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Chemical effects of a near-to-nature detention pond on a small urban headwater

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ABSTRACT

The near-to-nature approach has been established as best practice for stormwater management. However, pollutant mobility within such systems and its impact on small receiving waters are partly unexplained. The study takes place in an urbanised headwater catchment in south-western Germany with an area of 0.4 km^2. Runoff from roofs, roads, parking lots and gardens is collected in wells or trenches and stored in private and public dry detention basins. Accordingly, this study investigates pollutant input to a detention pond, removal efficiency and the associated effects on the receiving water.

Grab samples with high temporal resolution of the receiving water (16 flood events with 315 samples and 41 baseflow samples), the three inflows of the detention basin and its outflow (four flood events with 64 samples) were taken. The outflow of the dry pond is recovered in the hydro- and chemographs of the receiving water. Runoff from roads with increased traffic volume caused the highest PAH inputs and runoff from the residential area showed the highest zinc concentrations, which partly infringe European Environmental Quality Standards. Yearly pollutant inputs (DOC, TSS, PAH, nutrients, metals) from the settlement into the tributary are reduced in the detention pond by up to 80%.

1. Introduction and objectives

Near-to-nature stormwater management has been established as best practice for handling surface runoff. Rainwater management systems (RMS) effectively relieve the streams from hydraulic stress during flood events and thus protect the residents in the lower reaches of small water courses from flood damage. Stormwater runoff in settlement areas is often polluted by contaminants originating from impervious surfaces (Göbel et al., 2004; Keßler et al., 2012). By remobilizing the previously wet and dry deposited organic and inorganic substances from road and roof surfaces, pollutants are flushed into the retention basins (Dechesne et al., 2004; Scholz and Kazemi-Yazdi, 2009; Zgheib et al., 2011; Sébastien et al., 2014). The occurrence of xenobiotics in surface waters in high concentrations justifies investigating their environmental fate and pathways within small urban catchments (Simpson and Stone, 1988; Lee and Bang, 2000; Atasoy et al., 2006; Motelay-Massei et al., 2006; Meyer et al., 2010; Meyer et al., 2013). Especially the relevance of small urban headwater catchments and particularly the impact of single detention ponds as pollution sources for receiving waters are rarely investigated.

Hydrographs and pluviographs illustrate the reaction of the catchment on precipitation events. As trace substances for urban runoff, 16 EPA-PAH, metals (iron, manganese and zinc) and several anions and cations are considered (Sample et al., 2014). Their chemographs reflect the runoff generation processes and the transport of xenobiotics as an integral part of the watershed processes (Kurtenbach et al., 2006; Kurtenbach and Krein, 2007) and certain substances indicate distinct sources of runoff (Pailler et al., 2009; Meyer et al., 2011; Meyer et al., 2013). Considering flood event discharge and matching them with substance concentrations, loads can be calculated (Krein et al., 2013).

Several studies deal with the flow and nutrient reduction in detention ponds during flood events. Most of the studied wet and dry ponds receive water from roads and highways and are focused on pollutant removal and effects on biota (Revitt et al., 2004; Mrowiec, 2016; Stephansen et al., 2016), the modelling of water flows and improving the water quality (Somes et al., 2000; Vezzaro et al., 2012) or testing filter materials to enhance pollutant reduction (Nanbakhsh et al., 2007; Beutel and Larson, 2015).

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This case study takes place in a small urban headwater catchment of 0.4 km^2 with a near-to-nature stormwater system and focuses on one detention pond. The objective of this study is to assess the pollutant removal efficiency and annual loads of the detention basin within the residential area of Trier-Petrisberg, as well as its effects on the small receiving water Brettenbach. In this context, chemographs and hydrographs of the receiving water, detention pond outflow and inflows are observed. Discharge and electrical conductivity are continuously measured in the receiving water. Grab samples to measure polycyclic aromatic hydrocarbons (PAH), metals (Fe, Mn, Zn), nutrients (NH_4-N, PO_4-P, NO_3-N, SO_4-S), anions (Cl^-) and cations (Ca^{2+}, Mg^{2+}) of the receiving water are taken during baseflow and flood events. Grab samples regarding the pond inflows and the outflow of the detention pond were taken under flood conditions and analysed for PAH, metals, anions and cations.

2. Material and methods

2.1. Study area

The investigated headwater of the Brettenbach is a small urban catchment that covers an area of approximately 0.4 km^2 (Fig. 1) in the city of Trier. The study area is located at the southern height-terrace level of the Moselle River. Trier-Petrisberg is a former casern district, which has been completely restructured as a residential estate and service centre. During the conversion period, an infiltration-based RMS was built in 2004, followed by a period of progressive urbanisation until 2010.

The humid-temperate climate with temperate summers and moderately cold winters is characterised by convective rain in summer and advective precipitation in winter. The annual rainfall averages 784 mm and the mean annual temperature is about 9.1 °C (1961-1990) at the DWD-Station Trier-Petrisberg (German Weather Service, DWD, 2010).

Road and roof surface runoff is retained in a complex RMS of detention ponds (Fig. 1) to reduce the runoff volume by evapotranspiration and infiltration. The design is based on a centennial precipitation of 56 mm in 3 h, of which private property owners should store 30 mm in private ponds (Wintrich, 2009). Runoff of the service centre area (SC, 0.08 km^2) reaching the public stormwater RMS flows through a combination of storage basins. Runoff of the residential-only area (RA, 0.06 km^2) flows directly from the roads and pavements via a channel into the detention basin, whereas runoff of the main road (Road, 0.02 km^2) discharges through a swale into the basin (Bielefeld et al., 2002).

The rooting penetration of the soil is limited in many areas, as reflected by coefficients of permeability (k_f) within the catchment of 6×10^{-3} to 1×10^{-9} (Wintrich, 2009). The detention pond is designed to retain surface runoff from the settlement area and maintain a near-natural local water balance (Keßler et al., 2012). To achieve a suitable infiltration rate, in large parts of the detention pond rough-grained material is used to aerate the original soil material (working as an infiltration ditch). This leads to infiltration into the deeper soil layers to reduce the water volume in the pond. The pond is covered by grassland, comprises local transported soil material and does not contain any special filter material. A small reed basin has been installed at the pond inflow of the settlement area to retain particulate matter from the directly-connected rainwater sewer of the RA sub-catchment. During flood events, the outflow of the RMS is throttled on a maximum discharge of 16 l s^{-1}.

The discharges of the detention pond outflow and the receiving water have been investigated since August 2005. The change of the local water balance due to the near-natural rainwater management has been considered in detail (Keßler et al., 2012). The study showed that the low permeability of the local soil substrate has been compensated by the throttled overflow and the implementation of infiltration ditches within the detention basin. A long-term monitoring program showed that the decentralized RMS provides adequate maintenance of the local water balance and attenuation of stormwater peak flows. The groundwater level within the retention basin shows a strong natural dependency on seasonal and annual variations in climate but no significant increase over time.

2.2. Hydro-climatological measurements and water sampling

Discharge has been measured using Thomson flow-over weirs at the gauge of the receiving stream Brettenbach (streamflow), at one pond inflow (SC) as well as the pond outflow. Ten-minute-mean water level values have been recorded by ecoTech PDL level loggers (ecoTech Bonn, Germany) since August 2005. For 10-minute conductivity measurements of the stream flow, a WTW probe with data logger was used (Table 1). Conductivity is used as a tracer to clearly distinguish between soil water (pre-event water) and surface runoff (event water) in the catchment (Kurtenbach et al., 2006). This knowledge is used to interpret and verify the chemographs of Ca^{2+}, Mg^{2+}, Fe and Mn. Ca^{2+} and Mg^{2+} derive from the upper soil layer, which comprises loess. Moreover, the cement – which is part of the concrete used in settlement areas – contains Ca^{2+} and additionally augments the calcium concentrations of surface runoff. Increased concentrations of Fe and Mn are due to groundwater and the mid-soil layer, which comprises limonite. The concentrations of Cd, Cu and Pb were rarely above the limits of quantification and thus are not considered.

The hourly amount of precipitation is received from the DWD. The climatology station is located about 500 m from the area under investigation, at almost the same elevation above sea level as the monitoring site.

Every sample is a grab sample reflecting the water's performance only at the point in time when the sample was collected. Sixteen flood events (with an average of 20 samples) at the receiving water (stream flow) were sampled by an ISCO autosampler with one-litre PET bottles from November 2009 to May 2012. Forty-one baseflow samples were taken infrequently throughout the year and immediately before a sampled event. Four flood events were analysed between August 2011 and May 2012 at the three pond inflows and the pond outflow. Runoff at the inflows is generated within 10–20 minutes and ends immediately after the rain event. On average, four samples per event and sample location were taken within 3–5 h, covering the whole event. Neither the pond inflows nor the pond outflow generate baseflow. These samples were taken by hand in PET bottles, stored at 4 °C in the dark and processed immediately as described below.

2.3. Chemical analyses

The water samples were filtered through Whatman GF/F glass fibre filters (0.6 μm) and stored prior to analysis at 4 °C. Water samples for PAH analyses were not filtered. For Total Suspended Solids (TSS), the pre-weighed filter was dried after filtration and weighed again (DIN 38409-2). Dissolved Organic Carbon (DOC) of the water samples was analysed using the Apollo 9000 Analyzer (Tekmar Dohrmann, USA) according to DIN EN 1484. Nitrate, sulphate and chloride (Merck, Germany) were analysed by ion chromatography (761 Compact IC, Metrohm) according to DIN EN 10304-1. Ammonium (DIN 38406) and dissolvedphosphate (EN ISO 6878) were measured with UV/VIS spectroscopy (Lambda 2, Perkin-Elmer). Ca, Mg, Fe, Mn and Zn were analysed by atomic absorption spectrometry (flame AAS, Analytik Jena Continuum Source AAS ContrAA 300) according to EN ISO 38406. Determination of the 16 EPA-PAHs (EPA, 1984) was conducted by GC MS (HP 6890/5973inert, Agilent) (DIN