Towards sustainable urban stormwater management

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Abstract New directives for the management of urban stormwater prioritize infiltration and direct discharge into receiving waters. This requires innovative new stormwater facilities in urban areas. Besides hydraulic requirements for retention and infiltration capacity, the pollutants contained in the runoff water are of primary importance in future stormwater drainage concepts. Different urban surfaces are classified according to their potential for pollutant wash-off and the most crucial substances in view of hazardous effects in the aquatic and terrestrial environment are identified. Source control of hazardous pollutants by choosing alternative materials for the construction of buildings, roads and vehicles is considered to be most sustainable but will only be effective on a long-term perspective. In addition, new facilities for decentralized hydraulic retention combined with barrier systems for the most hazardous substances are proposed allowing for ecologically safe discharge of the stormwater into the local environment. Soil passage and new adsorber systems in the form of different granular adsorbents have been investigated and turned out to represent efficient retention systems which can well be integrated into infiltration and hydraulic retention facilities. It is suggested that the structures for stormwater handling are integrated into local landscaping in the surrounding of buildings in the form of ponds, reed-beds, ditches, etc. creating attractive blue-green environments.

Keywords Urban stormwater; runoff; roof; road; heavy metals; polycyclic aromatic hydrocarbons; source control; barrier systems; adsorber; granulated iron hydroxide

Introduction
Among the different types of urban wastewaters discharged directly or via wastewater treatment into the aquatic environment, surface runoff from impervious areas is presently strongly discussed in view of future changes concerning its quantitative and qualitative management within urban water systems. Traditionally, surface runoff was considered as an undesired water in developed areas which needed to be diverted as complete and as fast as possible from urban areas. For many decades, the combined sewer system was regarded to be the most feasible and most economic solution. Nowadays, still 70% of the Swiss sewer systems consist of combined sewers whereas most of the rest is constructed as separate sewers. In a few cases, direct decentralized infiltration into the underground is practiced. After fifty years of experience, the established urban wastewater system revealed considerable drawbacks which ask urban water engineers to question the achievements of traditional urban water management. Peak hydraulic loads in sewers and treatment plants, sewer overflows and direct contamination of receiving waters with untreated sewage, temperature shocks in treatment plants and receiving waters, decrease of treatment plant performance, and additional marked loads of heavy metals and organic micropollutants from diffuse sources in surface runoff are just some arguments against further promotion of the existing systems (Boller, 1997).

In the nineties, a new approach toward urban stormwater management was discussed and found its support in new legislation in several European countries. This will lead to considerable changes of stormwater management in near future offering ample opportunities to introduce innovative new elements for the design of modern urban water systems. Apart from preventing the mentioned disadvantages by separating stormwater from domestic and
industrial wastewaters, the inherent value of stormwater within residential and industrial areas is on its way to be rediscovered. Retention facilities in the form of gravel and green roofs or as elements of the surrounding landscape in so called blue-green environments, infiltration sites to enhance small water cycles and groundwater recharge, rainwater harvesting and runoff use for different purposes in households, office buildings and industries are some possibilities to be considered in the design of new or renovated urban areas.

However, new facilities for stormwater handling should not only be based hydraulic criteria but be designed with consideration of the stormwater quality. Sustainable solutions may only be developed when the pollutant fluxes are known and can be controlled by either source control measures or pollutant barriers including appropriate disposal of the accumulated waste. In contrary to earlier concepts which considered surface runoff as clean water, the rainwater from impervious areas may be polluted with a series of contaminants from dry and wet deposition, from abrasion and corrosion of materials as well as from the interaction of the rain water with different surface materials. The contaminants are typically washed off from surfaces in a very dynamic way in the so-called first-flush leading to extreme peak loads at the beginning of runoff. Therefore, creative stormwater handling facilities have to be designed not only as hydraulic elements but also as a barrier for different contaminants in order to prevent the pollution of the environment along the routes of stormwater flow (Boller, 1998).

Classification of urban surface areas

Surface runoff in urban areas may originate from different surfaces consisting of various materials and on which different activities take place leading to a wide spectrum of potential pollutants and their concentrations and loads in the runoff water. The surface, especially of roofs, may reach from inert materials with minor interactions with the rainwater on one side to highly reactive surfaces such as metal sheets or organic linings on the other. Considering surfaces with motorized traffic, the hazard potential in surface runoff may be small on parking and shipment lots with low traffic whereas roads with high daily traffic volumes lead to significant pollutant loads.

In order to assess the potential hazards from surface runoff in urban areas the constructed surfaces may be classified according to their materials reactivity and to the activities taking place on them. It becomes clear that on roof surfaces chemical interactions with the materials in contact with the precipitation are dominating the contaminant wash-off whereas on roads the emission of abrasion products from cars and roads represent the source of hazardous substances in the runoff. Since not in all cases intense and costly monitoring of the runoff quality is possible, new guidelines have to be set up for urban water engineers that help to reduce the potential for environmental impairment by improving the management tools.

In Table 1, such a classification is given according to the new directives presently under discussion in Switzerland (VSA, 2002). Table 2 shows how roads are classified as a function of traffic parameters.

Urban surface runoff quality

From the large variety of urban surfaces in contact with rainwater, it becomes clear that also the washed-off substances vary considerably with respect to type of contaminants, concentrations, loads and dynamic first-flush behaviour. Concerning the type of pollutants, priority lists may be established from which substances of highest environmental concern are visible. The statistics on constructed area reveal that roads cover 50–60%, roofs 25–35%, and parking lots and driveways about 10–15% of the total impervious area on a regional basis. This means that the water from roofs and roads represent by far the major contribution to
urban surface runoff and that focus must be put on substances emitted from these surfaces. In Table 3, a list of important contaminants and in Table 4 their weight mean concentrations in the runoff water from different roofs and roads show that heavy metals such as Pb, Cd, Cu, Zn, PAH and eventually pesticides are the most crucial quality parameters.

In contrary to roof runoff, the analysis of road runoff shows clearly that most of the contaminants are bound to particulate matter. 80–90% of the heavy metals and PAH are present in particulate form. Therefore, removal of road dust by road cleaning or retention by treating the runoff water are efficient means to reduce pollutant loads. On the other hand, large proportions of the emitted colloidal pollutants may not be found in runoff, but being

<table>
<thead>
<tr>
<th>Surface area</th>
<th>Indication of pollution potential in surface runoff</th>
<th>Classification of pollution</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofs and green areas</td>
<td>Good and efficient retention of water and contaminants on the roof</td>
<td>Low</td>
<td>Application of pesticide containing linings ask for discharge into sewer</td>
</tr>
<tr>
<td>Green areas and green roofs without pesticide containing linings</td>
<td>Contamination similar to rain water. Slow accumulation of pollutants in infiltration sites.</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Roofs of inert materials and low metal content</td>
<td>Rapid accumulation of heavy metals in infiltration sites. The total metal surface is essential to decide on treatment measures prior to infiltration or direct discharge. For roofs with a metal area &gt; 20 m², treatment is recommended. Roofs with a metal area &gt; 50 m² are classified in the next class.</td>
<td>Medium</td>
<td>Usual metal surfaces on roofs in contact with water are between 5% and 10% of the roof surface</td>
</tr>
<tr>
<td>Roofs of mainly inert materials and usual degree of metal containing installations such as Cu, Sn, Zn and Pb</td>
<td>The protection of soil and water requires treatment of the surface runoff from these roofs</td>
<td>High</td>
<td>Buildings with large metal facades also belong into this category</td>
</tr>
<tr>
<td>Parking lots, driveways, roads</td>
<td>Low pollution potential under normal use. Retention of present contaminants in soil when surface made permeable.</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Driveways, private and public parking in residential areas, bicycle tracks and small roads</td>
<td>Loss of fuel, contaminants from maintenance work, shipment and storage of goods may lead to diffuse soil and groundwater pollution</td>
<td>Medium</td>
<td>Handling of hazardous substances asks for discharge into sewer system.</td>
</tr>
<tr>
<td>Shipment and storage space and working areas without handling hazardous substances</td>
<td>Increased soil and groundwater pollution potential. If made permeable some organics may be biodegraded in top soil.</td>
<td>Medium to high</td>
<td>Requires assessment.</td>
</tr>
<tr>
<td>Public parking with high traffic density (e.g. shopping centers)</td>
<td>Pollution potential depends on traffic volume, type of vehicles, way of driving, etc. Perpendicular to the road, heavy metals and PAH accumulate in soils. Runoff should not be discharged beyond the contaminated road shoulder. For medium and high classified roads pretreatment is considered to be necessary prior to infiltration or direct discharge.</td>
<td>Depending on traffic volume</td>
<td>See Table 2.</td>
</tr>
</tbody>
</table>
exported by wind and spray formation into or beyond the road shoulders. Figure 1 shows that especially Zn and Cu are bound to particles below 10 µm diameter which explains their relatively higher mobility in the environment.

**Runoff dynamics**

Water and substance flow during a runoff event show a strong dynamic behavior depending on rain intensity, dry and wet atmospheric deposition, dry period, surface properties, emission activities and other factors. Obviously, flat surfaces and especially green roofs show a much greater retention capacity for water and contaminants than inclined areas. During
most rain events, typical first-flush effects of the major contaminants are observed which are especially pronounced on steep roofs and roads. According to their origin, chemical speciation, and wash-off behaviour, the contaminants show different first-flush patterns. Typical examples for TOC, Cu, atrazine and mecoprop are depicted in Figure 2 showing the concentration pattern relative to the concentration at the end of a runoff event, and at the beginning for mecoprop, respectively. The patterns can be interpreted as follows:

- atrazine shows a typical atmospheric washout pattern with high concentrations in the precipitation at the beginning of rainfall and a fast decrease to background levels. No additional atrazine is taken up from roof interactions.
- TOC is an example of particulate deposition wash-off from a steep fibreglass roof.
- Cu shows a strong first-flush with values up to 100 times higher concentrations at the beginning of runoff compared to values after 10 mm of runoff. The wash-off of Cu corrosion products is slower than the flush of particulate matter.
- mecoprop contained in surface linings of flat roofs is migrating into the runoff water. Hydrolysis takes place only after wetting the roof surface and becomes effective throughout the whole rain event after 2 mm of runoff.

The amount of metals washed off from roofs is strongly depending on the amount of metal sheets used and in contact with the rainwater. An investigation in different Swiss residential and industrial areas reveal that 70% of the metals on roofs consist of copper sheets and most of the rest of zinc installations. Nowadays, an average of 6% of the roof surface area are metal sheets in contact with runoff water, corresponding to about 2.9 m² of mainly copper sheets per inhabitant. Examples of the concentrations and the first-flush behaviour of copper from different roofs and a copper façade are shown in Figure 3. The data indicate

![Figure 1](https://iwaponline.com/ws/article-pdf/4/1/55/417238/55.pdf)  
**Figure 1** Particulate fraction of heavy metals as a function of particle size; 100%: 1178 mgZn/l, 168 mgCu/l, 85 mgPb/l, 8.3 mgCd/l, respectively

![Figure 2](https://iwaponline.com/ws/article-pdf/4/1/55/417238/55.pdf)  
**Figure 2** First flush patterns of different pollutants in roof runoff

![Figure 3](https://iwaponline.com/ws/article-pdf/4/1/55/417238/55.pdf)  
**Figure 3** First flush behaviour of Cu in the runoff from surfaces containing different degrees of Cu sheets. ns may easily reach values far beyond 1 mg Cu/l
that the Cu concentration level in the runoff of a roof covered with copper sheets is two orders of magnitude higher than from a copper free roof and that first-flush concentrations may easily reach values far beyond 1 mg Cu/l.

**New pathways for the stormwater**

The new priorities for urban stormwater drainage systems such as (1) decentralized infiltration, (2) discharge into receiving water through separate sewers, (3) discharge into combined sewers will ask for substantial changes in urban drainage systems. Since these new directives are applied only for new or renovated buildings and roads, the new pathways will only be realized step by step and it will take decades to put them into widespread practice. Whatever system is applied, the new solutions require to always combine hydraulic and qualitative aspects of stormwater drainage. In most cases, the facilities for hydraulic retention and storage of the water may be constructed in a way that pollutants can be partially or fully removed at the same time.

In order to infiltrate runoff water into the underground, discharge it into receiving waters or make beneficial use of the rainwater, certain quality criteria have to be fulfilled. As described earlier, the constituents in raw runoff water from roofs and roads may cause undesired environmental pollution such as

- accumulation of heavy metals and PAH in soils of infiltration sites and groundwater contamination
- peak loads during first-flush in receiving waters with low dilution rates and accumulation of pollutants in sediments
- accumulation of pollutants in waste sludges in combined sewer systems and direct discharge into receiving waters through stormwater overflows and may have insufficient quality for further use in household and industry such as
- hygienic parameters, other suspendend matter and biofilm producing substances.

There are basically two ways to control the runoff quality (1) by source control and (2) by barrier systems.

**Source control**

The key to advances in sustainability is the control of pollutant emissions at the source. Since especially accumulating hazardous substances in soils and sediments may only be effective in decades from now, restrictions concerning the use or production of certain materials or products on a legal basis are in most cases politically not feasible. Information and education of the stakeholders with respect to environental and ecotoxicological issues, new guidelines for the use of materials in buildings and cars as well as sensibilisation of the public through the media are possible ways to increase efforts on source control. In Switzerland, a guideline for the use of metal sheets on roofs and facades was established in which copper, zinc and lead are shown to have considerably higher corrosion rates than other metal sheets. Recommendations are given to change to metals or inert materials with lower environmental impact (KBOB, 2001). In addition, the new Swiss stormwater guidelines require treatment of runoff water from copper and zink roofs which persuaded many architects to favour other materials.

However, one has to be aware of the fact that large amounts of metal surfaces are already installed on buildings and that it will take decades to replace them by more sustainable materials. Until this goal will be reached, metal corrosion will continue and contribute to the undesired longterm emission of heavy metals into the environment. In order to avoid further spreading, the pollutant fluxes may be controlled by especially designed barrier systems.
Barrier systems

The pollutant barriers presently proposed for future stormwater handling are (1) systems with natural soil passage and (2) innovative new filters with granulated adsorber materials.

Natural soil passage

Humus containing natural soil has proven to have a pronounced adsorption capability for heavy metals and PAH, if the pore system allows for a relatively homogenous water flow pattern. The desired soil material is usually available on site during construction works and can be used in infiltration basins or other types of stormwater treatment. The optimal soil configuration reaching the requirements for adequate permeability and sufficient retention capacity can be described with the soil parameters shown in Table 5 (VSA, 2002).

Soil layers may be introduced in different ways into the runoff pathways. Figure 4 illustrates some solutions in the form of runoff treatment in road shoulders, infiltration basins with direct infiltration to the underground or trough and trench systems and retention filter basins with sealed bottom layer leaving it open whether the runoff is infiltrated or directly discharged.

The soil passage is an efficient retention process for the crucial heavy metals and PAH. Investigations into the accumulation of these substances in road shoulders show clearly that most of the pollutants are “screened off” in the top 30–50 cm of the soil. In a field study, a

<table>
<thead>
<tr>
<th>Layer thickness</th>
<th>pH</th>
<th>Humus content</th>
<th>Clay content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top soil A-horizon</td>
<td>30 cm</td>
<td>&gt; 6.5</td>
<td>&gt; 4%</td>
</tr>
<tr>
<td>Sub soil B-horizon</td>
<td>50 cm</td>
<td>&gt; 5.5</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Figure 4 Runoff systems with soil passage in infiltration sites (a,b) and as treatment for direct discharge into receiving waters (c,d,e)
two-dimensional investigation into a 35-year-old road side was carried out (Mikkelsen et al., 1997). Soil samples were taken up to 30 m from the road and down to a depth of 2.0 m. The results reveal that high values of both total and exchangeable metal concentrations were associated with the upper 30 cm of the soil and with the old plough layer in about 60 cm depth. Beyond this layer the concentrations decrease rapidly to background levels. The same pattern was found for PAH and AOX. Perpendicular to the road, the contaminants accumulated to a distance of 9–10 m from the road side in an exponentially decreasing way. Figure 6 shows the relative metal soil concentration pattern in the top 30 cm of the soil as a function of the distance from the road side.

The drawback of soil passage is that a natural good is used to control the contaminants in the runoff water and sooner or later turns into hazardous waste.

Remediation or deposition of the relatively large contaminated soil volumes have to be considered in a later stage and needs to be included in cost evaluations. For certain applications it is worthwhile to replace the soil by special adsorber layers with considerably higher specific retention capacities using less space and offering easier disposal alternatives.

Passage through adsorber systems
It was suggested to introduce special adsorption layers as a new element of urban drainage systems. In recent years, several pilot and full scale experiments have been carried out using artificial granulated media with specific adsorption characteristics (Steiner and Boller, 1997).

Among different media proposed as adsorbing layers such as zeolites, activated carbon, aluminum oxide, iron oxide coated sand, peat and wood chips, a new adsorber in the form of granulated iron hydroxide (GIH) in a cristallized structure of $\beta$-FeOOH (akaganeite) has proven to be especially suited for the removal of heavy metals and dissolved organic...
matter. In order to establish optimal pH conditions and to reach sufficient hydraulic conductivity, a 1:1 mixture with granulated calcite (CaCO₃) has shown to be most favorable. With the GIH with its high internal surface of 300 m²/g (BET measurement) large adsorption capacities were achieved for Cu, Zn and DOC. In Figure 7, the adsorption isothermes for the three parameters illustrate that in the concentration range of typical surface runoff waters one order of magnitude higher adsorption capacities may be reached compared to natural soils.

Continuous column experiments over a two years period (corresponding to 20 years of rainfall) confirmed the high adsorption capacity for Cu from roof runoff. At the end of the experiments at hydraulic loads of 0.1–0.2 m/h, profile measurements along the columns still showed a 90% removal in the top 4.5 cm and 99% in the first 14.5 cm, respectively (Steiner, 2002). The data were used to set up a mathematical model for performance prediction. It could be demonstrated that columns of 30 cm thickness may easily reach life cycles of 30 years and more for moderate to high runoff concentrations.

In full scale, the GIH adsorbers are operated as unsaturated intermittently loaded filter columns, thus avoiding undesired anaerobic conditions. For the runoff from roofs with high dry deposition rates or from roads, prefiltration is necessary to avoid longterm clogging of the adsorber media. In the past two years, full scale GIH adsorbers have been installed at different sites in Switzerland for the treatment of the runoff water from

- a copper façade of 2300 m² in the form of an infiltration trench around the building
- a large copper roof of 1500 m² in an infiltration gallery
- a copper roof of 940 m² for rainwater use in toilets.

Special attention was given to the façade runoff where extremely high Cu concentrations of up to 100 mg Cu/l were measured and its treatment in an infiltration trench. Two sampling stations were installed at two sides of the building exposed to different meteorological conditions. Each site was equipped with sampling stations for the façade runoff and for the effluent of the 2 m long lysimeters containing the GIH adsorber. Samples were taken automatically to follow runoff dynamics. Evaluation of the mean event concentrations (MEC) and peak loads from 28 runoff events revealed typical MEC in the façade runoff between 1000–5000 µg Cu/l. Despite the strong dynamic behaviour of the inflow, the removal efficiency of the adsorber reached always 95.0–99.7% (Steiner and Boller, 2002).

In principle, the adsorber media may be installed in all types of presently executed systems for stormwater infiltration or direct discharge according to the examples shown in Figure 4. Instead of contaminating natural soil, the adsorber will accumulate the contaminants on a much smaller solid volume. At the end of the life cycle, processing of the spent adsorber is a possible option.

In recent experiments treating the surface runoff from Zurich airport, different adsorber media were tested in pilot adsorber columns. Different types of natural soils, granulated aluminium oxide, granulated clinoptilolite, wood chips and a GIH/CaCO₃ mixture were evaluated with respect to their retention capacity for heavy metals and DOC. Preliminary results reveal that GIH and granulated aluminum oxide performed best (Eugster et al., 2001).

**Blue-green environments**

Stormwater drainage may not only be considered as systems to divert undesired water from urban areas, but also as a valuable element for landscaping the surrounding of buildings and roads. For a long time, stormwater flows were hidden in the urban environment in subsurface canal systems. Nowadays, architects and engineers are called upon to make the water visible and integrate it into so-called blue-green environments. The new technical systems for stormwater management may be designed in a way that their major tasks such...
as retention, contaminant barrier, infiltration or direct discharge may be combined in a creative manner to fulfil also aesthetic requirements. Surface runoff in open channels, small creeks, ponds, reed beds and other planted systems can be considered as elements of landscaping as proposed by Swedish (Bengtsson et al., 2001) and Swiss (BUWAL, GSA Bern) engineers. The water may additionally be used for irrigation and recreation. The use of rainwater in households for toilet flushing and textile washing is becoming a popular alternative to benefit from the runoff of roofs, although the installations for runoff harvesting do not pay off in many cases (Jolliet et al., 2000). In the case of recreation and reuse, the risk from microbial parameters in addition to the one from chemical contaminants has to be considered in the design.

Conclusions

New directives for stormwater handling in urban areas will be accompanied by considerable changes of present urban drainage systems. Stormwater will be retained in the urban environment in decentralized form. Surface and subsoil infiltration of runoff from impervious areas will be practiced in on-site installations. Where infiltration is not feasible or prohibited, direct discharge into receiving waters is the alternative. The discharge of surface runoff into combined sewers will decrease and be restricted to sites where the above alternatives are not appropriate. Surface runoff will be beneficially used on its way back to nature in the form of different kinds of retention facilities as landscaping elements in residential and industrial areas. Furthermore, the use of roofwater for toilet flushing and other purposes will gain importance, especially in areas where drinking water resources are not abundant.

Whatever solutions for separate stormwater handling are chosen, the quality of the runoff water has to be considered carefully. According to the kind of surface and the activities taking place on them, numerous kinds of pollutants are washed off showing extremely dynamic concentration and load variations. In order to avoid long-term pollution of soils, groundwater and sediments and shock-loads in receiving waters, a two-way strategy has to be followed by (1) avoiding diffuse spreading of hazardous substances by source control measures, and (2) by combining hydraulic runoff and infiltration installations with technical barrier systems in the form of soil passage or artificial adsorber layers in runoff installations.

The implementation of the new ideas on stormwater management will take decades and will only be realized step by step. Renovation of the drainage systems may be considered as part of a more integral concept of a new urban water cycle in which water supply and wastewater handling may at the same time undergo marked changes toward separation of streams and fluxes of different quality levels on a decentralized basis. Rainwater use, grey and black water handling, urine separation, nutrient processing, dry toilets and other alternatives are presently subject of intense research and full scale experimental studies. The new urban water concepts challenge engineers and scientists to invent, study and introduce innovative technologies and developments to meet the functional, ecological and the socioeconomic requirements for a sustainable urban water cycle of the future.

References


