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DESIGN COMPARISON OF EXPERIMENTAL STORM WATER DETENTION SYSTEMS TREATING CONCENTRATED ROAD RUNOFF

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ABSTRACT

Urban drainage systems are vital infrastructure assets, which protect our cities from flooding and transmission of waterborne diseases. The objective of this research was to assess the treatment efficiencies of experimental stormwater detention (extended storage) systems receiving concentrated runoff that had been primary treated by filtration with different aggregates. Five detention systems with different packing order arrangements of aggregates and plant roots were used in the system to test the effects of gravel, sand, ecosoil, block paving and turf on the water treatment performance. Inflow water, polluted by road runoff, was collected by manual abstraction with a 2 litter beaker from randomly selected gully pots the near by main roads. Several parameters such as BOD_5, NO_3, PO_4, NH_4, SS, TS, DO, pH, EC, NTU and temperature were examined based on standard method book. Results showed that concentrations of biochemical oxygen demand (BOD_5) in contrast to suspended solids (SS) were frequently reduced to below international secondary wastewater treatment standards. The BOD and SS concentrations within the outflow from the planted system compared to the unplanted gravel and sand systems were similar. However, BOD in the outflow of system 5 was lower than other systems. The denitrification process was not completed. This resulted in higher outflow than inflow nitrate-nitrogen concentrations. An analysis of variance indicated that some systems were similar in terms of most of their treatment performance variables including BOD and SS. It follows that there is no need to use additional aggregates with high adsorption capacities in the primary treatment stage from the water quality point of view.

Key words: Environment, hydrology, water resources, infrastructure planning, storm water

INTRODUCTION

‘SUDS’ is the acronym for Sustainable Urban Drainage System. A singular or series of management structures and associated processes designed to drain surface water runoff in a sustainable approach to alleviate capacities predominantly in existing conventional drainage systems in an urban environment is defined as SUDS (Anonymous, 1999; Butler and Davies, 2000; Anonymous, 2000). In the United Kingdom maintenance of all public SUDS structures above ground is usually the responsibility of the local authority (Anonymous, 1998). Above ground, SUDS structures are defined as swales, ponds, basins and any other ground depression features. In contrast, the maintenance of underground SUDS structures is usually the responsibility of the local water authority. Underground SUDS structures include culverts, infiltration trenches, filter strips and underground detention systems (Nuttall *et al.*, 1998; Butler and Davies, 2000; Anonymous, 2000).

New developments proposed for Brownfield sites or on the periphery of urban developments may be unable to obtain planning permission if existing local sewers have no spare capacity for stormwater drainage, and if the storm water discharge from the proposed site cannot be controlled. In the absence of suitable watercourses that can accommodate direct stormwater discharges, alternative technologies such as at

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source' stormwater storage and detention systems are required (Butler and Davies, 2000).

Stormwater runoff is usually collected in gully pots that can be viewed as simple physical, chemical and biological reactors. They are particularly effective in retaining suspended solids (Bulc and Slak, 2003). Currently, gully pot liquor is extracted once or twice per annum from road drains and transported (often over long distances) for disposal at sewage treatment works (Butler *et al.*, 1995; Memon and Butler, 2002). A more sustainable solution would be to treat the entire road or car park runoff locally in potentially sustainable stormwater detention systems such as underground storage systems and stormwater ponds reducing transport and treatment costs (Guo, 2001). Furthermore, runoff treated with stormwater detention systems can be recycled for irrigation purposes. Underground stormwater storage and detention systems are defined as a subsurface structure designed to accumulate surface water runoff, and where water is released from as may be required to increase the flow hydrograph. The structure may contain aggregates with a high void ratio or empty plastic cells and act as a water recycler or infiltration device (Butler and Parkinson, 1997).

An underground stormwater detention system comprises a number of components forming a structure, which is designed to reduce storm water flow. The system captures surface water through infiltration and other methods. The filtered stormwater is stored underground in a tank. The water is often cleaned and filtered before it is infiltrated or discharged to the sewer or watercourse via a discharge control valve. The system benefits include runoff reduction of minor storms, groundwater recharge and pollution reduction. This detention system is predominantly applied in new developments.

The objectives of this study were to advance knowledge and understanding by formulating design guidelines for vertical flow storm water detention systems treating road runoff predominantly by extended storage in a cold climate such as the South east of Scotland. The objectives were to assess:

1. The function of turf (absent versus present) and different aggregates such as Ecosoil as components of a primary treatment filtration stage before the underground detention systems;
2. The overall passive treatment performance of vertical flow storm water detention systems.

MATERIALS AND METHODS

System design and operation

Five detention systems (Fig. 1) were located outdoors at the King's Buildings campus (the University of Ed inburgh, Scotland) to assess the system performance during a relatively cold spring and summer (31/03-19/08/04). In flow water, polluted by road runoff, was collected by manual abstraction with a 2 L beaker from randomly selected gully pots on the campus and the nearby main roads.

Five storm water detention systems based on plastic cells (boxes with large holes) were used. Each system had the following dimensions: height= 85 cm, length= 68 cm and width= 41 cm. Two plastic cells on top of each other made up one detention system (Fig. 1). The bottom cell (almost 50% full at any time) was used for water storage only. The top cell contained the aggregates. Different packing order arrangements of aggregates and plant roots were used in the systems (Tables 1 and 2) to test for the effects of gravel, sand, Ecosoil, block paving and turf on the water treatment performance.

The filtration system was designed to operate in vertical flow batch mode. Gully pot liquor compares well with concentrated road runoff (by a factor of at least 30 depending on gully pot spacing), and was used in the experiment as a 'worst case scenario' liquid replacing road runoff. All detention systems (Tables 1 and 2) were watered approximately twice per week with 10 litters gully pot liquor as slow as possible, and drained by gravity afterwards to en-courage air penetration through the soils (Cooper *et al.*, 1996; Gervin and Brix, 2001). The added water was detained in the collection cell of the system until the next occasion. From the second occasion, two litters of the inflow and outflow from each filter were collected manu-ally from the gullies and collection cells of the filters respectively to be analysed in the lab.

The relative quantity of gully pot liquor used per system was approximately 3.6 × the mean annual rainfall volume to simulate a 'worst case scenario'. The hydraulic residence times were in the order of one hr. Biodegradation was enhanced by encouraging natural ventilation of the aggregates from the top via the natural air, and from the bottom via the air pocket above the storage water and between the aggregates (Fig. 1). Considering industrial scale systems, vertical ventilation pipes should be installed to encourage passive ventilation as well.

Analytical methods

The biochemical oxygen demand (BOD5) was determined in the inflow and outflow water samples with the OxiTop IS 12-6 system. The measurement principle is based on measuring pressure differences estimated by piezoresistive electronic pressure sen-sors. Nitrification was suppressed by adding 0.05 mL of 5 g/L N-Allylthiourea (WTW Chemical Solution No. NTH 600) solution per 50 ml of sample water.

Ammonia nitrate and orthophosphate phosphorus were determined by automated colorimetry in all water samples from reaction with hypochlorite and salicylate ions in solution in the presence of sodium nitrosopentacyan oferrate, and reaction with acidic molybdate to form a phosphomolybdenum blue complex, respectively (Allen, 1974). A Whatman PHA 230 bench-top pH meter (for control only),

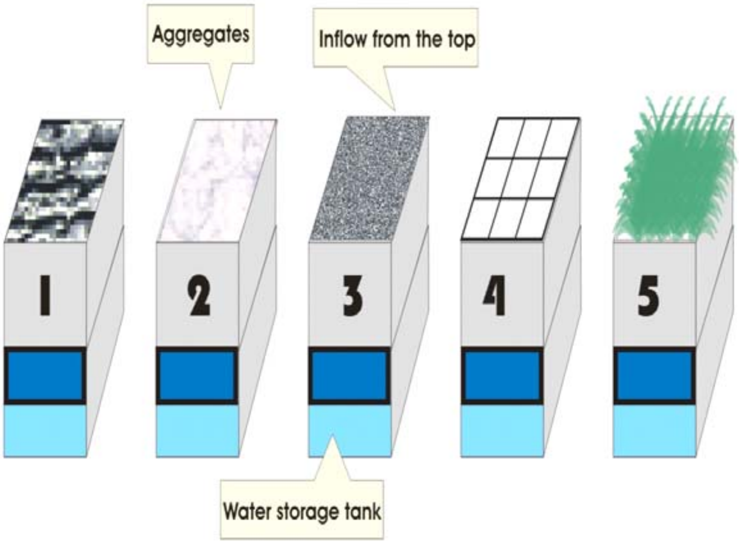

Fig. 1: System design for detention cells

Table 1: Systematic and stratified experimental setup of gravel filled storm water detention system content and operation

System	Planted	Additional media type^a	Natural aeration restricted
1	No	-	No
2	No	Sand	No
3	No	Sand and Ecosoil	No
4	No	Sand, Ecosoil and block paving	Yes (due to block paving)
5	Yes	Sand, Ecosoil and turf	No

Table 2: Packing order of the storm water detention systems

Height (mm)	System 1	System 2	System 3	System 4	System 5
861-930 (top)	Air	Air	Air	Block paving and 6 mm gravel within spaces	Air
791-860	Air	Air	Air		Turf
751-790	Air	Air	Sand and Ecosoil	Sand and Ecosoil	Sand and Ecosoil
711-750	Air	Sand	Sand and Ecosoil	Sand and Ecosoil	Sand and Ecosoil
661-710	6 mm gravel	6 mm gravel	6 mm gravel	6 mm gravel	6 mm gravel
451-660	20 mm gravel	20 mm gravel	20 mm gravel	20 mm gravel	20 mm gravel
437-450	Sand	Sand	Sand	Sand	Sand
431-436	Geotextile	Geotextile	Geotextile	Geotextile	Geotextile
201-430	Air	Air	Air	Air	Air
0-200 (bottom)	Water	Water	Water	Water	Water

a Hanna HI 9142 portable waterproof dissolved oxygen (DO) meter, a HACH 2100N turbidity meter and a Mettler Toledo MPC 227 conductivity, total dissolved solids (TDS) and pH meter were used to determine DO, turbidity, and conductivity, TDS and pH, respectively. An ORP HI 98201 redox potential meter with a platinum tip electrode HI 73201 was used to measure pH. Composite water samples were analysed. All other analytical procedures were performed according to the standard methods book (Anonymous, 1998).

Metal concentrations which were determined in the raw gully pot liquor and the outflow waters from the experimental place 16 June 2004. Water samples for metal determinations were stored at 19 °C until analysis.

An Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) called TJA IRIS and supplied by Thermo Elemental (USA) was used to analyse selected wastewater, Ecosoil and grass cutting samples. The purpose was to screen samples economically to determine various trace element concentrations and potential contaminants. Analytical precision (relative standard deviation) was typically 5-10 % for three individual aliquots.

RESULTS

Comparison of costs

The overall capital and maintenance costs were calculated for each detention system for the first year of operation. Maintenance included litter removal and grass cutting. Material prices were requested for a volume of 100 m^3 per aggregate to obtain realistic figures for a scaled up detention system (indus-trial operation size). The five system configurations have standardised cost ratios of approximately 1.0: 1.1: 1.2: 1.3: 1.6 based on Edinburgh prices in March 2004. However, the actual prices are subject to negotiation (e.g., quantities ordered) and fluctuation on the market.

Inflow water quality is presented in Table 3. The overall filtration performances are summarised in Table 4 that should be compared with Table 3. The overall system performance figures calculated as reduction efficiencies from equation:

$$\text{Change (\%)} = \frac{(in - out) \times 100\ \ (\%)}{in}$$

are summarised in Table 4.

These overall performances have been calculated based on outflow quality of each filter relative to inflow quality of water.

DISCUSSION

The standard deviations for all inflow parameters (except for DO, pH and temperature) are high (Table 3) due to the random selection of gully pots and seasonal variations (Butler and Parkinson, 1997; Scholz, 2004).

Table 3: Gully pot liquor (inflow to systems): water quality variables

Variable	Unit	Number of samples	Mean	SD^a	Mean (spring^b)	Mean (summer^c)
BOD^d	mg/L	30	37.8	55.30	50.3	29.4
Nitrate-nitrogen^e	mg/L	34	1.0	1.54	0.5	1.4
Ammonia-nitrogen	mg/L	34	2.1	1.85	2.4	1.9
Ortho-phosphate-phosphorus	mg/L	34	0.2	0.12	0.1	0.2
Suspended solids	mg/L	30	596.5	1430.40	725.6	483.5
Total solids	mg/L	30	442.8	848.58	311.4	518.9
Turbidity	NTU	35	81.3	81.67	108.0	58.7
Dissolved oxygen	mg/L	33	3.2	1.47	2.9	3.3
pH	-	35	6.99	0.286	6.79	7.16
Redox potential	mV	35	178.0	110.62	106.2	238.5
Conductivity	µS/cm	35	224.7	223.25	338.5	128.9
Temperature (air)	ºC	34	18.0	3.92	16.2	19.4
Temperature (gully pot)	ºC	34	17.4	4.66	14.6	19.7

^{a} standard deviation; ^{b}31/03-21/06/04; ^{c}22/06/04-19/08/04; ^{d}five-day biochemical oxygen demand; ^{e}includes nitrite-nitrogen. ∗(31/03-19/08/04)

Table 4: Relative reduction percentage of outflow variables

	Change (%) per wetland system^a														
Variables	System 1			System 2			System 3			System 4			System 5		
Ables	Y^b	SP^c	SU^d	Y^b	SP^c	SU^d	Y^b	SP^c	SU^d	Y^b	SP^c	SU^d	Y^b	SP^c	SU^d
BOD^e	92	95	89	93	95	90	90	90	90	93	93	92	94	96	92
$NO_3{}^f$	-1372	-1483	-1338	-1667	-832	-1918	-695	-482	-759	-1020	-564	-1158	-393	-853	-254
$NH_4{}^g$	81	74	87	89	86	93	86	78	94	86	76	96	89	82	96
$PO_4{}^h$	-74	16	-120	-64	12	-102	-33	12	-55	-56	8	-88	-74	2	-113
SS^i	78	67	92	80	69	94	79	69	93	80	69	93	78	66	94
Turb^j	91	92	90	90	91	89	84	81	88	85	81	90	71	83	51

***** (31/03/04-19/08/04)

^{a} Change (%) = $\frac{(in - out) \times 100 \ (\%)}{in}$, where in= inflow and out=outflow; Y^b overall mean for the whole period of data collection (31/03/04-19/08/04); SP^c mean of the spring (31/03/04-21/06/04); SU^d mean of the summer (22/06/04-19/08/04) BOD^e five-day biochemical oxygen demand (mg/L);NO3 ^{f}nitrate-nitrogen (mg/L); NH4^g ammonia-nitrogen (mg/L); PO4^h otho-phosphate-phosphorus (mg/L); ^{i}suspended solids (mg/L); ^{j}turbidity (NTU).

The gully pot liquor was less polluted in summer than in spring. For example, BOD, SS and turbidity in summer were 42, 33 and 46% lower, respectively (Table 3). There are various reasons for this including the observation that the higher temperature in summer compared to spring results in a faster biodegradation rate within the gully pot (Table 3). Moreover, the retention time of the gully pot liquor in summer is likely to be longer than in spring due to less frequent rainfall events. A longer retention time correlated positively with a higher biodegradation rate (Anonymous, 1998; Butler and Davies, 2000; Scholz, 2004). Reduction efficiencies for BOD and SS (Table 4) are comparable to findings reported else-where (Bulc and Slak, 2003; Scholz, 2004) for highway runoff treatment with constructed wetlands. The reductions of BOD (Table 4) were acceptable for most systems if compared to minimum American and European standards for the secondary treatment of effluent. Biochemical oxygen demand in contrast to SS (Table 4) outflow concentrations did not exceed the US thresholds of 30.0 mg/L (Tchobanoglous *et al.*, 2003). However, some European standards or those of individual regional agencies (Cooper et al., 1996; Shutes et al., 2001; Lim *et al.*, 2003) are more stringent; e.g. BOD < 20 mg/L. The BOD outflow concentration was also lower than the UK standard (Scholz, 2004) for secondary treated wastewater of 20 mg/L (Table 4). Comparison of BOD in the filters showed that there was no significant difference between the BOD concentrations in the outflow from the planted system compared to the unplanted gravel and sand systems (filters 1-4) as for SS ($P > 0.05$). However, filter 5 has lower BOD concentrations in the outflow compared to the other filters.

The removal of suspended solids (SS) was nearly similar in spring and summer. Although the SS reduction efficiencies are better for sum-mer than spring, but all filters demonstrated a positive capability to filter SS in spring as well as throughout the experimental period. The overall performance of all the filters for SS was similar with findings of Clark *et al.*, (1994), who had reported SS removal efficiency for the same filters as 75%-85%. Reduction efficiencies of turbidity are slightly higher for filter 1 and 2 than filter 3 and 4. Filter 5 shows poor reductions for turbidity. The decrease in reduction efficiencies of turbidity from spring to summer (from 83% to 51%) is probably due to the dieback of turf in summer.

A regression analysis has shown that BOD, ammonia nitrogen, nitrate-nitrogen and ortho phosphate-phosphorus can be estimated with conductivity and total dissolved solids using a second order polynomial equation. For example, concerning BOD, nitrate nitrogen and ammonia nitrogen with conductivity, the corresponding coefficient of determination (r^2) for filter 4 are 0.60, 0.71 and 0.76, respectively. This would result in the reduction of costs and sampling effort. However, statistical relationships between other variables were not significant.

Furthermore, it has been suggested that mature and viable microbial biomass, in contrast to aggregates with high adsorption capacities (e.g., Ecosoil) and turf, is responsible for the high overall filtration performances (Cooper *et al.*, 1996; Scholz and Martin, 1998). However, it is difficult to classify objectively a biological system as mature without having undertaken intensive microbiological work.

Finally, analysis by ICP-OES of selected inflow and outflow samples for a suite of cations showed that all waters generally contained low concentrations of heavy metals. Measured elemental concentrations were either low (barium, calcium, magnesium and manganese), close to the detection limit (iron) and for most heavy metals (including aluminium, copper and cadmium) below the detection limit. Dissolved zinc was the pollutant measured in highest concentration. The mean inflow concentration for zinc was 0.14 mg/L and the corresponding out flow concentrations were 0.07 mg/L (standard deviation: 0.05 mg/L).

Ecosoil did not contribute to elevated nutrient concentrations due to very low total nitrogen, total phosphorus and total potassium concentrations of 65, 46 and 1367 mg/kg, respectively. A recent soil quality analysis for areas in Glasgow where SUDS were considered for implementation showed total nitrogen, total phosphorus and total potassium concentrations of 1612, 605 and 4562 mg/kg, respectively (Scholz *et al.*, 2005). It follows that Ecosoil does function only as a very weak fertiliser, and that it is therefore unlikely to contribute to eutrophication after the release of the treated stormwater to the nearby watercourse.

Furthermore, Ecosoil contained only trace amounts of heavy metals (except for aluminium): 1036, 24 and 7 mg/kg dry weight of aluminium, zinc and nickel, respectively. All other metal concentrations were below the detection limit of the instrument. However, even the aluminium concentrations are similar to values reported elsewhere for urban soil (Scholz *et al.*, 2005).

The influence of turf (System 5; (Fig. 1)) on the organic matter content of the outflow was studied. The BOD and SS concentrations within the outflow from the planted system compared to the unplanted gravel and sand systems were similar (Tables 3 and 4). However, BOD in the outflow of system 5 was lower compared to all other systems.

Moreover, grass on top of filter 6 (Fig. 1) was cut when the length was greater than 10 cm for optical reasons and to reduce the overall nutrient load. Total nitrogen, total phosphorus and total potassium concentrations were 3001, 640 and 6909 mg/kg fresh weight, respectively. The presence and harvesting of grass seemed to have a positive effect on the overall nitratenitrogen outflow concentration that was lower for system 5 if compared to the remaining systems (Tables 3 and 4).

However, it is concluded that Biochemical Oxy-gen Demand (BOD) outflow concentrations were below the UK threshold of 20 mg/L for secondary treated wastewater. The storm water detention system did show signs of overloading resulting in relatively high-suspended solids (SS) and nitrate, nitrogen concentrations, and further treatment would be required. Moreover, denitrification was not completed, and longer retention times are therefore suggested. Nitrate, nitrogen was lower in the outflow of the planted system (turf on the top). An analysis of variance indicated that there was no significant difference between most systems in terms of their treatment performance (e.g., BOD and SS) despite of their different setups. It follows that all systems regardless of their pretreatment function as covered wastewater stabilization ponds.

Gully pot liquor (concentrated storm water runoff) in relative quantities exceeding three times the mean annual rainfall was used for all systems. Therefore, it is likely that the SS con-centration would be much lower in the field under real conditions.

Ecosoil did contain relatively low concentrations of nutrients and metals (except for aluminium). It follows that higher investment costs for more complex systems are not justified based on a water quality analysis alone.

However, further research in the potential hydraulic and structural benefits of additional aggregates such as Ecosoil is required.

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