SUSTAINABLE DRAINAGE

A Review of Published Material on the Performance of Various SUDS Components

Prepared for
The Environment Agency
by
Professor C J Pratt, Coventry University
Updated February, 2004

CONTENTS

This review does not make any claim to be comprehensive, nor to include all those references which are significant. It is an attempt to draw attention to those publications which have appeared in conference proceedings and journals which most frequently contain outputs of relevance to sustainable drainage in the UK and overseas. Readers are advised to review the references given in the papers cited as these are not necessarily listed in this review and may give valuable additional information.

CONSTRUCTED WETLANDS

Bavor H.J., Davies C.M. and Sakadevan K., 2001. Stormwater treatment: do constructed wetlands yield improved pollutant management performance over a detention pond system? *Wat. Sci. Tech.*, 44(11-12), pp.565-570.

Bray R.J., 1999. Design experience of source control treatment systems on commercial developments . *Proc.* Standing Conf. on Stormwater Source Control, Volume XVII, Coventry University, ISBN 0 905949 80 3.

Bray R.J., 2000. Design of the 'treatment train' at Hopwood Park motorway service area on the M42 . *Proc.* Standing Conf. on Stormwater Source Control, Volume XIX, Coventry University, ISBN 0 905949 88 9.

Bray R.J., 2001. Environmental monitoring of sustainable drainage at Hopwood Park motorway service area M42 Junction 2. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.58-70.

Cutbill L. and Barnes R., 1994. Artificial wetlands for stormwater treatment . *Proc.* Standing Conf. on Stormwater Source Control, Volume VII, Coventry University, ISBN 0 905949 21 8.

Daukas P., Lowry D. and Walker W.W., 1989. Design of wet detention basins and constructed wetlands for treatment of stormwater from a regional shopping mall in Massachucetts. In: *Constructed Wetlands for Wastewater Treatment,* Ed. D.A. Hammer, Lewis Publishers, ISBN 0 87371 184 X, pp.686-694.

Ellis J.B., Shutes R.B.E., Revitt D.M., Forshaw M. and Winter B., 2001. SUDS and constructed wetlands: how compatible are they?. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.147-158.
Ellis J.B., Shutes R.B.E., Revitt D.M., Forshaw M. and Winter B., 2003. Overcoming the dark side: issues and protocols for urban stormwater constructed wetland operation and maintenance. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.135-145.

Ferlow D.L., 1993. Stormwater runoff retention and renovation: a back lot function or integral part of the landscape? In: *Constructed Wetlands for water Quality Improvement,* Ed. G.A. Moshiri, Lewis Publishers, ISBN 0 87371 550 0, pp.373-382.

Heal K., 2000. Sediment quality in sustainable urban drainage structures in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Horner R.R., 1989. Long-term effects of urban stormwater on wetlands. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.451-466.

Koob T., Barber M.E. and Hathhorn W.E., 1999. Hydrologic design considerations of constructed wetlands for urban stormwater runoff. *Journal Am. Wat. Res. Assoc.*, 35(2), pp.323-331.

Lansdown R.V. and Topping D., 1994. Policy and practice for collection, transport and treatment of highway runoff . *Proc.* Standing Conf. on Stormwater Source Control, Volume VII, Coventry University, ISBN 0 905949 21 8.

Livingston E.H., 1989. The use of wetlands for urban stormwater management. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.467-490.

Martin E.H., 1989. Mixing and residence times of stormwater runoff in a detention system. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.164-179.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Nuttall P.M., Boon A.G. and Rowell M.R., 1997. Review of the design and management of constructed wetlands. *Report 180,* Construction Industry Research and Information Association, London, ISBN 0 86017 485 9.

Pontier H., Williams J.B. and May E., 2001. Metals in combined conventional and vegetated runoff control systems. *Wat. Sci. Tech.*, 44(11-12), pp.607-614.

Pontier H., May E. and Williams J.B., 2001. Constructed wetlands for the treatment of runoff from the Newbury Bypass. *Journal CIWEM*, 15(2), pp.125-129.

Revitt D.M., Shutes R.B.E., Jones R.H., Forshaw M. and Winter B., 2003. Practical experience of the use of vegetated ponds for the treatment of highway runoff. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.19-29.

Scholes L.N.L., Shutes R.B.E., Revitt D.M., Forshaw M. and Purchase D., 1998. The treatment of metals in urban runoff by constructed wetlands. *Sci.Tot.Env.*, 214, pp.211-219.

Scholes L.N.L., Shutes R.B.E., Revitt D.M., Purchase D. and Forshaw M., 1999. The removal of urban pollutants by constructed wetlands during wet weather. *Wat. Sci. Tech.*, 40(3), pp.333-340.

Shutes R.B.E., Revitt D.M., Lagerberg I.M. and Barraud V.C.E., 1999. The design of vegetative constructed wetlands for the treatment of highway runoff. *Sci.Tot.Env.*, 235, pp.189-197.

Shutes R.B.E., Revitt D.M., Mungur A.S. and Scholes L.N.L., 1997. The design of wetland systems for the treatment of urban runoff. *Wat. Sci. Tech.*, 35(5), pp.19-25.

Shutes R.B.E., Revitt D.M., Scholes L.N.L., Forshaw M. and Winter B., 2001. An experimental constructed wetland system for the treatment of highway runoff in the UK. *Wat. Sci. Tech.*, 44(11-12), pp.571-578.

Tucker C.G.J., 1999. An end-of-pipe treatment system for storm drainage systems. *Proc.* Standing Conf. on Stormwater Source Control, Volume XVII, Ed. C.J. Pratt, Coventry University, ISBN 0 905949 80 3.

Whitaker D., Elkin D., Pearson R., Mader S. and Faha M., 2002. Integrating stormwater management and wetlands mitigation in the 'front yard' of the Intel Ronler Acres Campus in Hillsboro, Oregon. *Proc.* 9th Int Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-007-003.pdf).

Wong T. H. F. and Breen P. F., 2002. Recent advances in Australian practice on the use of constructed wetlands for stormwater treatment. *Proc.* 9th Int Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-007-004.pdf).

Wulliman, J.T., Maxwell M., Wenk W.E. and Urbonas B., 1989. Multiple treatment systems for phosphorus removal. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.239-257.

DETENTION BASINS

A number of studies of the performance of detention basins have been conducted in the USA, mainly being concerned with water quality aspects. The City of Austin, Texas, has been the site of monitoring programmes since 1975 (Veenhuis et al., 1989). Of particular interest is the data collected at the Barton Creek Square Mall where a dry basin, with gravel base which filters the outflow, have been monitored.

The dry basin receives the runoff from some 19ha of the total impermeable area at the Mall of 41ha. The basin has a storage capacity equivalent to 15mm rainfall from its catchment and flows leave either through the 900mm depth of sand and gravel bottom via a perforated pipe, or via an overflow, if the basin fills completely. The removal efficiencies of suspended and dissolved material have been determined. Within individual storm events samples were obtained in which the suspended solids concentration in the outflow exceeded that in the inflow in some cases, even when outflow was solely via the bottom of the basin through the perforated pipe. However for dissolved solids, this excedence of inflow concentration by outflow was common throughout the samples in an event. For 36 storms reported in 1982-84, the mean removal efficiency for suspended solids was 78% and for dissolved solids –13%.

Average removal efficiencies of BOD, total phosphorus, TOC, COD and dissolved zinc were between 60-80%. Average loads of total nitrite plus nitrate nitrogen in the outflow were about 110% of that in the inflow, being said to be due to the oxidation and mineralisation of previously deposited material. The results given were for storms during which all outflow passed through the base of the basin before release. It was noted that some re-suspension of previously trapped pollutants occurred, which could pass out of the basin unfiltered during larger storms, when the overflow operated.

The observations from this site lead to new US design recommendations. Where the dry pond was located over an aquifer recharge zone, it was required to be lined to prevent the infiltration of nitrate-rich waters. Clogging of the filter media and problems arising from its renewal resulted in the design guidelines specifying that a sediment trap must precede discharge into the basin.

A second study in the USA was undertaken on a dry basin in Topeka, Kansas (Pope and Hess, 1989). The basin received runoff from a 5ha residential area, where some 49% was impermeable: the maximum depth of storage was some 1.4m and the maximum volume some 4,800m^3. Outflow was via an outlet box with a 100mm outlet and high-level overflow. The water quality sampling over a 14-month period showed that dissolved solids, ammonia plus nitrogen, and TOC had higher output loads on average than discharged into the basin (-78.5, -9.0 and -3.0%, respectively). However the detention efficiencies for a number of other parameters were positive, namely: suspended solids (2.5%); COD (15.5%); nitrite plus nitrate nitrogen (20.0%); ammonia nitrogen (69%); total phosphorus (18.5%); dissolved phosphorus (0%); total lead (66.0%); and total zinc (65.0%).

These studies illustrate the concern that detention basins, if poorly designed, can act as sources of pollutants, transporting or re-suspending material, deposited during previous events. Very little information on the performance of wet and none on dry detention basins was available in the UK up to 1988 (Ellis, 1989). Hall et al.(1993) drew upon overseas experience in their recommendations for design of dry basins for the UK. There is still no known UK data on water quality performance of dry basins.

An interesting alternative form of detention basin has been developed in France, where the substructure of the highway has been similarly used for storage and attenuation of flows with some water quality improvements (Raimbault, 1990; 1993a; 1993b; 1994; 1999). This style of construction, called ‘reservoir’ by the French, may be thought more appropriately described as a tank, as may that incorporating cellular boxes within a liner (Andoh et al., 2000; Andoh et al., 2001). Water quality data for one such reservoir structure over a four-year period showed decreased pollutant concentration in the outflow by 64% for suspended solids and 79% for lead, as compared with a comparable, traditional impermeable surface with positive drainage (Legret et al., 1996).

The introduction of sustainable urban drainage in Scotland led to monitoring of hydraulic performance at Duloch Park, Dunfermline, which is on-going (Jefferies, 2001; Schluter et al., 2002). Two detention basins have been monitored which receive only highway runoff. The flow attenuation is dependent upon the outflow control and the basin design. It has been found that where the outlet control is of a vortex flow type good peak flow reduction is achieved, however where a simple pipe outlet is used the peak reduction is poor. No water quality analyses have been undertaken to date, but visual observations indicate that the basins are effective at trapping coarse/medium sands near to the inlets and other particle sizes across the basins generally. The basins also accumulate wind-blown litter. None of the basins has any form of under-drainage and the bases have become swampy, hampering maintenance.

DETENTION BASIN REFERENCES

Andoh R.Y.G., Faram M.G., Stephenson A. and Kane A.S., 2001. The Hydro integrated system for stormwater management. *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.105-112.

Andoh R.Y.G., Stephenson A. and Kane A., 2000. Sustainable urban drainage using the Hydro Stormcell storage system. *Proc.* Standing Conf. on Stormwater Source Control, Volume XIX, Ed. C.J. Pratt, Coventry University, ISBN 0 905949 88 9.

Ellis J.B., 1989. The development of environmental criteria for urban detention pond design in the UK. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.14-28.

Hall M.J., Hockin D.L. and Ellis J.B., 1993. *Design of Flood Storage reservoirs.* CIRIA, ISBN 0 7506 1057 3.

Jacopin Ch., Bertrand-Krajewski J.L. and Desbordes M., 1999. Characterisation and settling of solids in an open, grassed, stormwater sewer network detention basin. *Wat. Sci. Tech.,*39(2), pp. 135-144.

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme,* Section 3.3 Detention Basins; Section 5.3 Performance Observations – Detention Basins. SNIFFER, Edinburgh, EH3 6RT.

Legret M., Colandini V. and Le Marc C., 1996. Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. *Sci.Tot.Env.*, 189-190, pp.335-340.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Piel C., Perez I. And Maytraud T., 1999. Three examples of temporary stormwater catchments in dense urban areas: a sustainable development approach. *Wat. Sci. Tech.,*39(2), pp.25-32.

Pope L.M. and Hess L.G., 1989. Load-detention efficiencies in a dry-pond basin. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.258-267.

Raimbault G., 1990. Reservoir structures: an extension of the possibilities of porous pavements. *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.833-838.

Raimbault G., 1993a. French researches on reservoir structure hydraulics. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, Canada, ISBN 1 55056 254 1, pp.1121-1126.

Raimbault G., 1993b. New designs for reservoir structures. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, Canada, ISBN 1 55056 254 1, pp.1127-1132.

Raimbault G., 1994. French developments in reservoir structures. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume VIII, ISBN 0 905949 24 2.

Raimbault G., 1999. French developments in reservoir structures. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.212-228.

Schluter W., Spitzer A. and Jefferies C., 2002. Performance of three sustainable urban drainage systems in east Scotland. *Proc.* 9th Int Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-004-004.pdf).

Veenhuis J.E., Parrish J.H. and Jennings M.E., 1989. Monitoring and design of stormwater control basins. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.224-238.

DETENTION PONDS

An early study in the USA by Hvitved-Jacobsen et al. (1984) commented that the then design of ponds was limited to meeting hydraulic criteria and that very little was then known about water quality aspects. Their study aimed to assess the removal efficiencies of a pond in Orlando, Florida, as a means of developing more general US design criteria. They found that about 99% of the total phosphorus during seven years usage had accumulated in the sediments at the bottom of the pond. Also, some 85-90% of the total nitrogen input had been removed, probably by denitrification. They concluded that a permanent oxidised sediment layer of some depth is a key factor in good nutrient removal efficiencies. Therefore, a shallow pond with sediments dominated by inorganic matter, providing good oxygen conditions at the water-sediment interface, seemed important.

In the UK, Hall et al. (1993) provided guidance on the design of detention ponds which included both hydraulic and water quality criteria. Many ponds exist which were designed without regard to water quality criteria, being seen as solely flood control devices. One such pond built in 1987, the Stenton Pond in Fife, was monitored between April 1998 and February 1999 (Jefferies, 2001; Macdonald et al., 1999). Results published for an event of 18.2mm lasting some 12 hours showed that for total suspended solids, the event mean concentration between inlet and outlet in the pond increased by 0.3%, however the load decreased by 82.5%. Similar comparisons for BOD gave both EMC and load decreasing by 45.2% and 90%, respectively, whilst ammoniacal nitrogen increased by 136% (EMC) and decreased by 69%(load). Other storm events showed reductions of all three determinands and weekly baseline sampling indicated all three lower at the outlet. This suggested that, whilst there may not be an immediate improvement in water quality during an event, the pond probably effects improvement over a longer time.

The loads of heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) were all much reduced at the oulet, ranging from 74-93%. The EMC for copper alone showed a slight increase at the outlet, otherwise EMCs were also reduced for the other heavy metals (37.6-69%). Sediment analysis showed that metals were accumulating on the pond floor (Heal, 2000). After 12 years, Pb and Ni had reached concentrations worthy of concern and Cd and Cu were close to such levels.

The introduction of sustainable urban drainage in Scotland led to monitoring of hydraulic performance of two detention ponds at Duloch Park, Dunfermline, which is on-going (Schluter et al., 2002). Some preliminary data is reported which shows good reduction through the ponds of suspended solids, BOD and ammoniacal nitrogen concentrations, but far less improvement in COD. Other observations from this site and ponds at some six other locations in Tayside are detailed by Jefferies et al. (2001), with comments on water and sediment qualities and habitat. This latter aspect of habitat and pond management has been discussed by Jones (2002) and guidance given on timings and the nature of maintenance operations.

A study in Australia of a 1.5ha detention pond and of a nearby 0.45ha constructed wetland, both receiving stormwater inflow from two recently established residential developments, has reported significantly better performance from the wetland, with reference to the mean removal efficiency of faecal coliforms (Bavor et al., 2001). Comparison of the particle size distributions of sediments within each system showed that the detention pond contained considerably more fine particles (<2um) and the wetland a high proportion of particles greater than 62um in size. The sampling regime did not identify whether the particle sizes entering each system with the stormwater were significantly different, but did conclude that faecal coliforms, nitrogen and phosphorus in the stormwater were largely associated with the fine particle fraction. It might be inappropriate to select a pond system in a catchment where stormwater runoff is likely to transport a high clay fraction.

The results of a 33-month study are used by Revitt et al. (2003) to identify relevant guidelines pertaining to the design, construction and operation/maintenance of vegetated ponds for the treatment of highway runoff. Large variability in the efficiency of removal of listed determinands, based upon grab samples, raised concern about using this type of sampling approach. In addition to grab samples obtained at the inlets and oulets during wet and dry weather conditions on a horizontal, sub-surface flow, constructed wetland and on a vegetated balancing pond, automatically controlled storm event samplea were obtained from the constructed wetland. Revitt et al. comment on critical design aspects and of appropriate maintenance, which affect sustained, optimal performance of these systems.

DETENTION PONDS REFERENCES

Bavor H.J., Davies C.M. and Sakadevan K., 2001. Stormwater treatment: do constructed wetlands yield improved pollutant management performance over a detention pond system? *Wat. Sci. Tech.*, 44(11-12), pp.565-570.

Bray R.J., 2000. Design of the 'treatment train' at Hopwood Park MSA M42 . *Proc.* Standing Conf. on Stormwater Source Control, Volume XIX, Coventry University, ISBN 0 905949 88 9.

Daukas P., Lowry D. and Walker W.W., 1989. Design of wet detention basins and constructed wetlands for treatment of stormwater from a regional shopping mall in Massachucetts. In: *Constructed Wetlands for Wastewater Treatment,* Ed. D.A. Hammer, Lewis Publishers, ISBN 0 87371 184 X, pp.686-694.

Ellis J.B., 1989. The development of environmental criteria for urban detention pond design in the UK. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.14-28.

Ellis J.B., 1991. General issues of design, operation and maintenaance of stormwater control systems to meet water quality criteria. *Proc.* Standing Conf. on Stormwater Source Control, Volume III, Coventry University, ISBN 0 905949 15 3.

Ellis J.B., 1994. Highway discharge quality: pollution potential and treatment. *Proc.* Standing Conf. on Stormwater Source Control, Volume VII, Coventry University, ISBN 0 905949 21 8.

Grizzard T.J., Randall C.W., Weand B.L. and Ellis K.L., 1986. Effectiveness of extended detention ponds. In: *Urban Runoff Quality – Impact and Quality Enhancement Technology*, Eds. B. Urbonas and L.A. Roesner, ASCE, ISBN 0 87262 577 X, pp.323-337.

Hall M.J., Hockin D.L. and Ellis J.B., 1993. *Design of Flood Storage Reservoirs.* CIRIA, ISBN 0 7506 1057 3.

Hartigan J.P., 1989. Basis for design of wet detention basin BMPs. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.122-144.

Heal K., 2000. SUDS ponds in Scotland - performance outcomes to date. *Proc.* Standing Conf. on Stormwater Source Control, Volume XX, Coventry University, ISBN 0 905949 99 4.

Heal K., 2000. Sediment quality in sustainable urban drainage structures in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Hvitved-Jacobsen T., 1990. Design criteria for detention pond quality. In: *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined sewer Technology,* Ed. H.C. Torno, ASCE, ISBN 0 87262 759 4, pp.111-130.

Hvitved-Jacobsen T, Yousef Y.A., Wanielista M.P. and Pearce D.B., 1984. Fate of phosphorus and nitrogen in ponds receiving highway runoff. *Sci.Tot.Envi.*, 33, pp. 259-270.

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme,* Section 3.6 Retention*(sic)* Ponds; Section 5.7-5.10 Performance Observations – Pond systems; Section 6.2 Algal studies at DEX ponds. SNIFFER, Edinburgh, EH3 6RT.

Jefferies C., Heal K.V. and B'Arcy B.J., 2001. Performance of sustainable urban drainage systems for urban runoff. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.159-169.

Johnstone C., 2000. Algal stress in urban ponds – an outline of a new investigation. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Jones M., 2002. Managing SuDS ponds containing rare species. *Proc.* Standing Conf. on Stormwater Source Control, Volume XXIII, Coventry University, ISBN 1 903818 26 5.

Krishnappen B.G., Marsalek J., Watt W.E. and Anderson B.C., 1999. Seasonal size distributions of suspended solids in a stormwater management pond. *Wat. Sci. Tech.,*39(2), pp. 127-134.

Lansdown R.V. and Topping D., 1994. Policy and practice for collection, transport and treatment of highway runoff . *Proc.* Standing Conf. on Stormwater Source Control, Volume VII, Coventry University, ISBN 0 905949 21 8.

Macdonald K., 2000. Monitoring the effectiveness of SUDS in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Macdonald K., Jefferies C. and Dring D., 1999. An assessment of a stormwater pond in the Scottish climate. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.882-889.

Marsalek P.M., Watt W.E., Marsalek J. and Anderson B.C., 2003. Winter operation of an on-stream and stormwater management pond. *Wat. Sci. Tech.*, 48 (9), pp. 133-144.

Martin E.H., 1989. Mixing and residence times of stormwater runoff in a detention system. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.164-179.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

McLean N., 1998. *The Effectiveness of Two SUDS Ponds Serving Highway Runoff.* Unpublished MSc Dissertation, University of Abertay, Dundee.

McLean N., 2000. The performance of two SUDS ponds serving highway runoff. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Mulhern P.F. and Steele T.D., 1989. Water quality ponds – are they the answer? In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.203-213.

Oldham J., 1994. Ssustainable developments for large, mixed-use developments . *Proc.* Standing Conf. on Stormwater Source Control, Volume IX, Coventry University, ISBN 0 905949 23 3.

Pettersson T.J.R., 1998. Water quality improvement in a small stormwater detention pond. *Wat. Sci. Tech.*, 38(10), pp.115-122.

Revitt D.M., Shutes R.B.E., Jones R.H., Forshaw M. and Winter B., 2003. Practical experience of the use of vegetated ponds for the treatment of highway runoff. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.19-29.

Rushton B., 2002. Enhanced parking lot design for stormwater treatment. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-002-002.pdf).

Sargent R., 1995. Recent developments in source control in the Forth RPB Region. *Proc.* Standing Conf. on Stormwater Source Control, Volume XII, Coventry University, ISBN 0 905949 51 X.

Schluter W., Spitzer A. and Jefferies C., 2002. Performance of three sustainable urban drainage systems in east Scotland. *Proc.* 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-004-004.pdf).

Schueler T.R. and Helfrich M., 1989. Design of extended wet pond systems. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.180-202.

Scholz M., 2003. Design, operation and maintenance optimisation of sustainable urban stormwater ponds. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.31-41.

Spitzer A., 2000. Post construction monitoring at DEX – first results. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Spitzer A. and Jefferies C., 2003. Hydraulic and water quality performance of two SUDS ponds and treatment trains in the Dunfermline Eastern Expansion Area – a field and modelling study. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.159-170.

Stanley D.W., 1996. Pollutant removal by stormwater dry detention pond. *Water Environment Research*, 68(6)

Tucker C.J., 1992. Design of a combined flood control and pollution treatment pond, Pershore, Worcestershire. *Proc.* Standing Conf. on Stormwater Source Control, Volume V, Coventry University, ISBN 0 905949 17 X.

Watt W.E. and Marsalek J., 1994. Comprehensive stormwater pond monitoring. *Wat. Sci. Tech.,* 29(1-2), pp.337-345.

Watt W.E., Marselek J. and Anderson B.C., 1999. Stormwater pond perceptions vs. realities: a case study. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.105-122.

Wu J.S., Holman B. and Dorney J., 1989. Water quality study on urban wet detention ponds. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.280-289.

Wu J.S., Holman R.E. and Dorney J.R., 1996. Systematic evaluation of pollutant removal by urban wet detention ponds. *Journal Env. Eng*., 122(11), pp.983-988. ISSN 0733-9372.

Wulliman, J.T., Maxwell M., Wenk W.E. and Urbonas B., 1989. Multiple treatment systems for phosphorus removal. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.239-257.

Vikstrom M., 2003. Modelling of temperature effects on removal efficiency and dissolved oxygen concentrations in stormwater ponds. *Wat. Sci. Tech.*, 48 (9), pp. 145-154.

FILTER DRAINS

Early research was conducted by Perry and McIntyre (1986) on a filter drain on the M1 motorway near Luton. Comparison was made between the water quality performance of a filter drain, a sedimentation tank and a lagoon. The filter drain effluent pollutant concentrations were found to be significantly lower for individual storms as compared with untreated highway runoff and with passage through the sedimentation tank. One storm event reported showed that, comparing the filter drain with untreated runoff, the effluent total suspended solids and oil concentrations were 28 and 92mg/l; and 3.7 and 30mg/l, respectively. An estimate of the mean annual removal efficiencies for total suspended solids, some heavy metals determinands, COD and oil indicated that the treatment was achieved best in the order lagoon, filter drain and then sedimentation tank. The predicted annual performance of the lagoon and of the filter drain were very similar, but it was noted that the removal efficiencies vary considerably between storms and between seasons.

In the USA in the late 1990s research was undertaken on the water quality improvement capability of filter drains at a site on the Millcreek Expressway in Cincinnati, Ohio (Sansalone, 1999). The lateral, sheet flow runoff from a 15m long x 20m wide section of highway pavement was intercepted by a 600mm wide strip of porous pavement, discharging into a 300mm wide x 900mm deep filter drain below. The porous pavement was 100mm thick and, apart from infiltrating the runoff, filtered particulate matter from the inflow. Waters could infiltrate the adjacent soil or be discharged from the filter media via a pipe, the flow from which was monitored and sampled. The average daily vehicle usage of the expressway was some 140,000 cars and 15,000 commercial vehicles.

Laboratory studies were conducted to determine the sorption capacity of the porous pavement/filter drain system, with a definition of exhaustion being defined as when 90% of the influent concentration appeared in the effluent. The results determined are indicated in the table below.

mg sorbed/mg of porous pavement and filter drain media				
Zn	**Cd**	**Cu**	**Pb**	**Fractionation**
11839	522	>>2045	>>2785	Dissolved
633	33	2965	1202	Particulate-bound

Two-years of site data were used to compute the event mean concentrations for dissolved and particulate-bound heavy metals. The EMC values were converted into mass loadings as shown below.

	Dissolved EMCs (ug/l)				**Particulate-bound EMCs (ug/l)**			
Metal	Zn	Cd	Cu	Pb	Zn	Cd	Cu	Pb
EMC	3890.5	9.2	82.7	16.4	440.2	2.8	52.7	51.5
	Annual dissolved mass flux (mg/m^2 of pavement area)				**Annual particulate-bound mass flux (mg/m^2 of pavement area)**			
Metal	Zn	Cd	Cu	Pb	Zn	Cd	Cu	Pb
Mean	2582	6.1	54.8	10.9	291.8	1.86	34.9	34.1
	Annual dissolved mass loading (mg)				**Annual particulate-bound mass loading (mg)**			
Metal	Zn	Cd	Cu	Pb	Zn	Cd	Cu	Pb
Mean	38730	92	822	164	4377	28	524	512

The volume of an event to infiltrate the adjacent soil varied with storm characteristics and antecedent conditions, with reported percentage infiltration volumes ranging from around 10 – 32% of inflow volume. The heavy metal and total suspended solids removal efficiency results showed that the filter drain system was an effective trap, mainly in the porous pavement, however the metal element removal efficiencies were somewhat lower than the laboratory results. Field observations for dissolved metals showed removal efficiencies for Zn >95%; Cu >85%; Cd >80%; and Pb varying between 70-95%. The equivalent results for the particulate-bound metals were Cu and Pb 85-95%; Zn 75-95%; and Cd 79-90%.

Concern was expressed about the potential for clogging of the system and the effect this would have on the design life of 10 years. Research is continuing.

Further UK research on filter drains was not conducted until 1999, when the promotion of Sustainable Urban Drainage Systems prompted the instrumentation of a filter drain in Lang Stracht, Aberdeen (Wigham, 2000). The filter drain is some 750m long, receives inflows from 44 road gullies, and has 21 inspection chambers and 11 catch pits. The filter drain discharges into the Denburn via a perforated pipe, which is positioned with its invert 0.5m above the base of the drain. The drain is surrounded by single-sized filter material, within a geotextile wrapping, and the top of the construction is covered with 150mm soil. The drain flows and the depth of water in the filter material have been recorded at two catch pits along the filter drain and a number hydrographs and depth-time plots obtained (Jefferies, 2001). The percentage runoff, outflow from the perforated drain, ranged from 0.8 –196%, with a mean value of some 42%. Three events over 100% were due to snowmelt augmenting inflows and to difficulties of separating events. The lag time between peak rainfall intensity and peak flow varied from zero to some 11.5 hours, with a mean value of around 3.5 hours. Clearly the antecedent conditions have influenced the filter drain's response. Monitoring is on-going.

FILTER DRAIN REFERENCES

Cooper R.A., 2002. French drains to mitigate groundwater in residential araes. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-012-004.pdf).

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme,* Section 3.4 Infiltration Systems; Section 5.4 Performance Observations – Filter Drains. SNIFFER, Edinburgh, EH3 6RT.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Perry R. and McIntyre A.E., 1986. Impact of motorway runoff upon surface water quality. *Proc.* Conf. on the Effects of Land Use on Fresh Water, pub. Ellis Horwood, ISBN 0745800548.

Sansalone J.J., 1999. In-situ performance of a passive treatment system for metal source control. *Wat. Sci. Tech.,*39(2), pp. 193-200.

Schluter W., Spitzer A. and Jefferies C., 2002. Performance of three sustainable urban drainage systems in east Scotland. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-004-004.pdf).

Wigham J., 2000. Investigating the effectiveness of in-ground SUDS in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

GENERAL PLANNING, DESIGN, OPERATION AND MAINTENANCE

Apostolaki S., Jefferies C. and Souter N., 2001. Assessing the public perception of SUDS at two locations in eastern Scotland . *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.28-37.

Argue J.R., 2001. Recent developments in Australian 'source control' technology and practice. *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.120-146.

Argue J.R., Boubli D. and Coombes P.J., 2003. Innovative water cycle design/maintenance at a difficult site: Heritage Mews in Western Sydney, Australia. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.121-134.

Balmforth D., Percy C. and Bray R.J., 2003. A risk assessment approach to the adoption of sustainable drainage. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.205-214.

Berry C., 2000. Practical application of SUD system. *Proc.* Standing Conference on Stormwater Source Control, Volume XX, Coventry University, ISBN 0 905949 99 4.

Bray R.J., 1999. Design experience of source control treatment systems on commercial developments. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume XVII, ISBN 0 905949 80 3.

Bray R.J., 2000. Design of the 'treatment train' at Hopwood Park motorway service area on the M42 . *Proc.* Standing Conf. on Stormwater Source Control, Volume XIX, Coventry University, ISBN 0 905949 88 9.

Bray R.J., 2001. Maintenance of sustainable drainage – experience on two EA demonstration sites in England. *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.93-104.

BRE, 1991. Soakaway Design. *Digest 365*, Building Research Establishment, ISBN 0 85125 502 7

Carroll B., Hopkins A. and Howes H.R., 2001. Strategic planning and the implementation of sustainable drainage. *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.3-9.

CIRIA, 2000. Sustainable Urban Drainage Systems: Design Manual for Scotland and Northern Ireland. *CIRIA C521,* Construction Industry Research and Information Association, London, ISBN 0 86017 521 9.

CIRIA, 2000. Sustainable Urban Drainage Systems: Design Manual for England and Wales. *CIRIA C522,* Construction Industry Research and Information Association, London, ISBN 0 86017 522 7.

CIRIA, 2001. Sustainable Urban Drainage Systems: Best Practice Manual. *CIRIA C523,* Construction Industry Research and Information Association, London, ISBN 0 86017 523 5.

D'Arcy B. and Roesner L.A., 1999. Scottish experiences with stormwater management in new developments. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.78-92.

Echols S.P., 2003. A new slit-flow sustainable urban drainage strategy. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.113-119.

Ellis J.B., D'Arcy B.J. and Chatfield P.R., 2002. Sustainable urban drainage systems and catchment planning. *Journal CIWEM* , 16, November, pp.286-291.

EPA, 1980. Porous Pavement: Phase I - Design and Operational Criteria. *Report EPA 600/2 80 135*, US Environmental Protection Agency. http:www.epa.gov/ednnrmr/repository/abstrac2/abstra2.htm.

Fenner R.A., 2001. Is urban drainage sustainable without improving maintenance. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.81-92.

Hall M.J., Hockin D.L. and Ellis J.B., 1993. *Design of Flood Storage reservoirs.* CIRIA, ISBN 0 7506 1057 3.

Harris S. and Worrell P., 2003. The role of ecology in the planning for sustainable drainage systems. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.43-50.

Heal K.V. and Drain S.J., 2003. Sedimentation and sediment quality in sustainable urban drainage systems. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.215-225.

HR, 1982. Reduction of Flow in Urban Drainage Systems. *Report EX1049*, HRWallingford

Jones M. and Fermor P., 2001. Sustainable drainage systems – maximising the opportunities to meet bio-diversity targets. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.38-46.

Makropoulos C.K., Butler D. and Maksimovic C., 2001. Elements of a decision support system for sustainable urban drainage. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.71-80.

May D., Hunt G. and Jennings P., 2003. Henry Box Site, Witney – drainage solution. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.63-70.

Powell A., Biggs J., Williams P., Whitfield M., Logan P. and Fox G., 2001. Bio-diversity benefits from SUDS – results and recommendations. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.47-57.

Pratt C.J., 1999. Design guidance for porous/permeabble pavements. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.196-211.

Ross C., 2001. Newcastle Great Park: the use and development of sustainable urban drainage systems within the site. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.17-27.

Schofield D. and Stevens D., 2003. Sustainable drainage systems - design versus implementation: a potential conflict. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.193-203.

Schueler T.R., 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. *Publication No. 87703*, Metropolitan Washington Council of Governments, Washington, DC 20006, USA.

Smith D.R., 2000. *Permeable Interlocking Concrete Pavements.* Interlocking Concrete Pavement Institute, Washington, DC 20005-6542, USA.

Stovin V.R. and Swan A.D., 2003. Application of a retrofit SUDS decision-support framework to a UK catchment. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.171-180.

Townsend M. and Paul P., 2003. Sustainable drainage systems (SUDS) – overcoming the national problems in England and Wales. . *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.13-17.

Wild T.C., McKissock G., D'Arcy B.J., Shaffer P. and Elliott C., 2003. An evaluation of SUDS guidance in Scotland. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.1-12.

Wilson S., 2003. Structural design of plastic stormwater drainage tanks. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.227-236.

Woods Ballard B. and Malcolm M., 2003. Whole life costing for sutainable drainage schemes. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.181-192.

WRc, 1998. Control of Pollution from Separately Sewered Areas: Manual of Good Practice. *Report No. PT 2039*, WRc Swindon, SN5 8YF.

INFILTRATION PITS AND TRENCHES

Despite the extensive use that has been made of infiltration pits, or soakaways as they are commonly known in the UK, over decades, there has been only limited examination of their performance. There has been widespread concern about the hydraulic performance of these devices, with general expectation that failure through blockage by silts and debris, would necessitate reconstruction within a limited time period. However in terms of the millions of infiltration pits in existence, few, if any, failures have warranted reporting in the scientific and technical press.

In recent years there has been growing concern about the impact on groundwater quality which infiltration waters might have and, associated with the development of the concept of Sustainable Urban Drainage Systems, has gone the introduction of specific legislation and guidelines to protect groundwater quality. Again, despite the concerns, there has been very little investigation of the pollutional impact of infiltration devices on soil and groundwater.

Other European countries have had long experience of the use of infiltration devices and were first to provide data on their performance. Holmstrand (1984) provided details of trench systems used in Sweden on individual properties and as interlinked systems with development. Two aspects of the monitored performance were particularly noteworthy. The Swedish sites of the devices were reported to be in soil of a boulder clay, impermeable nature. In itself this made the choice of infiltration trenches seem unlikely and possibly make the use of the word infiltration somewhat misleading. The benefit from the use of the devices was in maintaining an adequate level of soil moisture, preventing consolidation of the soil with unacceptable settlement of buildings. Such settlement had occurred at one site due to the paving over of the site, resulting in limited soil moisture recharge, before the infiltration trench approach was adopted.

From monitoring of the water balance at a residential development in Gothenburg, equipped with infiltration trenches, Holmstrand reported that up to two-thirds of the water discharged to the trenches in a year was not passed to the outfall from the system. It was stated that the soil conditions prevented downward infiltration into the subsoil and that the waters were lost by evaporation from the soil and by plant transpiration. This mechanism for loss has never been included within UK design or considered within the operations of infiltration devices. The redrafting of the Building Research Digest on Soakaways (1991) did make recommendations for the use of trench systems, on the grounds of infiltration and cost of material efficiencies, but did not consider the evaporation loss mechanism. In the absence of detailed knowledge of infiltration system performance, BRE 365 (1991) adopted a very conservative approach in the design methodology, until appropriate factors of safety could be identified and applied.

Minagawa (1990) reported field observations of the silting of sedimentation/infiltration chambers and of porous pipes within interconnecting infiltration trenches over some five years at three residential areas in Tokyo. The infiltration capacity of the chambers was effectively reinstated after removal of 150mm of the crushed rock and deposits at the bottom of the chambers. Little change in the infiltration capacity of the porous pipe/trench systems was observed, presumably because of the effective operation of the chambers in limiting the movement of silts out of the chambers.

The move to extend the range of shapes of infiltration system in the UK, beyond the cylinder or cube envisaged in earlier design guides such as BRE Digest 151, has led to a limited usage of trenches, as at Shire Hall, Reading (Pratt, 1995), and to other shaped devices. Nixon (1990) detailed the design of a drainage blanket system, installed below traditional block paved roadways and parking areas, into which the system of roof and gully drains discharged. The site in Cirencester was underlain by well-draining soils and the drainage approach had been chosen because the off-site sewers were overloaded, and the blanket design was used because there were Roman remains on site which required no excavation below one metre depth, in order to preserve them.

In the late 1990s pervious pavements, particularly those surfaced with small element, porous and permeable concrete blocks, began to be widely constructed. By the beginning of 2000 some 350,000m^2 of this type of surfacing had been installed over free-draining aggregate sub-base stone. Some two thirds of this area was underlain by a permeable geotextile, allowing infiltration of stormwater into the subgrade. One such site was reported by Carpenter (2000) at Bognor Regis where soil infiltration rate was rather low and which would not generally be thought suitable for stormwater infiltration. Unlike the Swedish experience (Holmstrand, 1984), the stormwater infiltrates the subgrade at the Bognor Regis site, albeit slowly, where the storage capacity of the sub-base stone is used to balance inflow and outflow.

The need for concern for the potential for contamination of groundwater cannot be understated. A study of the impact of highway runoff on soil and groundwater conducted in Switzerland is informative in the context of stormwater infiltration below such surfaces (Mikkelsen et al., 1997). Two sites were studied. At the first one, highway runoff was discharged via a pipe from a kerb inlet gully into a depression on the grass-covered verge. The road carried some 37,000 vehicles per day in 1993 and the drainage had been in service since at least 1959. The second site was located in an industrial city where highway runoff was discharged into 3m deep soakaways. Traffic density was some 2300 vehicles per day in1990 and the three soakaways were constructed in 1949 and 1982.

At the first site high concentrations of heavy metals, a number of polyaromatic hydrocarbons and adsorbed organically bound halogens were found in the upper 500mm of runoff sludge and soil, but the concentrations decreased rapidly to background levels farther down. At the second site the runoff sludge was some 200mm deep and traces of contamination were not found farther than another 200mm below that level. Similar findings were reported for two soakaways investigated at Brandon, Suffolk (Pratt, 1995, 1996). High concentrations of total organic carbon and heavy metals were associated with fine, organic material accumulation in the first 400mm of sediment in the base of the soakaways. Below 400mm the pollutant levels appeared to approach those of background levels.

For both the Swiss and UK sites, it was suggested that the formation, and continued presence, of a layer of sludge at the base of the soakaway is important in retaining pollutants by filtration and sorption, resulting in significant build-up of copper, zinc, cadmium, PAHs and halogens in that layer. It was concluded at the Swiss sites that 'the leaching of heavy metals is limited and that contamination of potable groundwater with metals is of little practical concern within a reasonable time frame. This conclusion also holds for the PAHs which are known to adsord well in soil systems, and for the type of pollutants included in the organically bound halogen analysis.'

Mikkelsen et al. (1997) went on to say, 'however, it is stressed that soluble components such as pesticides, de-icing salts etc. may pass directly through the infiltration systems. Thus, an assessment of possible groundwater contamination with such substances demands other methods of investigation, including mass balances, in situ measurement of concentrations in soil solutions, and assessment of the potential degradation of pollutants during passage of infiltration systems.' These statements highlight the possible dangers from dissolved pollutants and from liquids in transport on highway surfaces drained to infiltration devices with the potential to contaminate groundwater.

Long-term maintenance is a concern with infiltration systems. Observations from Tokyo, Japan (Haneda et al., 1996) suggest that such systems may operate satisfactorily with significant benefits in the reduction of direct discharges to watercourses. A key factor in such continued satisfactory operation is the design, operation and maintenance of inlet structures to the underground devices. Where roof waters discharge into sediment/debris traps, the underground, stone-filled trenches retained their 'infiltration capacity as it had been at the beginning after 11 years of service'. However where the waters entered the system from paved surfaces, carrying considerably more silt and debris, the infiltration rates fell rapidly due to blockage. This confirmed the previous findings by Minagawa (1990). Excavations of infiltration trenches revealed less silt within the stone fill and on the base of the trenches than expected. Built around 1977, before the widespread use of geotextiles, little soil was found to have entered the stone fill from the side-walls, although tree roots were found. Extensive use was made on site of U-shaped collecting channels and of silt traps: these played an important role in the pre-trapping of materials before entry to the infiltration trenches. BRE365 (1991) suggests the use of wet sumps and T-piece inlets to distributor pipes in trench systems, in order to limit conveyance of silts into the trench system.

In Denmark an important long-term investigation of infiltration trench performance has been established in a densely built-up area of Copenhagen (Warnaars at al., 1999). Some 600m^2 of roof and paved surface area discharges to twin infiltration trenches, via a common manhole in which flow monitoring equipment is installed. The system was constructed in 1994 and the period of observations reported ended in June 1997. The in situ soil permeability was determined for the trenches in 200mm increments throughout the 0.8m overall depth. Variation was evident with both depth and between the two trenches, despite them being only 7m apart: one trench had an average soil infiltration rate for the side walls of 2.2×10^{-6} m/s, whilst the second was some ten times less. Over the observation period the soil infiltration rate appeared to decrease from 30-70%, however this assessment was made for a limited number of events. It was pointed out that this decrease was less than the difference in initial value between the two trenches (a factor of 10) and would be less than the uncertainty normally expected in the determination of soil infiltration rates when limited time and money were invested in the ground investigation.

To guarantee against flooding, the top of both trenches were not higher than the basement level in adjacent buildings and each trench was equipped with an overflow at that level into a municipal sewer. The storage capacity of the trenches was exceeded seven times in the observation period ($2^3/_4$ years) and the water level caused overflow during 21 days. Even had there been no overflow, it was stated that no single event would have caused severe problems. Furthermore, the performance was generally deemed satisfactory and it was thought that the infiltration of stormwater, even in soil of low permeability, in central urban areas was of greater potential than previously anticipated. Other periods of data collection are planned after 5 and 10 years of operation.

Two recent studies, one on-going, have addressed the need for field observations in the UK of the performance of infiltration systems. One study at Wallingford, focused on the hydraulic performance of perforated concrete ring soakaways (Abbott at al., 2000; Abbott and Comino-Mateos, 2001); the second in Aberdeen aims to monitor both hydraulic and water quality aspects (Jefferies, 2001; Kelso et al., 2000). The Wallingford study illustrated the difficulties existing in the determination of an appropriate design soil infiltration rate. Initial soil infiltration rates were not determined on the full depth of the proposed soakaway, which may explain why the observed performance reflected an infiltration rate some 10 times less than predicted. Observations of the actual infiltration from the soakaway, occurring within 24-hour periods during different storm events, showed values of 6.4-8.9% of fill volume instead of the 50% recommended by BRE and CIRIA design approaches, despite similar maximum depths of filling. This variation was in a short period of a year and does not reflect the long-term changes in infiltration rate, expected with silt and debris blockage, and resulted in times to empty for the soakaway of 2-3 weeks. Despite this, the soakaway was not observed to overflow, which indicates that such systems can function satisfactorily with much longer emptying periods (Abbott and Comino-Mateos, 2001).

The Aberdeen study is based upon a purpose-built research infiltration trench. Quantity and water quality of the inflow are being measured and any reduction in infiltration rate and any dissolved pollutant dispersion will be monitored.

A review of the performance of a range of infiltration systems over a 20-year period at Akishima-shi, Tokyo, is given by Imbe et al. (2002). The paper provides a comparison of performance with an adjacent district with traditional pipe drainage. The results provided for the percentage discharges off-site from 109 rainfall events, which produced either >30mm or had a peak intensity >20mm/h, over a 20-year period was around 14% for the infiltration systems and some 59% from the traditional area (Note. There is some discrepancy between the text and Table 2). The performance of the two drainage systems under typhoon conditions from September 2001 are also reported: the typhoon runoff lasted some 35 hours and produced 220mm, from which the infiltration system discharge only 13% and the traditional system 79%! A water balance over the period 1996-2000 for the two catchments reveals the figures given in the table below. The authors report that there has been no 'significant degradation in the performance of the infiltration system… over the past 20 years.'

Average annual rainfall,	Catchment	Groundwater recharge		Surface runoff		Evapo-transpiration	
mm		mm/year	%	mm/year	%	mm/year	%
1,647	Infiltration	751	43	161	9	735	48
	Traditional	464	27	660	39	524	34

INFILTRATION PITS AND TRENCHES REFERENCES

Abbott C.L. and Comino-Mateos L., 2001. In situ performance monitoring of an infiltration drainage system and field testing of current design procedures. *Journal CIWEM*, 15(3), pp.198-202.

Abbott C.L., Comino L. and Angood C., 2000. Monitoring performance of infiltration drainage systems. *Report SR569*, HR Wallingford.

Argue J., 1994. Multi-objective stormwater source management practices for arid zone residential developments. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume VIII, ISBN 0 905949 24 2.

Argue J., 1998. Australian practices in stormwater management revisited. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume XV, ISBN 0 905949 64 1.

Balades J.D. and Chantre P., 1990. Urban storm drainage and compensating techniques: experience in Bordeaux (France). *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.777-782.

Balades J.D., Bourgogne P., Madiec H. and Teniere C., 1993. Assessment of reduction in pollution flow using various compensating techniques. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, USA, pp.1163-1168.

Barraud S., Gautier A., Bardin J.P. and Riou V., 1999. The impact of intentional stormwater infiltration on soil and groundwater. *Wat. Sci. Tech.*, 39(2), pp.185-192.

Borges de Souza V.C., Goldenfum J.A. and Barraud S., 2002. An experimental and numerical study of infiltration trenches in urban runoff control. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-012-001.pdf).

Carpenter V., 2000. Sustainable Urban Drainage Systems: Bognor Regis Sports Centre – Case Study. *Proc.* Standing Conf. on Stormwater Source Control, Volume IXX, Coventry University, ISBN 0 905949 88 9.

Chocat B., Bardin J.P. and Gautier A., 1999. Filtration devices for urban drainage: 50-year experience in Lyons. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.181-195.

Fujita S., 1994. Japanese experimental sewer system and the many source control developments in Tokyo and other cities. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume VIII, ISBN 0 905949 24 2.

Haneda M., Kagawa A. and Maruyama K., 1996. Study on durability of underground infiltration facilities through long-term survey. Proc. 7th Int. Conf. on Urban Storm Drainage, Hannover, Germany, pp.599-604.

Harrington B.W., 1989. Design and construction of infiltration trenches. In: *Design of Urban Runoff Quality Controls,* Eds. L.A. Roesner, B. Urbonas and M.B. Sonnen, ASCE, ISBN 0 87262 695 4, pp.290-306.

Holmstrand O., 1984. Infiltration of stormwater: research at Chalmers University of Technology, results and examples of application. In: Planning and Control of Urban Storm Drainage, Eds. P. Balmer, P-A Malmqvist and A. Sjoberg, ISBN 91 7032 128 0, pp.1057-1066.

Imbe M., Okui H., Hashimoto C. and Musiake K., 2002. Monitoring and analysis of implemented infiltration system over past 20 years. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-009-003.pdf).

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme,* Section 3.4 Infiltration Systems; Section 5.11 Performance Observations – A soakaway study. SNIFFER, Edinburgh, EH3 6RT.

Kelso T., Orr D. and Pokrajac D., 2000. Field monitoring of soakaway performance. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Koyama T. and Fujita S., 1990. Pollution abatement in Tokyo "ESS". In: *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined sewer Technology,* Ed. H.C. Torno, ASCE, ISBN 0 87262 759 4, pp.245-267.

Leeson T., 1999. Ravenswood: sustainable urban drainage – case study of a housing development in England. *Proc.* Standing Conf. on Stormwater Source Control, Volume XVIII, Coventry University, ISBN 0 905949 83 8.

Malmquist P-A. and Hard S., 1981. Groundwater quality changes caused by stormwater infiltration. In: *Urban Stormwater Quality, Management and Planning*, Ed. B.C.Yen, Water Resources Pub., Littleton, CO 80161, USA, pp.89-97.

Mikkelsen P.S., Hafliger M., Ochs M., Jacobsen P., Tjell J.C. and Boller M., 1997. Pollution of soil and groundwater from infiltration of highly contaminated stormwater – a case study. *Wat. Sci. Tech.,* 36 (8-9), pp.325-330.

Mikkelsen P.S., Weyer G., Berry C., Walden Y., Colandini V., Poulsen S., Grotehusmann, D. and Rohlfing, R., 1994. Pollution from urban stormwater infiltration. *Wat. Sci. Tech.,* 29(1-2), pp.293-302.

Minagawa K., 1990. The storm water infiltration system in housing complexes and the follow-up survey. In: *Drainage Systems and Runoff Reduction,* Eds. Y. Iwasa anfd T. Sueishi, (Proc. 5th Int. Conf. on Urban Storm Drainage, Vol.2), Osaka, Japan, pp. 771-776.

Niemczynowicz J., 1990. Swedish way to stormwater enhancement by source control. In: *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined sewer Technology,* Ed. H.C. Torno, ASCE, ISBN 0 87262 759 4, pp.156-168.

Nixon J., 1990. Infiltration blanket, Tower St., Cirencester, Glos. *Proc.* Standing Conf. on Stormwater Source Control, Volume I, Coventry University, ISBN 0 905949 14 5.

Pratt C.J., 1995. Infiltration drainage – case studies of UK practice. *Project Report 22,*Construction Industry Research and Information Association, London, SW1P 3AU; also known as National Rivers Authority R & D Note 485.

Pratt C.J., 1996. Research and development in methods of soakaway design. *Journal CIWEM,* 10(1), pp.47-51.

Pratt C.J., 1995. Infiltration drainage – case studies of UK practice. *Project Report 22,* Construction Industry Research and Information Association, London, SW1P 3AU; also known as National Rivers Authority R & D Note 485.

Thomas J., 1994. The use and design of deep soakaways – an NRA groundwater quality view. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume XI, ISBN 0 905949 37 4.

Walker C.R., 1994. Large diameter deep auger bored soakaways for the A20 between Folkestone and Dover. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume XI, ISBN 0 905949 37 4.

Warnaars E., Larsen A.V., Jacobsen P. and Mikkelsen P.S., 1999. Hydrologic behaviour of stormwater infiltration trenches in a central urban area during $2^3/_4$ years of operation. *Wat. Sci. Tech.,*39(2), pp. 217-224.

Woolhouse C., 1990. Practical problems to implementation of soakaway drainage. *Proc.* Standing Conf. on Stormwater Source Control, Volume II, Coventry University, ISBN 0 905949 14 5.

Yura T., Takahashi Y., Suzuki K. and Jinbo H., 1999. Plan to introduce stormwater infiltration facility and sustainable maintenance system with accompanying large scale housing site. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.990-997.

PERVIOUS SURFACES

The United States has led the way in the study and production of design guidance on pervious surfaces (EPA,1980; Scheuler, 1987; Smith, 2000) and, although the number of reports on actual performance are limited, they do begin in the 1970s (Bachtle,1974; Diniz, 1976; Jackson and Raga, 1974).

Moving to the 1980s, studies began to address the water quality aspects of pervious pavements (Day et al., 1981). Laboratory investigations were made of the runoff, retention and throughflow of pollutants from four different surfaces. The surfaces were a traditional concrete pavement; two large element, permeable block surfaces (grass-concrete types); and a continuous-laid permeable concrete surface (similar to Grasscrete). Various artificial rainfalls containing pollutants were applied to the surfaces and the water volume and quality of the surface runoff and of the percolated waters were measured. Each of the permeable surfaces was constructed in a box with a drainage layer at its base, over which was some 300mm of a typical subsoil. Each permeable surface was laid on the manufacturer's recommended substructure on top of the soil. The substructure was typically 50mm sand over 150mm gravel. Top soil was used to fill the voids in the pavement surfaces.

The mean percentage surface runoffs for the two large elemental, permeable block surfaces were zero; for the continuous-laid permeable surface 0.5%; and for the concrete paved surface the mean value was 78% with no event value less than 50%. These results have a bearing on the runoff quality observations.

The pollutant concentrations in runoff, which did occur from the continuous-laid permeable surface, were greater than the corresponding ones for the concrete slab, except for organic phosphorus and heavy metals. However, the pollutant load being discharged in the surface runoff was much less for the continuous-laid surface than for the concrete slab, because of the significant differences in the runoff volumes. In the case of lead in the runoff, the mass from the concrete slab was found to be 350 times greater than from the permeable surface.

Samples of the percolating waters were obtained from near the top of the subsoil layer below the permeable surfaces. Some of the pollutants were retained in the soil: total, ortho and organic phosphate phosphorus better than 75%; organic nitrogen 70-80%; and the heavy metals were well retained in each of the three permeable pavements (lead 94-98%; zinc 90-97%; and chromium 45, 81 and 94%). The scatter in the results for chromium indicated the difficulty of reproducibility in laboratory rigs.

Samples taken towards the base of the subsoil layer showed that phosphorus removal, particularly ortho phosphorus, increased with depth and the presence of clay-sized particles. Organic nitrogen was over 80% removed at or before this level in the construction. The effluent samples showed nitrate/nitrite was being leached from the pavement structures; ammonia and TOC were not well treated with percentage removals on a mass basis of 26-78% and –5-76%, respectively.

A similar laboratory study was reported by Hogland et al.(1990) concerning pollutant transport and retention with porous concrete asphalt. This Swedish construction consisted of a 40mm surfacing layer with 15-24% voids overlaying two layers of free-draining aggregate. The upper layer of aggregate, some 40mm deep, formed of 4-25mm stones and acted as a levelling course, below which was a 300-700mm sub-base layer of 30-70mm stones. In practice the construction is separated by a geotextile layer from the sub-grade, which is typically boulder clay and effectively impermeable.

Artificial rainfall using highway runoff was applied to twelve test samples of the porous pavement over various periods to simulate the pollutant retention of the pavement in service for between 1.5 to 30 years. The laboratory constructions had a 500mm sub-base layer over 500mm boulder clay. After the simulated time span for an experiment the pavement was dismantled and the pollutant concentrations at various depths within the construction was determined. The concentrations varied with depth, with the highest for all pollutants analysed being at the geotextile on the base of the construction, except for chloride and nitrite/nitrate, the latter being highest in the porous concrete asphalt.

Sediment accumulated on top of the geotextile, much of it organic in nature, which would adsorb heavy metals, accounted for their elevated levels at that depth in the pavement. Nitrite/nitrate and ammonia concentrations were also higher at the geotextile than within the sub-base generally. In the soil below the geotextile, sulphur showed an eleven-fold increase on the initial value in the soil; ammonia, zinc and total phosphorus up to a four-fold increase; otherwise other pollutants displayed lower values. Analyses conducted on samples obtained from a operational pavement during its reconstruction showed total phosphorus, total solids, copper and cadmium at their highest concentration in the boulder clay below the geotextile, whereas most other pollutants were at the highest levels on the geotextile. The lowest concentrations were at the mid-depth in the sub-base stone, suggesting that pollutants were either trapped in the porous surface, or transported to the base of the construction, where they might be retained or discharged from the sub-base drain, located just above the geotextile.

Analyses of drain effluent showed that concentrations of suspended solids, total solids, chromium and aluminium were markedly lower than typical discharges from impermeable surfaces, and that concentrations of copper, zinc and lead were reduced. but less so. An increase in concentration was found for nitrite/nitrate, ammonia and chlorides, thought in part due to the use of deicing agents.

Recently, Raimbault et al. (1999) have examined samples of porous ashalt concrete pavements to identify the location of pollutants within the construction. They found that most of the heavy metal contamination was located in the porous surfacing after 8 years of usage, with little migration of particulate pollution within the structure. Examining the clogging process of the surface, it was found that 14-40% of the particles were <100um and that only a small quantity of clay size particles could adversely affect the permeability of the surface.

A similar comparison of the performance of two different surfaces, but restricting observations to water quantity, was conducted on two similar car parking areas in the City of Dayton, Ohio (Smith, 1984). One car park was surfaced with grass-concrete and equipped with only one gully to receive surface runoff; and the second was surfaced with impermeable asphalt and drained via a number of gullies. The observations showed that runoff volume from the grass-concrete car park into the drain ranged from 0-35% of the runoff from the asphalt surface (mean value 10% for eleven storms; no runoff at all from four of the eleven). The storm for which the highest percentage runoff was monitored from the permeable surface was not the largest storm, but one which followed immediately a previously wet day, from which there had been no runoff. This was an early indication that antecedent moisture conditions were important and the number of dry days between storms determined the effectiveness of the pavement to absorb stormwater. As an example, a storm which followed twelve, dry days produced only 20% runoff from the grass-concrete as compared with the asphalt, despite the storm being of high rainfall intensity, producing peak runoff rates of 21.8 l/s (grass-concrete) and 223.6 l/s (asphalt).

In Sweden in the 1980s, the use of porous concrete asphalt, laid on free-draining, crushed stone aggregate sub-base, was beginning and early observations suggested that this form of pavement offered important stormwater discharge quantity and quality benefits (Hogland et al., 1987 & 1990; Larson, 1990). Used for car parking areas and for highways in residential developments, the 'Unit Superstructure' was claimed to produce significant peak flow and discharge volume reductions, whilst being up to 25% cheaper, when taking all construction and drainage costs into consideration. Usually the Swedish construction had no impermeable membrane undersealing the subgrade, which was generally clay or rock. A geotextile was laid between the sub-base stone and the subgrade to prevent the movement of soil into the structure, but not to impede the flow of water into or out of the sub-base. Most water was discharged from the sub-base through drains at the low points in the subgrade at the edge of the construction.

In France around this same time in the 1980s, highway constructions were also being formed with free-draining, crushed stone sub-base, sometimes contained within an impermeable membrane. They were termed 'reservoir' structures and had either an impermeable asphalt surface or a porous concrete asphalt one (Raimbault, 1990; 1993a and 1993b). Where the surface was impermeable, stormwater from the highway and from adjacent roofs was discharged into the sub-base through gullies and roof drains, to percolate downhill within the sub-base and to be discharged to a sewer at a suitable location. Where the stormwater from highways infiltrates the soil, there is always concern about the impact of pollutants upon groundwater quality. This was investigated at one of these reservoir constructions at Rezé, near Nantes in France (Legret and Colandini, 1998).

The porous construction was built in 1988 over a 700m section of residential road where traffic usage was some 1600 vehicles per day. The subgrade was weathered clay over which was placed a woven geotextile on which the construction materials were placed. The surface comprised a 60mm layer of 14mm porous concrete asphalt, over two 100mm layers of porous bituminous-bound, graded aggregates, above a 300mm layer of 10-80mm crushed stone. Stormwater percolating through the construction either infiltrated the subgrade or was intercepted by a perforated sub-base drainage pipe.

In 1996 samples of soil in the 200mm immediately beneath the construction were analysed for heavy metals and the results compared with the French Agricultural Soil Threshold Standard (in italics, units mg/kg soil): lead 39 (*100*); copper 11 (*100*); cadmium 0.08 (*2*); and zinc 111 (*300*). Further laboratory-based investigations suggested that lead and, to a lesser degree, copper and zinc concentrations decease rapidly with depth of soil, being generally nil below 350mm. Cadmium on the other hand was not retained well and could migrate to 700mm, or beyond, in favourable soil conditions. Legret et al. (1998) stated that 'it is not advisable to install reservoir structures with which the infiltration process is the only means to drain off stormwater, in a zone where the formation level of the structure would be too close to the groundwater table.'

Also in the late 1980s, water quality sampling was undertaken on a small elemental, permeable block-surfaced car park at Nottingham Trent University during its first three years of operation (Bond et al., 1999; Pratt et al., 1989 and 1990; Schofield, 1994). The concrete surfacing blocks were laid on 50mm, 5-10mm gravel, which was spread over a geotextile layer, used to prevent the gravel from falling into the voids in the free-drainage aggregate sub-base below. The sub-base layer varied in thickness from 300 to 400mm across the width of the pavement, thereby causing the internal waters to flow to a drain pipe which passed through the membrane wall to the monitoring point. Four different stone types were used for the sub-base, each contained within a separately drained, impermeable membrane, so that all throughflow could be monitored separately at the outfall of the drain from each of the membrane-lined compartments. The four stone types used were 6-20mm gravel, 4-50mm blast furnace slag, 3-40mm granite and 5-50mm carboniferous limestone.

The four different sub-base stones produced a different range of values in water quality parameters, although any one parameter was remarkably consistent storm event by event. For instance, the pH and alkalinity of the effluent were lower for the blast furnace slag sub-base discharges as compared with those from the limestone sub-base. Similarly, hardness and lead were lower in discharges from the limestone sub-base. The order of the parameter change with stone type was limestone, granite, gravel then blast furnace slag, the direction of change depending upon the parameter of interest.

Over some two years of monitoring, the water quality parameters for the four permeable pavement sections showed small, slow variations with time. Blast furnace slag effluent showed a gradual decrease in hardness, whilst both granite and blast furnace slag exhibited slow decrease in conductivity. Suspended solids concentration variation over the period was limited to a range from near zero to 50mg/l, after an initial period of sediment flushing due to material brought to the site on the construction materials. This range of SS concentrations is considerably less than is typical for discharges from impermeable surfaces, where fluctuations of 30 to 300mg/l occur frequently during storm events, and peak concentrations of some 1000s mg/l are not uncommon. The consistency of concentration of suspended solids in the effluent is in marked contrast to the variability occurring with impermeable surfaces between consecutive events, where antecedent conditions and the storm characteristics determine solids washoff. A limited number of determinations of hydrocarbon concentration in the effluent were attempted but, in all cases, they were below the level of detection.

Associated with this field study, a laboratory investigation was also made of the locations of pollutant retention within the permeable structure (Pratt, 1990). Urban stormwater was collected from gully pots and pumped onto small scale, full-size models of the blast furnace slag, granite and limestone structures, to simulate ten year's rainfall. In all but one case, that of sediment accumulation for the granite, most of the mass of total sediment, organic material and lead were retained in the 50mm gravel layer on the geotextile. None of the stone used was pre-washed and in the case of granite, the stone was found to have significant initial sediment content, which affected the results by suggesting a more widespread presence of sediment than was actually derived from the stormwater inflow. Overall, this result indicated the significance of the geotextile in limiting the transport of sediment and sediment-associated pollutants deep into the permeable construction. This finding is in contrast with that from the Swedish investigation (Hogland et al., 1990), where the geotextile played no part in restricting ingress as it was positioned at the base of the construction.

The Nottingham laboratory studies also allowed an insight to be gained of the factors affecting the sediment trapping efficiency. Tests suggested that, for the geotextile used (Terram 1000), a sediment concentration of 600g/m^2 inorganic/organic sediment mix could limit flow, such that it took 24 hours for waters in the 50mm gravel layer to drain. The nature of the geotextile selected will affect this result, as will the nature of the sediment and its supply. Schofield showed that selecting a geotextile with increased mass per unit area would increase sediment trapping. Increased suspended solids concentration in the percolating waters and increased deposition on the geotextile also both led to increased sediment trapping efficiency (Bond et al., 1999).

At the same time as the water quality study was being undertaken on the Nottingham permeable, concrete block car park, it was also monitored for stormwater discharges (Bond et al., 1999; Mantle, 1993; Pratt et al., 1989,1990and 1995). Being completely enclosed within an impermeable membrane outflow was limited to flows from the sub-base drains and to evaporation from the surface. As previous reported by Hogland et al. (1987, 1990), considerable reduction in peak discharge was observed. In addition, there was a reduction of the volume of stormwater discharged during the period of rainfall to about 40% of the total discharge, as compared with the performance of traditional impermeable surfaces, which discharge close to 100% runoff within the storm duration. The actual total discharge, on average, was also reduced to between 34% rainfall with blast furnace slag sub-base stone and to 47% with granite sub-base, because of water storage in the construction due to surface wetting and absorption. This result was in part due to the slower rate of outflow, extending the period of discharge to days sometimes, but also it was caused by the delay in the start of discharge after rainfall started. The start of discharge from the sub-base drain could be several hours after start of rainfall: hence the outflow hydrograph of a pervious construction was markedly different from that of a traditional, impermeable one.

The initial wetting loss before drain discharge from the pavement was 2.4-3.2mm, dependent upon the stone type used for the sub-base; and the runoff coefficient was 0.7-0.8, once drain discharge began (Pratt et al., 1995). It was found that the concrete, surfacing blocks could absorb 4-5mm rainfall. The stored water evaporated and Mantle (1993) reported loss rates from a specimen area of the car park structure of 0.2-5.5mm/day, which would amount over time to a not inconsiderable effective depth, as compared with total rainfall.

The same construction and permeable, concrete blocks as used at Nottingham were used at Shire Hall, Reading for the surfacing of infiltration trenches along one side of a 6500m^2 block-paved car park. The car park, constructed in 1986, was graded to fall to one side, at which a one metre wide infiltration surface intercepted the runoff. At installation, the infiltration rate of the concrete block surface, which contained a regular pattern of 50mm diameter, gravel-filled holes for inflow, was some 4,500mm/h. In 1992 after some six years use, the infiltration rate of the surface was 2,600mm/h, which was still sufficient to ensure full interception of runoff, being equivalent to a rainfall intensity on the whole car park of 60mm/h (Pratt, 1995).

The surface infiltration rate varies with the materials and nature of the pervious surface. Rates for porous concrete asphalt have been measured as high as 40-60,000mm/h (Pratt, 1995), but values are typically far lower and change over time as debris accumulates in pores in the surface or in inlets. Tests conducted at a new car park, surfaced with small element, porous concrete blocks, gave results of 550mm/h and 27,000mm/h, respectively, for infiltration through the block surface itself and through the gaps between blocks (Abbott et al. 2000). At a similar car park, but after some one year's use, it was noted that the presence of dirt and oil spillage on the pavement significantly reduced the infiltration rates for both the blocks and the gaps between them.

The studies initiated at the car park at Nottingham Trent University in the late 1980s were extended through the '90s in laboratory experiments examining, not only the retention but also, the degradation of oil within the permeable construction. The previous study had failed to identify hydrocarbons in the effluent from the permeable structure, despite visual evidence of surface contamination through car sump leakage.

A full-size model of the permeable construction at the Nottingham car park, 610mm by 610mm surface area, was built and supplied with artificial rainfall and clean mineral oil regularly each week over a period which extended to four years (Bond, 1999) . The research aimed to determine whether the retained oil could be degraded through microbial action i.e. could the free-draining structure act as an aerobic digestor. Accordingly, the model was seeded with a commercially available bacterial inoculum and nutients. Both liquid and granular forms of nutrient were tried, with the latter giving better degradation results, and the levels of nutrient concentrations in the effluent were low.

The model drained through its base and samples of effluent were analysed for oil and grease, total nitrogen, phosphate phosphorus and potassium. Results reported by Bond et al. (1999) showed that some 98.7% of the applied oil was retained/degraded over the period and that, with an input oil concentration 1800mg/l, the effluent oil concentration was only in the range 3.8-39.5mg/l. The fact that degradation was occurring was established by the measurement of elevated levels of carbon dioxide within the pavement and by the use of a second model, which allowed a mass balance for oil to be calculated. The measured oil degradation rate using granular nutients was equivalent to 356g/m^2/year and it was estimated that the mean residence time of the oil in the structure was some 7 months.

Examination of the component materials within the permeable structure showed that around 60-90% oil was retained on the geotextile, from where it would be slowly released and degraded. The long term capacity of the structure to retain oils was investigated by immersing samples of the component materials in an oil bath for 15 minutes and then allowing them to drain for 25days before weighing. These tests showed that some 9.5kg oil could be retained in total per square metre surface area, with the concrete surfacing blocks, gravel bedding layer, geotextile and granite sub-base each retaining 12, 29, 5 and 54 %, respectively, of this total within the as-built structure. The actual oil retention capacity per unit weight of each component was approximately 17, 36, 3190 and 7g oil/kg material, respectively, for the materials in the same list order.

Using the above results, a hypothetical car park design was assessed for its potential to become saturated with oil (Pratt, 1999a). The car park was assumed to have some 4690m^2 impermeable surface area, all of which drained to a permeable surface side strip of 310m^2 . Using the same oil input concentration, 1800mg/l, which is 100 times the concentrations identified in the literature as likely in highway runoff, the permeable strip was estimated to have a 44-year life before saturation. If the total area of the car park was constructed as a permeable structure, the time to saturation was estimated to exceed 100 years. This appears to suggest that oil saturation may not be a major problem where supply is evenly spread over time at this high level.

Throughout the 1990s the concept of Sustainable Urban Drainage Systems was promoted and this encouraged the development of commercial surfacing products, such as used in the study reported by Abbott et al. (2000). A large number of pervious surfaced car parks have been constructed and, particularly in Scotland, there has been considerable interest in monitoring a few of them. The National Air Traffic Service (NATS) car park in Edinburgh is surfaced with small element, porous concrete blocks and its effluent water quality has been compared with that from a similarly monitored tarmac-surfaced car park. Observations of water quality parameters during one rainfall event on both surfaces revealed that concentrations of heavy metals in the drain effluent from the porous surface were lower than those in effluent from the tarmac surface, with the exception of copper (Macdonald and Jefferies, 2001). The concentration of hydrocarbons in the effluent from the porous surface were some 70% lower and much lower than the concentration typical in urban stormwater.

A second porous concrete block-surfaced car park at the Bank of Scotland, South Gyle, Edinburgh has been monitored for both quantity and quality parameters (Schluter and Jefferies, 2001). Outflow monitoring showed that the discharge volume was just under 50% of rainfall, with the initial wetting loss before outflow being of the order of 1.65mm. The outflow characteristics were said to be heavily influenced by the antecedent conditions. Water quality analyses showed mean heavy metals concentrations Cd <0.068; Pb 1.8; Cu 5.2; Ni 1.7; and Zn 22.2 ug/l. Hydrocarbon concentrations were up to 3.5mg/l for the event producing the highest rate of outflow at 2.9 l/s, although for spot samples and smaller events the results were much lowere and sometimes below detection.

In England, Abbott et al. (2000) has provided similar observations at Wheatley Motorway Service Area, Oxfordshire from another porous block-surfaced car park. The car park area monitored was 6250m^2 and surfaced with porous concrete blocks. The amount of water draining from the sub-base during rainfall events varied from 4-47% of the rainfall volume, with an average value of only 22.5%. Some events took 2-3 days to outflow after rainfall ceased, with the result that subsequent rainfall-runoff might occur, superimposed on the previous event discharge. This produced the impression of a 'base flow' release from the sub-base. The event percentage runoff had to be calculated after accounting for any base flow component in the runoff and indicated values ranging from 30-120% (mean value 67%).

The surface infiltration rate of the porous blocks was assessed, both through the blocks themselves and via the gaps between blocks. There was a large variation in block infiltration rate (250-14,000mm/h), which was also the case with the tests on the gaps, but here the infiltration rates were some 50 times higher (11,000-229,000mm/h). The infiltration tests were repeated after a 10-month interval, which revealed that the blocks in some cases had become largely impermeable, although the gaps still performed well.

All three of the latest UK studies of large porous surfaces report similar findings concerning the modification of the outflow hydrograph and confirm the initial, smaller site results obtained on the Nottingham permeable concrete block-surfaced, 'reservoir' structure, reported by Pratt et al. (1995). The peak ouflow is markedly reduced (at Wheatley a peak rainfall intensity of 12mm/h was limited to 0.4mm/h at the outflow); and the duration of discharge is extended, sometimes considerably; and there is a significant lag between start of rainfall and start of outflow (at the Bank of Scotland car park this varied from some 40-140 minutes). The total volume of outflow is reduced (in the Wheatley case the percentage runoff was only 67% on average; whereas at the Bank of Scotland site, it was 47% on average; and at NATS was only 22% [although this construction is not undersealed, the subgrade has a low infiltration capacity]). In all cases, the hydrograph is strongly affected by the antecedent conditions, such that a 'base flow' may exist, discharged from the pavement for several days, and subsequent rainfall events be superimposed upon it.

The problem of surface clogging on pervious surfaces remains a concern. Kobayashi (1999) has presented useful details on Japanese experience in the use of manual and automatic washing/suction techniques on both porous asphalt and block surfaces. It has been possible to raise the infiltration rate from around 0.4mm/h to 400mm/h, the best performance being achieved with the higher jetting pressures combined with suction.

Pagotto et al. (2000) report results from two one-year studies on a conventional asphalt surface (1995-96) and on a porous asphalt one (1997-1998) on a French motorway. They give comparative data for rainfall, runoff and traffic data as context for the runoff water quality data, given in terms of both concentrations and total loads of pollutants. Data of pollutant concentrations is provided for the mean value of 25 analyses of TSS, COD, TKN, total hydrocarbons, heavy metals (Pb, Cu, Cd, Zn in total, dissolved and particulate phases). In all cases the concentrations from the porous surface are less, in many cases less than 60%, of those from the conventional surface. Similar results are given for the total loads discharged by runoff waters and by sediments during the two periods from the two surfaces: in the case of sediments, the porous surface discharged only some 10% sediment-associated pollutants as did the conventional surface. The retention of fine particulate pollution within the porous surface is identified as significant in producing the reduction in hydrocarbon and metals discharge.

Dierkes et al. (2002) have conducted laboratory tests on full-scale model pervious pavements under artificial rainfall, which was highly contaminated with heavy metals. This provides a useful extension to knowledge from laboratory tests, first conducted by Hogland et al.(1990). The rigs were constructed with different sub-base materials and the equivalent of 50 years of operational pollutant loadings were applied to each. The table below shows the concentrations of heavy metals in the synthetic rainfall, the mean concentrations of heavy metals in the effluent and the percentage of the metals retained in the materials at the end of the event.

	Lead	cadmium	Copper	Zinc
Synthetic rainfall	180ug/l	30ug/l	470ug/l	660ug/l
Sub-base stone	Effluent (mean conc., ug/l); *(% retained in sub-base)*			
Gravel	<4; *98*	0.7; *98*	18; *96*	19; *97*
Basalt	<4; *98*	0.7; *98*	16; *96*	18; *98*
Limestone	<4; *98*	3.2; *88*	29; *94*	85; *88*
Sandstone	<4; *89*	10.5; *74*	51; *89*	178; *72*
German limits on disposal to ground, ug/l	25	5	50	500

Dierkes et al. (2002) also report the results of similar laboratory tests on different surfacing blocks. Four types were investigated: concrete blocks with large joints between blocks; porous blocks with close joints; and two styles of grass-concrete blocks with soil infill. Most pollutants of the four heavy metals tested were retained by the grass-concrete block systems and least by the blocks with large joints. They suggest that the joints should be filled with suitable material to limit the movement of heavy metals into the pavement, but probably adversely affects the infiltration capacity of the surface. (Davies et al. (2002) report on laboratory research into joint blockage and the affect of pavement surface slope on surface water interception efficiency.)

They extended their study to investigate the pollutant build-up on a 15-year old permeable pavement, car park, subject to high usage. After determining the surface infiltration rate, the surface was lifted and the underlying materials were excavated in one bay. The found that 'the heavy metals and hydrocarbons after 15 years of operation were very low. The highest highest concentrations do not reach the permissible limits. In the underlying soil a slight increase of hydrocarbons was to be observed, but this does not endanger soil and groundwater.'

Dierkes et al. (2002) go on to report on some tests with surface cleansing machines. A newly developed machine raised the infiltration capacity of a 'blocked' surface from some 0.4mm/h to 540mm/h, a value said then to meet the German regulation.

Hunt et al. (2002) describe the early results from three types of permeable pavement constructed at two locations in North Carolina, USA, as full-scale research facilities from which to determine their impact in reducting in surface runoff. At one site at Kinston, the pavement had a portion surfaced with a grass-concrete block system (634m^2) and a second with a grass-plastic grid system (244m^2). Details are presented of the design considerations and of the rainfall/flow monitoring arrangements. Monitoring began in June 1999 and it was decided to restrict the data set to events with at least 12.7mm. Fifty such storms have been recorded, of which only 12 have produced any measured surface runoff. The authors recommend that, on the results to date, it is reasonable to assign a rational runoff coefficient ranging from 0.20 to 0.50. The second site is at Wilmington, where a 316m^2 porous concrete car park surface has been built. Monitoring is at a very early stage and will continue into 2003.

Imbe et al. (2002) detail the results from a number of rainwater infiltration systems over a 20-year period, including 2405m^2 of permeable pavements. The location is a 27.8ha housing complex in Tokyo, of which some 3.2ha were studied for the paper.

Newman et al. (2002) continue the research into bio-degradation within permeable pavements previously reported by Pratt et al.(1996; 1998) providing information on new molecular biological techniques developed to quantify bacterial diversity. It has been found that the complexity of the microbial population increases with time and that the original, commercial inoculum has been replaced after four years by a population selected by the pavement conditions. They state that the protozoan community has an important role in the oil degradation process, such that any design changes of the pavement structure needs to ensure the maintenance of both protozoan and bacteria.

CIRIA has published another report in the SUDS series on pervious surfaces, which provides an overview of the types, their hydrological/hydraulic performance, their impact on water quality, and details current approaches to their hydraulic and structural design (Pratt et al. (2002).

An interesting and thorough comparative study at a car park in Tampa, Florida, USA is reported by Rushton (2002). Eight sub-catchments were established with four different types of drainage system, two of each: permeable paving, concrete pavement and asphalt surfacing each with a swale collector for excess surface runoff; and an asphalt surfacing without a swale, but with a lined, surface channel for excess runoff. All eight sub-catchments had garden areas onto which waters could flow from either a swale or from a channel. Over two years of data were collected of rainfalls, runoff, water quality parameters and sediment/soil contaminants. Over the two years, the permeable pavement with swale had the lowest percentage runoff, being on average for the two locations 10-17%, the other systems were of the order of twice or three times these figures. The paper gives both information on concentrations and loads of contaminants. The pollutant loads passing downstream may be reduced by retaining the stormwater in the sub-catchment, allowing time for infiltration and evaporation, as well as for chemical and biological processes to occur. Not surprisingly, the permeable paving with swale had the best load removal efficiency for ammonia, nitrate, total nitrogen, total suspended solids, copper, iron, lead, manganese and zinc, with most removal rates greater than 75%. Phosphorus was an exception to this pattern, where surface flows along the swales collected an increased load, which was attributed to landscaping practices. Sediment samples implicated the asphalt surfacing as a source of metals and PAHs in the soil saples in some cases approached significantly toxic levels. A copy of the complete report of the research is available from the author.

The performance, modelling and on-going developments in pervious pavements in the UK were reported in four papers at the Second National Conference on Sustainable Drainage, Coventry, 2003 (Abbott et al., 2003; Kellagher et al., 2003; Newman et al., 2003; and Wilson, 2003). The need for high quality field data on hydraulic and pollution control performance of SUDS systems is well recognised and Abbott et al. (2003) detail such observations from two pervious pavements: a porous block pavement at the Wheatley Motorway Service Area (M40) and a porous asphalt pavement at a supermarket in Wokingham. Both sites showed substantial reduction in storm peaks, attenuation of the storm runoff duration and significant reduction in outflow volumes, as compared with storm volumes. Kellagher et al. (2003) discuss some the desirable hydraulic design criteria for SUDS systems and observe that pervious pavements mimic greenfield site characteristics without the need for throttling devices to be installed, allowing outflows to be restricted 1 or 2 l/s/ha. They review current modelling capability for pervious pavements and note the difficulties which remain in estimating key parameters, such as ‘initial loss’, and seasonally variable factors, such as ‘evaporation’, which may affect the future use of time series rainfall to model significantly wet periods eg November 2002. Newman et al. (2003) described a new and novel approach to oil retention within pervious pavements, where the quantities were large from a spillage and not the result of drips from engines. The work reported was laboratory-based and indicated early performance well inside that required for Class 1 oil interceptors, as defined in BS EN 858-1: 2002. Wilson (2003) gave details of one of the new plastic units available as sub-base stone alternatives.

PERVIOUS SURFACES REFERENCES

Abbott C.L., Comino L. and Angood C., 2000. Monitoring performance of infiltration drainage systems. *Report SR569,* HR Wallingford.

Abbott C.L., Weisgeber A. and Woods Ballard B., 2003. Observed hydraulic benefits of two UK permeable pavement systems. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.101-111.

Bachtle E.R., 1974. Ecological parking lot has porous pavement. *Public Works* (USA), 105, part 2, pp.78-79, February.

Bardin J-P., Barraud S., Alfakih E. and Dechesne M., 2002. Performance assessment of stormwater infiltration strategies: a multi-indicator approach. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-010-001.pdf).

Bond P.C., 1999. *Mineral Oil Biodegradation Within Permeable Pavements: long-term Observations.* Unpublished Thesis, Coventry University.

Bond P.C. and Pratt C.J. 1998. Developments in permeable/porous pavements: observations on mineral oil bio-degradation. *Proc.* Standing Conf. on Stormwater Source Control, Volume XV, ISBN 0 905949 64 1.

Bond P.C., Pratt C.J. and Newman A.P., 1999. A review of stormwater quantity and quality performance of permeable pavements in the UK. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.248-255.

Bray R.J., 1994. Design experience of source control treatment systems on commercial developments . *Proc.* Standing Conf. on Stormwater Source Control, Volume XVII, Coventry University, ISBN 0 905949 80 3.

Davies J.W., Pratt C.J. and Scott M.A., 2002. Laboratory study of permeable pavement systems to support hydraulic modelling. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-009-001.pdf).

Day G.E., Smith D.R. and Bowers J., 1981. Runoff andPollution Abatement Charateristics of Concrete Grid Pavements. *Bulletin 135,* Virginia polytechnic Institute and State University, Virginia 24060, USA

Dierkes C., Kuhlmann L., Kandasamy J. and Angelis G., 2002. Pollution retention capability and maintenance of permeable pavements. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-010-003.pdf).

Diniz E.V., 1976. Quantifying the effects of porous pavements on urban runoff. *Proc.* Nat. Symp. on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, USA, pp.63-70.

Hogland W., Larson M. and Berndtsson R., 1990. The pollutant build-up in pervious road construction. *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.845-852.

Hogland W., Niemczynowicz J. and Wahlman T., 1987. The Unit Superstructure during the construction period. *Sci.Tot.Env.,* 59, pp.411-424.

Hunt B., Stevens S. and Mayers D., 2002. Permeable pavement use and research at two sites in eastern North Carolina. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-010-002.pdf).

Imbe M., Okui H., Hashimoto C. and Musiake K., 2002. Monitoring and analysis of implemented infiltration system over past 20 years. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-009-003.pdf).

Jackson T.J. and Ragan R.M., 1974. Hydrology of porous pavement parking lots. *Proc.* ASCE, Hydraulics Division, 100, HY2, pp.1739-1752.

Jacobsen P. and Harremoes P., 1981. The significance of semi-pervious surfaces in urban hydrology. In: *Urban Stormwater Hydraulics and Hydrology,* Ed. B.C.Yen, Water Resources Pub. Littleton, CO 80161, USA, pp.424-433.

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme*, Section 3.5 Pervious Surfacing; Section 5.6 Performance Observations – Pervious Paving: NATS Porous Paved Car Park. SNIFFER, Edinburgh, EH3 6RT.

Jefferies C., Heal K.V. and B'Arcy B.J., 2001. Performance of sustainable urban drainage systems for urban runoff. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.159-169.

Kellagher R., Woods Ballard B. and Weisgerber A., 2003. Modelling of pervious pavements. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.91-99.

Kobayashi M., 1999. Stormwater runoff control in Nagoya City. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.825-833.

Larson R., 1990. Swedish experience with design and construction of pervious asphalt constructions. *Proc.* Standing Conf. on Stormwater Source Control, Volume I, Ed. C.J. Pratt, Coventry University, ISBN 0 905949 14 5.

Legret M. and Colandini V., 1998. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. *Proc.* 3rd Int. Conf. on Innovative Technologies in Urban Storm Drainage, Lyon, France, pp.517-524.

Legret M., Colandini V. and Le Marc C., 1996. Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. *Sci.Tot.Env.*, 189-190, pp.335-340.

Legret M., Demare D., Colandini V., Balades J.D. and Madiec H., 1993. Behaviour of metallic pollutants in a pervious road construction. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, Canada, pp.1201-1206.

Legret M., Nicollet M., Miloda P., Colandini V. and Raimbault G., 1999. Simulation of heavy metal pollution from stormwater infiltration through a porous pavement with reservoir structure. *Wat. Sci. Tech.,*39(2), pp. 119-125.

Macdonald K., 2000. Monitoring the effectiveness of SUDS in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Macdonald K. and Jefferies C., 2001. Performance of sustainable urban drainage systems for urban runoff. *Proc.* 1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.170-181.

Mantle J.D.G., 1993. *On-site Reduction and Attenuation of Urban Stormwater Runoff.* Unpublished Thesis, Nottingham Trent University.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the

Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Newman A.P., Coupe S.J., Puehmeier T., Morgan J.A., Henderson J. and Pratt C.J., 2002. Microbial ecology of oil degrading porous pavement structures. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-010-004.pdf).

Newman A.P., Pratt C.J., Coupe S.J. and Cresswell N., 2001. Oil bio-degradation in permeable pavements by inoculated and indigenous microbial communities. *Proc.*4th Int. Conf. on Innovative technologies in Urban Storm Drainage, Lyon, France, pp.425-432.

Newman A.P., Shuttleworth A., Puehmeier T., Wing Ki K. and Pratt C.J., 2003. Recent developments in oil retaining porous pavements. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.81-89.

Niemczynowicz J., 1990. Swedish way to stormwater enhancement by source control. In: *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined sewer Technology,* Ed. H.C. Torno, ASCE, ISBN 0 87262 759 4, pp.156-168.

Pagotto C., Legret M. and Le Cloirec P., 2000. Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Wat. Res.,* 34 (18), pp. 4454-4454.

Pratt C.J., 1990. Permeable pavements for stormwater quality enhancement. In: *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined sewer Technology,* Ed. H.C. Torno, ASCE, ISBN 0 87262 759 4, pp.131-155.

Pratt C.J., 1995. Infiltration drainage – case studies of UK practice. *Project Report 22,*Construction Industry Research and Information Association, London, SW1P 3AU; also known as National Rivers Authority R & D Note 485.

Pratt C.J., 1999a. Developments in permeable pavements: further observations on mineral oil bio-degradation. *Proc.* Standing Conf. on Stormwater Source Control, Volume XVII, ISBN 0 905949 80 3.

Pratt C.J., 1999b. Design guidance for porous/permeabble pavements. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.196-211.

Pratt C.J., Mantle J.D.G. and Schofield P.A., 1989. Urban stormwater reduction and quality improvement through the use of permeable pavements. *Wat. Sci. Tech.,* 21, pp.769-778.

Pratt C.J., Mantle J.D.G. and Schofield P.A., 1990. Porous pavements for flow and pollutant discharge control. *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.839-844.

Pratt C.J., Mantle J.D.G. and Schofield P.A., 1995. UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality. *Proc.*2nd Int. Conf. on Innovative technologies in Urban Storm Drainage, Lyon, France, pp.337-344.

Pratt C.J., Newman A. and Bond P.C., 1998. Mineral oil bio-degradation within a permeable pavement: long-term observations. *Proc.* 3rd Int. Conf. on Innovative Technologies in Urban Storm Drainage, Lyon, France, Volume 1, pp.501-508.

Pratt C.J., Newman A. and Brownstein J., 1996. Bio-remediation processes within a permeable pavement: initial observations. *Proc.* 7th Int. Conf. on Urban Storm Drainage, Hannover, Germany, pp. 1455-1460.

Pratt C.J., Wilson S. and Cooper P., 2002. Source Control using Constructed Pervious Surfaces*, CIRIA C582*. Construction Industry Research and Information Association, London. ISBN 0 86017 582 0.

Puehmeier T., 2002. Recent studies on oil degrading porous pavement structures. *Proc.* Standing Conf. on Stormwater Source Control, Volume XXIII, Coventry University, ISBN 1 903818 26 5.

Raimbault G., 1990. Reservoir structures: an extension of the possibilities of porous pavements. *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.833-838.

Raimbault G., 1993a. French researches on reservoir structure hydraulics. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, Canada, ISBN 1 55056 254 1, pp.1121-1126.

Raimbault G., 1993b. New designs for reservoir structures. *Proc.* 6th Int. Conf. on Urban Storm Drainage, Niagara Falls, Canada, ISBN 1 55056 254 1, pp.1127-1132.

Raimbault G., 1994. French developments in reservoir structures. *Proc.* Standing Conf. on Stormwater Source Control, Coventry University, Volume VIII, ISBN 0 905949 24 2.

Raimbault G., 1999. French developments in reservoir structures. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.212-228.

Raimbault G., Nadji D. and Gauthier., 1999. Stormwater infiltration and porous material clogging. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.1016-1024.

Rushton B., 2002. Enhanced parking lot design for stormwater treatment. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-002-002.pdf).

Schluter W. and Jefferies C., 2001. Performance comparison of porous paved and traditional car parks. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.182-191.

Schluter W., Spitzer A. and Jefferies C., 2002. Performance of three sustainable urban drainage systems in east Scotland. *Proc.* 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-004-004.pdf).

Schofield P.A., 1994. *Urban Stormwater Quality Improvement Through the Use of Permeable Pavements.* Unpublished Thesis, Nottingham Trent University.

Smith D.R., 1984. Evaluation of concrete grid pavements in the United States. *Proc.*2nd Int. Conf. on Concrete Block Paving, Delft, The Netherlands, pp.330-336.

Stenmark C., 1992. Local infiltration of urban stormwater in cold climate. *Proc.* 5th Int. Conf. on Urban Storm Drainage, Osaka, Japan, pp.809-814.

RETENTION / INFILTRATION BASINS

Very little information is available on the performance of infiltration basins in either quantity or water quality aspects. These basins are also called retention basins as they retain all, or most, of the inflow for subsequent infiltration to the soil, hence it is difficult to monitor outflow water quality, except as an impact upon groundwater quality, which has not been attempted.

Some information is available from Bordeaux, France (Chocat et al., 1999). An infiltration basin, holding 80,000m^3 over an area of some 2ha, was constructed at Venissieux in 1975. Inflow to the basin first passed through a sand trap before entering the basin, in which the base was covered with a geotextile and 400mm sand. In 1988 the basin was divided into two and in 1990 the geotextile and sand layer were renewed. The basin now comprises sand traps, a settling basin of 1.1ha, from which flow passes through a flow regulator and hydrocarbon separator before entering an infiltration basin of 0.9ha. The Venissieux catchment is 380ha of mixed industrial, agricultural and residential land use. Groundwater is 3-5m below the base of the basin.

Water samples have been collected at the inlets to the basin; at the outlet from the settling basin and in the infiltration basin, before and after the hydrocarbon separator. In addition, soil samples were collected and cores obtained through the base of the infiltration basin to a depth of 1.5m. The settling basin has achieved decreases in suspended solids of between 20 and 70%. Examination of the soil cores showed that solids less than 2mm were seriously contaminated by heavy metals and mineral oils, although this decreased with depth until between the base of the geotextile and 0.5m into the subgrade the pollution was slight, despite the 20 years of infiltration. No data was reported on the possible impact on groundwater quality.

A second study on the Venissieux basin and on two others by Gautier et al. (1999) has provided important

Two systems were identified in the UK by Pratt (1995), but they have not been monitored. The infiltration basin at Ipswich has been in existence for some 25 years with little or no maintenance being conducted. The Yellowham Hill basins were constructed in 1991 as part of a road improvement scheme, are situated over an aquifer and could provide valuable data on the possible impact of highway runoff (Codling, 1992).

Unlike many of the other forms of Sustainable Urban Drainage Systems implemented in Scotland in recent years, retention basins and other infiltration devices have not been employed because ground conditions are generally unsuitable. In England there are extensive regions of the country, which would be suitable for this type of drainage as is the case in France.

Dechesne et al. (2002) report on research to identify 'contamination indicators' for the clogging of the topsoil in retention basins and of the potential for contamination of the underlying soil and groundwater, based on sites in the area of Lyon, France. Soil samples from ten locations in a retention basin, constructed in1987 and receiving runoff from a lorry park, were analysed for eight heavy metals at four depths in the samples. A rapid decrease in pollutant concentrations with depth are reported, with most concentrations within acceptable values. Dependent upon whether the contamination indicator is based upon average or maximum pollutant concentrations, Dechesne and co-authors identified that the soil in the basin was not polluted below 600mm, based on average values, but had some pollution down to 1.10m, based on maximum values after 14 years operation.

Also from France, Raimbault et al. (2002) have reviewed the sizing of retention basins in the light of time-varying infiltration capacity due to clogging. In addition, they point to the problem of waterlogging due to heavy rainfall or to wetter seasons than assumed in the designs. A suggestion is made that retention basins and similar infiltration structures, such as pervious pavements, could be fitted, retrospectively if need be, with under-drainage discharging at a controlled rate, to ensure emptying of the structure when soil conditions inhibited infiltration. The paper recommends mathematical simulations of time series rainfalls for sizing retention systems, incorporating consideration of temporal changes in infiltration capacity and of the use of under-drainage systems.

RETENTION / INFILTRATION BASIN REFERENCES

Carpenter V., 2000. Sustainable Urban Drainage Systems: Bognor Regis Sports Centre – Case Study. *Proc.* Standing Conf. on Stormwater Source Control, Volume IXX, Coventry University, ISBN 0 905949 88 9.

Codling A., 1992. Design and construction of infiltration basins at A35 Yellowhan Hill. *Proc.* Standing Conf. on Stormwater Source Control, Volume V, Coventry University, ISBN 0 905949 17 X.

Chocat P.B., Bardin J.P. and Gautier A., 1999. Filtration devices for urban drainage: a 50-year experience in Lyons. In: *Sustaining Urban Water Resources in the 21st Century.* Eds. A.C. Rowney, P. Stahre and L.A. Roesner, ASCE, ISBN 0 7844 0424 0, pp.181-195.

Dechesne M., Barraud S. and Bardin J-P., 2002. Performance of stormwater infiltration basins on the long term. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-009-002.pdf).

Gautier A., Barraud S. and Bardin J.P., 1999. An approach to the characterisation and modelling of clogging in stormwater infiltration facilities. *Proc.* 8th Int. Conf. on Urban Storm Drainage, Sydney, Australia, pp.1007-1015.

Nixon J., 1990. Infiltration blanket, Tower St., Cirencester, Glos. *Proc.* Standing Conf. on Stormwater Source Control, Volume I, Coventry University, ISBN 0 905949 14 5.

Pratt C.J., 1995. Infiltration drainage – case studies of UK practice. *Project Report 22,*Construction Industry Research and Information Association, London, SW1P 3AU; also known as National Rivers Authority R & D Note 485.

Raimbault G., Berthier E., Mosini M-L. and Joannis C., 2002. Monitoring and analysis of implemented infiltration system over past 20 years. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-009-004.pdf).

Yousef Y.A., Wanielista M.P. and Harper H.H., 1986. Design and effectiveness of urban retention basins. In: *Urban Runoff Quality – Impact and Quality Enhancement Technology*, Eds. B. Urbonas and L.A. Roesner, ASCE, ISBN 0 87262 577 X, pp.338-350.

SWALES AND FILTER STRIPS

Swales and buffer strips have long been used in the USA, although despite that little has been published on their performance. Scholl (1987) reported the cost savings which might be achieved by the use of swale drainage over that of a porous pavement. The only data found on the performance characteristics was published by Yousef et al.(1987) giving detailed water quality analyses at two locations alongside an interstate highway.

The results were obtained during natural rainfall-runoff and during pump-circulation tests, using waters from an adjacent retention/detention pond. The data showed that both total and dissolved concentrations of metals analysed were lower in swale flow than in highway runoff. However the swale flow contained higher concentrations of the nutrients, P and N, than highway runoff. When the removal of dissolved heavy metals and nutrients was considered on a total mass basis, the removal efficiencies increased considerably as some flow infiltrated. Yousef et al. recommended that swales should be constructed in soils which could dry between runoff events; have good infiltration rate; and at limited longitudinal slope to extend the contact time and slow the forward flow. They concluded by saying that 'swales alone should not be used for management of highway runoff based upon quality improvement and should be used as a transport channel to a more appropriate treatment process'.

Yu and Benelmouffok (1990) reported field observations on a filter strip which received runoff from a shopping mall. A shallow, v-shaped, 'level spreader' at the upstream edge of the filter strip ensured even distribution of stormwater, which then flowed over the grass strip. The filter strip had a width varying between 15 – 45m and discharged into a watercourse. The efficiency of pollutant removal was improved with increased width and a minimum width of 22m was recommended for filter strip design. Eight storm events were sampled and the pollutant removal efficiencies reported were for suspended solids 71%; zinc 51%; lead 25%; total phosphorus 38%; and nitrate-nitrite 10%. The density and height of the grass were stated as important factors in pollutant removal.

The introduction of swale drainage systems into the UK has been somewhat limited. In England a swale system was constructed at Stockley Park, Hillingdon, between 1990-92 to intercept and transport surface runoff from a golf course laid out on a previous landfill site (Pratt, 1995). Waters were conveyed to one corner of the site and stored prior to discharge to a foul sewer at 10 l/s between 21.00 and 06.30. No performance data has been collected at the site.

With the development of the Sustainable Urban Drainage Systems concept, a number of sites in Scotland were developed using swale drainage (Jefferies, 2001). The nine of the 15 swales are associated with residential developments, 3 with industrial premises, 2 with leisure and retail and 1 with highway drainage (Gilmour, 1998; Jefferies et al., 1998). Four swales have been monitored but only two, at Emmock Woods and West Grange, both in Dundee, for any length of time. The initial wetting loss and the percentage runoff has been assessed at both sites. At Emmock Woods the swale initial wetting loss has been estimated to be 5mm, as compared with the adjacent road's value of 0.7mm. The corresponding pair of percentage runoff values is 6.5% and 41%, respectively. At West Grange the figures are for initial wetting loss 1.2mm and 0.3mm (road); percentage runoff 37% and 53% (road). At both sites increased lag times before runoff and reduced peak flows from the swale have been monitored. Pollutant concentrations have been in general very low, with significant removal of suspended solids and most chemical determinands observed at both locations.

In Australia, vegetated swales are becoming a common feature of water-sensitive urban design, but there is still somewhat limited, rigorous information available on performance in relation to design parameters. Fletcher et al. (2002) established controlled experiments on newly constructed swale in Brisbane. The experimental swale was 65m long, top width 4m, with a longitudinal slope of 1.6%, side slopes of about 1:13, and it received runoff from a catchment of 1.03ha. The inflows were dosed with a synthetic mix of pollutants, matched to typical stormwater characteristics (total suspended solids 150mg/l, total nitrogen 2.6mg/l and total phosphorus 0.3mg/l). water samples were taken at the inlet, outlet and at three points along the swale. The results showed that the swale provided substantial reduction in pollutant concentrations: reduction for TSS ranged from 73-94%, for TN ranged from 44-57% and for TP from 58-72%. For load, the equivalent results were TSS 57-88%, TN 40-72% and TP 12-67%. The treatment performance diminished with increasing flow rate for TSS, reflecting the importance of sedimentation and infiltration in their removal. TN and TP were less dependent on flow, reflecting the likely influence of rapid chemical processes. The field data was used to develop a first-order kinetic decal model of the swale's pollutant removal performance. The paper contains references to other work in the Southern Hemisphere. The results of Fletcher et al. (2002) with regard to TP are in contrast to those reported by Rushton (2002), who reported raised TP after flow along swales, but did suggest landscaping practices could explain this. Rushton (2002) gives a valuable overview of the benefits achieved from a network of swales, filter strips and small wet detention ponds combined with car parking areas surfaced with either permeable paving, concrete or asphalt.

Backstrom (2003) reports on a field study of swale performance at Lulea, in northern Sweden, carried out between 2000-2002. The paper details the results from experiments on particle trapping during simulated runoff events; pollution control during seven rainfall-runoff events; and the pollution control exhibited by three swales during snowmelt. In the latter case, Backstrom provides data of grab samples from snow and meltwater for total and dissolved parameters (SS, Cu, Pb and Zn). Total metals and suspended solids were retained to a large degree in the snow-covered swale (78-99% removal), however dissolved Cu and Zn showed increased release in the meltwater. Concern is raised as to the final fate of pollutants, even if there is initial trapping within the swale, and reference is made to other studies of pollutant retention in surface soils and of throughflow to groundwater (Wigington et al., 1986; Mikkelsen et al., 1997 [see INFILTRATION PITS AND TRENCHES]; Dierkes and Geiger, 1999).

The introduction of SUDS to school developments is reported by Bray (2003) in a paper which gives helpful cost comparisons with traditional drainage approaches in both capital and maintenance terms. The opportunities for pupils to engage with the water environment and of the concerns for safety which this raised are outlined. The design and installation issues with the implementation of swale drainage to a major UK highway (A120, near Stansted) are described by Macer-Wright et al. (2003). Their paper also provides cost comparisons with the traditional concrete channel approach, which shows significant construction cost savings with the SUDS approach. The plans for dealing with vehicle over-run and possible rutting, and of pollution incident management are mentioned.

SWALES AND FILTER STRIP REFERENCES

Backstrom M., 2003. Grassed swales for stormwater pollution control during rain and snowmelt. *Wat. Sci. Tech.*, 48 (9), pp. 123-132.

Brannigan D., 1999. *Pollution Monitoring: A Study of Pollution Removal Through a Grass Swale.* Unpublished MSc Dissertation, University of Edinburgh.

Bray R.J., 1994. Design experience of source control treatment systems on commercial developments . *Proc.* Standing Conf. on Stormwater Source Control, Volume XVII, Coventry University, ISBN 0 905949 80 3.

Bray R.J., 2000. Design of the 'treatment train' at Hopwood Park MSA M42 . *Proc.* Standing Conf. on Stormwater Source Control, Volume XIX, Coventry University, ISBN 0 905949 88 9.

Bray R.J., 2003. Sustainable drainage solutions for local authority school sites. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.51-61.

Deletic A., 1999. Sediment behaviour in grass filter strips. *Wat. Sci. Tech.*, 39(9), pp. 129-136.

Dierkes C. and Geiger W.F., 1999. Pollution retention capabilities of roadside soils. *Wat. Sci. Tech.*, 39(2), pp. 201-208.

Escarameia M., Gasowski Y. and May R., 2002. Grassed drainage channels – hydraulic resistance characteristics. *Water and Maritime Engineering,*154(4), December, pp.333-341.

Fletcher T.DD., Peljo L., Fielding J., Wong T.H.F. and Weber T., 2002. The performance of vegetated swales for urban stormwater pollution control. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-013-003.pdf).

Gilmour D., 1998. *The Operation and implementation of Swales in Scotland.* Unpublished MSc Dissertation, University of Abertay, Dundee.

Honeyman M.J. and Baird I.A., 2001. Newhall Valley water management strategy. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.10-16.

Jefferies C. (Ed.), 2001. *SUDS Monitoring Programme*, Section 3.2 Roadside Swales; Section 5.2 Performance Observations – Swales. SNIFFER, Edinburgh, EH3 6RT.

Jefferies C., Heal K.V. and B'Arcy B.J., 2001. Performance of sustainable urban drainage systems for urban runoff. *Proc.*1st Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 06 0, pp.159-169.

Jefferies C., McKissock G., Logan F., Gilmour D. and Aitken A., 1998. *Preliminary Report on Swales in Scotland.* Sustainable Urban Drainage Scotland Working Party.

Logan F., 1998. *A Comparative Analysis of the effectiveness of a Grass Swale and a Filter at Reducing Pollutant Loads in Urban Runoff.* Unpublished MSc Dissertation, University of Edinburgh.

Macdonald K., 2000. Monitoring the effectiveness of SUDS in Scotland. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Macdonald K. and Jefferies C., 2000. Roadside swales for source control. *Proc.* Standing Conf. on Stormwater Source Control, Volume XX, Coventry University, ISBN 0 905949 99 4.

Macdonald K. and Jefferies C., 2003. Performance and comparison of two swales. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.147-157.

Macer-Wright R., Brock M. and Ripton P., 2003. A study of a design and implementation of a sustainable drainage system (SUDS) at the A120 Stansted yo Braintree. *Proc.* 2nd Nat. Conf. on Sustainable Drainage, Coventry University, ISBN 1 903818 27 3, pp.71-80.

McKissock G., 2000. Routine monitoring of best management practice drainage systems. SUDS Monitoring Workshop, 26 January 2000, Edinburgh University. Organised by the Sustainable Urban Drainage Systems Monitoring Group, organiser C. Jefferies, University of Abertay, Dundee, Scotland.

Patty L., Real B. and Gril J.J., 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from runoff water. *Pestic. Sci.*, 49, pp.243-251.

Pratt C.J., 1995. Infiltration drainage – case studies of UK practice. *Project Report 22,*Construction Industry Research and Information Association, London, SW1P 3AU; also known as National Rivers Authority R & D Note 485.

Rushton B., 2002. Enhanced parking lot design for stormwater treatment. *Proc*. 9th Int. Conf. on Urban Drainage, *Global Solutions for Urban Drainage*, Eds. E W Strecker and W C Huber, Portland, Oregon, USA. ISBN 0 7844 0644 8 (40644-002-002.pdf).

Scholl J.E., 1987. Parking lot drainage design: Gainsville, Florida. *Proc.* 1987 Nat. Conf. on Hydraulic Engineering, Williamsburg, VA., USA. ASCE, pp.147-152.

Spitzer A., 1999. *Monitoring the Performance of a Swale in Emmock Woods, Dundee.* Unpublished Undergraduate Project Report, University of Abertay, Dundee.

Wigington P.J., Randall C.W. and Grizzard T.J., 1986. Accumulation of selected trace metals in soils of urban runoff swale drains. *Water Resources Bulletin*, 22(1), pp. 73-79.

Yousef Y.A., Hvitved-Jacobsen T., Wanielista M.P. and Harper H.H. 1987. Removal of contaminants in highway runoff flowing through swales. *Sci.Tot.Env.*, 59, pp391-399.

Yu S.L. and Benelmouffok D., 1990. Field tests of urban best management practices for controlling stormwater pollution. In: *Drainage Systems and Runoff Reduction,* Eds. Y. Iwasa and T. Sueishi, (Proc. 5th Int. Conf. on Urban Storm Drainage, Vol.2), Osaka, Japan, pp. 805-808.