a negative effect on metal removal and that this effect can be minimised or eliminated by using a submerged zone (Blecken et al., 2009b).

Since only limited research has been done regarding the effect of a submerged zone on metal removal it is difficult to compare these results with other studies. It has been shown that a submerged zone with an embedded carbon source in stormwater biofilters improves metal removal significantly: especially Cu removal was enhanced while Pb and Zn removal was only effected slightly (Blecken et al., 2009a). Similarly, in the study at hand, Zn removal is enhanced slightly too, while Pb removal is not affected. The effect on Cu treatment was ambiguous since removal was enhanced for one group and deteriorated for the other two.

In contrast to the retrofitted submerged zone in this study the submerged zone of Blecken et al. (2009a) contained an embedded carbon source (pea straw and wood chips). Since Cu has a clear affinity to organic matter the lack of an embedded carbon source (i.e. solid organic matter) might explain why Cu removal was not enhanced in this study: formation of (insoluble) Cu-organic matter complexes (which contribute to the enhanced Cu removal) was not enabled to the same degree as in the cited study where the carbon source was added. Thus, a comparison of the results at hand with Blecken et al. (2009a) indicates that it may not be the submerged zone itself, but rather the embedded carbon source, which is the main factor enhancing Cu removal. However, it is unclear what amount of organic matter is present in the columns with the retrofitted submerged zone; since nitrogen removal was enhanced in the columns at hand (yet unpublished) due to increased denitrification. For this to occur, some carbon (possibly from biomass turnover or stormwater input) must be available in the submerged zone. If this assumption that organic matter is provided by biomass turnover is true, this might explain the increasing Cu removal at the samplings A to C: little biomass detritus would have accumulated in the beginning, but given the availability of organic matter in the filter media, accumulation over time would be expected. Thus, the rate of Cu-organic matter complexation increased with time and enhanced removal after some months of establishment. Possibly by flooding the filter media by retrofitting the submerged zone, some organic matter and thus Cu was suspended and flushed out during subsequent sampling events (samplings G and H). Stabilising conditions after establishing of the submerged zone might explain the again increasing Cu removal over time after retrofitting. To validate these assumptions regarding Cu treatment, it would be necessary to investigate if organic matter from biomass turnover is present in the filter media, if it is in its dissolved or solid form and if it is flushed out after retrofitting of the submerged zone. Furthermore, if a carbon source is provided by plant detritus, the characteristics of this detritus could possibly explain the different Cu treatment in the groups with the different plant species (Figure 2). However, given only the existing data from this study, this impact remains to be hypothetical. Thus, given these differences in metal removal, the effect of different plant species on metal removal in general and on Cu-organic matter complexation in particular.

Given the very high removal rates both before and after retrofitting of the submerged zone and the unclear trends after retrofitting (both better and worse treatment for Cu, enhanced treatment in only two of the three groups), the detected (statistically) significant effect of the retrofitting has to be judged in context. Even if Zn treatment is enhanced significantly the practical implications of this are small since the mean removal was already above 98% before retrofitting the submerged zone. The same applies for Cu where even for the worst sampling after retrofitting the mean removal is still sufficient (89 %). Furthermore, after retrofitting Cu, removal increases with time and reaches at the last sampling, I, the same range as before retrofitting. Thus, possibly the detected effect would have been eliminated if the experimental run time had been extended.

Given the comparatively small effect on metal removal, retrofitting of a submerged zone is not recommended as being worthwhile if metals are the main target pollutants. However, if nitrogen removal is of concern, a submerged zone can be retrofitted to facilitate improved denitrification, without jeopardising the metal removal too much. Furthermore, if prolonged drying is expected, a retrofitted submerged zone might even enhance metal removal significantly (cf. Blecken et al., 2009b).

## 5 CONCLUSION

The heavy metal treatment in the tested biofilters was very efficient. Substantial loads (commonly exceeding 95%) of Cu, Pb and Zn were removed from the stormwater. This study confirms therefore that stormwater biofilters are a good management strategy to treat urban stormwater.

Retrofitting of a submerged zone into standard stormwater biofilters neither enhances nor degrades Cu, Pb and Zn removal by a practically significant amount. Thus, retrofitting is not recommended as being worthwhile if metals are the key pollutant group since no clear benefit can be obtained. However, since it has commonly been shown that nitrogen removal is significantly enhanced by introducing a submerged zone into stormwater biofilters, retrofitting can be recommended without compromising metal treatment.

## LIST OF REFERENCES

APHA/AWWA/WPCF. (1998). Standard Methods for the Examination of Water and Wastewater, 20th edn. *American Public Health Association/American Water Works Association/Water Pollution Control Federation, Washington, DC, USA.*

Blecken, G.-T., Viklander, M., Muthanna, T. M., Zinger, Y., Deletic, A., & Fletcher, T. D. (2007). The influence of temperature on nutrient treatment efficiency in stormwater biofilter systems. *Water Science and Technology, 56*(10), 83-91.

Blecken, G.-T., Zinger, Y., Deletic, A., Fletcher, T. D., & Viklander, M. (2009a). Impact of a submerged zone and a carbon source on heavy metal removal in stormwater biofilters. *Ecological Engineering, 35*(5), 769-778.

Blecken, G.-T., Zinger, Y., Deletic, A., Fletcher, T. D., & Viklander, M. (2009b). Influence of intermittent wetting and drying conditions on heavy metal removal by stormwater biofilters. *Water Research, 43*(18), 4590-4598.

Bradl, H. B. (2004). Adsorption of heavy metal ions on soil and soil constituents. *J. Colloid Interface Sci., 277*, 1-18.

Bratieres, K., Fletcher, T. D., Deletic, A., & Zinger, Y. (2008). Nutrient and sediment removal by stormwater biofilters; a large-scale design optimisation study. . *Water Research, 42*(14), 3930-3940.

Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2001). Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environment Research, 73*(1), 5-14.

Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water Quality Improvment through Bioretention Media: Nitrogen and Phosphorus Removal. *Water Environment Research, 78*(3), 284.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C., & Winogradoff, D. (2003). Water quality improvement through bioretention: Lead, copper, and zinc removal. *Water Environment Research, 75*(1), 73.

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommentdations for Future Directions. *Water Air and Soil Pollution, 186*, 351-363.

Dietz, M. E., & Clausen, J. C. (2006). Saturation to improve pollutant retention in a rain garden. *Environ. Sci. Technol., 40*, 1335-1340.

Duncan, H. P. (1999). *Urban Stormwater Quality: A Statistical Overview*: Report 99/3, Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia.

Eriksson, E., Baun, A., Scholes, L., Ledin, A., Ahlman, S., Revitt, M., et al. (2007). Selected stormwater priority pollutants -- a European perspective. *Science of The Total Environment, 383*(1-3), 41-51.

Fletcher, T. D., Zinger, Y., & Deletic, A. (2007). *Treatment efficiency of biofilters: results of a large-scale column study.* Paper presented at the rainwater & urban design 2007, Sydney, Australia.

Förstner, U., Ahlf, W., & Calmano, W. (1989). Studies on the Transfer of Heavy Metals between Sedimentary Phases with a Multi-Chamber Device: Combined Effects of Salinity and Redox Variation. *Marine Chemistry, 28*, 145-158.

Hsieh, C.-H., Davis, A. P., & Needelman, B. A. (2007). Nitrogen Removal from Urban Stormwater Runoff Through Layered Bioretention Columns. *Water Environment Research, 79*(12), 2404-2411.

Kim, H., Seagren, E. A., & Davis, A. P. (2003). Engineered Bioretention for Removal of Nitrate from Stormwater Runoff. *Water Environment Research, 75*(4), 355-367.

Lau, Y. L., Marsalek, J., & Rochfort, Q. (2000). Use of a Biofilter for Treatment of Heavy Metals in Highway Runoff. *Water Quality Research Journal of Canada, 35*(3), 563-580.

Melbourne Water. (2005). *WSUD Engineering Procedures: Stormwater*: CSIRO Publishing.

Muthanna, T. M., Viklander, M., & Thorolfsson, S. T. (2008). Seasonal climatic effects on the hydrology of a rain garden. *Hydrol. Process., 22*, 1640-1649.

Passeport, E., Hunt, W. F., Line, D. E., Smith, R. A., & Brown, R. A. (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. *Journal of Irrigation and Drainage Engineering-Asce, 135*(4), 505-510.

U.S. EPA. (2004). U.S. Enivironmental Protection Agency. Stormwater Best Management Practice Design Guide. Volume 2. Vegetative Biofilters. Cincinatti, OH, USA.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society, 24*(3), 706-723.

Zinger, Y., Fletcher, T. D., Deletic, A., Blecken, G.-T., & Viklander, M. (2007). *Optimisation of the nitrogen retention capacity of stormwater biofiltration systems.* Paper presented at the NOVATECH 2007, Lyon, France.