Treatment of urban and highway stormwater runoff for dissolved and colloidal pollutants

Traitement des pollutions dissoutes et colloïdales du ruissellement pluvial de chaussées urbaines et autoroutières

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RESUME

Le présent exposé décrit le principe de construction de trois ouvrages de traitement des eaux de ruissellement dans le but d'appliquer et de démontrer l'efficacité des technologies visant à réduire la charge de polluants urbains déversée vers les milieux récepteurs. Le concept à pour but, non seulement, de réduire les pollutions particulaires mais aussi les pollutions dissoutes associées aux colloïdes. Les opérations unitaires qui permettent d'atteindre cet objectif sont décrites. Différentes technologies de traitement des eaux pluviales sont mises en œuvre et intégrées dans la conception de chaque ouvrage. Dans l'un de ces ouvrages on pratique l'enrichissement en fer des sédiments de fond, dans un autre, on ajoute des sels d'aluminium à l'entrée des effluents et dans le troisième, on utilise des filtres à éléments filtrants fixes. On présente, également, les résultats de laboratoire portant sur l'élimination du phosphore par élément filtrant fixe.

ABSTRACT

The design of three stormwater treatment facilities, aiming at implementing and demonstrating technologies that efficiently reduce diffuse urban pollutant loads onto receiving waters is presented. The designs aim at reducing not only particulates, but also dissolved pollutants and pollutants associated with colloids. Unit operations that are efficient in this respect are discussed. Different technologies for extended treatment of stormwater runoff are applied in the design of each facility: One facility applies iron enrichment of bottom sediments; another applies the addition of aluminium salts to the incoming stormwater; and the last facility applies fixed media filters. Laboratory results regarding the removal of phosphorus by fixed media are presented.

KEYWORDS

Colloidal pollutants ; extended treatment ; soluble pollutants ; stormwater ; wet detention ponds.

INTRODUCTION

Design of stormwater treatment facilities is subject to at least two major challenges. The first challenge relates to the fact that stormwater runoff events are rare. On an annual basis, a stormwater treatment facility only receives runoff a few percent of the time. Runoff events are often separated by long intermittent dry weather periods, and the facility must manage high inflow rates upon long dormant periods. The second issue is that rather large pollutant loads from urban surfaces are mixed into quite large stormwater runoff volumes, resulting in low concentration levels. Consequently, the task is to treat rather low pollutant concentrations to even lower levels.

A further complication arises from the need for stormwater detention, required to minimize the hydraulic load on receiving waters. Furthermore, the facilities are often placed in areas of recreational value, and must therefore be designed with urban landscape architecture in mind. Consequently, stormwater treatment facilities must at the same time be capable of stormwater pollutant treatment, stormwater flow detention and be an asset of the urban landscape. It is an engineering objective to combine the demands for treatment, retention and recreational values into management facilities with little requirement for land, low investment cost, low operational costs and low maintenance requirements.

During the last decades, numerous technologies for management of stormwater runoff have evolved. Some of the most reliable and effective technologies are infiltration systems, wet detention ponds and artificial wetlands. Of these, especially wet detention ponds are capable of meeting all the above stated requirements.

By design, the traditional concept of a wet detention pond applies sedimentation as the major unit operation for treatment. It makes use of the fact that a significant part of the pollutants occurring in stormwater are associated with particles that settle out of the water column under non-turbulent conditions. Other unit operations occur to an unknown extend, namely plant uptake of dissolved pollutants, sorption of dissolved matter and colloids to surfaces, as well as flocculation of fine particles and colloids. The later unit operations act on the dissolved and colloidal fraction of the stormwater pollutants – i.e. those fractions which are most mobile in the aquatic environment and consequently possess the highest risk of causing adverse effects.

Hitherto, unit operations that are effective in removing soluble and colloidal pollutants have seldom been actively incorporated in the design of wet detention ponds. These unit operations have, however, been intensively studied on laboratory scale (e.g. Genc-Fuhrman, in press). Consequently, there is a need for full scale demonstration of the viability of these technologies. The European Commission has on this background funded a LIFE-Environment project (titled TREASURE) that will demonstrate robust, efficient and rather simple technologies for reduction of soluble and colloidal pollutants in stormwater runoff prior to discharge into receiving waters. The technologies will be incorporated as recreational elements in the urban landscape, hereby creating sustainable urban stormwater drainage solutions and increasing the public acceptance of the systems.

It is the objective of this work to present the stormwater treatment facilities designed in TREASURE and to discuss the unit processes applied. Laboratory experiments on pollutant sorption are presented and it is outlined how the knowledge gained from the laboratory experiments is used in the design of the full-scale treatment facilities.

1 METHODS

In the context of TREASURE, three facilities are constructed for treatment of stormwater runoff from urbanized areas. The facilities are located in the Danish cities of Silkeborg, Århus and Odense. All facilities are wet detention ponds, however, with additional unit operations for removal of dissolved and colloidal pollutants.

1.1 Catchment characteristics

The sites represent different catchment sizes and characteristics, covering residential areas, industrial areas as well as urban highways. The catchments have been selected to cover a wide range of land use and of stormwater quality, hereby allowing the knowledge obtained in the project to be generally applicable.

The catchment in Silkeborg is 25 ha with 8.8 ha being impermeable. It consists to around one third of housing areas and to two thirds of an urban highway. The treatment facility will be located in a large city park stretching from the outskirts and into the city. It will discharge to the urban lake 'Silkeborg Langsø'.

The catchment in Århus is 55 ha with 26 ha being impermeable. It consists to app. 80% of multi-storey residential buildings and to app. 20% of roads. The treatment facility will be placed at the lake 'Brabrand Sø', to which the water is also discharged. 'Brabrand Sø' is highly sensitive and declared as EU NATURA 2000 habitat.

The catchment in Odense is 27 ha with an impermeable area of 11.4 ha. It consists of light industry and the associated roads. The facility is located in a green area in the outskirts of Odense in conjunction to a sensitive marshland. The facility discharges into the marshland and the marshland ultimately drains into the Bay of Odense.

1.2 Unit operations for stormwater treatment

Each facility incorporates the unit operations of sedimentation, filtration and treatment by aquatic macrophytes. In addition hereto, the facility in Århus applies sorption to iron-enriched bottom soil, the facility in Silkeborg applies coagulation/flocculation by aluminium addition, and the facility in Odense applies fixed media sorption (Figure 1).

1.2.1 Sedimentation

The concentration of particulate matter in stormwater runoff is low compared to many environmental systems, e.g. activated sludge in settling tanks. The distance between stormwater particles is therefore large, and settling occurs as free, gravitational settling – i.e. settling in quiescent water as described by Stokes' Law or modifications hereof (e.g. Fredse and Deigaard, 1992).

However, the actual settling velocity of a particle of a given density, size and shape is not only governed by gravitation and drag – as assumed by e.g. Stoke's law – but also by dispersion and mixing. If the random movement caused by dispersion and mixing is greater than the downwards movement, the particle will not settle. In this case, particles are only removed from the water phase when the combined transport processes cause random impact with surfaces to which the particles may adsorb.

Nevertheless, settling has mostly been described ignoring turbulence (Rasmussen and Larsen, 1996), and the knowledge on unhindered settleability of stormwater particles is consequently based on studies in quiescent water. Under these conditions, most studies indicate that settling velocities as low as 10^{-4} to 10^{-5} m s^{-1} are needed to remove the majority of suspended solids (Pisano, 1996).

1.2.2 Aquatic macrophytes

Emergent aquatic macrophytes are often integrated in the design of wet detention ponds, but also where plants have not been actively included in the design, emergent as well as submerged macrophytes tend to colonize a pond. Macrophytes fulfil numerous purposes with respect to pollutant removal, and their combined effect is predominantly beneficial. From a treatment point of view, macrophytes should consequently be actively included in the design of wet detention ponds (Brix, 1997).

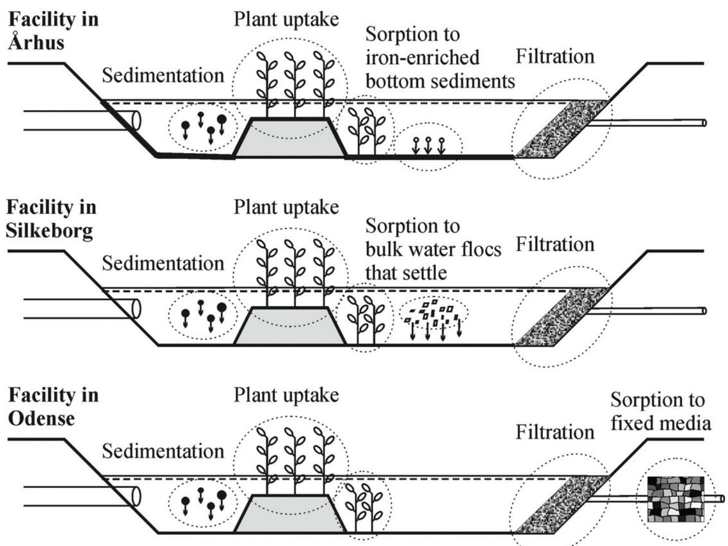

Figure 1 : Unit operations incorporated in the 3 facilities

Not all of the pond should, however, be covered with emergent macrophytes as this would cause poor reaeration of the pond. In order to avoid similar problems with floating species, e.g. duckweed, the open-water zones must be kept large enough to allow wind to break up the vegetation cover.

The practical way of permanently controlling the emergent macrophytes is to control the water depth. Emergent macrophytes will colonize the shallow parts of the pond, but do not thrive at deeper water levels. Most wetland macrophytes thrive at water depth above 0.3 m, however, e.g. the common reed can tolerate permanent inundation up to 1 m (Reed et al., 2006).

1.2.3 Filtration

Filtering stormwater through a porous media (e.g. sand) causes fine particles to be retained and a colmation layer to be formed on the filter surface. Hereby the hydraulic capacity of the filter is reduced and the filter capacity becomes controlled by the depth and hydraulic conductivity of the colmation layer. Assuming this layer to be homogenous with a well-defined depth and with conductivity much lower than the conductivity of the underlying filter material, the flow through the colmation layer occurs as saturated flow and can, as a first estimation, be described by Darcy's law, ignoring the underlying soil. However, in many environmental applications, the properties of the colmation layer are highly variable and it can be prudent to introduce a leakage factor, L, equal to the hydraulic permeability of the colmation layer divided by its depth. Hereby the filtration rate can be calculated as $Q = A\,h\,L$, where A is the surface area of the filter and h is the water depth over the filter (e.g. Vollertsen and Hvitved-Jacobsen, 2003).

For colmation layers formed beneath a permanent water surface, the reported hydraulic properties of colmation layers from infiltration of wastewaters and river beds lead to an estimation of the leakage factor to around 10^{-5} to 10^{-6} m s^{-1} (Houston et al., 1999; Calver, 2001; Vollertsen and Hvitved-Jacobsen, 2003). For stormwater infiltration through a filter with intermittent loading, a design leakage factor of around 10^{-4} s^{-1} seems to be a conservative choice (Dechesne et al., 2005).

1.2.4 Sorption to iron-enriched bottom soil

Ferric iron binds phosphate under aerobic conditions, and the content of iron in aquatic sediments is recognized as a significant parameter in the binding capacity. Jensen et al. (1992) found that an iron content of 15 gFe gP^{-1} can control the bulk water phosphate, and that an increasing Fe:P ratio causes decreasing bulk water concentrations. Iron has been shown effective for controlling phosphorous release from shallow lakes (Hansen et al., 2003; Smolders et al., 2001), and iron is furthermore likely to control several heavy metals in lake sediments as these are strongly associated with iron and manganese oxides (Stead-Dexter and Ward, 2004).

Applying iron to immobilize pollutants, it is crucial that the redox potential of the sediments is sufficient to avoid ferric iron to be reduced to ferrous iron. If ferric iron is reduced, the bound phosphate, heavy metals and probably also other pollutants, are released into the bulk water phase. It is therefore essential to ensure that the uppermost parts of the stormwater pond sediments do not become anaerobic.

1.2.5 Aluminium addition

The addition of aluminium salts has been practiced for restoration of eutrophic lakes in terms of phosphorous removal from the water column and immobilization of phosphorous in the lake sediments (Cooke et al., 2005). Also for ponds, the addition of aluminium has been found effective (May and Baker, 1978). The applied dosing ranges for efficient removal of orthophosphate and organic bound phosphorous from lakes are reported between 1.5 and 30 g Al m^{-3}, with cost-effective dosing around 2 - 6 g Al m^{-3} (Auvray et al., 2006; Cooke et al., 2005). The need of dosing aluminium to stormwater entering a wet detention pond is expected to be in the same range.

Due to the fact that the aluminium complexes formed are insensitive to variable redox conditions, anaerobic release of phosphorus and bound colloids is not an issue when applying aluminium. However, if pH rises above 8.5-9 – as can be the case during periods with intense photosynthesis in soft waters – $Al(OH)_3$ is ionized to $Al(OH)_4^-$, causing a release of the sorbed phosphorous and colloids. Furthermore, if pH falls below app. 5, the toxic aluminium ion, Al^{3+}, is released.

1.2.6 Fixed media sorption

Certain materials have proven efficient in binding pollutants. For example, materials containing calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) like marble, limestone, dolomite rock and different types of shells from marine organisms are efficient in removing especially phosphorus (Westholm, 2006). Also, certain organic materials, materials containing iron oxides and materials containing aluminum oxides provide efficient pollutant absorption (e.g. Genc-Fuhrman, in press).

Due to its eutrophying effects, phosphorous is a key pollutant in stormwater. To demonstrate phosphorus removal by sorption in fixed media filters, various calcareous filter media have proven effective (e.g. Brix et al., 2001; Vohla et al., 2005). Calcareous filter media can remove phosphorus by either adsorption on mineral surfaces or precipitation with Ca^{2+} ions in solution. For the low phosphorus levels characteristic for stormwater runoff, the primary mechanism is believed to be adsorption (Tunesi et al., 1999).

When designing fixed media filters for sorption, several parameters regarding the filter media must be considered. It is essential that the selected filter media has a high sorption capacity for the targeted pollutant(s). This allows for a long-term use of the filter without the need for changing the filter media. Furthermore, the sorption equilibrium concentrations must be low in order to reduce the rather low pollutant concentrations typical for stormwater runoff. The sorption capacities vary considerably with material characteristics; e.g. for phosphorus, sorption capacities for calcareous filter media are in the order of 0.2 – 5 mg P $(gTS)^{-1}$ (Westholm, 2006). Due to the low concentrations of phosphorous in stormwater, filter media capacities for stormwater treatment are in the lower end of this interval.

The kinetics of the intended sorption process must be fast, as the kinetics determines the minimum contact time required to achieve the desired pollutant removal. For many sorption media, the contact time requirement is the governing design parameter when sizing fixed media filters.

1.2.7 Laboratory determination of sorption kinetics

The rate at which pollutants are adsorbed by a filter media is a key factor in sizing the filter. In the context of TREASURE, two calcareous shell sands were treated with artificial phosphate solutions. 5 g of filter media was mechanically agitated in 100 mL phosphate solutions of varying initial concentration at pH 8 and 20°C. The residual phosphate concentration in solution was measured after 0, 0.5, 2 and 24 hours by the ascorbic acid method (APHA et al., 2005).

2 RESULTS

2.1 Sorption experiments

The results of the sorption experiments (Figure 2) clearly demonstrate that the sorption process is not instant. It is also evident that shell sand (a) has much better sorption properties than shell sand (b). Indeed, shell sand (b) releases phosphorus into solution when the initial concentration is less than 150 mgP m^{-3}. Also with respect to a low sorption equilibrium concentration, shell sand (a) performs well, hereby securing low phosphorous concentrations in the treated stormwater runoff.

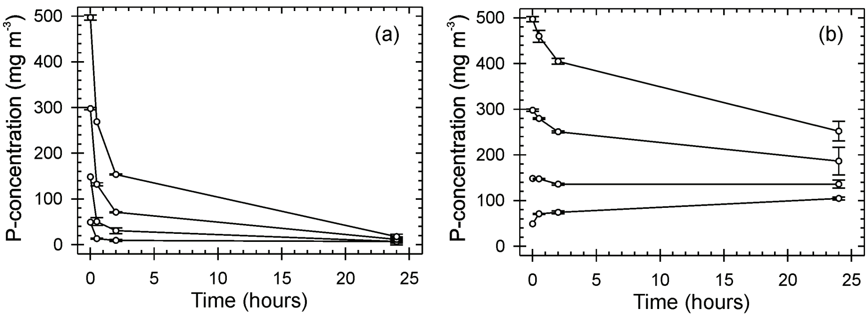

Figure 2. Kinetics of P-sorption by two calcareous shell sands.

With respect to the sorption kinetics, shell sand (a) provides faster sorption compared to shell sand (b), and a contact time of 30 – 60 minutes yields good sorption efficiency for shell sand (a). In conclusion, shell sand (a) is one of the media tested in the full scale filters established in Odense (Figure 1).

2.2 Implementation of the unit operations

The knowledge gained on the unit operations are combined and implemented in the design of the three stormwater treatment facilities. All ponds will contain an easily accessible fore-bay, acting as the primary sedimentation chamber. The fore-bay is designed to retain primarily inorganic particles of size down to app. 0.1 mm. Sedimentation of finer particles takes place in the main water volume of the pond.

The pond bottom will have varying water depths, with the deepest parts around 1.5 m. Within the pond, there will be areas with lower water depths, planted with emergent macrophytes, giving the impression of small islands and forelands. Furthermore, the embankments will be shallow and planted.

In the pond in Århus, iron salts will be added to such a concentration that the binding capacity is sufficient for 1-2 years. In the pond in Silkeborg, aluminium salts will be flow proportionally mixed into the incoming stormwater.

The treated water is discharged from the ponds through sand filters. As the colmation layer formed on the filter surface is influenced by the construction and loading pattern of the filter, several different sand filter layouts are tested. I) A vegetated horizontal sand filter in level with the permanent water surface. II) A sloping sand filter in the embankment above the permanent water level. III) A vertical sand filter, build as a reinforced and permeable structure and placed above the permanent water level.

For the facility in Odense, the stormwater enters the fixed media filters after sand filtration. Such an initial filtration step is crucial to avoid clogging of the sorption filter and thereby reducing its hydraulic capacity. The filters will be compartmentalized so that the sorption efficiency of different sorbents can be tested and compared.

2.3 Landscaping

To ensure public acceptance and a significant contribution to the aesthetic value of the landscape, the ponds are designed to follow the natural landscape structures. Embankments are kept gradual and the permanent water level is kept close to the natural level of the surrounding terrain. The embankments are planted with macrophytes as are sections of the wet ponds themselves, providing habitats for birds, amphibians and aquatic insects. Although a technical facility, the desired overall impression of the wet detention ponds is that of a natural aquatic habitat with a diverse flora and fauna.

3 MONITORING OF THE FULL SCALE FACILITIES

The stormwater treatment facilities will be completed by January 2008 and closely monitored until September 2009. For this purpose, each site is equipped with monitoring devises for continuous monitoring, namely meters for flow, pH, dissolved oxygen, turbidity, temperature and precipitation. In addition hereto, flow proportional sampling of the stormwater entering and exiting the pond will be conducted. The samples will be analyzed for numerous water quality parameters, including nutrients, heavy metals and organic micropollutants.

The monitoring results will be applied to quantify the individual effects of the unit operations included in the pond design. Furthermore, the treatment efficiency of each unit operation will be compared with respect to different pollutants.

4 CONCLUDING REMARKS

The main result of the TREASURE project is the demonstration and verification of treatment facilities obtaining very high pollutant removal in urban stormwater and road runoff by removing soluble and colloidal bound pollutants from the runoff. The project intends to demonstrate how the treatment concept of a semi-natural lake extended with units operations for filtration and sorption at the same time is robust and achieving excellent treatment performance.

By full scale comparison of the relative effectiveness of different unit operations for stormwater treatment, the project aims at achieving a knowledge base that can be applied in future designs of advanced stormwater management.

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