Water Quality and Sediment Behaviour of the Future: Predictions for the 21st Century
(Proceedings of Symposium HS2005 at IUGG2007, Perugia, July 2007). IAHS Publ. 314, 2007.

71

Assessing the effects of design and climate change on sediment removal in urban stormwater ponds

CATHERINE T. MORGAN[1], KATE V. HEAL[2], STEVE G. WALLIS[1] & REBECCA J. LUNN[3]

1 *School of the Built Environment, Heriot-Watt University, Riccarton, Edinburgh EH14 4AS, UK*

2 *School of GeoSciences, The University of Edinburgh, Crew Building, The King's Buildings, West Mains Road, Edinburgh EH9 3JN, UK*
k.heal@ed.ac.uk

3 *Department of Civil Engineering, University of Strathclyde, John Anderson Building, 107 Rottenrow, Glasgow G4 0NG, UK*

Abstract Urban stormwater pond design normally only considers single storm events, does not explicitly consider climate change and is often inconsistent, with some approaches emphasising flow attenuation and others emphasising water quality enhancement. These design issues were explored for sediment removal (by settling) through modelling generic cylindrical ponds sized using current UK guidance. Results showed that ponds designed for flow attenuation had a higher sediment removal efficiency than those designed for water quality enhancement (78% *vs* 21% removal of incoming sediment, respectively, for the 1 in 2 year storm event). Sediment removal efficiency remained almost unchanged when multiple rather than single storm events were routed through ponds, but decreased with increasing storm event magnitude. Overall, decreased sediment removal is likely from the more frequent and intense storm events predicted due to climate change. Urban stormwater ponds designed for flow attenuation are more successful for both flow and sediment attenuation.

Key words climate change; design; modelling; ponds; retention basins; Scotland; sediment; SUDS; urban stormwater

INTRODUCTION

During the last decade stormwater ponds have been increasingly used worldwide to minimise the impact of urbanisation on the water environment. In these systems (also known as retention ponds or basins in the UK), which are normally defined as containing a permanent pool of water, flow attenuation occurs by temporary storage of runoff followed by a delayed and slow release to the receiving watercourse. Water quality improvement occurs primarily by the capture of sediment in the pond, through the settling of suspended solids, since many of the major pollutants carried by surface runoff are attached to sediment particles. Sediment removal is highly dependent on pond design, particularly the characteristics of the permanent pool of water. A larger permanent pool enhances settling by increasing residence time, as well as providing habitat for aquatic vegetation, which enhances filtration and pollutant removal by nutrient uptake and microbial degradation.

Despite the widespread deployment of urban stormwater ponds there is still considerable variability in the guidance for pond design. Some approaches stress designing for flow attenuation, e.g. in the UK, the Construction Industry Research and

Information Association) (CIRIA, 1993) recommended that ponds should be sized to attenuate the 1 in 25 and 1 in 100 year flood events, whilst other approaches emphasise design for water quality enhancement. In the UK, the normal approach for pond design for water quality enhancement is to size the permanent pool to hold one or more treatment volumes (*Vt*), defined as the volume of runoff generated by the first 12–15 mm of rainfall on the impervious catchment surface, thereby capturing the first flush of storm runoff which is typically the most polluted. Recent research suggests that one *Vt* may be an acceptable size criterion for ponds for most low risk urban sites (McLean *et al.*, 2005), smaller than the three to four *Vt* previously recommended (CIRIA, 2000).

The aims of this research were to investigate the effects on sediment removal efficiency of three aspects of current design methodology for urban stormwater ponds. Firstly, the different design approaches (flow attenuation and water quality enhancement); secondly, single *vs* sequential storm events (since normally only single storm events are considered, whereas, in reality, events often occur in sequence); and thirdly whether ponds designed using the current recommended methodology will provide adequate water quality improvement for the increased frequency and magnitude of storm events predicted as a result of climate change. The impacts of these design issues were explored through simulations of sediment capture by settling in generic cylindrical ponds.

MODELLING APPROACH

The mathematical model consisted of two components: a flow model and a sediment transport model; and in both cases the pond was modelled as a deterministic, lumped system. The pond was assumed to be cylindrical, having a single inlet and a single outlet device.

Flow model

Flow through the pond was modelled using a standard storage routing method (Mays, 2001) that is based on the following conservation of water volume equation:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = Q_i - Q_o \tag{1}$$

where V is the volume of water in the pond, Q_i is the volumetric inflow rate of water, Q_o is the volumetric outflow rate of water and t is time. Equation (1) was solved to give the outflow hydrograph, assuming that the inflow hydrograph was known. Outflow from the pond occurred through a v-notch weir, and was calculated using a standard head-discharge equation (Chadwick & Morfett, 1998). Equation (1) was solved numerically using a standard time-weighted finite difference method (Griffiths & Smith, 1991) to give a nonlinear approximation, which was solved in a standard way using Newton-Raphson iteration (Chapra & Canale, 1998).

Sediment transport model

The sediment transport model computes the temporal distribution of suspended sediment concentration in the pond outflow (outflow sedigraph) for any specified distribution of suspended sediment in the inflow (inflow sedigraph). The model is based on a mass balance of sediment and caters for several transport mechanisms. It recognises that the concentration of suspended sediment in a stormwater pond (particularly during an inflow event) may not be uniform and that several flow-related processes, such as short-circuiting and flow-dependent settling, are likely to occur. Where short-circuiting occurs, the sediment has little opportunity to mix with the rest of the water in the pond and to settle. Whether it settles or not depends on the flow conditions and on the sediment characteristics. For example, heavy sediment particles are likely to settle under all flow conditions but light ones will only settle when the flow is weak, being carried out of the pond in the outflow otherwise. Elsewhere in the pond, the water is essentially static and suspended sediment in these areas settles under quiescent conditions. The above features were catered for by dividing the pond into two (lumped) zones, each individually well mixed, and between which suspended sediment can diffuse. Zone 1 contains the pond volume that is involved in short-circuiting and in which flow-dependent settling occurs, while Zone 2 contains the remaining pond volume in which quiescent settling occurs. Inflow to, and outflow from, the pond take place only in Zone 1. The conservation of sediment in the zones is described by the following two equations, which equate the rate of change of sediment mass to the sum of sediment fluxes:

$$\text{Zone 1} \quad \frac{\mathrm{d}(V_1 C_1)}{\mathrm{d}t} = Q_i C_i - Q_o C_1 - \varepsilon(C_1 - C_2) - A_1 U_1 C_1 \tag{2}$$

$$\text{Zone 2} \quad \frac{\mathrm{d}(V_2 C_2)}{\mathrm{d}t} = -\varepsilon(C_2 - C_1) - A_2 U_2 C_2 \tag{3}$$

where V is volume, C is suspended sediment concentration, Q is flow rate, ε is the inter-zone diffusion rate, A is surface area and U is settling velocity. Subscripts 1, 2, i and o refer, respectively, to Zone 1, Zone 2, inflow and outflow. In equation (3) the fluxes are inter-zone diffusion and settling, whilst equation (2) also contains inflow and outflow fluxes. Equations (2) and (3) were solved using a similar finite difference form as for the flow model to give the temporal variation of C_1 and C_2, for a specified distribution of sediment in the inflow. Suitable values of ε and U were selected and it was assumed that volumes, flows and surface areas were known from the flow model.

Simulations

The models were used to simulate sediment removal in an urban stormwater pond typical of those constructed in Scotland during the 1990s. To ensure that the simulated pond volume was realistically matched to inflow events, the simulations were based on Linburn Pond, located in the Dunfermline Eastern Expansion (DEX) development in eastern Scotland (56°4′N, 3°24′W). The pond was modelled with a single 90° weir, with the weir crest 3 m above the base of the pond. Simulations focused on the 24 h

duration inflow event, which is representative of the hydrological conditions in eastern Scotland. Inflow hydrographs were triangular and symmetrical with the peak inflow occurring after 12 h. The analysis of a 30-year daily rainfall record for Tullyallan (23 km distant), combined with a simple rainfall–runoff model (Morgan, 2007) showed that the peak inflow of the 1 in 25 year, the 1 in 2 year and the Q90 events were 250, 125 and 28.7 L s^{-1}, respectively.

In all simulations, the inflow sedigraph consisted of a symmetrical triangular distribution with a peak concentration of 100 mg L^{-1}. For the 1 in 2 year event, the duration of the sedigraph was 9.6 h, corresponding to the time taken for 12–15 mm of the runoff generating rainfall to have occurred. For the Q90 event, however, the runoff generating rainfall was less than 12–15 mm, so it was assumed that the sedigraph duration was the same as for the inflow hydrograph, i.e. 24 h. Since it is well known that the sediment in the runoff from urban developments consists of particles of various sizes, for each simulation case the model was run five times using sediment of different nominal sizes. The final sediment removal results were then calculated as a weighted average of the five individual simulations, the weighting being based on the typical particle size distribution of sediment in the inlets to urban stormwater ponds in the DEX development (Morgan, 2007).

In Zone 2 values of quiescent settling velocity were as given by Ellis *et al.* (1995). In Zone 1 flow-dependent settling followed a simplified version of the Hjulstrom curve (Hjulstrom, 1935) and varied linearly between zero (high flows) and the quiescent settling velocity (low flows) (Morgan, 2007). To undertake the sediment simulations the inter-zone diffusion rate (ε) and the ratio of the volumes of Zone 1 to Zone 2 needed to be calibrated. From trial simulations undertaken to find a suitable combination of these constants, ε was set at 0.01 m^3 s^{-1} and the volume ratio at 1/9. Under these conditions, the model of Linburn Pond captured about 30% of incoming sediment, which is typical of its known performance (Morgan, 2007). All the simulations were undertaken using a time step of 0.24 h, based on the results of a time-step sensitivity analysis (Morgan, 2007).

The first set of simulations explored sediment removal in ponds designed for flow attenuation or for water quality enhancement. There is no widely accepted definition of the level of flow attenuation that a stormwater pond should provide. Here the criterion adopted was that the former pond should be sized to reduce the peak outflow to half the peak inflow for the 1 in 25 year event. The basis of this criterion was early studies showing that urbanisation can increase peak flows to between two and five times those of the pre-developed catchment (e.g. Savini & Kammerer, 1961). Simulations with the flow model showed that a pond of radius 75 m and permanent pool volume of 53 014 m^3 was required to achieve this. The pond designed for water quality enhancement was sized so that the permanent pool volume was equal to one treatment volume (*Vt*), following the recommendations of McLean *et al.* (2005). For Linburn Pond, *Vt* was calculated to be 2550 m^3 for 15 mm rainfall depth, so that the radius of a stormwater pond designed in this way would be 16.45 m (($2550/(3 \times \pi))^{0.5}$), recalling that the outlet weir crest is located 3 m above the pond base. Simulations were then carried out that considered sediment removal in both these ponds, focusing on more frequent events (1 in 2 year and Q90) because it is believed that such events may be more influential than rare flow events for pond water quality (McLean *et al.*, 2005).

As well as simulating the single Q90 event for both pond designs, some multiple Q90 event scenarios were also undertaken for both pond designs. Two scenarios were considered. Firstly, a second identical inflow event occurring immediately after the first event, but with no sediment in the second inflow, and secondly, a second identical inflow event occurring immediately after the first event with sediment in the second inflow. The former scenario is more realistic since there is limited opportunity for sediment accumulation on urban surfaces between storm events, whilst the latter scenario represents "worst case" conditions.

RESULTS AND DISCUSSION

A typical model output (Fig. 1) shows flow rates and sediment concentrations for the inflow and outflow of a pond designed for water quality enhancement during a single 1 in 2 year event. The flow attenuation is very poor for this pond design, because the pond's surface area is very small and because, as in all simulations, the water level in the pond was at the weir crest at the start of the simulation. The sediment concentration in the outflow reflects the two-zone model structure. The main sediment peak is controlled by passage through Zone 1, whilst the small increase in sediment concentration after 20 h is due to movement of sediment by the slower process of diffusion from Zone 2.

Results for flow attenuation and sediment removal for ponds designed for flow attenuation or water quality enhancement are shown in Table 1. In both storm events the pond designed for flow attenuation reduced the peak outflow by over 50%, meeting the requirement that the peak outflow should be at most half the peak inflow, in contrast to the very poor flow attenuation in the pond designed for water quality. The
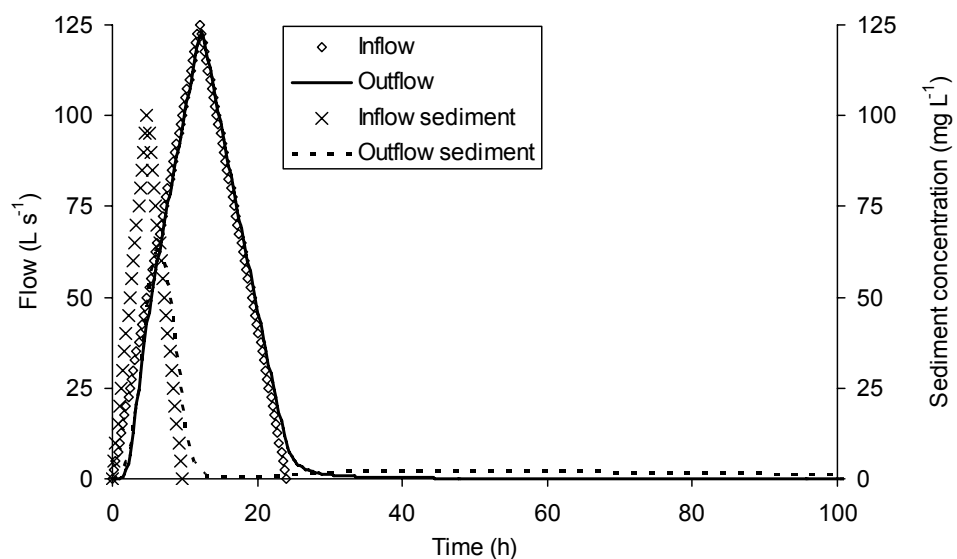

Fig. 1 Flow and sediment concentrations in the inflow and outflow of a pond designed for water quality attenuation during a 1 in 2 year storm event. The sediment concentrations shown are for the finest (<0.001 mm diameter) and dominant particle size (79% by mass).

Table 1 Peak flow reduction and sediment removal in ponds designed for flow attenuation and water quality enhancement for the Q90 and 1 in 2 year storm events.

Pond design	Storm event	Peak inflow ($L s^{-1}$)	Peak inflow reduction (%)	Inflow sediment mass settled (%)
Flow attenuation	Q90	28.7	94	98
Flow attenuation	1 in 2 year	125	69	78
Water quality	Q90	28.7	4.0	48
Water quality	1 in 2 year	125	2.0	21

pond designed for flow attenuation had higher sediment removal efficiencies than the pond designed for water quality enhancement in both storm events.

Most design guidance for urban stormwater ponds focuses on attenuation of individual storm events and assumes that the pond is drained down to the permanent pool prior to a storm event. However, in temperate climates, such as the UK, storms may occur in quick succession, often with very short intervening dry antecedent periods. Consequently, if there has been a recent storm event and little storage volume remains in the pond, the attenuation of subsequent rainfall events is expected to be significantly reduced. The sediment removal and inflow peak reduction when single and multiple Q90 storm events and sediment inputs were routed through ponds designed for flow attenuation or water quality enhancement is shown in Fig. 2.

In all cases, sediment removal was higher in the pond designed for flow attenuation than the pond designed for water quality enhancement for the same storm event sequence (Fig. 2(a)). Surprisingly sediment removal efficiency remained almost unchanged when multiple rather than single storm events were routed through ponds of both designs. The reason suggested to explain this is the large size of the permanent
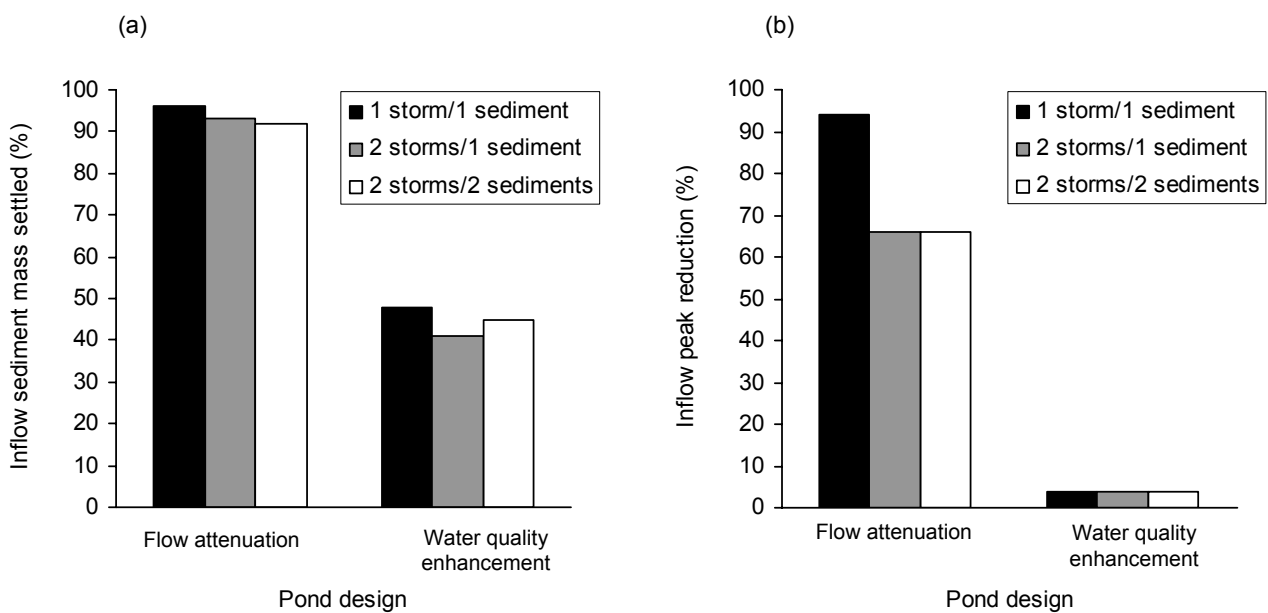
Fig. 2 (a) Sediment removal and (b) inflow peak reduction in ponds designed for flow attenuation and water quality enhancement for single and multiple Q90 storm events.

pools compared to the individual storm event volume (1240 m^3), which facilitated sediment settling before the onset of the second storm event. When the simulations were repeated for a generic infiltration pond with no permanent pool of water and sized to meet the flow attenuation criterion, sediment removal did decline from 53% in the single storm event to 39% in the two storms–one sediment input scenario. Furthermore, multiple storm events had a considerable impact on flow attenuation (Fig. 2(b)). In the pond designed for flow attenuation the peak inflow was only reduced by 69% in sequential storm events compared to 94% in a single storm event, whilst flow attenuation was very poor in the pond designed for water quality in all simulations.

Climate change is likely to produce an increase in the frequency and magnitude of rainfall events, which is expected to impact on the flow attenuation and water quality enhancement performance of urban stormwater ponds designed according to the current recommended methodology. Recent global climate model simulations have predicted increases in the frequency and intensity of heavy rainfall at northern latitudes (Ekström *et al.*, 2004), consistent with observations of changing rainfall intensity in the UK (Fowler & Kilsby, 2003). The results presented in Fig. 2 show that more frequent occurrence of small storm events will have little effect on sediment removal by urban stormwater ponds under Scottish conditions, although flow attenuation performance is very significantly impacted. However, the simulations conducted with different storm sizes showed that sediment removal decreased in both pond designs with increasing storm event magnitude from Q90 to the 1 in 2 year event (see Table 1).

CONCLUSIONS

Using a generic modelling approach it has been demonstrated that the methodology used to design urban stormwater ponds, i.e. whether they are designed for flow attenuation or for water quality enhancement, has a significant effect on pond performance. Ponds designed for flow attenuation are more successful in terms of both flow *and* pollutant attenuation (measured here as removal of suspended sediment).

REFERENCES

Chadwick, A. & Morfett, J. (1998) *Hydraulics in Civil and Environmental Engineering* (third edn). E & FN Spon, London, UK.
Chapra, S. C. & Canale, R. P. (1998) *Numerical Methods for Engineers: with Programming and Software Applications* (third edn). McGraw-Hill, Boston, USA.
CIRIA (Construction Industry Research and Information Association) (1993) *Design of Flood Storage Reservoirs*. CIRIA B014, CIRIA, London, UK.
CIRIA (2000) *Sustainable Urban Drainage Systems—design manual for Scotland and Northern Ireland*. CIRIA C521, CIRIA, London, UK.

Ellis, J. B., Hall, M. J. & Packman J. C. (1995) Modelling water quality for urban flood storage reservoirs. *Environ. Int.* **21**, 177–186.

Ekström, M., Fowler, H. J., Kilsby, C. G. & Jones, P. D. (2004) New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. *J. Hydrol.* **300**, 234–251.

Fowler, H. J. & Kilsby, C. G. (2003) A regional frequency analysis of United Kingdom extreme rainfall from 1961–2000. *Int. J. Climatol.* **23**, 1313–1334.

Griffiths, D. V. & Smith, I. M. (1991) *Numerical Methods for Engineers.* Blackwell Scientific Publications, Oxford, UK.

Hjulstrom, F. (1935) Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bull. Geol. Inst. of Uppsala* **25**, 221–527.

Mays, L. W. (2001) *Water Resources Engineering.* John Wiley & Sons, New York, USA.

McLean, N., Campbell, N., Bray, R. & D'Arcy, B. J. (2005) New approaches to detention basins and ponds. In: *Proc. Third National Conf. on Sustainable Drainage* (ed. by A. P. Newman, C. J. Pratt, J. W. Davies & J. M. Blakeman), 19–29. School of Science and the Environment, Coventry University, Coventry, UK.

Morgan, C. T. (2007) Assessment of the design of stormwater ponds for flow attenuation and water quality treatment. PhD Thesis, Heriot-Watt University, Edinburgh, Scotland, UK.

Savini, J. & Kammerer, J. C. (1961) Urban growth and the water regime. *US Geol. Survey Water Supply Paper 1591-A.*