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Short communication

Accumulation of heavy metals in a constructed wetland treating road runoff

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ABSTRACT

The long-term performance of a constructed wetland treating highway runoff has been studied with respect to heavy metal removal in a temperate, maritime Irish climate. The accumulation of heavy metals in both the sediment and the plants growing in the wetland have been quantified over a 6 year period of operation as well as the spatial distribution of the metals' deposition. Based on the measured accumulation and projected runoff loads over a 6 year period, the removal efficiencies were 7% (Cd), 60% (Cu), 20% (Pb) and 73% (Zn), values which are much less than the apparent removal efficiencies for the system determined from monitoring the inlet and outlet of discrete storm events which were 95% (Cd), 88% (Cu), 86% (Pb) and 95% (Zn). The study also quantified that an almost negligible mass metals had accumulated in the vegetation compared to the sediment. There was a strong correlation between the spatial accumulation of Cu, Pb and Zn with most of these metals deposited at front of the wetland in the sediment. Finally, although the wetland was initially planted with *Typha latifolia* over one half and *Phragmites australis* the other half, after 6 years of operation the *Phragmites* had spread to colonise almost all of the wetland.

1. Introduction

Constructed wetlands are increasingly being installed as systems to treat highway runoff. Typical pollutants in highway runoff include hydrocarbons, nutrients, PAHs and heavy metals (Sansalone and Buchberger, 1997; Hvitved-Jacobsen et al., 2010). The most problematic heavy metals with regards to ecological toxicity are Hg, Cd, Pb, As, Cu, Zn, Sn, and Cr (Ali et al., 2013), although Cu and Zn are also essential trace elements. Heavy metals in road runoff tend to be associated with fine particulate matter, particularly in first flush loads (Barbosa and Hvitved-Jacobsen, 1999; Zhao et al., 2010). The streams/rivers into which typically highway runoff is diverted needs to be protected from heavy metals due to their impact on biodiversity, particularly since they are essentially non-biodegradable.

Constructed wetlands provide the environment for a variety of different attenuation processes for treatment of highway runoff. Physical treatment occurs as a result of decreasing flow velocities in the wetland which promotes sedimentation, evaporation, adsorption, and filtration. Biological processes include decomposition, plant uptake and removal of nutrients, plus biological transformation and degradation (Kadlec and Wallace, 2009). Several full-scale trials using a variety of different constructed wetland configurations to intercept and treat road runoff have been reported, e.g. Cheng et al. (2002), Walker and Hurl (2002), Bulc and Slak (2003), Revitt et al. (2004), Adhikari et al. (2011), Headley and Tanner (2012), etc. Such studies have demonstrated that the wetlands can promote efficient flood attenuation, reduction of peak discharges and overall enhancement of the water quality with respect to hydrocarbons, solids and heavy metals. Removal efficiencies reported of typical heavy metals associated with road runoff (i.e. Cu, Zn Cd, Ni and Pb) however, have been mixed with some studies reporting almost no removal and others up to 90%. Most studies investigating the relative importance of the different heavy metal removal mechanisms have found that sedimentation seemed to

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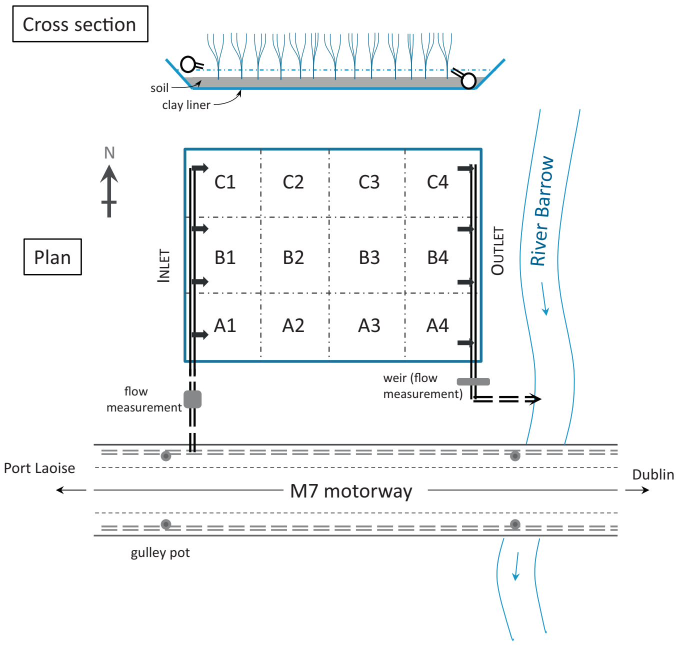

Fig. 1. Plan and cross section schematic of wetland system (with reference cell numbers).

be the dominant process compared to macrophyte uptake (Lung and Light, 1996; Mays and Edwards, 2001; Walker and Hurl, 2002). More research is still needed however, to better understand the complex interactions between contaminants, soil, plant roots, and microorganisms in the rhizosphere (Williams, 2002; Vangronsveld et al., 2009).

The construction of motorways in Ireland intensified in the last decade with traffic numbers on many roads now exceeding the 30,000 vehicles per day threshold for implication of mitigation methods as set down in Irish and UK guidance (NRA, 2008). The EU Water Framework Directive legislation is also applying pressure for the control of discharges to any receiving water whether ground or surface. Hence, the use of constructed wetlands as a possible mitigation method to treat highway runoff in Ireland was tested with the first wetland established as a pilot trial in 2005. This wetland was intensively researched for the first year and then has been periodically checked over the subsequent 6 years to present.

2. Materials and methods

2.1. Constructed wetland experimental site

The constructed wetland was built adjacent to a new motorway linking the towns of Kildare and Portlaoise in the east of Ireland. The plan area dimensions of the base were 12.7 m wide by 18.2 m length with a cross sectional slope of 1%. The depth of the wetland was no greater than 0.4 m at any point. The runoff drainage area of highway for the wetland was a 980 m straight length of hot rolled asphalt carriageway (total width 11.6 m) with a standard kerb and gulley construction, the surface runoff discharging into a piped drainage system via on-line gully traps installed at 20 m intervals. The runoff entered the wetland via four equally spaced 100 mm diameter pipe inlets across the inlet width to ensure even flow distribution (see Fig. 1). The outlet pipes at the same spacings had adjustable T-pieces as weirs to control the water level within the wetland (at approximately 0.3 m depth). A compacted clay base was laid to produce a relatively impermeable layer ($K < 1 \times 10^{-9}$ m/s) with a nominal 100 mm layer of local topsoil was added on top. The wetland first received flows in December 2004 and vegetation was planted on 5th May 2005. The north half of the wetland was planted with 500 *Phragmites australis* and the south half with 500 *Typha latifolia* – approximately 4 plants/m^2. Since opening the motorway has had an average traffic count of just over 30,000 vehicles per day over the 6 year period (with 10.5% on average as HGV) which has been slowly increasing.

2.2. Storm event sampling and analysis

The site was installed with an ISCO 674 0.1 mm tipping bucket rain gauge and ISCO 750 area velocity flow module to measure the flow into the wetland. A V-notch weir system with an ISCO 730 bubble module to measure the depth was installed at the outflow and a relationship between depth and flow over the V-notch was established. These devices were connected to two ISCO 6712 automatic samplers which took sequential 300 ml samples of the runoff and effluent on a flow based criteria. Between summer and autumn 2005 six major storm events were captured and fully sampled.

Storm runoff samples were analysed for total suspended solids as well as priority heavy metal pollutants (Cd, Cu, Pb and Zn) commonly found in urban runoff (Eriksson et al., 2007). The water quality analysis was carried out in the laboratory using acid digestion followed by analysis with a Varian Liberty AX sequential ICP-AES machine (see Supplementary Information for details). For 5 out of the 6 storms the storm runoff samples for heavy metals were also fractionated into their particulate and dissolved forms by filtering the sample through 0.45 μm filter paper. The discrete sample results were converted to EMC values using the mid-point volume method (Charbeneau and Barrett, 1998).

After this intensive period flow monitoring in 2006, instrumentation was removed (except the rain gauge) and the site periodically visited over the next 6 years where small adjustments were made to ensure the inlet and outlet pipes were level (using a Trimble 4700 GPS system).

2.3. Sampling and analysis of sediment and vegetation

After 6 years of operation the amount of heavy metals and suspended solids that had accumulated in the wetland were calculated by sampling sediment and vegetation in the summer of 2011. The wetland was divided into 12 cells of equal area (each 19.3 m^2) as referenced in Fig. 1. Two samples of sediment were taken from each cell (total of 24 sediments samples) using a tube augur. Samples of the fresh topsoil that was used to fill the wetland during construction were also analysed to determine the initial concentration of heavy metals in the wetland. Each sediment sample was then analysed for suspended solids concentration and heavy metal (Cd, Cr, Cu, Ni, Pb and Zn) concentration in the laboratory using acid digestion to extract the metals followed by ICP-AES analysis. For each sediment sample the depth of sediment to the clay liner was measured and the density of the sediment also calculated. The pH of the water and redox of the water as well as in the sediment was also measured in each cell at the time of sampling in situ with a field probe (YSI 556MPS).

Two complete plants (stem and roots) were carefully dug up and taken from each cell (total of 24 plant samples). In addition, the number of plants in a 1 m^2 quadrat within each cell was counted to give a representative density from which the total number in each cell was calculated. By the summer 2011 the *P. australis* had colonised all but one square (A4) of the wetland with the *T. latifolia* only still growing in a small area near the outlet zone. The plant samples were taken immediately to the laboratory for analysis