Urban drainage impacts on receiving waters

Impact des drainages urbains sur les eaux réceptrices

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ABSTRACT
The paper deals with the causes and consequences of urban storm drainage impacts on receiving waters and discusses available methods and tools for implementation of structural as well as non-structural measures to improve surface water quality from the deleterious effects of such intermittent urban discharges. Pollution of receiving waters must be understood on the basis of the characteristics and processes of controlling interactions within the urban water and wastewater system in order that an operational procedure for improved quality of the surface waters and adjacent corridor can be achieved. The main aspects of such a procedure involve water quality and biotic criteria as well as modelling systems which enable the user to link together the effect of changes within the catchment or surface water system with a specific quality and ecological improvement of the receiving waters.

RÉSUMÉ
L'article traite des causes et conséquences de l'impact du drainage urbain des eaux d'orage sur le milieu récepteur et discute des méthodes disponibles et des outils pour la mise en oeuvre des mesures structurelles ou non-structurelles capables d'améliorer la qualité de l'eau de surface en la mettant à l'abri des effects désastreux dus à ces rapports intermittents indésirables. La pollution des eaux réceptrices doit être envisagée sous l'angle du contrôle des interactions entre rejets urbains et réseaux d'assainissement de sorte qu'une procédure opérationnelle puisse être élaborée pour l'amélioration de la qualité des eaux superficielles et du milieu naturel voisin. Les principaux aspects d'une telle procédure mettent en oeuvre des critères de qualité de l'eau et des critères biotiques ainsi que des modélisations capables de quantifier l'influence des modifications du système de collecte sur la qualité des eaux réceptrices.

1 Introduction

During the last 100–200 years urbanization has modified and degraded what were previously high quality surface waters in many countries through the world. Changes in surface water morphology and water quality have typically been a consequence of changes in land use and inadequate urban planning. Regulation and drainage of rural areas for intensive agricultural use have added to this undesirable modification of surface water processes. The challenge today concerning urban drainage impacts is to achieve a diverse and stable aquatic ecosystem and to create valuable recreational and amenity areas. Encouraged by the public and stimulated by political interests and legislative requirements, scientists, city planners and engineers need to develop appropriate methods and tools to enable the urban water and wastewater cycle to operate at a higher quality and more sustainable level.
The quality and habitat of a receiving water system is defined in terms of a combination of physical, chemical and biological characteristics. A receiving water system is not just affected by dry and wet weather discharges from the catchment but also influenced by the historical development of the catchment and the actual operation of the entire wastewater system including the receiving waters. Each part of the system has its own characteristics; the challenge is based on analysis of the entire

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system to identify why a specified quality and habitat level may not be met and to propose efficient structural and non-structural solutions for improvement. In this respect, inpacts can be considered in the context of a regulatory or analysis framework that includes social and institutional as well as scientific and technical issues. An impact is therefore defined as the outcome of effects which result in changes exceeding a required or desirable threshold.

2 Receiving Water Impacts and Processes

2.1 *Characteristics of the catchment system*

Generally two types of wet weather pollutant sources exist:

- Discharges from combined sewer systems (CSOs) by which a mixture of domestic and industrial wastewater, urban surface runoff and sewer deposits are discharged into receiving waters. Depending on the rain and the design and operation of the sewer system, the relative importance of these three parts may vary. Often the sewer deposits play a dominating role.
- Discharges from surface runoff outfalls (stormwater runoff, SWR or stormwater overflow, SWO) by which mainly the runoff from urban or highway surfaces is discharged.

In addition, final effluents from wastewater treatment plants may have enhanced concentrations of especially sludge and ammonia under high flow conditions.

2.2 *Characteristics of the loading*

The CSOs and SWRs are different with respect to the volume discharged, the concentrations of pollutants and the frequency of discharge. In a well designed and operated combined sewer system, the annual amount of CSO volume discharged should be reduced compared with SWR from a comparable separately sewered system. CSO is characterized by the relative importance of the three components: wastewater, surface water and sewer deposits. Pollutants in terms of biodegradable organics, suspended solids and ammonia may be important and depending on the requirements for local trade effluent treatment, a relatively high amount of heavy metals and organic compounds may be also discharged. Pollutant concentrations in SWR are generally lower compared with CSO, but due to the relatively higher amount af water volume discharged on an annual basis, both heavy metals and organic micropollutants may be important (Ellis, 1986).

Table 1. Characteristic values for selected SMCs of pollutants in CSO and SWR in Denmark, (Hvitved-Jacobsen et al., 1994).

Pollutant	CSO	SWR
SS (mg/l)	100–200	30–100
COD (mg/l)	60–200	40–60
BOD_5 (mg/l)	25	5
tot N (mg/l)	10	2
tot P (mg/l)	2.5	0.5
Pb (μg/l)	100–150	50–150
Zn (μg/l)	300–500	300–500
Cd (μg/l)	1–1.5	0.5–3
Cu (μg/l)	30–40	5–40
E. coli (100 ml^{-1})	10^7–10^8	10^3–10^4

The concentration of a pollutant in CSO and SWR may be defined in terms of an event mean concentration (EMC) and a site mean concentration (SMC). The variability of pollutant concentration is high from event to event and from site to site. At a specific site, the standard deviation of the EMCs are typically of the same order of magnitude as the SMC. The SMCs may also vary considerable, not just between countries but also within a country, cf. Table 1.

2.3 *Characteristics of the pollutants discharged*

The time scale of the pollutant effect on the receiving water is an essential factor to be considered (Figure 1). The typical recovery time after a CSO event considering the time constraints shown in Figure 1, is in the order of 5–7 days. With a frequency of 5–10 events per year this implies a local violation of traditional standards during some 25 to 100 days per year. For SWR the recovery period is even shorter being typically 1–2 days.
Basically the effect of a pollutant is acute or accumulative. If the effect is acute, the impact from single events are important, particularly those of extreme frequency. The maximum pollutant EMCs are consistently observed to occur in response to the initial 12–15 mm of effective rainfall-runoff with significantly lower runoff concentrations occurring thereafter. Therefore, the pollutant rate which discharges to a receiving water system can be a better indicator of the acute impact of individual storms. A "first-flush" of sediment and sediment-associated pollutants typically occurs during the initial periods of storm flow with some 65–75% of the total SS load being discharged with the first 25–30% of the runoff volume (Verbanck et al., 1994).
If the effect is of the cumulative type, it is important to consider the discharge over a certain time period, typically a year. In this case the variability of the pollutant load from storm to storm is not important, and the computational description can be based on the SMC and the volume discharged during the period.

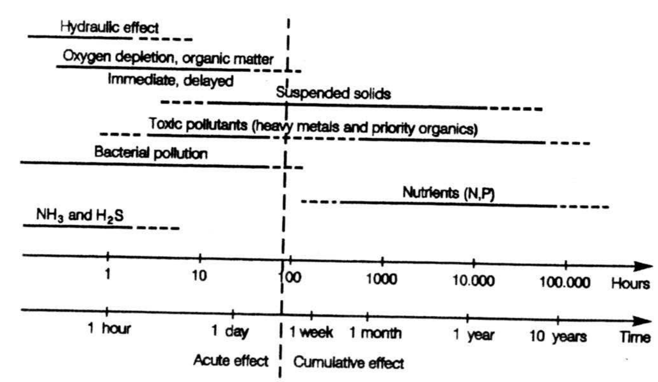

Fig. 1. Time scale for receiving water effects from intermittent pollutant discharges.

2.4 *Processes in receiving waters*

The impacts of intermittent discharges from CSO, SWR or wet weather shock loads from treatment plants on the quality of receiving waters must be assessed from the quantified determination of the increase – or decrease – in receiving water mass concentration or amount of pollutant accumulated.

This is because they relate to any possible violation of water quality criteria or standards as well as disturbance of the biotic equilibrium. The varying responses are a result of process interactions which take place in the receiving water:

- Physical processes, e.g. transport, mixing, dilution, sedimentation, erosion, thermal effects and reaeration.
- Biochemical and physico-chemical processes, e.g. transformation of organic matter, adsorption and desorption of heavy metals and organic micropollutants.
- Biological processes, e.g. die-off of bacteria and viruses and changes in benthic communities.

The episodic wet weather processes are superimposed upon the normal dry weather process variations and the importance of this interaction must therefore be dealt with. It should also take into account the integrated negative impacts that urbanization has on receiving waters due to processes which peturb the long term physical, chemical as well as biological characteristics. The combination of changed physical habitat and altered water quality brought about by engineered regulation of the urban drainage system must be recognised as the major environmental consequences of urban runoff.

3 Water Quality and Habitat Changes

Receiving water impacts must be evaluated in terms of the individual characteristics of each site. This impact evaluation needs to consider four basic categories of concern which affect the value of the receiving water for such uses as water abstraction, ecological habitat, recreation and amenity.

- Physical habitat changes
- Water quality changes
- Public health risks
- Aesthetic deterioration and public perception

3.1 *Physical habitat changes*

Urbanisation can permanently modify the nature, form and behaviour of receiving water bodies. Open stream channels in urban areas may be concrete lined or "canalised" to keep the flood channel from changing position and to provide for improved storm flow conveyance or may have been changed to accomodate site development. The most severe modifications involve complete containment. Where natural channels remain in urbanised areas they are typically punctuated by reaches where the stream channel is constrained or modified.
These modified and loaded urban stream channels will have altered fluvial dynamics typified by increased sedimentation and high erosion potential which influences stream morphology and channel characteristics as well as local habitat and substrate conditions. The physical processes may impose long-term changes to the stream channel far downstream from the immediate urbanised area. The recognised result is that the main channel-forming process is the dominant flood flow.

3.2 *Water quality changes*

Dissolved oxygen depletion and fish kills: Dissolved oxygen (DO) depletion from urban intermittent discharges, especially CSO, is a well known phenomenon. Soluble and fine particulate

organics are transported in the water phase and exert an immediate DO depletion and the scouring effect on the sediments in the receiving systems from increased flow during rain may add to this phenomenon, (Kreutzberger et al., 1980). Settleable solids accumulate at the bottom and result in a delayed DO depletion due to an increase in the SOD or sediment oxygen demand, (Hvitved-Jacobsen and Harremoës, 1982; Hvitved-Jacobsen, 1986). Typical undisturbed SOD levels vary between 0.15 and 2.75 g/m^2/d, which can account for a permanent deficit of about 1.5–2.5 mg/l in the DO regime of the receiving water. Such delayed effects may last for 1–2 days. If the intermittent discharges are frequent, the diurnal DO fluctuation may be dampened and the overall DO level may be reduced, (Huber, 1986).
Fish kills, especially for small rivers, are the most apparent effect of acute reduced DO levels. Reported data reveal varying impacts for various species at different exposures and temperature level. Sublethal effects on fish, e.g. reduced growth, may be a result of reduced DO concentration level. (Figure 2).

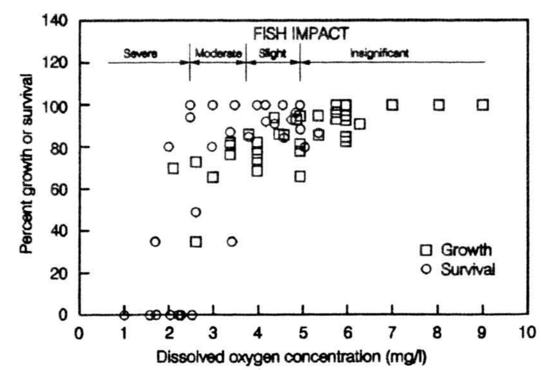

Fig. 2. Impact of long term DO concentrations on fish growth and survival, (Limo-Tech Ltd, 1987).

Eutrophication: Excessive growth of macrophytes and algae is typically caused by nutrients from either non-urban sources or wastewater treatment plant outlets. However, urban runoff into especially stagnant or semi-stagnant waters like shallow lakes, may locally result in eutrophication problems.

Sediment and toxic pollutant impacts: Sediments influence the fate of many toxic and bioaccumulative materials in urban receiving water ecosystems and constitute both a sink and a potential source of pollutants. In general, materials accumulating on the bed of receiving waters provide a poor habitat for most plant and animal species. Materials discharged from CSO and SWR may contribute a range of adsorbable and settleable pollutants derived from sewer deposits, wastewater and urban surfaces. Due to the nature and amount of biodegradable organics, anaerobic conditions may prevail in such receiving water sediments and accumulated metals, hydrocarbons and bacteria can then impose long term impacts on the sediment community. Localised acute effects may also follow storm flow induced scour and resuspension of toxic substances such as hydrocarbons, heavy metals and ammonia, in addition to increased sediment oxygen demands. Bed disturbance resulting from elevated shear stress (3–5 N/m^2) can increase SOD levels into the range of 240–1500 g/m^2/d and depress normally near-saturation, in-stream levels down to 2 mg/l or less (Ellis, 1986). Such effects will be superimposed upon the short term impacts associated with the sewer pollutant discharge and sediment quality criteria (SQC) are required to interpret and assess the ecological significance of such sediment-associated pollutants. Ideally, such criteria should be developed from dose-response data describing acute and chronic toxicity impacts of individual contaminants on specific organisms based on considerations of both an "effects threshold" approach and recovery times (Ellis et al., 1995).

Impact on biological communities: The generic characteristics of urban receiving water ecology are habitat instability and ecotoxicity. The urban stream is dominated by taxa which can tolerate successive erosional-depositional sequences and transient, low-quality food sources with short retention times for organic matter (Pederson and Perkins, 1986). Regulators and water users in both Europe and North America are increasingly accepting that in-stream ecological protection must be recognised as an independent objective of stormwater management. If this is accepted, it is necessary to measure the achievement of such objectives in biological terms rather than being expressed through any proxy chemical parameters. It might also prove to be cost-effective to utilise biological and bioassay procedures for monitoring and predicting actual receiving water impacts at both intermediate and long term time scales. There is in addition, a need to predict the likely rates of recovery of urban ecosystems damaged by episodic toxicity events.
Investigations undertaken in the UK and the Netherlands into the effects of CSO on biological communites have shown a complex pattern of response, (Seager and Abrahams, 1990; Lijklema et al., 1989). The most important biological effects were found to be physically induced and restricted to the immediate downstream mixing zone; up to perhaps 250–300m from the outfall. Increased flow and high bed shear during storm events caused the removal of planktonic organisms and benthic invertebrate species; and changes in turbidity affected the light regime which in turn caused changes in phytoplankton turnover rate. Large increases in the number of oligochaetes, particularly tubificid worms, were also observed downstream of CSOs as a result of accumulated organic deposits. Similar patterns of reduced biotic community status and diversity have been noted in North American studies where faunal changes and biotic disruption through urban environments have been observed (Pratt et al., 1981; Garie and McIntosh, 1986).

Groundwater impacts: Many county and metropolitan authorities in the United States have discontinued or severely restricted conventional deicing applications to urban surfaces because of concerns over potential groundwater contamination from infiltrating runoff (Lord, 1989) and rising groundwater levels in urban areas is an increasingly common problem in Europe. The non-agricultural use of herbicides for the control of vegetation in urban areas is also giving rise to levels above the drinking water standard in adjacent groundwaters. As much as 34% of applied herbicide can be lost in surface runoff and resulting groundwater triazine levels can frequently exceed 1.5–2.0 g/l (Ellis et al., 1996). At present, the transport mechanisms and underlying factors that determine the transmission of toxic organic pollutants from hard surfaces to groundwater are poorly understood. Until this situation changes allowing the formulation of more accurate risk assessments of the possible impacts on groundwater quality, the use of herbicides in urban areas will continue to be a significant environmental issue.

Quality impacts and monitoring: Although urban runoff discharges are intermittent in nature, the resultant water quality problems can be of either an acute or a chronic nature, whose effects should

be evaluated on the basis of extreme event statistics and accumulated loadings, respectively. It is evident that dynamic, high-rate processes will require a high sampling and monitoring frequency at the end-of-pipe or in the mixing zone, whereas the chronic effects can be observed independently from the individual event and on a wider spatial scale beyond the mixing zone.

3.3 *Public health risks*

The design of CSO and SWR means that untreated sanitary wastewaters and contaminated effluents will always discharge to urban receiving waters. This must raise public health risks related to potential exposure risks, particularly if the receiving waters are used for contact recreational purposes. In addition to bathing and sailing activities, shellfish consumption in areas exposed to urban runoff is a potential health risk.
It is widely recognised that urban runoff contains a wide variety and frequently high numbers of pathogenic bacteria and viruses. Mandatory bacterial levels are often violated in urban receiving waters, especially during the first-flush period of storm events (House et al., 1993). The current EU guideline limit for contact water sport of 100 MPN per 100ml is typically exceeded for more than 80% of the time with effective rainfall depths as little as 5 mm (Ellis, 1993). Bacteria also become encapsulated in bed sediment where survival times become considerably extended. With a return period for CSO discharge of 1–3 months, sediments near outfalls are potentially permanently contaminated with *E.coli, faecal coli and faecal streptococci.*
The true bacteriological impacts of urban discharges in terms of recreational risk remain uncertain and controversial. Many American states, such as North Carolina, have specified that the EPA freshwater criteria will not be applicable during or immediately following wet weather periods. However, even mandatory compliance with either FC or enterococci criteria will not guarantee absence of other pathogens such as *Pseudomonas* or *Salmonella.*

3.4 *Aesthetic deterioration and public perception*

Research into the public's perception of water quality, rivers and river corridors, and the potential for the compatible management of rivers for a range of water uses including recreation and nature conservation, has been undertaken in the USA and UK (House et al., 1993). Results from these investigations suggest that the public has a clear idea of what they consider to be a polluted river but are less certain of what constitutes clean water. The public perceive most urban rivers as being polluted, even those which may be of good chemical and biological quality. Differences between the user groups showed walkers to be the most critical of water quality with canoeists and anglers being less critical. This reflects the importance of water use and possibly the degree of contact with the water. The recently formed UK Environmental Agency is considering the introduction of aesthetic impact parameters in their new General Quality Assessment (GQA) scheme for water quality classification and this will inevitably downgrade urban waters subject to sewage-derived contaminants.

4 Quality and Ecological Criteria

The complex dynamic and event based nature of intermittent urban discharges and the associated complicated acute and chronic effects, make it more difficult to propose a criterion similar to the standards and control strategies for continuous discharges. Several researchers have suggested that development of criteria for effects from intermittent discharges are required in order to assess sewer

performance and to provide ecologically relevant receiving water goals. Pollutant concentration profiles or the resulting effect curves must be defined in terms of magnitude, duration and frequency of rain events together with a specification of which organisms should be protected in order to observe required water uses. Criteria in this form can then be applied in conjunction with modelling procedures for assessing sewer performance in relation to receiving water quality objectives.
Much of the research effort to date has been directed towards the problems of continuous urban discharges from wastewater treatment plants and from industrial premises. In contrast, comparatively little attention has been given to the development of appropriate control criteria for intermittent discharges of urban stormwater. One of the principal difficulties with the study of this problem is that pollution arising from urban stormwater discharges is stochastic in nature. This means that conventional monitoring approaches based on routine "spot" sampling are generally inappropriate. Intensive studies are needed which exploit automated sampling devices and continuous monitoring equipment to allow water quality during – including before and after – rainfall events to be assessed.

4.1 *Biological monitoring*

Biological monitoring techniques have been recognised as being useful in the assessment of the effect of repeated and complex discharges on receiving water quality and the development of meaningful water quality criteria. Because biological communities will take time to recover, their status will often reflect the recent pollution history at the site. However, the biota also reflect the integrated total of their physical and chemical environment, which in waters affected by urban stormwater discharges may be complex given the varying mixture of different pollutants.
Biological assessment procedures for determining the impact of episodic pollution can be categorised into single and multi-species approaches. The former include the use of indicator species, biosensors and bioaccumulators whereas the latter include the use of community structure indices (biotic, diversity and comparative indices) and functional methods (metabolism, colonisation). Interpretation of the highly variable response of aquatic communities to intermittent pollution from urban catchments and the development of water quality criteria can be greatly assisted by the development of ecotoxicological techniques in field-based studies and laboratory simulations.

In situ acute toxicity methods: Acute toxicity of discharges from CSO have been assessed using caged freshwater shrimps, Gammarus pulex, (Seager and Milne, 1990) and the acute toxicity of these discharges have been proved to be statistically significant. The combination of tissue metal threshold levels with acute and chronic LC values and event return frequency has also been suggested as a protocol for monitoring water quality standards (Ellis et al., 1995).

In situ bioaccumulation methods: Gammarus and asellus species have been used frequently in urban runoff bioaccumulation tests. Ellis et al.,(1995) have identified an initial enhancement of adsorbed metals in these species which subsequently declines and is overtaken by accumulation within the soft tissue. An automated biomonitoring device based on the measurement of gill ventilation responses has been used by Seager and Maltby (1989).

Laboratory simulations: Fish species as well as invertebrates have been used in such simulation experiments. The most usual experimental design is to apply a constant dose of toxin or mixture of toxins in the water and measure either lethal or sub-lethal responses of the test organisms for a fixed

period of time. However, this investigation approach is unlikely to yield predictive data appropriate to a field situation where the concentration and toxic effect of toxins may fluctuate markedly due to changes in the pollution input or variation in the properties of the site itself such as flow, pH, alkalinity and temperature.

Community assessments: Community status and diversity indices have been widely used for assessing the impact of effluents on macroinvertebrate communities. The former is normally expressed as a biotic score, as species richness (total taxa) or as some index of diversity. One simple method involves the comparison of downstream biotic scores against percentile bands for the distribution differences in upstream scores. A 40% difference threshold may be taken as being indicative of a biological impact. However, site-specific conditions may overshadow effects of discharges for many of the biological components in the urban ecosystem. Nevertheless, the use of invertebrate community data (based on weighted biotic scores and paired percentile differences) can give a useful severity index when used in conjunction with fungal assessment and aesthetic evaluation of litter and gross solids. Such rapid bioassessment protocols may offer the most cost-effective means of assessing the impacts of urban runoff especially if a degraded site can be referenced against a "non-impaired" site.

4.2 *Water quality criteria for intermittent discharges*

The conventional approach to deriving standards is to specify a quantitative consent level for intermittent discharges such as a maximum acceptable concentration (MAC value) as expressed by the 99 percentile or some other statistic in conjunction with a simple mass balance method. Compliance is then assessed by taking a series of spot samples throughout the year and calculating the appropriate statistic. Whilst this approach has given encouraging results, the implication still remains that unsatisfactory discharges of unspecified quality could still occur on three days or more (app.>1%) per year. The basic question therefore remains as to whether this level of pollution risk is acceptable and if such statistical standards are suitable for translation into design criteria for sewerage systems. What is required is an approach to setting standards which takes into account not only the concentration of pollutants, but also the duration and frequency of polluting events combined where possible with ecological criteria.
Both the UK and Denmark have developed guidelines which specify magnitude, duration and frequency of allowable DO concentrations for the protection of freshwater fish. The UK procedure (Figure 3.a) is based on 3-dimensional specification of 1 hour and 24 hour criteria utilising extrapolations of laboratory and literature based LC50 data (Water Research Centre, 1990). The Danish water quality criterion (Figure 3.b) is fundamentally similar to that of the UK (Hvitved-Jacobsen, 1984). The criterion selected is that half the fish population may be killed at the DO concentration and duration indicated for the rarest events (from 8 to 16 years return period). The criterion is given for two durations of exposure time, 1 and 12 hours. The Danish criterion is now in operation and applied for sewerage renovation projects, (Hvitved-Jacobsen and Dahl, 1994). The recommended short duration standards of both the UK and Danish methods may make enforcement by the appropriate water authorities difficult to achieve, especially for the low values having a low probability of recurrence. In practice, compliance with the standards can only be evaluated through mathematical modelling.
Mancini (1989) has proposed wet weather criteria based upon acute toxicity values (1 hour exposure), characteristic duration of runoff and of rain interval and expected stream concentration of the toxicant. Consideration of both the probability of extreme runoff events and the possible relation-

ship with subsequent events, can then allow this type of analysis to indicate whether further treatment is needed. The method does not formulate a standard having any stochastic component, but accounts for the variability by a transformation of the concentration of the runoff after dilution in the receiving water.

5 Wet Weather Water Quality Modelling

5.1 *Characteristics of urban runoff modelling*

From a modelling point of view it can be concluded that it is very important whether the pollutional effect is a result of a pollutant having an acute or chronic effect, (Harremoës, 1986). If an acute effect is the basis for the water quality model then the model must, as a fundamental characteristic, include the possibility to simulate the effect related to a single event. On the other hand, if a chronic effect is to be modelled, the pollutant loadings from urban runoff can typically be converted to a constant discharge. This approach is therefore similar to models based on continuous discharges, e.g. like well known eutrophication models.
The type of discharge, whether from CSO, a SWR/SWO or a treatment plant under transient load, are different with respect to the volume discharged and the concentrations of pollutants in the water phase; e.g. acute effects will typically originate from CSOs.

5.2 *Deterministic and stochastic modelling*

A deterministic model is characterised by its well defined processes and constant process parameters. The level of variability associated with the use of deterministic urban runoff quality models when simulating acute effects is considerably greater than that of dry weather models. This is primarily because the wet weather processes are generally less documented than for dry weather situations and because the variability from event to event of both pollutant loadings and characteristic model parameters are typically large. These problems associated with deterministic modelling make it interesting to consider the stochastic modelling principle, e.g. the grey-box model concept, (Jacobsen et al., 1995).

5.3 *Examples of model systems*

Systems to be used in urban runoff modelling will not be discussed here. However, the following systems which have been particularly designed for this purpose will be mentioned:

- LEVEL II/SWMM (USEPA)
- WALLRUS/MOSQITO/STOAT/MIKE 11, (Fiddes and Clifforde, 1990)
- MOUSE/SAMBA/DOSMO, (Lindberg and Joergensen, 1986;
- Schaarup-Jensen and Hvitved-Jacobsen, 1990)
- FLUPOL/KALPLAN, (Bujon and Herremans, 1992)

The main interests – concerning the acute effects – are in most cases associated with the statistical properties of the detrimental effects. A model system must therefore typical include the coupling of a site specific historical rainfall series, an urban runoff model, a receiving water quality model and a criterion for evaluation of model results.

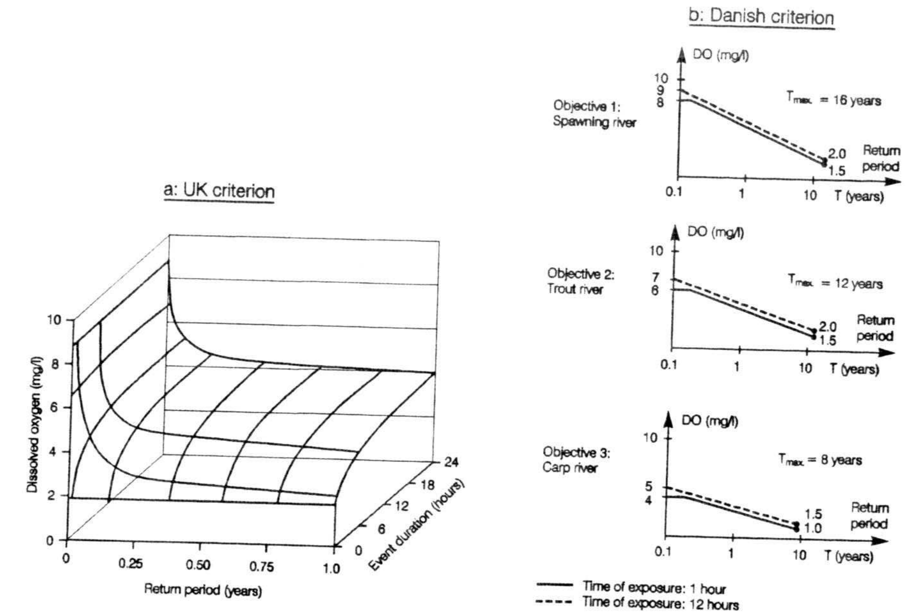

Fig. 3. The UK DO criterion for intermittent discharges, (Water Research Centre, 1990), and the water quality criterion recommended by the Danish Water Pollution Control Committee for the DO concentration in rivers receiving discharges of CSO, (Hvitved-Jacobsen, 1984).

5.4 *Ecotoxicological modelling*

The redistribution or partitioning of pollutants both during and after a storm event between water, solids/sediment and biota is of interest to both acute and chronic impacts. Equilibrium partitioning between sediment, normally expressed as the suspended solid fraction, and the dissolved (or freely available) fraction, is a commonly adopted approach to toxic risk assessment. The dissolved concentration is most representative of the bioavailable fraction but such modelling approaches need verifying by bioassay methods. Partition modelling needs to be extended to the biotic phase and already joint toxicity and bioaccumulation are being considered in the development of future Dutch water quality standards. However, many severe problems remain to be solved and indeed may not be capable of solution beyond a certain point. This means that in dealing with episodic urban runoff impacts, ecotoxicological modelling may have to give way to more pragmatic methods.

6 Research Needs and Trends

There is a trend to take a more holistic view of urban drainage. This trend has been clearly demonstrated during recent international conferences, e.g. the 2nd International Conference on Innovative

Technologies in Urban Storm Drainage (Novatech 95) and a UNESCO Workshop on Integrated Water Resources Management in Urban and Surrounding Areas. In view of a sustainable development in urban areas, there is a need to continue this trend.

Examples of this trend are: the sewer, the treatment plant and the local receiving water system being considered as an entity; planning, sustainable integrated development and ecological enhancement of urban rivers and river corridors (Ellis, 1995). Technical means are not just looked upon as pollution control devices but more and more as an integrated and "innovative" part of the natural water system. Furthermore, institutional aspects, socio-economic consequences and public involvement are of increasing importance (Clifforde et al., 1995).

What is still needed is research concerning the development of methods and tools which may give a more clear load-effect relationship for intermittent discharges and which may improve the possibilities for model simulations. In addition, techniques and measures supporting post-failure recovery are of crucial importance; recovery analysis is essential to the integrity and success of sustainable urban runoff management and in mitigating the long term receiving water impacts of urban discharges.

7 References

BUJON, G. and L. HERREMANS (1992), KALPLAN: A model to forcast the impact of permanent or intermittent influent on river quality, Proceedings of INTERURBA, Wageningen, The Netherlands, April 6–10, 1992; appendix A.

CLIFFORDE, I., G. MORRIS and B. CRABTREE (1995), The UK response to the challenge of urban stormwater management, Wat. Sci. & Tech., 32 (1), 177–183.

ELLIS, J. B. (1986), Pollutional aspects of urban runoff, In: H.C. Torno, J. Marsalek and M. Desbordes, Nato ASI Series, vol.G10, Urban Runoff Pollution, Springer-Verlag, Berlin, 1–38.

ELLIS, J. B. (1993), Achieving standards for the recreational use of urban waters, In: D. Kay and R. Hanbury, Recreational Water Quality Management, Ellis Horwood, London, 155–174.

ELLIS, J. B. (1995), Integrated approaches for achieving sustainable development of urban storm drainage, Wat. Sci. Tech., 32 (1), 1–6.

ELLIS, J. B., R. B. SHUTES and D. M. REVITT. (1995), Ecotoxicological approaches and criteria for the assessment of urban runoff impacts on receiving waters, In: E.E. Herricks, Stormwater Runoff and Receiving Systems, CRC Press, Boca Raton, Florida, 113–125.

ELLIS, J. B., D. M. REVITT and N. LLEWELLYN (1996), Transport and the environment: Effects of organic pollutants on water quality, Journ. Inst. Water Eng. & Mgt., 20, (In Press).

FIDDES, D. and I. T. CLIFFORDE (1990), River basin management: Developing the tools, Journ. Inst. Water & Env. Mgt., 4,

GARIE, H. L. and A. MCINTOSH (1986), Distribution of benthic macroinvertebrates in a stream exposed to urban runoff, Water Resources Bull., 22(3), 447–455.

HARREMOËS, P. (1986), Interaction between quantity and quality models for urban storm drainage, In: C. Maksimovic and M. Radojkovic, Urban Drainage Modelling, Pergamon Press, Oxford, 1–15.

HOUSE, M. A., J. B. ELLIS, E. E. HERRICKS, T. HVITVED-JACOBSEN, J. SEAGER, L. LIJKLEMA, H. AALDERINK and I. T. CLIFFORDE (1993), Urban drainage – impacts on receiving water quality, Wat. Sci. Tech., 27 (12), 117-158.

HUBER, W.C. (1986), Modelling urban runoff quality: State-of-the-art. In: Modelling Runoff Quality, eds., Torno, H.C., Masalec, J. and Desbordes, M., Springer Verlag, Heidelberg.

HVITVED-JACOBSEN, T. (1986), Conventional pollutant impacts on receiving waters. In: H.C. TORNO, J. MARSALEK and M. DESBORDES, NATO ASI Series, vol. G10, Urban Runoff Pollution, Springer-Verlag, Berlin, 345–378.

HVITVED-JACOBSEN, T., N. B. JOHANSEN and Y. A. YOUSEF (1994), Treatment systems for urban and highway run-off in Denmark, The Science of the Total Environment, 146/147, 499–506.

HVITVED-JACOBSEN, T. (1984), Forurening af vandløb fra overløbsbygværker (Pollution of rivers from overflow structures), report submitted to the Danish Water Pollution Control Committee, Draft to publication no. 22 and translated by the UK Water Research Centre, Aalborg, Denmark, pp 97.

HVITVED-JACOBSEN, T. and A. DAHL (1994), Water quality concerns in the management of combined sewer overflows to streams – a case study from the municipality of Aalborg, Denmark, Proceedings from an UNESCO Workshop on Integrated Water Resources Management in Urban and Surrounding Areas, May 29 – June 2, 1994, Gelsenkirchen, Germany, pp. 20.

HVITVED-JACOBSEN, T. and P. HARREMOËS (1982), Impact of CSOs on the DO in receiving streams. In Urban Stormwater Qality, Management and Planning, ed. Yen, B.C., Water Res. Publ. Littleton, Colorado, 226–235.

JACOBSEN, J., H. MADSEN and P. HARREMOËS (1995), Modelling of transient impact of rain events on the oxygen content of a small creek, Proceedings from an International Symposium on Uncertainty, Risk and Transient Pollution Control, July 26–28, 1995, Exeter, UK.

KREUTZBERGER, W. A., R. A. RACE, T. L. MEINHOLZ, M. HARPER and J. IBACH (1980), Impact of sediments on dissolved oxygen concentrations following combined sewer overflows. J. Wat. Poll. Contr. Fed., 52 (1), 192–201.

LIJKLEMA, L., R. M. ROIJACKERS and J. G. M. CUPPER (1989), Biological Assessment of effects of CSOs and stormwater discharges. In: Urban Discharges and Receiving Water Quality Impacts. (Adv. Wat. Poll. Control No. 7), ed., Ellis, J.B., Pergamon Press, Oxford, pp. 37–46.

Limno-Tech Ltd. (1987), Assessment of Existing CSO Related Conditions. Dept. of Env. Services, Richmond, Virginia.

LINDBERG, S and T. W. JOERGENSEN (1986), Modelling of urban storm sewer systems. In: C. Maksimovic and M. Radojkovic, Urban Drainage Modelling, Pergamon Press, Oxford, 171–181.

LORD, B. (1989), Program to reduce deicing chemical use, In: L.A. Roesner, B. Urbonas and M.B. Sonnen, Design of Urban Runoff Quality Controls, Amer.Soc. Civil Eng., New York, 421–435.

MANCINI, J. L. (1989), Urban discharges and water quality criteria: Towards the development of wet weather criteria. In: Urban Discharges and Receiving Water Quality Impacts, ed., J. B. Ellis Advances in Water Pollution Control No. 7, Pergamon Press, pp. 65–73.

PEDERSON, E. R. and M. A. PERKINS (1986), The use of benthic invertebrate data for evaluating impacts of urban runoff, Hydrobiologia, 139, 13–22.

PRATT, J. M., R. A. COLER and P. J GODFREY (1981), Ecological effects of urban stormwater runoff on benthic invertebrates inhabiting the Green River, MA, Hydrobiologia, 83, 29–42.

SCHAARUP-JENSEN, K. and T. HVITVED-JACOBSEN (1990), Dissolved oxygen stream model for combined sewer overflows, Wat. Sci. & Tech., 22 (10/11), 137–146.

SEAGER, J. and L. MALTBY (1989), Assessing the impact of episodic pollution. Hydrobiologia 188/189: 633–640.

SEAGER, J. and R. ABRAHAMS (1990), The Impact of Storm Sewerage Discharges on the Ecology of a Small Urban river. Watr. Sci.Tech. 22 (10/11): 163–171.

SEAGER, J. and I. MILNE (1990), Ecological Impact of combined sewer overflow discharges. In: Drainage Models and Quality Issues. eds., Iwasa, Y. and T. Sueishi, Proc. of the 5th International Conference on Urban Storm Drainage, Suita, Osaka, Japan, July 23-27, 1990, volume 1, 529–534.

VERBANCK, M. A., R. M. ASHLEY and A. BACHOC. (1994), Origin, occurrence and behaviour of sediments in sewer systems, Water Research, 28, 187–194.

Water Research Centre. (1990), Proposed Water Quality Criteria for the Protection of Aquatic Life from Intermittent Pollution, Report PRS2498-NM, Water Research centre, Medmenham, UK.

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Stormwater detention & BMPs

Rétention des débits d'orages et méthodes de gestion optimale (BMPs)

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ABSTRACT

The Paper outlines the considerations involved in stormwater hydrological and pollutant mobilisation processes, and the selection of stormwater detention and pollution control Best Management Practices (BMPs). In addition, it provides a summary of the major BMPs commonly used, including material on their purpose, description and performance. A Table is included providing broad indications of pollutant removal and flow attenuation capacities of each BMP. The non-structural range of BMPs summarised includes the modification of the use and disposal practices of household chemicals, land uses and management practices, on-site programs of runoff management, the management of pollutant build-up, and sewer infiltration management. The structural range of BMPs summarised includes infiltration and local disposal systems, retention or restoration of natural vegetated channels, inlet controls, detention basins, retention ponds and wetlands, and in-pond treatment.

RÉSUMÉ

L'article expose brièvement les principes appliqués dans les procédés de gestion des débits d'orages et des pollutions associées, ainsi que le choix des méthodes de gestion optimale (BMPs "Best Management Pratics") des rétentions des apports des orages et du contrôle de la pollution. De plus, l'article donne un résumé des méthodes BMPs les plus couramment employées, avec indication du matériel utilisé et de ses performances. Un tableau donne des indications générales sur la dépollution et la capacité d'atténuation du débit de chaque BMP. La panoplie des BMPs non structurelles présentées comprend la modification de l'usage des produits ménagers, l'utilisation des sols, les programmes de régulation locale des débits, la maîtrise des polluants et l'infiltration des effluents. La panoplie des BMPs structurelles présentées comprend les systèmes d'infiltration et d'élimination locale, la végétalisation des lits fluviaux, des organes de contrôle des apports, des bassins de rétention, des polders ainsi que le traitement par lagunage.

1 Background

The Overview outlined the changing context of urban drainage, in relation to the growing community awareness regarding the need for environmental protection, and urban stormwater resource and open space values. This paper reviews the experience in the application of a range of urban stormwater management practices, and their performance in securing protection of environmental values. It comprises an overview of catchment processes and environmental values, and an evaluation of the overall management approaches and the individual management practices.

While the primary focus of this Paper is on quality management, quantity or runoff rates are also critical, both in respect to the generation of pollutants and peak flows. Consequently, it is necessary to undertake an integrated analysis of management practices in relation to both flows and quality. Similarly, while the primary focus is on separate stormwater and sewer systems, the management practices outlined can reduce inflow of stormwater into combined systems.

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2 Overview of catchment processes & environmental values

2.1 *Hydrological and pollutant mobilisation processes*

The natural processes of rainfall interception by vegetation and natural depressions, together with soil infiltration and storage and groundwater recharge/discharge, largely determine the volume of runoff relative to rainfall depth, and the rate of discharge. Vegetation is an important modifier of runoff processes through enhancement of interception and infiltration capacity, and evapotranspiration drawdown of soil moisture storage. Urbanisation causes major changes to the landscape. It introduces large areas of impervious surfaces, changes vegetation and soil permeability on remaining pervious areas, changes the surface drainage morphology and the interflow and throughflow to groundwater. These changes greatly increase the volume and rate of discharge and associated pollutants in stormwater runoff.

Vehicle traffic and other urban activities superimpose a range of external pollutant loads on the impervious areas. The application of fertilisers, herbicides and pesticides to pervious areas, and the resultant over-spray of these substances to adjacent impervious surfaces, can further contribute to the pollutant load on the urban landscape. Much of this deposition is mobilised by surface runoff and is transported to receiving water bodies.

The replacement of vegetated waterways or overland flow paths with pipes or concrete lined channels, and the filling and drainage of natural depressions and wetlands, substantially diminishes natural interception of runoff constituents as well. The associated increases in volumes and peak flows, especially during small rainstorms, contributes to the enhanced transport and remobilisation capacity of constituents, and exacerbates downstream flow and pollutant levels. While differences in climates, soils and urban forms and activities will result in differences in distribution of water across various runoff pathways, the basic processes remain the same. The primary focus of the stormwater management practices is to limit or prevent the changes imposed by urbanisation, or to ameliorate the impact of these changes. It is normally not feasible to return urban areas to pre-development storm water runoff response conditions, and limiting impacts to a practical level has to be the goal of stormwater management practices and programs.

2.2 *Environmental values & ambient flow & quality guidelines*

The major environmental value categories of urban and receiving waters commonly comprise the conservation of aquatic ecology; water-based and related recreation; landscape and open space aesthetic values; and water supply (municipal, stock, irrigation, industrial). The protection of these use values are defined in terms of ambient water quality guideline values. The principal urban stormwater flow and pollutant categories impacting on the water quality and ecology of receiving waters comprise increases in the variability and peak flows, and elevated catchment exports of sediment and suspended solids loads, BOD, nutrient, bacteria and trash and debris. Toxicants in discharges may impact on aquatic ecology.

As discussed in the Overview, the identification of the critical pollutants is an important consideration in the assessment of management practices. In the case of toxicants, both the acute (short-term effect) and chronic (long-term exposure or bio-accumulating effect) need to be considered. The interpretation of toxicants is complicated however by their rapid adsorption onto suspended particulate material, and by questions of their bio-availability.

2.3 *Discharge & pollutant load reduction goals*

In addition to identification of the critical pollutants, the required level of pollutant load reduction can be critical in determining the appropriateness of management measures. While the flow and water quality guidelines identify the flow regimes and ambient quality required on a continuous basis to sustain the designated environmental values, these ambient conditions need to be defined in terms of the level of permissible flows and pollutant loading consistent with the protection of the values. Unlike flood damage in which the extreme events are critical, stormwater quality impacts are related primarily to first flush and/or the cumulative effects of a large number of small scale storm events, 85 to 90 percent of which are less than a 1 in 1 year frequency (Hall, et al, 1993; Urbonas, et al, 1995). Therefore, water quality control must target the volumes typically associated with storms having a recurrence interval of usually less than 1 in 1.

2.4 *Urban planning & environmental regulation administrative context*

The administrative context will also have an important bearing on the assessment of the stormwater management measures. The catchment management planning-based approach considers the environmental values to be sustained, and land uses and associated management practices across the catchment that need to be provided to maintain these values. This is often a multi-objective-based process. Implementation is via planning and regulatory controls.

In the purely regulatory or licence-based administrative approach, the regulatory agencies may prescribe the BMPs to be applied across the catchment, or require the development of a management plan as the basis for licensing.

Implementation is primarily regulatory control-based. An information focussed administrative approach provides education material critical to both the catchment management strategy and regulatory-based approaches. In the absence of other formalised procedures, it may be the only available activity for influencing outcomes.

3 Review of management practices

As outlined above, catchment management strategies are used to identify the environmental values to be protected and the critical pollutant control needs. Individual management practices need to be understood in this wider metropolitan or catchment stormwater management strategy context, as well as in the context of the collective benefits arising from a treatment train-based approach. It is important to recognise that stormwater BMP design and performance assessment are still a growing engineering science. Table 1 summarises the pollutant removal ranges recorded by a number of investigators for a number of control practices. As the ranges imply, it is not possible to provide definitive designs to meet specified and consistent performance requirements at this time.

In addition to the environmental costs and benefits, a further category of considerations requiring assessment comprise the physical opportunities and constraints peculiar to the urban area. They comprise:

- greenfield development, with opportunities for an integrated quantity, quality and open space approach;
- retrofitting within existing development where open space and hydraulic head are extremely constrained;
- retrofitting within existing development where access to open space and hydraulic head exist;

- retrofitting within existing development in association with urban redevelopment, where there may be opportunities to establish new overland flow corridors and easements for the installation of BMPs;
- in-fill (greenfield) development within existing development, where drainage routes and grade may be restricted by the surrounding existing development.

Common to all are good housekeeping practices, pollutant source management (eg. covering of loading docks), education, regulation of illegal dumping practices, and management of construction and maintenance practices. In view of the diverse range of pollutant and peak flow reduction requirements, and the local physical, social and economic constraints, the design, operation and maintenance requirements will be site specific.

Table 1. Representative Pollutant Removal and Flow Attenuation Capacities

BMP	Pollutant Removal							Flow Attenuation	
	Trash	Solids	P	N	BOD	Metals	Bact	Peak	Volume
Percolation trenches/pits	■	■	■	□	■	○	■	□-■	□-■
Grassed swales	NA	□	□	□	□	▫	□	▫-□	▫
Grassed buffer zones	NA	▫	▫	▫	▫	▫	▫	▫-□	▫
Pervious pavements	■	▫	○	■	○	■	□	▫	▫-□
Infiltration basins	■	■	■	□	■	○	■	□-■	□-■
Vegetated waterways	NA	□	□	▫	□	▫	□	▫-□	▫
Inlet controls/traps	●	□	▫	▫	□	▫	▫	NA	NA
Detention basins (wet, dry)	NA	●	■	□	■	○	●	□-○	▫
Retention ponds/wetlands	NA	○	■-○	□-■	□-■	○	■-●	□-■	▫
Aeration	NA	NA	NA	NA	●	NA	NA	NA	NA
Street sweeping	○	□-■	▫	▫	▫	▫	▫	NA	NA

Key: Removal efficiency
● 80-100% ○ 60-80% ■ 40-60% □ 20-40% ▫ 0-20%
NA - not applicable

Notes: Level of pollutant removals will be subject to the level of provision of BMP volume or surface areas relative to catchment runoff.
In the case of catchments having silty clay or clay soils, higher levels of BMP volume or surface areas relative to catchment runoff will be required to achieve these levels of removal.
Level of flow attenuation in the case of Retention Ponds & Detention Basins is a function of storm frequency, storage provision & spillway design.
Pollutant removal levels of street sweeping is dependant on equipment used and frequency of sweeping.
As a general rule, the higher the inflow pollutant concentration the greater the level of removal.

4 Technical summary of individual practices

A. *Non-structural best management practices*

i) Modify use & disposal practices of household materials
Purpose: To promote the use and management of household chemicals, pesticides, solvents, oils, fertilisers, antifreeze, etc such as to minimise the potential for washoff or leaching or direct disposal into the stormwater system.

Description: This group of BMPs comprises:

- the education of the community regarding the potential impacts of common household chemicals on water quality and aquatic ecology, the provision of information on good practices and available disposal services, and on the receiving water in respect to stormwater discharges;
- the use of planning, environmental and building ordinances and regulations to control use of materials or practices having the potential to impact on water quality and ecology; and
- the provision of information and guidelines and display sites demonstrating environmentally sensitive practices.

There has been wide application of these approaches. While it is difficult to assess the overall effectiveness of these programs, their application has yielded greater public awareness of the impacts of disposal practices, and hopefully, a reduction of pollutants reaching receiving waters.

ii) Land uses and management practices
Purpose: To minimise the potential for pollutant generation as a result of land development, and to protect significant hydrological and terrestrial features of the proposed development site.

Description: The adoption of land use capability assessment mapping and land use zoning and management practices consistent with minimising the effects of urbanisation on receiving waters.

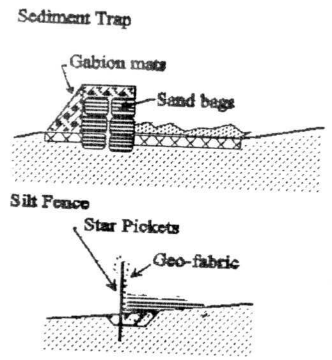
Performance: Generally, this is an accepted practice for all new development. The lack of documented management techniques for different hazard conditions often limits the systematic application of this approach.

iii) On-site programs of runoff management
Purpose: To minimise runoff and the export of pollutants from house blocks, construction or industrial sites.

Description: This group of BMPs comprises a range of measures, including:

- minimisation of impervious areas and the direction of impervious area drainage to on-site pervious areas;
- maintenance of vegetative cover or mulching;
- provision of on-site interception and retention of runoff from construction, chemical and other handling and storage areas;
- the revision of municipal standards to promote on-site detention and retention of stormwater.

Performance: Wide application of these Practices is considered cost effective for minimising pollution.



i v) M a n a g e m e n t o f p o l l u t a n t b u i l d - u p
Purpose: To reduce the discharge of pollutants to stormwater systems, by limiting the at-source build-up of pollutants on impervious surfaces, or those collected locally in stormwater gullies or catchpits.

Description: Management Practices within this category comprise the use of mechanical equipment for street sweeping, washing and vacuuming, to remove the build up; the use of gully mechanical cleansing equipment to remove gully sediment and other material; and the provision of an effective solid waste management program.
Street sweeping/washing and gully eduction are widely adopted municipal practices, established primarily to maintain safety and aesthetic standards, and to maintain the hydraulic capacity of the installed stormwater system. With a growing perception of the stormwater pollution control benefits of this Practice, there has been a shift to vacuuming based mechanical equipment. Research and development is proceeding into the adaptation of stormwater entry pits to provide a more effective trash and sediment interception control. There is also a growing recognition of the inter-dependence of waste streams, and the need for the provision of effective and comprehensive solid waste management program, to minimise illegal dumping of wastes, and to shift away from inappropriate water borne waste disposal.

Performance: While street sweeping is recognised as an effective means for removing debris and gross pollutants from the street surface, the effectiveness in water quality control terms is questionable. The US NURP program (US EPA, 1983) did not find street sweeping leading to statistically significant reductions in runoff Equivalent Mean Concentrations (EMCs), and the potential benefits were masked by data variability. Further research is continuing.

v) S e w e r i n f i l t r a t i o n m a n a g e m e n t
Purpose: For separate sewer and stormwater systems, to minimise the potential for sewer overflows associated with stormwater infiltration and discharges into sewers.

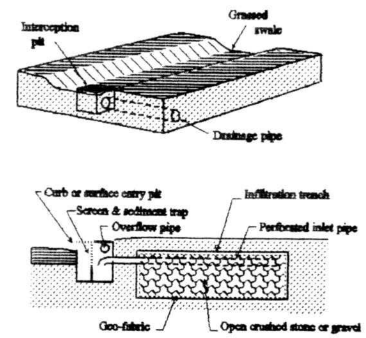
Description: This group of BMPs comprises a range of measures, including:
- the use of plastic and other sewer pipe materials minimising the number of open joints;
- the rehabilitation (lining) of ageing sewers;

- the detection and remediation of illegal stormwater connections; and
- the establishment of sewer block and break detection and remediation programs.

These Practices are being implemented by sewerage authorities on a case-by-case basis when wastewater infiltration problems are detected and are judged to be a significant problem.

B. *Structural best management practices*

i) I n f i l t r a t i o n & l o c a l d i s p o s a l s y s t e m s
Purpose: To promote the interception of surface runoff and infiltration into the soil and groundwater to reduce surface runoff, peak flows and associated pollutant mobilisation and transport, and to promote groundwater recharge.



Description: These Practices provide for the interception and infiltration of stormwater through the use of:

- mulching and vegetation on pervious surfaces, and their protection against compaction by vehicles or pedestrians;
- grassed swales and grassed filter strips;
- rock-filled percolation trenches or pits for temporary stormwater storage and infiltration;
- underground or "at-surface" linear prismatic exfiltration trenches, for the interception, temporary storage and infiltration of stormwater;
- infiltration basins to provide temporary surface storage and infiltration of stormwater; and
- porous pavements to enable stormwater infiltration into the sub-base and soil.

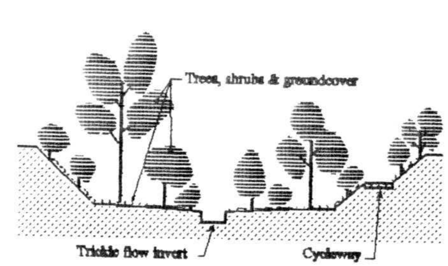
Swales, filter strips or soakage pits may be integrated into landscape treatment of public or private open space areas, or into the streetscape. They also provide benefits in terms of restoring a more natural local water balance.
Exfiltration trenches are located to collect runoff from several lots/properties, thereby reducing runoff volume, peak flows and pollutants from frequent events. Trenches generally serve small drainage areas (< 2 ha), requiring some runoff pretreatment to reduce the influx of solids and premature clogging, and are only feasible in soils with good percolation capacity, and locations with water table and bedrock situated well below the trench bottom.

Constraints to their wide application include steep slopes or erodible soils; active clays; and perched groundwater table areas. Care is required to ensure that water supply aquifers are not contaminated as a result of recharge by polluted stormwater. Several different types of porous pavement are used in urban areas – porous asphalt, porous concrete, perforated concrete blocks, and artificial turf; all of these can be used with or without a storage reservoir under the pavement, filled with gravel or rock. Constraints to the application of this Practice include vehicle loadings, volume of traffic, risk of hazardous chemical spills, and steep slopes.

Performance: While the local interception and detention storage of swales and pits reduce the peak discharge from local areas, or for larger areas for smaller events, their effectiveness is diminished for major events due to the greater probability of soil moisture saturation (less available soil storage) under those conditions. The practices are effective in enhancing soil moisture and associated sustainability of surface vegetative cover, thereby enhancing the armouring of surfaces against erosion, and the interception of particulates. There is reported however, a high level of failure of infiltration based techniques, often resulting from inappropriate sizing relative to the catchment area, lack of pre-treatment and maintenance, and groundwater mounding. The build-up of groundwater mounding and the sealing of infiltration surfaces are the two major causes of failure of infiltration basins. The provision of pre-treatment to intercept fines is critical to the protection of the porosity of surface soils and groundwater quality.
Exfiltration trenches help to reduce runoff peaks for frequent storms, reduce runoff volumes, enhance groundwater recharge and provide moderate to high removals of such stormwater pollutants as suspended solids, phosphorus, nitrogen, oxygen demanding substances, trace metals and bacteria. Good design and maintenance are very important; a high percentage of these structures fail because of clogging or ground water mounding. Well-operating porous pavements reduce surface runoff, with smaller storm runoff being contained completely, reduce runoff peaks by runoff interception and storage in the underground reservoir, and enhance percolating runoff quality by filtration through the pavement and sorption of pollutants onto fill materials (Azzout et al., 1994; Pratt et al., 1995). Regular maintenance with special equipment, sometimes using high pressure spraying and suction, is required to sustain good performance of these systems. There has been a high rate of failure of monolithic porous asphalt and concrete in eastern U.S.A., and abandonment of this practice in other countries.

ii) Retention or restoration of natural vegetated channels
Purpose: To utilise or restore natural stream channels and floodways within urban areas or to construct vegetated channels to secure economies, retard discharges and reduce peak flows, and to enhance the interception of suspended solids and nutrients and open space and landscape values.

Description: Where natural or restored streams have sufficient hydraulic capacity, and are sufficiently stable to sustain elevated flows, they can provide substantial economic, environmental and social benefits (Lawrence et al., 1995). Extensive planting is used to armour channel surfaces against erosion, reduce velocities and provide an attractive open space – landscape corridor. The capacity of natural streams and landscaped waterways to store large volumes of water (flood routing), reduces the peak flow propagation downstream associated with hard-lined channel designs.

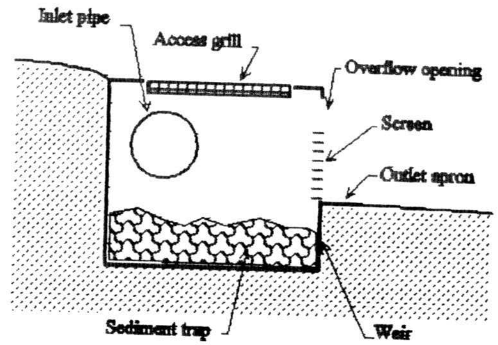


In the case of the constructed vegetated channels, the provision of a small concrete or stone dry weather flow channel or pipe is suggested to enable drainage of grassed inverts between storms. Control is also required over the rate of sediment deposition, to ensure the viability of grass and other ground covers. A common approach is the requirement for Gross Pollutant Traps on drains discharging to a natural or constructed vegetated channel. The traps also control litter.
The restoration or construction of vegetated channels in respect to enhancement of stream ecology is complex. If it is accepted that disequilibrium and disturbance is the "normal" condition for urban waterways/channels, then the goal of ecological sustainable development of the channel becomes the restoration of the entire spectrum of low to high frequency perturbations. Ecosystem recovery analysis is needed to ensure the success of a sustainable restored stream.
There are movements across almost all countries to recover, at least in part, the stream values of urban drainage corridors. The application of this approach is rapidly gaining acceptance, in view of its enhancement of adjacent land values, its more environmentally sympathetic treatment, and the open space values it affords. One of the implementation difficulties associated with the approach is the vulnerability of channel surfaces pending establishment of the vegetation armouring and biomass necessary to achieve the design hydraulic roughness coefficients (Mannings n of 0.04–0.055). Unless the dry weather flow channel or pipe incorporates capacity for sediment transport, there will be a requirement to intercept stormwater sediment prior to discharge into the natural stream/waterway, in order to sustain channel grass cover.

Performance: The Practice represents a low cost solution as compared to concrete pipes or channels, and affords enhanced land, open space and recreation values, and opportunities for conservation of riparian and wetland habitats and related biota. The enhanced in-channel water storage can reduce the velocities and peaking of downstream storm flow, and enhance the sedimentation of suspended solids and associated pollutants during storm flows.

iii) Inlet controls (gross pollutant traps & filter inlets)
Purpose: To intercept litter, trash and organic debris, and coarse silt and larger fractions in stormwater discharges to help protect the physical and biological functions and open space values of downstream waterways, and to protect groundwater quality and infiltration zones.

Description: Techniques utilised include fixed screens and open baskets located across flow paths to intercept suspended and floating solids; floating booms or fixed baffles to intercept floating solids, scums and oil; sedimentation basins to intercept settleable solids; fine screens (swirl separators, geo-fabric booms) to separate trash and other suspended solids; and sand or other media filters to intercept fine suspended solids. The Traps may be located on main drainage lines, or may be integrated into drainage entry pits or inlets. The basins may be open, for easy removal of material, or in ground and covered, consistent with meeting local landscape requirements. Collected solids may be removed by excavator, back-hoe or gully cleansing truck and transported to landfill areas, or be treated and re-used as a soil conditioner.



There has been extensive application of gross pollutant traps, sometimes adopted under the misconception that they remove a wide range of pollutants. They can be an important component of the treatment train. Gross pollutant traps can have significant head losses, necessitating careful hydraulic design. In other respects, they are usually compact, and can sometimes be retrofitted into established urban areas. The high organic nature of solids they remove is difficult to handle, and research is proceeding on different handling techniques and insitu chemical and biological treatment. Unless maintained on a routine basis, odour complaints can occur. Maintenance costs can be high; in-situ treatment can transform trapped material into a well aerated soil conditioner having economic value. Filter inlets are a high cost and extremely high maintenance solution, and are limited to areas where available land is at a premium.

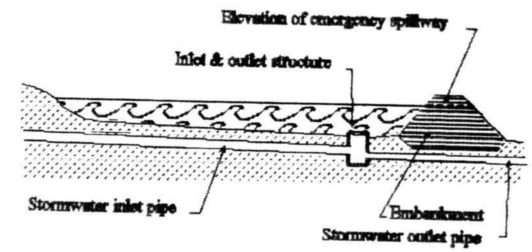
Performance: The traps are extremely effective in interception of coarser sediment fractions, trash and debris. Their limited hydraulic capacity in respect to screening can result in their over-topping and reduced effectiveness for significant storm events. Filter inlets or basins are reported as achieving a high interception level for suspended solids, phosphorus, BOD, heavy metals. They do plug quickly and need consistent maintenance to function properly (Urbonas, 1996). Plugged filters back-up stormwater, causing surface flooding or stormwater bypass.

iv) Detention basins

Purpose: To temporarily store flows for sufficient time to enable reduction in downstream stormwater or sewer pipe flows to levels which can be accommodated without exceeding hydraulic capacity. Extended detention basins may also provide suspended solids and other pollutant interception capacity, but this is often secondary to their primary hydraulic flow retardation function.

Description: Detention basins range from swales within residential blocks, to major basins servicing an entire catchment. They comprise an impoundment created by an embankment or excavation,

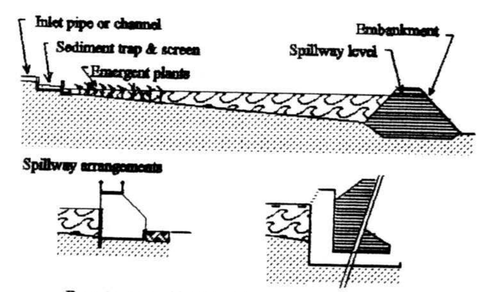
and by restriction of their outlet flow capacity. Their use for stormwater pollution control requires extended stormwater detention (24 to 48 hours), to enable sedimentation of suspended solids and associated nutrients, oxygen demanding substances, organic material and bacteria.
There has been wide adoption of stormwater detention basins, mainly associated with urban development within catchments in which there are downstream hydraulic constraints through established urban areas. Detention can also reduce the extent of major infrastructure augmentation works downstream. Detention basins are also being adopted for water quality enhancement and as part of a wider pollution control treatment train. Attention is required in their design to ensure the safe spillage of excess flows, such that life and property are not at risk downstream, and to ensure the provision of community safety. Close attention is also required to the potential for flood impacts resulting from their backwater effects.



Performance: Properly designed extended detention basins can achieve significant pollutant removals. The combined use of detention basins as flood and pollutant controls can yield economic benefits in terms of deferment of costly hydraulic infrastructure augmentation downstream and the provision of alternative water pollution interception measures. The use of on-site detention basins has become popular with local governments in many countries, partly in view of the authorities ability to transfer the cost of their construction to the land development. However, there are growing concerns regarding the ability to ensure their proper maintenance and operation in the longer term.

v) Retention basins, ponds & wetlands

Purpose: To establish a permanent water impoundment and aquatic plants as the basis for the interception of suspended solids, nutrients, toxicants and bacteria.



Drop structures with reinforced overtopping embankment, or side channel spillway.

Description: Retention ponds are small lakes with a permanent pool of water and some emergent vegetation, while wetlands are shallow basins with most of the surface covered by emergent vegetation. The retention of water enables settling of suspended material, contact with and adsorption by active sediments, and interception and take-up by emergent and submerged plants, algae and fauna. The interception of the gross sediment and trash before discharge into a pond or wetland, is very important to their function. Ponds and wetlands require minimal maintenance, and provide significant open space/landscape enhancement and constitute a productive ecosystem.

In the case of combined sewer systems, retention basins will be subject to much more intensive sediment and organic loading, and will require periodic removal of accumulated material to prevent re-mobilisation as a result of biological reduction processes. Basins in this context are more likely to be concrete lined, as necessary to undertake periodic removal of accumulated material. Wetlands in this situation are more likely to comprise gravel beds with emphasis on plant take-up and harvesting.

There has been extensive application of this Practice in many countries. There are questions regarding the adequacy of storage volume provided in many cases. Concerns have been raised regarding the potential for nuisance mosquito breeding, but with appropriate attention to edge treatment and shaping, this does not appear to be a major problem.

Physical constraints limiting the application of this practice include open space requirements, and hydraulic constraints associated with potential backwater impacts. Given the high peak nature of urban runoff events, the performance of wetlands will be constrained by their limited hydraulic retention time, unless incorporated together with substantial hydraulic detention. This requirement is addressed in two possible ways; the combination of flow detention capacity and pond/wetland processes within the one basin (wet detention basin), or the adoption of treatment train comprising upstream flow detention basins followed by a downstream retention pond or wetland. Sediment and trash interception prior to discharge into ponds or wetlands is required in order to protect the emergent and submerged plants, defer the need for costly and disruptive dredging, and to protect the landscape quality. The cost of maintaining ponds and wetlands is significantly less than for an equivalent area of parkland (Lawrence et al., 1995). Subject to gentle grading of edges, community concerns regarding the risk of small children drowning has not been an issue.

Performance: The performance of retention ponds is a function of their hydraulic retention time, the organic loading (BOD) on ponds (potential to de-oxygenate the sediments, resulting in the remobilisation of pollutants), and the depth of the ponds (minimise the potential for thermal stratification). Depths typically need to be limited to 1.5 to 3.0 m, but greater depths in some instances have been satisfactory. The promotion of emergent aquatic plant growth, namely the establishment of littoral zones, significantly enhances the performance of ponds.

Suspended solids and total phosphorus interception rates are reported at 50 to 70% at 10 days, to 80 to 90% at 30 days retention time (Lawrence et al., 1995). On-line ponds are most common, but off-line ponds are adopted in some communities. Reports generally agree on the variability in removal effectiveness, including the possibility of negative efficiencies for individual events where short-circuiting enhances resuspension, or high BOD associated with the event leads to de-oxygenation of the sediments and release of pollutants. Whilst overall, fairly high levels of performance might be expected, it is important to recognise that currently design models are limited in their capacity to predict either event based or annual removal efficiency. Consequently, caution is urged when developing stormwater management practices and regulatory approaches. Ponds/wetlands are also perceived by the community as valuable conservation and landscape features, attracting a diverse

range of water birds and aquatic biota. However, large flocks of birds can also constitute a point source of contamination, reducing the pollution interception function of the facility.

vi) In-pond physical, chemical & biological treatment

Purpose: To enhance the pollutant interception performance, and/or ecological and beneficial use values of lakes, ponds and wetlands by direct physical or chemical treatment or by biological manipulation.

Description: Management Practices within this category comprise a wide range of physical, chemical and biological treatment techniques, including:

- use of surface mixers or suspended air roses to destratify and mix waters of ponds and lakes;
- application of chemicals (alum or gypsum) to enhance the coagulation & sedimentation of suspended fines;
- treatment of sediments with nitrate N, to re-establish their adsorption capacity;
- harvesting of aquatic plants or algae, as a means of maintaining a nutrient uptake capacity and removal.

The removal of sediment to re-establish or maintain pond volume is an ongoing maintenance requirement.

Research has demonstrated that in Australia, ponds having an elevated turbidity under hot summer conditions are subject to temperature stratification, even at depths as shallow as 2 metres. In these cases, opportunities exist for reduction in remobilisation of pollutants by the application of aeration techniques. In the case of Inlet Traps, the treated material would be more economically attractive for re-use as a soil conditioner. Chemical treatment to enhance coagulation and sedimentation of suspended fines, is widely used in Australia in association with off-stream interception ponds on construction sites. There are however concerns regarding the ecological impact of adding large quantities of chemicals to stream systems. Sediment renovation using nitrate *N* injection has been applied in Germany and Sweden. Sediment bio-remediation techniques are being assessed in a number of countries.

There is now wide recognition of the importance of aquatic macro-plants in enhancing the interception of suspended solids and nutrients, in re-aerating the sediments and thereby limiting nutrient release, and in transforming carbon into less biologically available forms. While there has been wide application of weed harvesting, this has focussed more on clearing weeds from recreation areas than on water quality management. Stocking of lakes and ponds to enhance the recreational fishery may result in overgrazing of zooplankton, resulting in significant increases in algal numbers.

Performance: The application of aeration practices have the potential to yield significant improvement in interception performance in some cases, while chemical treatment is limited to special applications. The literature suggests limited benefits in harvesting aquatic plants in terms of nutrient interception of stormwater wetlands and ponds.

C Bibliography

Agriculture and Resources Management Council of Australia and New Zealand (ARMCANZ), (1996), Draft Guidelines for Urban Stormwater Management, Dept Primary Industry and Energy.

AZZOUT, Y., BARRAUD, S., CRES, F.N. and ALFAKIH, E (1994). Techniques alternatives en assainissement pluvial: choix, conceptions, réalisation et entretien. Technique et Documentation - Lavoisier, Paris, France.

BALADES, J.D., GUICHARD, T., LEGRET, M. and MADIEC, H. (1994), Gestion de la Pollution des Eaux Pluviales par Chaussées Réservoirs en Milieu Urbain, TSM, CETE du Sud-Ouest, Bordeaux, France.

COLORADO S.W.T.F. (1990), BMP Practices Assessment for the Development of Colorado's Stormwater Management Program, Final Report to Colorado Water Quality Control Division, Denver CO.

ELLIS, J.B. (1996), "Sediment Yield and BMP Control Strategies in Urban Catchments", pp.555-564 in Walling, DE and Webb, B (Edits), Erosion and Sediment Yield, IAHS Publ. No 236, Wallingford UK.

EPA (1983), Results of the Nationwide Urban Runoff Program, Final Report, U.S. Environment Protection Agency NTIS Access No.PB84-18552, Washington D.C.

GALLI, J. (1992), Analysis of Urban BMP Performance and Longevity, Met. Wash. Council of Governments, Publ. No 92711, Washington DC

GELDOF, G., JACOBSEN, P. and FUJITA, S. (1993), "Urban Stormwater Infiltration Perspectives", in Proceedings Sixth International Conference on Stormwater Drainage pp.963–968

GRIZZARD, T.J., RANDALL, C.W., WEAND, B.L. and ELLIS, K.L. (1986), Effectiveness of Extended Detention Ponds, Urban Runoff Quality Enhancement Technology, Urbonas, B.R. and Roesner, L.A., Editors, American Society of Civil Engineers, New York, NY.

HALL, M.H., HOCKIN, D.L. and ELLIS, J.B (1993), The Design of Flood Storage Reservoirs, Butterworth Heineman, London

HARTIGAN, J.P. (1989), Basis for Design of Wet Detention Basin BMPs, Design of Urban Runoff Quality Controls, American Society of Civil Engineers, New York, NY. pp.122–144

HERATH, S., MUSIAKE, K. and HIRONAKA, S. (1993), Evaluation of Basin Scale Effects of Infiltration Systems, in Proceedings Sixth International Conference on Urban Storm Drainage, pp.1181–1186

HERATH, S. and MUSIAKE, K. (1991), Design of Infiltration Facilities for Urban Flood Control, Proceedings International Symposium on Environmental Hydraulics, Hong Kong, pp.1425–1430

Land Systems EBC Pty Ltd (1993), Better Drainage: Guidelines for the Multiple Use of Drainage Systems, NSW Department of Planning.

LAWRENCE, A.I. and GOYEN, A.G. (1987), Improving Urban stormwater Quality: An Australian Perspective, in Proceedings 4th International Conference on Stormwater Drainage.

LAWRENCE, A.I., LISTON, P., BRESNAN, S., WADE, A. and FALKLAND, A.C. (1995) Performance review of Australian Capital Territory stormwater pollution control strategies, in Proceedings Australian Water and Wastewater Association Federal Convention 1995.

LAWRENCE, A.I. and PHILLIPS, B.C. (1993), A Review of Best Management Practices in Australia, in Proceedings, Sixth International Conference on Urban Stormwater Drainage.

Ministry of Environment and Energy (MOEE), (1994). Stormwater management practices planning and design manual. ISBN 0-7778-2957-6, MOEE, Toronto, Ontario.

PRATT, C.J. (1990), Permeable Pavement for Stormwater Quality Enhancement, Urban Stormwater Quality Enhancement, American Society of Civil Engineers, New York, NY, pp.131–155

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. in Proceedings of the 2nd Conference on Innovative Technologies in Urban Storm Drainage, May 30–June 1, 1995, Lyon, France, pp.337–344.

ROESNER, L.A., URBONAS, B.R. and SONNEN, M.B. (1989), Editors, Design of Urban Runoff Quality Controls, American Society of Civil Engineers, New York, NY

SCHUELER, T.R. (1987), Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices, Metropolitan Washington Council of Government, Washington, D.C.

SCHUELER, T.R., CUMBLE P.A. and HERATY, M.A. (1992), Current Assessment of Urban Best Management Practices; Techniques for Reducing Non-point Source Pollution in the Coastal Zones, (Review Draft). Publ. No 92703 Metropolitan Washington Council of Governments, Washington, D.C.

SCHUELER, T.R. and GALLI, J (1992), The Environmental Impact of Stormwater Ponds, Affects of Urban Runoff on Receiving Systems, American Society of Civil Engineers, New York, NY.

SCHAVER, E. (1992), Sand Filter Design for water Quality Treatment, Affects of Urban Runoff on Receiving Systems, American Society of Civil Engineers, New York, NY.

SMITH, D.R. (1984), Evaluation of Concrete Grid Pavements in United States, in Proceedings Second Conference on Concrete Block Paving, Delft, Australia.

STRECKER, E and DRISCOLL, E.D. (1992), The Use of Wetlands for Stormwater Pollution Control, US EPA, Washington DC.

UDFCD, Urban Storm Drainage Criteria Manual: Volume 3 - Best Management Practices, Urban Drainage and Flood District, Denver CO.

URBONAS, B. and STAHRE, P. (1992), Stormwater - Best Management Practices and Detention, Prentice Hall, Englewood Cliffs, NJ, 1993.

URBONAS, B.(1996). Stormwater Sand Filtration: A Solution or a Problem, APWA Reporter, American Public Works Association July 1996.

URBONAS, B., ROESNER, L.A. and GUU, C.Y. (1996), Hydrology for Optimal Sizing of Urban Runoff Treatment Control Systems, in Water Quality International, London England.

U.S. EPA. (1983), Results of the Nationwide Urban Runoff Program. U.S. EPA., Washington, D.C., PB84-185-552.

US EPA, (1986), Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality, U.S. Environmental Protection Authority, EPA440/5-87-001, Washington D.C. Sept 1986.

VALIRON, F and TABUCHI, J.P. (1992), Maitrise de la Pollution Urbaine par Temps de Pluie, Etat de L'Art. Technique et Documentation, Lavoisier, Paris.

VEENHUIS, J., PARISH, J., JENNINGS, M (1989), Monitoring and design of stormwater Control Basins, Design of Urban Runoff Quality Controls, American Society of Civil Engineers, New York, NY.

WADA, Y. and MIURA, H. (1993), A Simulation Model of Stormwater Infiltration Facilities to Reduce Urban Storm Runoff, in Proceedings Sixth International Conference on Urban Storm Drainage, pp.1169–1174

WHELANS, HALPERN GLICK MAUNSELL, THOMPSON PALMER, and Institute for Science and Technology Policy, Murdoch University, (1993), Water Sensitive Urban (Residential) Design Guidelines for the Perth Metropolitan Region, Dept of Planning and Urban Development, Water Authority of Western Australia, and Environmental Protection. Authority.