# Quantifying the Effects of Urban Stormwater Management – Towards a Novel Approach for Integrated Planning

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## ABSTRACT

Integrated planning of stormwater management requires a quantitative description of positive and negative effects of possible measures. We suggest quantifying these effects with generic performance indicators within eight categories: building physics and services, landscape quality, urban climate, biodiversity, groundwater, surface water, direct costs and indirect environmental costs. The results indicate that the defined performance indicators allow an objective pre-selection of measures based on their ability to reach local stormwater management goals. The final selection of measures should be based on an evaluation for a specific city quarter (to reduce indicator uncertainty) and reviewed by local stakeholders.

## KEYWORDS

Stormwater management, social, environmental and economic performance indicators, cost–benefit analysis

# INTRODUCTION

Stormwater runoff from impervious surfaces can lead to significant impacts on receiving lakes and rivers regarding hydraulics (Krejci et al. 2004), trophic state (SenGUV 2002), toxic impacts (Burkhardt et al. 2009) and bathing water quality (Oppermann 2011). In addition, traditional stormwater drainage prevents utilizing the positive potential of rain water (i) for building services (e.g., cooling systems, (SenStadt 2010)), for improved urban landscape quality (Dreiseitl and Grau 2009) and the reduction of urban heat exposure (Harlan et al. 2006), (ii) for increased biodiversity (Oberndorfer et al. 2007) and for reinstating a more natural water cycle (Kravčík et al. 2007). Stormwater measures that focus on infiltration can also affect groundwater resources positively or negatively (Göbel et al. 2004). Finally, implementation of stormwater measures can lead to a reduction or an increase in both direct and indirect costs and in the use of resources.

To reduce the negative impacts of impervious surfaces and make use of the potential benefits of stormwater, a number of measures can be applied at different spatial levels:

- at the building level: e.g., green roofs, rain water use or local infiltration (SenStadt 2010)
- at the city quarter level: e.g., de-paving of impervious areas, artificial ponds, filters at manholes, adapted street cleaning (Zweynertl et al. 2007)
- at the catchment area level in combined and separate sewer systems: e.g., sewerage management, end-of-pipe treatment, storage in sewers (DWA 2005).

A wide range of stormwater measures are implemented today. However, a quantitative description of positive and negative effects is incomplete for most of these measures. As a result, we aim at filling this gap to help decision makers find optimal combinations of measures for their specific settings.

# METHODS

Goals of stormwater management are formulated for eight effect categories (effects 1 to 8 in Fig. 1). These goals depend on the local situation; if, for instance, the groundwater level is below a local target value, increased groundwater recharge (up to the target) would be one goal in the category "groundwater". For the selection of appropriate measures to fulfil local goals, these goals are broken down into generic performance indicators. In the above example, measures with a high value in the indicator "groundwater recharge rate" would be judged positively regarding the local goals in the category "groundwater".

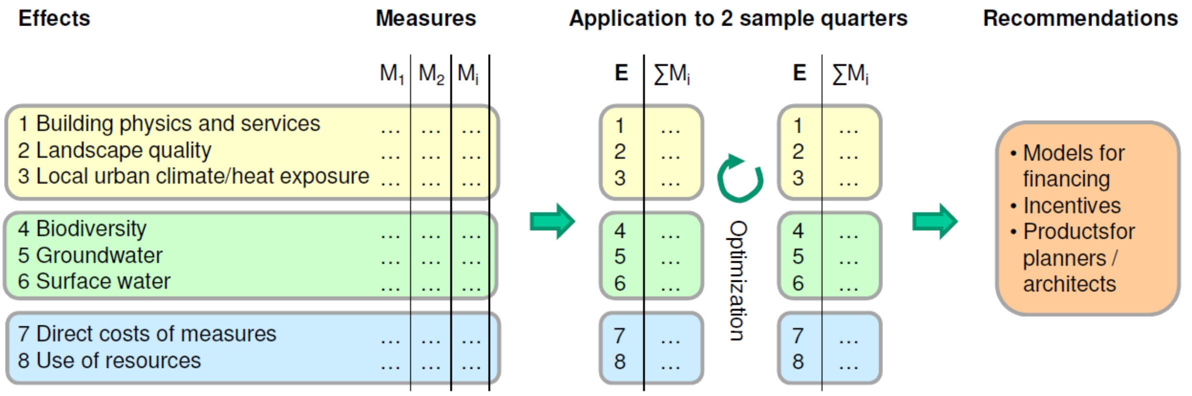


Figure 1: Adopted strategy.

The resulting measure-effect-matrix (Fig. 1) will allow choosing and evaluating specific combinations of measures by accounting for both costs and benefits. Costs are indicated within the direct cost category (effect 7 in Fig. 1), while indirect "environmental costs" are described through the use of resources (effect 8). Benefits which can be expected after implementing a stormwater measure are defined by various non-monetary effects in KURAS (effects 1-6 and 8 in Fig. 1). Additionally weighting factors can be used if, as a result of local settings/stake holder preferences, not all effects are equally important for a decision. Final comparison can be done by highlighting the impacts of single categories to decision makers or by calculating a combined value, such as the ratio between "mean benefit" and the cost of each combination of measures. The procedure will be demonstrated for specific combinations of measures for two sample city quarters in Berlin, including an optimization step via stakeholder involvement. Experiences will be translated into recommendations and applied products (such as guidelines or software tools) for planners and architects (Fig. 1).

# RESULTS AND DISCUSSION

### Definition of indicators

In the following section, local goals and related performance indicators for single measures are described for the eight effect categories in Fig. 1 (see also overview in Table 1).

Table 1: Goals and quantitative performance indicators for stormwater measures

| **Effect category** | **Goals of stormwater management (depending on local situation)** | **Performance indicators for single measures [unit] (generalizable)** |
|---|---|---|
| Building physics and services | Benefits from stormwater use for inhabitants of buildings | • Rainwater recycling and reuse for service water [%]<br>• Energy saving from cooling (or heating) [kWh $m^{-2}$ $a^{-1}$] |
| Landscape quality | Structural richness | • Variance in microrelief [m]<br>• Variance in plant height [m]<br>• Dry plant volume [kg $m^{-2}$]<br>• Proportion of open water surfaces [%] |
| | Usability | Scale from 0-3: no to high added usability (see text for details) |
| Urban climate | Increase in thermal comfort (via Predicted Mean Vote, Universal Thermal Climate Index or number of hot days/tropical nights) | • Evaporation rate [%]<br>• Green volume per connected impervious area [$m^3$ $m^{-2}$]<br>• Surface albedo [-] |
| Biodiver-sity | Species diversity | *α*- and *ß*-diversity (floristic and faunistic) [# of species] |
| | Habitat diversity | Structural diversity of vegetation [[# of different elements] |
| | Habitat connectivity | Average distance between measures [m] and species dispersal among measures [%] |
| | Rare species occurrence | Proportion of rare species [%] |
| Ground-water | Local groundwater level target | Change in groundwater recharge rate [mm] |
| | Avoid deterioration of groundwater quality | Change in electric conductivity, chloride, sulphate, zinc and bio-cide concentrations [%] |
| Surface water | *Combined sewer systems*: | |
| | Reduction of CSO impacts (hydrau-lic, oxygen and ammonia stress) | Reduction of one-year peak runoff rate [%] (compared to situation without the measure) |
| | *Separate sewer systems*: | |
| | Reduction of hydraulic stress | Reduction of one-year peak runoff rate [%] (compared to situation without the measure) |
| | Reduction of eutrophication | Reduction in P and N loading [%] (depending on total annual flow reduction and/or cleaning effect) |
| | Reduction of sediment contamination | Reduction in TSS loading [%] (depending on total annual flow reduction and/or cleaning effect) |
| | *Flooding (both separate and combined sewer systems)*: | |
| | Support flood prevention | Reduction of 30-year peak runoff rate [%] (compared to situation without the measure) |
| Direct costs | Minimize costs | Present value of annual costs per connected impervious area [€ $yr^{-1}$ $m^{-2}$] |
| Resource use | Minimize indirect environmental impacts | • Cumulative energy demand of non-renewable fuels [MJ $m^{-2}$]<br>• Abiotic resource depletion of minerals [kg Fe-eq $m^{-2}$]<br>• Global warming potential [kg $CO_2$-eq $m^{-2}$]<br>all per connected impervious area |

*Building physics and services.* Globally, the building sector is responsible for more than 1/3 of the total resource and 40% of the total energy consumption (UNEP, 2007 in: www.zebistis.ch). Centralized water supply and wastewater disposal can cause high monetary and environmental costs. Buildings are a main source for rainwater discharge into sewerage systems. Stormwater measures at the building level can reduce or even stop (zero emission strategy) such environmental impacts (see categories “groundwater” and “surface water” below) and improve local climate through evaporation (see category “urban climate” below). Rainwater can also be used directly (in toilets, gardens, etc.) or indirectly to cool and heat buildings in the process of evaporation and condensation-absorption as demonstrated in the WaterGy prototype in Berlin-Dahlem (www.watergy.de). This use can lead to a direct benefit for inhabitants through water and energy savings (Schmidt 2010a). The extent of this benefit can be measured through the indicators (i) rainwater recycling and reuse for service water [%], covering all types of rainwater usage, and (ii) energy saving [kWh $m^{-2}$ $a^{-1}$] for rainwater-based cooling or heating systems.

*Landscape quality.* Measures of stormwater management can enhance quality and aesthetics of urban landscapes/open spaces. Here, we focus on measures that form parts of the urban green infrastructure, such as green roofs or rain gardens (i.e. summary term for a variety of single or combined measures on ground level, ranging from simple infiltration systems, over vegetated plots to wetlands and open water surfaces). Stormwater management systems will be evaluated by custom utility analysis based on the description of design (i.e. structural richness) and accessibility/usability. Though the effects depend on the ensemble of the measure(s) in their specific surroundings, the potential to increase the landscape quality can also be classified for single measures based on generic performance indicators: Structural richness can be quantified in terms of microrelief, the variety in plant height (from moss to trees), plant volume and the proportion of open water surfaces. Usability will be evaluated on a scale from 0 to 3, based on the following criteria:

- 0 (no added usability): impervious area
- 1 (low): visually attractive (e.g. an inaccessible reed area in a court yard)
- 2 (medium): accessible for limited use (e.g. dedicated walkways and sitting areas within green infrastructure)
- 3 (high): optimized for use (e.g. boating on artificial pond or playground on infiltration system)

Biodiversity also adds to the value of a landscape for plants and animals (see category “biodiversity” below).

*Local urban climate/heat exposure.* Heat exposure can be significant in densely built-up urban areas. Heat is directly described by the air temperature at different levels (e.g. air temperature at 2 m height for pedestrians). The extent of adverse effects from heat exposure is evaluated in terms of human perception, i.e. based on the number of hot days (> 30 °C) or tropical nights (> 20 °C) at a certain location. The thermal comfort is defined by the human heat balance and its thermophysiological principles, which can be calculated as a function of air and radiation temperature, humidity and wind speed (VDI 2008). Examples are the Predicted Mean Vote (PMV) and the Universal Thermal Climate Index (UTCI).
Measures of stormwater management can reduce heat exposure, i.e. lead to a reduction in the number of hot days/tropical nights and therefore reduce thermal discomfort for humans. Performance indicators are primarily related to an increase in evaporation, measured by the evaporation rate (in relation to surface runoff and groundwater recharge) compared to the natural environment (Kravčík et. al 2007; Schmidt 2010b) and the green volume of a measure per connected impervious area. In addition the albedo of measures influences their heat absorption.

*Biodiversity.* Urban landscapes can harbour high floristic and faunistic biodiversity and provide novel habitats for rare and endangered species. Beyond its intrinsic value,

biodiversity facilitates and supports a large set of urban ecosystem services, partially linked to enhanced "landscape quality" (see above). For instance, Fuller et al. (2007) showed that species rich urban parks increase psychological wellbeing. Species and structurally rich vegetation along roadsides enhance air quality (e.g. Weber et al. 2014a) and increase attractiveness of open spaces (e.g. Weber et al. 2008; Weber et al. 2014b).
We address the genetic, species, ecosystem and functional level of biodiversity with a set of indicators to characterize biodiversity effects of different stormwater measures: Species diversity will be assessed by the indicators *α*- and *ß*-diversity, derived from floristic and faunistic surveys on implemented stormwater measures. The potential of these measures to provide habitats for rare and endangered species within the urban matrix will be estimated by the proportion of rare and endangered species. The provision of *novel urban habitats* will be estimated by the proportion of neobiota within the species pool. Structural diversity of vegetation will be used as a proxy to assess habitat diversity. Furthermore we analyse the degree of connectivity between these habitats and neighbouring urban green structures and the dispersal mode of the species pool to address fragmentation, isolation or stepping stone effects within urban landscapes. We analyse the influence of local parameters, different technologies and design variation on biodiversity patterns in order make recommendations to increase the biodiversity-friendliness of these measures.

*Groundwater.* Groundwater quantity and quality is affected by stormwater management measures which involve infiltration, such as the transformation of impervious to pervious surfaces or infiltration through trenches or swales. Regarding groundwater quality, the general target is to prevent deterioration (EU 2000; BBodSchV 1999; GrwV 2010). Accordingly, effects will depend on the source water quality (roof runoff, streets, etc.) and the quality of the ambient groundwater. Regarding quantity, an increased groundwater recharge could have both positive or negative effects depending on site conditions, reference status and local water table goals. Performance indicators for the selection and evaluation of measures based on local goals are (i) groundwater recharge rate [mm] with/without the measure for quantitative assessment and (ii) measure-induced changes [%] in the indicators electric conductivity (EC) and chloride, sulphate and zinc (as a representative for heavy metals) concentrations. In addition, two biocides associated with building materials – Mecoprop and Terbutryn – are considered, though complete quantification for all stormwater measures is not expected.

*Surface water.* In densely built-up urban areas stormwater runoff can have a major impact on receiving lakes and rivers. Among the most prevalent negative impacts related to stormwater discharges are hydraulic stress due to increased flow velocities (Borchardt 1992, Krejci et al. 2004), eutrophication due to nutrient loadings (Borchardt et al. 2003), sediment contamination due to particle-bound toxic substances such as heavy metals and, particularly in the case of combined sewer systems, depressions in dissolved oxygen (Riechel et al. 2010, Lammersen 1997) and elevated ammonia concentrations (Krejci et al. 2004, Lammersen 1997). In the case of *combined sewer systems*, surface water bodies are only affected by combined sewer overflows (CSO), which typically occur during major rain events. As a result, peak runoff reduction during a 1-year rain event is considered as a sole indicator for both hydraulic and pollution-based impacts.
In the case of *separate sewer systems*, hydraulic stress depends also on runoff peaks (1-year events), whereas pollutant loadings can also be relevant for less intense rainfall events and are therefore assessed on a larger temporal scale. As an example, the annual retention of total suspended solids (TSS) is chosen as an indicator since it represents a large portion of degradable organic matter, heavy metals and pathogens. Finally the eutrophication potential is assessed based on the loads of total phosphorus (P) and nitrogen (N) emitted with and without

the respective measure. In addition, the removal efficiency for the two selected biocides is quantified (see also category "groundwater" above).
Although not in the focus of this work, the retention capacity of stormwater measures for flood prevention during extreme rain events (30-year event) is added for the sake of completeness.

*Direct cost.* The implementation and operation of stormwater measures obviously involves direct costs. Apart from differences in absolute numbers, the relative extent of investment expenditures (including planning, land acquisition and construction) and operation expenditures (including personnel, maintenance and energy) may vary significantly among measures. As a result both investment and operational cost must be considered. Since stormwater measures have a long lifetime (e.g. infiltration systems ≥ 15 years, sedimentation basins ≥ 50 years), it is necessary to account for these costs over the lifetime of a measure. Here, all future investment and operational expenditures for a stormwater measure are summed in one indicator called "present value of annual costs", following the dynamic cost comparison approach by DWA and DVGW (2012). To allow comparison between measures of variable size, the indicator relates to the connected impervious area. The defined indicator can serve as a decision criterion to identify potentially cost-minimal solutions for future stormwater management.

*Use of resources.* Apart from their intended effects on the environment described above, measures for stormwater management affect the environment indirectly, since they require additional resources for infrastructure, operation and maintenance, e.g. building materials or electricity for pumping. Using the method of Life Cycle Assessment (ISO 14040/44 2006), all direct and indirect resource usages will be collected based on typical design features and assessed for environmental impacts concerning both the use of limited natural resources (e.g. fossil fuels, ores) and associated emissions (e.g. greenhouse gases). Measures will be evaluated with three indicators describing the cumulative energy demand of non-renewable fuels (VDI 1997), abiotic resource depletion of minerals (Goedkoop et al. 2009), and global warming potential. Similarly to "direct costs", indicators are calculated by year and connected impervious area.

**Exemplary evaluation of indicators**

The exemplary results in Fig.2 for effect 6 "surface water" (indicators: retention of N and P loading in a separate sewer system) and effect 7 "direct costs" (indicator: present value of annual costs) show two main points:

1. The chosen indicators allow pre-selection of measures. For instance the "retention soil filter" is very effective for the retention of P but not for N, whereas for most types of "green roofs" it is the other way round. Costs (excluding purchase of land) are highest for "intensive green roofs". On the other hand, measures at very different spatial scales, such as "retention soil filters" and two types of "infiltration" are similarly expensive per connected impervious area.
2. The range of cost and effect can be very large (> 100 % of the mean), indicating a high dependency on local settings and type of implementation (e.g., fertilized green roofs can be a nutrient source). Measures with low ranges are typically measures with low data availability.

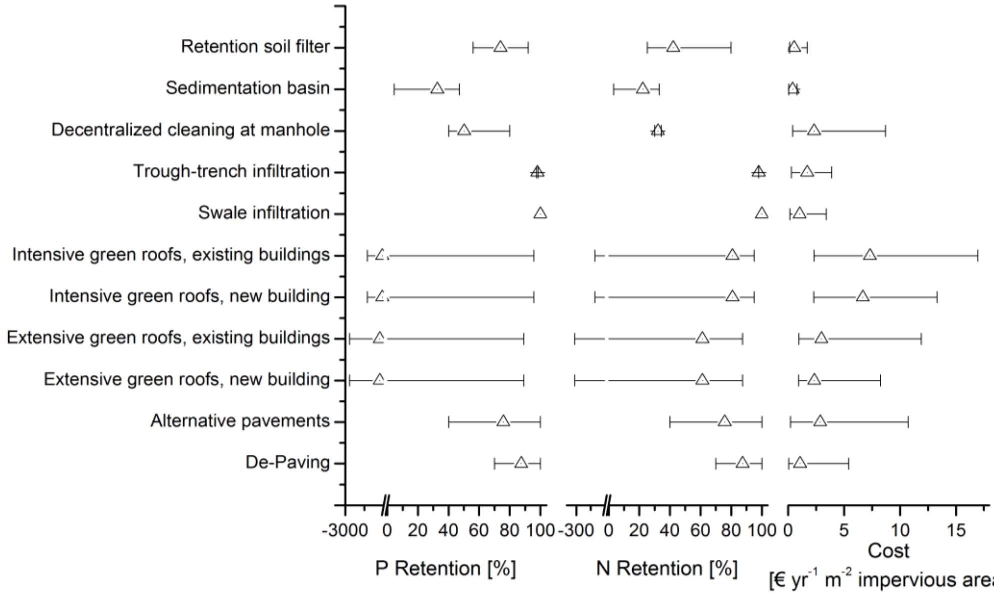


Figure 2: Average, minimal and maximal performance of selected stormwater measures regarding retention of phosphorus and nitrogen loading and present value of annual costs, including investment and operational costs and excluding land cost (adapted from Mutz et al. 2013).

# CONCLUSIONS

- As a first step in establishing a stormwater management strategy, local problems and related goals need to be assessed.
- Secondly, the indicators defined in this study allow a pre-selection of certain measures based on their ability to achieve these goals (e.g. reinstate a more natural hydrological cycle via measures that favor either evaporation or infiltration).
- To be applicable for a wide range of situations, more than one indicator needs to be considered for most effects (e.g. for effect 6 "loadings to surface water", nutrient retention should be complemented by indicators on hydraulics, hygiene, toxicity, etc.).
- As a third step, effects of measures must be evaluated for a specific city quarter to reduce their uncertainty. Finally, suggested combinations of measures should be reviewed by local stake holders.

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