# A REVIEW OF URBAN STORMWATER QUALITY PROCESSES

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Report 95/9
September 1995

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

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Duncan, H. P. (Hugh P.), 1951 -
A review of urban stormwater quality processes

Bibliography.
ISBN 1 876006 06 4

1. Storm sewers. 2. Urban runoff. 3. Water quality
4. Water quality management 5. Water - Pollution
I. Cooperative Research Centre for Catchment Hydrology.
II. Title. (Series: Report (Cooperative Research Centre for Catchment Hydrology); 95/9).

628.168

**Keywords**

Storm Sewage
Water Quality (Natural Waters)
Urban Areas
Runoff (Urban)
Pollution (Surface Water)
Stormwater Management
Contamination
Pollution Sources

ISSN 1039-7361

# PREFACE

The Cooperative Research Centre for Catchment Hydrology's Urban Hydrology research program comprises two main projects. Project C1 investigates methods for estimating runoff and pollution loads from urban catchments over a range of time and space scales. Project C2 brings together several studies aimed at improving design and management procedures for urban waterways.

This report was prepared for Project C1 by Hugh Duncan, seconded to the CRCCH from Melbourne Water, and forms part of a review of urban stormwater quality literature. The main objectives of the review are to assess the current status of urban stormwater quality research, to facilitate access to existing information, and to establish priorities for future work.

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# ABSTRACT

This document describes the physical processes which contribute to the contamination of urban storm runoff, and forms part of a broader review of the English language literature on urban stormwater quality research. The processes discussed are wet and dry deposition of contaminants from the atmosphere, interception on vegetation and artificial above-ground structures, buildup of contaminants on impervious surfaces, washoff from surfaces into formed channels or pipes, transport along channels and pipes, quality changes during storage, and the influence of receiving waters on the scale and detail of analysis.

Atmospheric deposition typically supplies as much nitrogen as is washed off in urban runoff, and a smaller proportion of suspended solids, phosphorus, COD, and heavy metals. The main pollutant sources accessed by interception processes are accumulated dry deposition on roofs and vegetation, and solution of roof and plant materials. Undiluted roof runoff may be highly toxic to fish. Buildup of material on impervious surfaces can be described as a dynamic equilibrium process between contributing and non-contributing areas. Surface load increases with antecedent dry period, but the shape of the curve cannot be determined with any accuracy.

Washoff appears to be the limiting process for urban stormwater pollution in most situations, and is associated most strongly with rainfall intensity. Although almost universally used in modelling, the exponential description of washoff is a poor measure of real physical processes. An alternative function based on rainfall intensity is proposed. First flush is by nature and definition a characteristic of small catchments.

Plant litter is a major source of organic matter and nutrients, but its contribution to receiving waters will not be fully recorded by conventional water quality measurements. The quality of urban storm runoff can be greatly improved by storage in ponds and wetlands. The main processes involved are settling of suspended material, averaging of dissolved material, and conversion of nitrogen between its chemical forms by bacteria. The size and nature of receiving waters help to define the optimum scale and detail of urban runoff quality analysis. Detail which is excessive, relative to the time and space scales of the ultimate objective, is not helpful in analysis and may be be detrimental.

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# A REVIEW OF URBAN STORMWATER QUALITY PROCESSES

## 1. INTRODUCTION

This report forms part of a review of the English language literature on urban stormwater quality research, which has been prepared by the Cooperative Research Centre for Catchment Hydrology to improve access to what is now a substantial body of literature. Other parts of the review process include an annotated bibliography of urban stormwater quality (Duncan 1995a), and a database of references set up on the MS-DOS version of the EndNote Plus® bibliography system (Duncan 1995b). Copies of the reports and database are available from the CRC for Catchment Hydrology Office at Monash University, Clayton, 3168, Australia.

The bibliography is a chronological review of urban stormwater quality, which emphasises the historical development of urban runoff quality, and briefly notes the objectives and conclusions of over 700 studies and publications. Many aspects of urban runoff quality have been addressed by these studies, some of them in considerable detail. The view that emerges is that the process is very complex - many factors influence the generation of pollutant loads in stormwater, and large spatial and temporal variations persist down to small scales.

The process is indeed complex, but it is not mysterious. There is little doubt that with sufficient effort, we could learn as much as we liked about any aspect of the process, limited only by the practicalities of measurement accuracy and cost. But because the effort and cost are substantial, we need to be very clear about what we already know, what we need to know, and why we need to know it. In other words, we need to understand our objectives.

This document describes the physical processes which contribute to the contamination of urban storm runoff. References are selectively quoted in the discussion of each process. Following the hydrologic cycle from cloud formation to receiving waters, the main processes are wet and dry deposition of contaminants from the atmosphere, interception on vegetation and artificial above-ground structures, buildup of contaminants on impervious surfaces, washoff from surfaces into formed channels or pipes, and transport along channels and pipes, possibly through intermediate storage, to the receiving waters.

Although typical or average magnitudes are frequently included, the emphasis here is on processes rather than data tabulation or analysis. Readers requiring more extensive summary information are referred to the review by Makepeace et al. (1995), who tabulate the observed range, likely problems, and relevant references for a very wide range of urban stormwater contaminants.

## 2. ATMOSPHERIC DEPOSITION

Atmospheric deposition includes both wet deposition or washout during rain, and dry deposition or fallout without rain. Dry deposition depends on atmospheric conditions close to the ground, while washout is affected by conditions over a wide range of altitude, and hence tends to be more uniform at small spatial scales (Hicks et al. 1993). They can be recorded separately by exposing rain gauges or flat plates at the appropriate times, but conventional rain gauges will collect some dry fallout as well as washout, and in some papers it is not entirely clear what has actually been measured. Where they are measured separately and compared, such as by Matheson (1951), Malmquist and Svensson (1977), and Randall et al. (1981), washout is always substantially larger than fallout, at least in the temperate climatic zones sampled by these studies.

## 2.1 Variability

Spatial variability of all forms of deposition can be very high at moderate to large scales. Pirrone and Keeler (1993) observed dry deposition fluxes of trace elements typically two to four times higher in Chicago than at a rural site nearby, and Malmquist and Svensson (1977) found that air quality generally improved, although less markedly, with distance from the centre of Goteborg in Sweden.

Weibel et al. (1966) reviewed a number of rainwater quality studies to that date, and concluded that in general, rainfall at a particular point tends to take on a quality that reflects the character of the land and human activities on it in the surrounding environment. Novotny and Kincaid (1981) reached a similar conclusion using data from Milwaukee, and Malmquist and Svensson (1977) found that both washout and total deposition in central Goteborg were two to four times higher than at a satellite suburb 30 km away. On the other hand, Poissant et al. (1994) found that rainfall quality tends to be spatially relatively uniform over the urban area of Montreal Island, and Randall et al. (1978) found little change with distance from Washington DC for any parameter other than lead. At a larger scale, Steinnes et al. (1994) used the concentration of trace elements in moss samples to estimate atmospheric deposition at 500 sites in Norway in 1977 and 1985. Deposition of elements influenced mainly by local point sources (chromium, iron, cobalt, nickel, and copper in this case) can vary by a factor of 10 to 50 across the country.

Steinnes et al. (1994) observed a general decline in deposition of trace elements associated with long range pollutant transport between 1977 and 1985. The largest change was for lead, which reduced by 50% over this period in the southern part of Norway. On the other hand, Brimblecombe and Stedman (1982) document a fourfold or greater increase in deposition of nitrate over the 100 years to 1980, in both Europe and North America.

Short term variation of rainfall quality with time can be very large, both within and between storms, and this variation is reflected in runoff quality for those parameters supplied mainly by rainfall (Ng & Marsalek 1984; Poissant et al. 1994). A seasonal effect has also been observed, with a tendency for concentrations to be higher in summer than in winter (Nicholls & Cox 1978; Rolfe et al. 1978; Altwicker et al. 1986). Rainfall event concentrations at a site appear to be log-normally distributed (Altwicker et al. 1986).

## 2.2 Magnitude

Fallout and washout can be a significant source of pollutants in stormwater. Rainfall and/or total deposition is repeatedly and consistently found to be the major source of nitrogen in urban runoff (Weibel et al. 1966; Kluesener & Lee 1974; Loehr 1974; Characklis et al. 1978; Goettle 1978; Malmquist 1978; Novotny & Kincaid 1981; Halverson et al. 1984; Ng & Marsalek 1984; Ebbert & Wagner 1987; Jassby et al. 1994). So strong is this effect that in some studies the load of nitrogen in total deposition is found to exceed the load in runoff, so that the ground surface is acting as a sink for nitrogen rather than a source (Simpson & Hemens 1978; Characklis et al. 1979b; Randall et al. 1981; Miller & Mattraw 1982). Total nitrogen concentration in urban rainfall is typically in the range 1.0 to 2.0 mg/L, and inorganic nitrogen often exceeds the threshold level for algal blooms of 0.3 mg N/L quoted by Weibel et al. (1966).

Matheson (1951) found that nitrogen fall in Ontario was substantial, and was mainly associated with rain. Some 61% of it came down on rain days, which comprised 25% of all days, and the remainder dusted down on dry days. Consistent with this, McKee (1962) found that total atmospheric nitrogen deposition tended to increase with annual rainfall, and observed that much of the organic nitrogen at that time took the form of pollen, spores, bacteria, and dust carried aloft by winds. It would be interesting to compare the present contribution of these natural sources with anthropogenic inputs (including nitrogen oxides in urban areas and ammonia in rural areas), to find the likely cause of the fourfold increase in nitrate deposition over 100 years observed by Brimblecombe and Stedman (1982).

Atmospheric deposition may also be a significant source of solids. Weibel et al. (1964) measured dustfall at Cincinnati, and found it was comparable in magnitude to suspended solids in storm runoff. Melanen (1984) in Finland, Sekine et al. (1990) in Japan, and Simpson and Hemens (1978) in South Africa measured significant inputs of solids in rainfall, whereas Ellis (1979) in London and Ng and Marsalek (1984) in Ontario observed that the contribution of solids from rainfall was small. As will very often be the case in this review, there are many differences between these studies other than their location, so the variability of results should not be seen as being in any way inexplicable. The average concentration of suspended solids in rainfall at urban sites is typically up to 20 mg/L.

The situation with phosphorus is rather similar. A number of observers find that rainfall is a significant source of phosphorus in runoff (Chalupa 1960; Weibel et al. 1966; Waller 1977; Characklis et al. 1978; Malmquist 1978; Simpson & Hemens 1978; Novotny & Kincaid 1981; Randall et al. 1981; Jassby et al. 1994), while a few find that it is not (Halverson et al. 1984; Ng & Marsalek 1984). Total phosphorus concentration in urban rain typically falls in the range 0.01 to 0.1 mg/L, and inorganic phosphorus may exceed the threshold level for algal blooms of 0.03 mg $PO_4$/L quoted by Weibel et al. (1966). Again the variability of results can be noted, but rainfall is often a significant source of phosphorus in urban runoff, and cannot safely be dismissed without local information to the contrary.

Horkeby and Malmquist (1977) found that deposition supplied half or more of the arsenic, cadmium, chromium, mercury, antimony, vanadium, and lead in runoff at Goteborg. These results are supported by Malmquist (1978), Miller and Mattraw (1982), Palmgren and Bennerstedt (1984), and Ebbert (1987) for lead, and Palmgren and Bennerstedt (1984) for cadmium. Other heavy metals which may be derived mainly from rainfall include zinc (Malmquist 1978; Miller & Mattraw 1982; Ng & Marsalek 1984), copper (Ng & Marsalek 1984; Ebbert & Wagner 1987; Ng 1987), and nickel (Ng 1987). Typical concentrations in urban rainfall are up to 0.3 mg/L for iron, 0.2 mg/L for zinc, 0.1 mg/L for lead, 0.05 mg/L for copper, and 0.01 mg/L for chromium and cadmium. As before, there is considerable variation. Zinc, copper, and some lead are presumably associated with corrosion of roofing materials, and so would depend upon their level of use in a given area.

Among the less commonly tested parameters, only COD (Characklis et al. 1978; Malmquist 1978; Miller & Mattraw 1982; Ebbert & Wagner 1987) and PCB's (Horkeby & Malmquist 1977) appear to have rainfall as a major source. COD in rainfall may be associated with the organic matter observed by McKee (1962). Polycyclic aromatic hydrocarbons (Herrmann 1984), hydrocarbons generally (Wakeham 1977), and bacteria (Geldreich et al. 1968), when measured in rainfall or deposition at all, appear to be minor contributors to urban runoff contamination.

Sources of contaminants deposited from the atmosphere by washout and dustfall have been investigated by Duysings et al. (1986) in the Netherlands, Prada-Sanchez et al. (1993) in Spain, and Steinnes et al. (1994) in Norway. Sources identified include seaspray, industrial activities, rural activities, local dust, and long range transport from other areas.

The scavenging process by which contaminants are taken up from the air by rainfall is addressed by Shivalingaiah and James (1984a; 1987). Randall et al. (1978; 1981) found that washout occurred rapidly and early in the storm, and was therefore almost independent of rainfall volume or intensity, although a slight correlation with antecedent dry period has been observed (Randall et al. 1978; Owe et al. 1982). Shivalingaiah and James (1986) developed a statistical model of dry dustfall based on wind, rain, and monthly mean dustfall and achieved some improvement over monthly mean data alone, while Owe et al. (1982) found a good correlation between dustfall and antecedent dry period. McMahon and Denison (1979) tabulate a range of wet and dry deposition parameters derived from a review of literature to that date.

### 2.3 Summary

Atmospheric deposition makes an important contribution to stormwater contamination. It typically supplies as much nitrogen as is washed off in urban runoff, and a smaller proportion of suspended solids, phosphorus, COD, and heavy metals. Spatial variability is high at large to moderate scales, with deposition being generally higher in urban areas and greatly influenced by local sources.

Source control of nitrogen in urban runoff will not be achieved through modification of the urban landscape, as that is not the major source. Effective control will be achieved only when air quality is addressed. The scale of the processes involved suggests that the issue is not confined to urban areas.

## 3. INTERCEPTION

Interception in this context is the interaction of rainfall with growing plants, plant debris such as leaf litter, and artificial structures such as buildings and roofs, before it reaches the ground. Such interactions can significantly affect the quality of the rainfall and the resultant runoff. Throughfall is rain which reaches the ground after passing through the tree canopy or dripping from it, while stemflow is the portion which runs down the tree trunks.

### 3.1 Plants and Plant Debris

Literature describing the effects of growing plants on urban water quality is very sparse. Halverson et al. (1984) measured contaminant loads of rainfall, throughfall, and stemflow in an urban area in Pennsylvania. Throughfall was significantly less acidic, and contained significantly higher loads of ammonia, nitrate, phosphorus, potassium, calcium, and sulphate than the rainfall. Stemflow showed a similar but less marked tendency. It is unclear from this study whether the contaminants derive from the trees themselves, or from dust and dirt deposited on the trees. But a similar study in a forested area of Illinois (Rolfe et al. 1978) found that nutrient fluxes in precipitation, throughfall, and stemflow were almost equal, which suggests that dust and dirt deposited on the trees in the urban environment is the major source of contaminants.

Shivalingaiah and James (1984a; 1987) developed algorithms for tree canopy contributions to runoff, based on linear buildup and exponential washoff of dust and dirt from the tree surfaces. While this is very similar in principle to standard formulations for washoff from impervious ground surfaces, a large leaf area could potentially make a substantial difference to total washoff load. However, in a review of data from several locations in the U.S., Bradford (1977) concluded that tree-landscaped areas typically produced below average pollutant loads in urban runoff. Perhaps time of year, street sweeping and leaf collection practices, density of development, and reduction of rainfall energy by the leaf canopy are influencing the observed results.

Fallen leaves, seeds, and flowers can certainly affect the quality of rainwater that passes through them. Phosphorus, nitrogen, and organic matter are greatly increased in runoff percolating through fallen leaves and crop residues (Timmons et al. 1970; Cowen & Lee 1973; Kluesener & Lee 1974; Cordery 1977; Prasad et al. 1980; Dorney 1986), and materials toxic to fish can be released from leaves and conifer needles (Tremolieres 1988). Leaves and seeds can be the major source of phosphorus in urban runoff (Cowen & Lee 1973; Kluesener & Lee 1974). Gavens et al. (1981) note that leaves can also be a natural source of aliphatic hydrocarbons.

Nutrient release from whole leaves is quite slow, with repeated leachings over several days needed to release the bulk of the nutrients, but fine chopping (Cowen & Lee 1973), drying, or freezing and thawing (Timmons et al. 1970) greatly speeds up the process. This can explain why nutrient levels in washoff from roads increase with traffic volume, as described by Shaheen (1975). Nutrients are also concentrated in moisture retained on fallen leaves after rain, which can lead to shock loadings in subsequent runoff events (Cowen & Lee 1973; Prasad et al. 1980), even if the leaves themselves are not carried away by the flow.

## 3.2 Buildings and Roofs

The most widespread contaminant from buildings is zinc from galvanised iron roofs and fittings (Yaziz et al. 1989; Forster 1990; Bannerman et al. 1993; Good 1993; Quek & Forster 1993; Thomas & Greene 1993). Zinc concentrations greater than 10 mg/L have been recorded in roof runoff and rainwater tanks, while copper levels up to about 0.2 mg/L have been occasionally observed (Good 1993; Quek & Forster 1993). Undiluted roof runoff appears to be highly toxic to fish (Good 1993). Malmquist and Svensson (1977) found that corrosion of metals in the catchment was a major source of zinc and copper in runoff from central Goteborg, and a minor source in a nearby satellite suburb. The contribution from corrosion depended on the duration of rainfall, the atmospheric concentration of sulphur dioxide, and the area of exposed metal in the catchment. Duncan and Wight (1991) summarised the results of five Australian surveys of rainwater tank water quality, and concluded that physical parameters other than zinc usually meet drinking water guidelines, while microbiological parameters very often do not.

Other effects which are frequently but not universally observed are an increase in pH as rainwater interacts with roofs and other surfaces (Halverson et al. 1984; Forster 1990), an increase in pollution with antecedent dry period (Yaziz et al. 1989; Forster 1993; Thomas & Greene 1993), and a strong first flush (Forster 1990; Good 1993; Quek & Forster 1993) which is more pronounced at high rainfall intensities (Yaziz et al. 1989). The increase in pH implies some form of acid reaction with the roofing material. The accumulation of dry deposition can lead to high pollutant concentrations, most notably of lead (Yaziz et al. 1989; Thomas & Greene 1993). Except for the solution of copper, zinc, and some lead from roofing materials, this behaviour is very similar to buildup and washoff from any other impervious surface, which is discussed in more detail below.

## 3.3 Summary

The main pollutant sources accessed by interception processes are accumulated dry deposition on roofs and vegetation, and solution of roof and plant materials. Solution of copper and zinc in roofing materials usually occurs, and undiluted roof runoff may be highly toxic to fish. Fallen leaves and other plant debris are a significant source of nitrogen and organic matter, and may be the major source of phosphorus in urban runoff.

# 4. BUILDUP

Buildup is the process by which dry deposition accumulates on impervious areas. It can be measured directly by thorough sweeping and washing of the impervious area after a buildup period under controlled or measured conditions. Alternatively, it can be estimated indirectly from runoff loadings by the simultaneous fitting of buildup and washoff processes, using a statistical or modelling approach. Buildup can not be measured directly from the pollutant loading of runoff, since runoff loadings result from the integrated effect of both buildup and washoff. Overviews of the buildup process are provided by Lager and Smith (1974), Overton and Meadows (1976), Roesner (1982), Huber (1986), and others.

## 4.1 Experimental Studies

One of the first systematic studies of buildup was the detailed and wide ranging investigation of Sartor and Boyd (1972), who measured buildup and washoff from streets in residential, commercial, and industrial areas from 12 U.S. cities, and assessed the effectiveness of street sweeping practices. Their conclusions are summarised by Sartor et al. (1974). In their investigations of buildup, they found that the major constituent of street surface contaminants was inorganic mineral-like matter, often called 'dust and dirt'. The organic fraction was small, but accumulated faster than the inorganic fraction, and was presumably derived mainly from fallen leaves. Industrial areas had the highest loads and accumulation rates, due to less sweeping, more unpaved areas, spillage from trucks, and breakup of roads. Residential areas had intermediate loads, while commercial areas had the lowest loads, due to better road surfaces and more frequent street sweeping. Dust and dirt on roads is strongly concentrated within 15 centimetres of the curb. Most pollutants are strongly associated with the finest fraction of dust and dirt, either because they are themselves fine particles, or because they are adsorbed on to other particles according to surface area rather than volume. Conventional street sweepers are ineffective at removing this fine fraction.

The most frequently used outcome of this work is the set of buildup graphs relating dust and dirt to land use and antecedent dry period, presented in an appendix to the report. Unfortunately, the authors' own explicit caveat on this unplanned addition to their work is never quoted with it. Their caution is well founded. The development of the buildup curves depends on an assumption which is now known to be incorrect, and the analysis contains a number of statistical problems.

The assumption implicit in the development of the buildup curves is that washoff is for practical purposes complete at the end of a storm and after street sweeping. This is strange, since in the main body of the report, the available initial load on the street is consistently shown to depend sensitively on rainfall intensity. The higher the rainfall intensity, the higher the ultimate runoff load. Furthermore, street sweeping is shown to be at most about 50% efficient, and rainfall possibly even less efficient at removing the accumulated contaminants. Nevertheless, both these effects are ignored in the buildup calculations. Buildup after sweeping and after storms of different intensity are pooled together, as are records from cities in different climatic zones, and in all cases accumulation is assumed to start from zero. Not surprisingly, when using all data they found no significant build-up relationships at all. Even using data trimmed to remove outliers there are few significant relationships, and they are heavily influenced by the trimming function. There are just too many variables - city location and climate, type of land use, time since cleaning, and type of cleaning (sweeping or rain) - and too few observations to permit effective analysis. The curves presented owe more to the assumptions and the trimming function than to the data. The standard of this section is very much at odds with the detail and structure of the remainder of the report. It is surely ironic that it has received by far the greatest attention from later writers.

The results of Sartor and Boyd (1972) provided the impetus for further work by others, which confirmed, qualified, and extended the results of the original study. Ellis (1979) obtained similar results for the composition of buildup - 50 to 80% inorganic solids, and BOD and COD fraction increasing with antecedent dry period - while Freund and Johnson (1980) also note a substantial buildup of leaves and grass. On the effect of land use, Terstriep et al. (1980) found commercial buildup *rates* were higher than residential buildup rates, and Yamada et al. (1993) found commercial *loads* were higher than residential loads, but lower than industrial area loads.

Ellis (1977) and Pitt (1979) both confirm that buildup on roads is concentrated near the curb. Furthermore, Shaheen (1975) and Ellis (1979) found that pollutants can be physically trapped on the road - the higher the curb the higher the pollutant load. Conversely, though, this shows that removal of deposited material from the road during dry weather, presumably by winds, can be a significant process. They conclude that buildup results from the combined effect of deposition (a function of traffic volume or time) and dry weather removal (a function of current load and physical constraints).

Shaheen (1975) also observed that the deposition of many pollutants on roads was proportional to the traffic volume. Traffic related pollutants fall into two main groups - those that originate directly from vehicles (rubber, oil, asbestos, metals, etc.) and those that are released by the breakup of leaves and seeds by vehicle movement (BOD, volatile solids, nutrients, etc.). A smaller group of roadway contaminants (litter, bacteria, cadmium, and PCB's) were not traffic related. Freund and Johnson (1980) found that lead was traffic related, but buildup of total solids was not.

The strong association of many contaminants with the finest particle sizes is confirmed in the context of buildup and washoff by Ellis (1977) and Freund and Johnson (1980), and further downstream by Urbonas (1991), Dempsey et al. (1993), and others. The inability of conventional street sweepers to remove this fine fraction is also confirmed (Ellis 1977; 1979; Pitt 1979). At a practical level, Sartor and Gaboury (1984) note that street sweeping needs to be more frequent than storms, just to get in first on most occasions and remove the material before it is washed off, and so will be generally more effective where long dry periods are common. Averaged over all particle sizes, street sweeping typically reduces street load by about 50% (Sartor & Boyd 1972; Malmquist 1978; Pitt 1979; Bender & Terstriep 1984).

Studies which measure buildup directly consistently show that street surface loads are very high compared to washoff in any single event. Pitt (1979) found the *load* of solids on streets immediately after cleaning by sweeping or rain was substantial, and depended on the street surface, with rougher surfaces having higher loads. For a rough surface of screenings in tar the load after cleaning was about 1,800 pounds per curb mile (500 grams per curb metre), equivalent to several months of buildup. Buildup *rate* was less dependent on the street surface, although poor quality asphalt gave a higher buildup rate, presumably due to breakup of the road surface itself. A typical buildup rate was about 400 pounds per curb mile (110 grams per curb metre) in the first month, and is shown reducing gradually with time. Malmquist (1978) also found street loads were high. Four repeated flushings (each equivalent to very heavy rain) were required before a marked drop in washoff loads occurred. Reinertsen (1981) observed that single rainfall events had little effect on surface concentrations, but many high intensity rain events in succession reduced the surface load by about 80%.

## 4.2 Buildup Functions

Buildup load increases with antecedent dry period (Pravoshinsky & Gatillo 1969; Sartor & Boyd 1972; Pitt 1979; Terstriep et al. 1980; Alley & Smith 1981; Yaziz et al. 1989; Yamada et al. 1993; Haster & James 1994), but small data sets and large scatter make the form of the relationship hard to determine. Sartor and Boyd (1972) and Pitt (1979) use a curve in which buildup rate decreases with time. Alley and Smith (1981) fit a straight line, while Pravoshinsky and Gatillo (1969) and Yamada et al. (1993) use statistical methods which imply a straight line. Terstriep et al. (1980), and Yaziz et al. (1989) present data without reference to any underlying function, and Haster and James (1994) specifically note that the shape of the curve cannot be determined with any accuracy. From a statistical viewpoint, none of the experimental data can support any function more complex than a straight line. But that says more about the wide scatter of the observed data than about any 'real' underlying relationship.

Several researchers have investigated the form of the buildup function at a more theoretical level. Baffaut and Delleur (1990) describe three algebraic forms for pollutant buildup: linear, in which $L_t=at$; exponential, in which $L_t=L_{max}(1-e^{-kt})$; and Michaelis-Menton, in which $L_t=L_{max}t/(c+t)$; where $L_t$ is the total buildup at time $t$, $L_{max}$ is a limiting load, and $a$, $k$, and $c$ are constants. Huber et al. (1987) also recognise a power function for buildup, in which $L_t=at^b$. The exponential and Michaelis-Menton formulations are inherently bounded functions. The linear and power functions are not bounded, but an upper bound may be artificially imposed. The exponential form is probably the most frequently used.

Some investigators have found that a higher buildup limit must be used to simulate washoff from more intense storms (Sartor & Boyd 1972; Baffaut & Delleur 1990; Srananthakumar & Codner 1992b), while others have found that very high buildup limits (Jewell et al. 1980; Alley & Smith 1981; Huber et al. 1987) or very fast buildup (White 1989) must be used for all storms to achieve a reasonable fit. These results also support the presence of very high street surface loads. Coleman (1993) takes the next step and proposes that buildup is not a limiting factor in determining washoff loads, nominating particle detachment as the critical process instead.

Much of the work quoted above, both practical and theoretical, indicates that surface loads are consistently high, even straight after washoff events. It does indeed follow from this that *buildup* is often not a limiting factor in determining washoff loads, and may therefore be less important than has often been believed. Assuming a higher initial load in an intense storm might be a useful modelling fix, but it is not physically realistic. If the load is there for an intense storm, it must be there for a mild storm too, and something about the *washoff* process is preventing its removal. Antecedent dry period may be important where buildup is low, either naturally or as a result of experimental procedures, but is unlikely to make much difference where the accumulated load is already high.

## 4.3 Descriptive View

A general descriptive view of contaminant buildup on impervious surfaces has been developed incrementally by Shaheen (1975), Sutherland (1980), Novotny et al. (1985) and James and Shivalingaiah (1986), among others. In this view, buildup is seen as a process of dynamic equilibrium acting between deposition and removal at any point, and between contributing and non-contributing areas. Sources include dustfall, vehicles, construction and demolition, vegetation, and garden chemicals. Removal processes include wind, vehicle induced eddies, decomposition, street sweeping, snow removal, and of course washoff by rain, which in this view is just another removal process (James & Shivalingaiah 1986). Some material moved off the road by wind or eddies will become trapped by vegetation or in other ways, and will be removed at least temporarily from the pool of windblown pollutants (Sutherland 1980). But extreme events which generate runoff or erosion from pervious areas may bring it back again (Pitt 1979; Srananthakumar & Codner 1992b). Because the system is in dynamic equilibrium, a larger departure from equilibrium will generate a larger restoring effect, which explains the possible curvature of the buildup function. The cleaner a surface is made, the faster it gets dirty again, by redistribution of material from surrounding areas (Novotny et al. 1985). Models based on this view can simulate a full range of buildup curves, from severely bounded at high vehicle and wind speeds, to almost linear buildup for low vehicle and wind speeds (James & Shivalingaiah 1985).

### 4.4 Summary

Buildup of material on impervious surfaces can be described as a dynamic equilibrium process acting between deposition and removal at a point, and between contributing and non-contributing areas. Buildup is mediated by natural and vehicle-induced winds, and is mainly a dry weather process. Buildup of many contaminants on roads is associated either directly or indirectly with vehicle movement.

Surface load increases with antecedent dry period, but the shape of the curve cannot be determined with any accuracy. The accumulated surface load is typically very high compared with the washoff load in any single event. This strongly suggests that buildup is often not a limiting factor in determining washoff loads.

## 5. WASHOFF

Washoff is the process by which accumulated dry deposition is removed from impervious surfaces by rainfall and runoff, and is incorporated in the flow. It can be measured directly from the pollutant loading of runoff, provided other potential sources such as erosion or point sources are measured or eliminated. It may be influenced by the mass of material available, which is in turn affected by the preceding buildup process. The important distinction between buildup and washoff was noted by Wanielista (1981), but the interaction between them has frequently been downplayed or ignored, most notably in the crusading paper of Whipple et al. (1977). These authors have either underrated the importance of the interaction, or overrated the ability of statistical analysis to separate the two effects. Conventional overviews of the washoff process are provided by Lager and Smith (1974), Preul (1974), Overton and Meadows (1976), Roesner (1982), and Huber (1986), while Sonnen (1980) gives a valuable and provocative alternative view.

### 5.1 Storm Characteristics

The washoff process has been the subject of a great deal of practical and theoretical work over many years. Some researchers, including Hartigan et al. (1978), Mance and Harman (1978), Characklis et al. (1979a), and Freund and Johnson (1980) have found or assumed that washoff depends on runoff *volume,* while others, such as Lager et al. (1971), Pope et al. (1978), Ichikawa (1981), Hoffman et al. (1982), and Aalderink et al. (1990) have opted for runoff *rate*. Alley et al. (1980) modelled washoff in terms of availability, bed armouring, and transport, and Akan (1987) developed a model based on flow shear stress.

Many studies, including those of Sartor and Boyd (1972), Yaziz et al. (1989), Baffaut and Delleur (1990), Bujon et al. (1992), and Kuo et al. (1993) relate washoff to rainfall *intensity*. Pravoshinsky and Gatillo (1969) consider the effect of rainfall *volume* on washoff, while Reinertsen (1981) uses both intensity and volume. Desbordes and Servat (1987) found that rainfall intensity and storm volume were more important than prior buildup. Price and Mance (1978) and Coleman (1993) associate washoff specifically with particle detachment by raindrop impact energy, which is a standard technique for erosion of pervious areas (Hudson 1971), while Shivalingaiah and James (1984a) note that rain energy promotes both suspension and transport in overland flow.

This apparent diversity of results centres around four main explanatory variables - rainfall rate and volume, and runoff rate and volume - and two main processes - shear stress generated by flow, and energy input from raindrops. The problem with the four explanatory variables is that they are all to some extent correlated with each other, and more so at longer time intervals. So correlation analysis is unlikely to discriminate accurately between them, particularly if other sources of statistical noise are present. In any case, it is quite possible that different processes dominate under different conditions or at different scales.

Fortunately, a recent study in Sweden described by Spangberg and Niemczynowicz (1992; 1993) provides further information. They measured turbidity, pH, conductivity, and temperature in runoff from a small asphalt car park at ten second intervals during rain and one hour intervals during dry periods continuously for about seven months. On this small catchment the turbidity pollutograph consistently lagged about 35 seconds behind the rainfall pattern, but preceded the flow hydrograph by about 60 seconds. If at this scale washoff (as measured by turbidity) consistently precedes flow, it cannot be caused directly by the flow. Washoff is preceded by rainfall, however, and so could be caused by it. The correlation coefficient between turbidity and rainfall exceeded 0.9 when the optimum lag was allowed for.

The effect of antecedent dry period on washoff is less clear than its effect on buildup. Although a number of researchers find some relationship (Wilkinson 1954; Eckhoff et al. 1969; Mance & Harman 1978; Aalderink et al. 1990; Forster 1993; Yamada et al. 1993), the effect is always described as small, or qualified in some other way. Yaziz et al. (1989) found a good relationship between washoff and antecedent dry period using data from a small experimental roof, while Pravoshinsky and Gatillo (1969) found a significant association when dry days and rainfall volume were fitted simultaneously. But Whipple et al. (1977) found no significant relationship for most parameters tested, and Weeks (1981) and Hoffman et al. (1982) found no significant effects at all. This is consistent with the observations on buildup noted previously. *Buildup* does generally increase with antecedent dry period, but only when the total surface load is small can this increase potentially carry through and affect *washoff.*

## 5.2 First Flush

The first flush or initial flush is a distinctive feature of washoff, and is related to both storm and catchment characteristics. A 'first flush' is said to occur when the incremental load exceeds the incremental flow at the start of a runoff event, when both flow and load are expressed as a fraction of the event total (Bedient et al. 1978; Griffin et al. 1980). First flush produces higher concentrations early in the event, and a concentration peak which precedes the flow peak. A 'flush' at any other time during a storm can be defined analogously (Helsel et al. 1979).

The first flush phenomenon has long been observed (Wardle 1893; Palmer 1950). It occurs very frequently in urban runoff, but by no means always (Burm & Vaughan 1966; Mance & Harman 1978; Urbonas & Tucker 1980; Revitt et al. 1981; Bellinger et al. 1982; Saget et al. 1992; Stephenson & Wimberley 1993). It is important to an understanding of basic washoff processes, and relevant to the design of management and treatment techniques.

The duration of first flush on a given catchment depends on the time of concentration (Palmer 1950; Weeks 1981), and so generally increases with catchment size. Correspondingly, first flush becomes less detectable as time of concentration increases (Vorreiter & Hickey 1994). Where the time of concentration is longer than typical storm duration, the concept is no longer applicable. First flush is by its very nature a characteristic of small catchments.

First flush increases with urbanisation (McElroy & Bell 1974; Helsel et al. 1979; Meister & Kefer 1981; Ichiki et al. 1993), and is apparently associated with the increased impervious area and higher runoff coefficient of urban land uses. Not surprisingly, initial flush is of little significance in runoff from areas of sandy soil (Wright 1993). The work of Spangberg and Niemczynowicz (1992; 1993) strongly suggests that the first flush is generated during overland flow.

The magnitude and lead time of first flush increase with rainfall intensity (Weibel et al. 1966; Inaba 1970; Yaziz et al. 1989), and its magnitude tends to increase with antecedent dry period (Wilkinson 1954; DeFilippi & Shih 1971; Tucker & Mortimer 1978). Lead time appears to be related to the mobility of the contaminant in question, with microorganisms peaking before solids (Weibel et al. 1966), dissolved solids before suspended solids (Fletcher et al. 1978), and volatile suspended solids before inorganic suspended solids (Inaba 1970). The likely mechanism of first flush is discussed in the following sections.

## 5.3 Catchment Characteristics

Land use and surface characteristics both affect the quality of washoff. Washoff loads can be increased one hundredfold or more by construction activity or other forms of soil disturbance in the catchment (Pisano 1976; Barfield et al. 1978; Konno & Nonomura 1981). Many potential management techniques have been proposed (Barfield et al. 1978; Guy 1978; MacNeill et al. 1988), of which sodding, paving, and possibly silt fences are among the more effective (MacNeill et al. 1988). Given this very high contribution from disturbed soil areas, which is more important: the state of urbanisation (land use), or the rate of urbanisation (disturbed soil area)? Including disturbed soil area as a basic land use, along with residential, industrial, and commercial uses, would help to resolve the question.

Zhen-Ren et al. (1993) found that washoff from residential areas was lower than from industrial or commercial areas, and Bannerman et al. (1993) concluded that streets and parking lots are among the critical source areas for all land uses. Asphalt surfaces give higher loadings than concrete, and poorly maintained surfaces give higher loadings than good surfaces (Sartor & Boyd 1972). Presumably the asphalt itself contributes to washoff contamination as it breaks up. Asphalt particles are a significant source of hydrocarbons in runoff (Hoffman et al. 1984).

Washoff from roads increases as vehicle movement on the wet road increases (Reinertsen 1981; Chui et al. 1982; Shivalingaiah & James 1984a). This can be attributed to particle detachment and suspension in the overland flow, encouraged by physical disturbance, and to the breakup of leaves and other plant debris, which releases soluble contaminants and produces smaller particles which are more easily transported by the runoff. Contaminants particularly associated with the roadway rather than the gutter, such as titanium from road marking paint (Ellis et al. 1981) and hydrocarbons from crankcase oil (Pope et al. 1978; Hoffman et al. 1982) tend to occur very late in the runoff hydrograph.

Street sweeping typically removes about half of the accumulated *buildup* from the swept surface, as noted in the previous section. This is mirrored in *washoff* quality only in the case of very heavy artificial rain (Malmquist 1978). Under natural rainfall, the improvement in washoff quality is smaller, and tends to be statistically marginal or insignificant (Bender & Terstriep 1984; Prych & Ebbert 1987). The Nationwide Urban Runoff Program of the USEPA concluded that street sweeping is generally ineffective for improving runoff quality (Sartor & Gaboury 1984; Torno 1984). Several reasons for this have already been noted. Firstly, many contaminants are associated mainly with small particles, and street sweepers do not remove these very efficiently. Removing half the 'dust and dirt' does not remove half the significant pollutants. Secondly, buildup is an equilibrium process, with physical movement of particles both to and from the road surface. Disturbing the equilibrium by cleaning results in faster apparent movement into the swept zone by redistribution from surrounding areas. Next, to be most effective in the long term, sweeping must occur more often than storm events. In areas of frequent rain, this can be hard to achieve in practice. Finally, sweeping directly affects buildup and, as proposed above, buildup is often not a limiting factor in determining washoff loads.

A factor which is rarely considered in this context, however, is the effect of fallen leaves and other plant debris. Leaves can be a major source of nutrients in urban runoff (Cowen & Lee 1973; Kluesener & Lee 1974; Cordery 1976; Freund & Johnson 1980; Pratt & Adams 1981), and street sweeping does pick up leaves effectively (Sartor & Gaboury 1984). This suggests that street sweeping should not be lightly dismissed as a management option, particularly where eutrophication downstream is likely, or already present.

## 5.4 Washoff Functions

Washoff is almost always represented by an exponential function (Metcalf and Eddy Inc et al. 1971; Nebraska University 1974; Medina 1979; Terstriep et al. 1980; Wada & Miura 1984; Akan 1988; Kuo et al. 1988; Patry & Kennedy 1989; White 1989, and others), although Hartigan et al. (1978) used a power function for washoff from pervious areas. Despite its almost universal use, or perhaps because of it, a number of problems have been identified in the use of the exponential form. Firstly, as noted by Alley et al. (1980), Huber and Dickinson (1988), and Srinanthakumar and Codner (1992b), an exponential washoff function cannot fit an increase in concentration at any time during the storm. Increased flow can lead to increased *load*, but the simulated *concentration* must always decrease. The standard adjustment to overcome this limitation is to assume that the washoff in any time interval depends on a higher power of runoff rate. If applied to rainfall intensity rather than runoff rate, this would accord with the conclusions of Price and Mance (1978) and Coleman (1993). Either way, it does arguably have a measure of physical reality.

Secondly, as noted previously, many researchers have found that it is necessary to assume a higher initial load for intense storms than for low intensity events, which is not physically realistic. Most interestingly, though, if an exponential form is assumed, the washoff coefficient is by no means constant, even during a single event. Within a storm, variation in the washoff coefficient has been related to cumulative runoff volume (Nakamura 1984; Srinanthakumar & Codner 1992b), time (Osuch-Pajdzinska 1987), and rainfall rate (Kuo et al. 1993), while between storms the coefficient appears to increase with antecedent dry period (Haster & James 1994). Exponential parameters also vary from one pollutant to another (Srinanthakumar & Codner 1992a), which is perhaps less surprising than the other changes. Incorporating effects such as these into simulation models can improve the goodness of fit (Srinanthakumar & Codner 1992b), but surely there is a suggestion in all of this that the washoff function is not fundamentally exponential at all. Similar doubts have previously been expressed (Jewell et al. 1980; Sonnen 1980), but only occasionally have alternatives been proposed (Price & Mance 1978; Shivalingaiah & James 1984a; Coleman 1993).

## 5.5 Descriptive View

How then can we describe the physical processes that occur during washoff from an impervious area? We must explain not only how some material is washed off, but also why most of it is not, since washoff is often small compared with total surface load. There appears to be no generally accepted comprehensive view of washoff, such as there is for buildup. However, a view which accords well with the observed information can be developed in the following way.

The process starts with a quantity of solid material on the surface. If the quantity is small, it may be a limiting factor, but more commonly the initial load will be large compared to a single washoff event. When rainfall starts, some of the material is loosened from the surface and suspended in the water film by the energy of the falling raindrops (Price & Mance 1978; Coleman 1993). As the water film builds up and begins to flow downslope, it also develops some ability to hold particles in suspension. So the solid material will not only be loosened, but will also be maintained in suspension in the overland flow by the sum of the rain energy and the flow energy (Shivalingaiah & James 1984b). Rainfall energy typically exceeds the flow energy of the resulting overland flow by a factor of several hundred (Hudson 1971), as can easily be shown by comparing the squares of their respective velocities.

If the rainfall intensity increases, more solids can be held in suspension in a given flow. Once initial losses are satisfied, flow is more or less proportional to rainfall intensity, but rainfall energy is proportional to a higher power of rainfall intensity (Price & Mance 1978). Thus suspended solids *concentrations* in overland flow should become somewhat higher, and *loads* should become much higher, as rainfall intensity increases. On the other hand, if the rainfall slackens the energy input decreases, and if the rain stops only the flow energy remains to hold particles in suspension. At such time, some of the material will be dropped from the flow, wherever it happens to be at the time. This explains the ease with which a second peak (McElroy & Bell 1974) or subsequent storm (White 1989) can generate further washoff: the material is not necessarily buried deep in cracks or shielded by larger particles, but remains where it was dropped in an established overland flow path until rainfall or flow energy increases again, or the surface dries out and wind driven buildup processes take over.

A first flush in which peak pollutant concentration precedes peak flow can occur because washoff is dominated by rainfall, not by flow, during the overland flow phase of runoff. But as rainfall intensity decreases, rainfall energy decreases even more rapidly. If a storm occurs entirely at an intensity where overland flow load is negligible, there can be no first flush from this source. This explains the observations of Weibel et al. (1966), Inaba (1970), and Yaziz et al. (1989), who found that the magnitude and lead time of the first flush increased with rainfall intensity.

When the flow has become concentrated in channels and gutters, the contribution of raindrops to the total flow energy becomes relatively less important, and in enclosed pipes it is obviously zero. It is only in overland flow that rainfall energy is a critical input. The concept that overland flow can be a prolonged and limiting process mediated by rainfall energy can potentially explain the conclusion of Bradford (1977) that tree-landscaped areas produce below average runoff loads, since the tree canopy reduces the rain energy of throughfall.

In the process proposed here, washoff depends mainly on rainfall intensity. Rainfall can vary at short time intervals, and since the washoff processes are nonlinear, using the average rainfall intensity over a longer period is not the same as using separate intensities for many shorter periods. Therefore a storm washoff factor of the form $\Sigma_n(aI^b)t$ is proposed as an explanatory variable for storm washoff, where $I$ is rainfall intensity in period $n$, $t$ is the length of each period, and $a$ and $b$ are parameters to be fitted. The time period $t$ should be as short as possible, and certainly no longer than the catchment time of concentration. While a function of the general form $aI^b$ has previously been embedded in a larger model (Price & Mance 1978; Shivalingaiah & James 1984b), and *peak* rainfall intensity has been used as an explanatory variable in statistical analysis (Desbordes & Servat 1987), the independent use and assessment of a cumulative storm washoff factor based on rainfall intensity appears to be completely unrecorded in the urban runoff literature. Yet it has a simple physical explanation, much supporting evidence, and only two parameters to be fitted. Further investigation of this methodology is strongly recommended.

### 5.6 Summary

Washoff of material from impervious surfaces is an overland flow phenomenon, and appears to be associated most strongly with rainfall intensity. Its relationship with flow is less satisfactory, particularly at short time intervals, and its association with prior buildup is tenuous, at best. Washoff seems to be the limiting process for urban stormwater pollution in most situations.

Although almost universally used in modelling, the exponential description of washoff is a poor measure of real physical processes. Despite the documented shortcomings of the exponential form, alternatives have only rarely been proposed. An alternative function based on rainfall intensity is presented here.

The first flush phenomenon, in which a disproportionate amount of material is carried away early in the storm, occurs very often but by no means always. First flush, like washoff generally, appears to depend on rainfall intensity, and is by nature and definition a characteristic of small catchments.

## 6. TRANSPORT

Transport in this context is taken to mean the movement of contaminants in urban runoff through gutters, pipes, and channels. In practice it is the transport of bed load, suspended matter, and natural and artificial litter which is of interest, since dissolved matter remains bound to the flow at all relevant time scales. Much of the research on transport is associated with combined sewers, but in many cases an analogous situation will apply in a separate storm drainage system.

Eckhoff et al. (1969) recognise three main stages of wet weather flow in a combined sewer. Firstly the raw sewage already in the pipes is pushed ahead of the rising flow, giving a first stage with the characteristics of raw sewage. If flows are sufficient, this is followed by scour in the sewer and washoff of surface debris, giving the worst quality flow. Pollutant levels then decrease to a steady state lower than dry weather values. Ellis (1979) notes a fourth possible stage. Drowning and containment of the combined sewer flow by increase in stage of the receiving stream can result in highly polluting slugs of runoff being released to the river as the flood level subsides. At this time, the maximum dilution capacity of the flood peak is not available, and major pollution loads may occur.

Field (1982) summarises the management alternatives for wet and dry weather wastewater transport and interception developed by the USEPA. Management options include maintenance review, catchbasins, new sewer design, sewer flushing, polymer injection, inflow reduction, insitu lining, impregnated concrete pipe and trenchless sewer, upstream storage and attenuation, flow routing and in-pipe storage, and a wide range of flow regulators. The emphasis is on optimal use of the existing sewerage system for the dual purpose of combined sewer drainage and overflow pollution control.

Where transport is prolonged, slower processes more typically associated with storage may become significant. At Lelystad, a town built on reclaimed land in the Netherlands, more than half the nitrogen and phosphorus is lost from the open canals forming part of the extensive drainage system, by sedimentation, chemical reaction, and incorporation into plants (Van den Berg et al. 1977; Uunk & van de Ven 1984).

## 6.1 Sediment

Overviews of sediment transport, deposition, and management are provided by Guy (1978), Shen (1981), Stephenson (1981), and Marsalek (1992). The strong association of many key contaminants with particles is repeatedly noted (Cullen 1980; Marsalek 1990; 1992; Herrmann et al. 1993). The effective removal of suspended solids from urban runoff will lead to a substantial improvement in many water quality parameters (Guy 1978; Dempsey et al. 1993).

Dempsey et al. (1993) note that contaminants associated with the finest particles will be transported as if they are dissolved, although they will react chemically as if they are immobilised on particles. Bertrand-Krajewski et al. (1993) distinguish between small particles which are transported as suspended load, and larger particles which may form either bed load or suspended load. Ellis (1979) discusses the difficulty of sampling larger suspended solids correctly, particularly with automatic samplers, due to non-uniform vertical distribution in the stream, and poor transport along the sampler tube.

Ellis (1977) observes a characteristic double peak in suspended solids concentration from a catchment in London, and subsequently notes a bimodal sediment size distribution (Ellis et al. 1981). It is proposed that the earlier, finer material comes mainly from prior deposition in the drain, and the later material with a wide size range comes directly from the catchment. While this may be true on a given catchment, it appears to be a risky generalisation, since behaviour must depend on characteristics of the drain and the storm, as well as the particle sizes (Shen 1981). A progressive change in sediment size and surface texture with distance downstream is observed during runoff from the same catchment, and is attributed to erosion and cementation processes (Roberts et al. 1988).

Deposition and flushing are investigated in detail by Pisano et al. (1979), who show that peak loads of suspended solids in combined sewers can be greatly reduced by flushing the pipes during a low flow period. This could be of value where treatment capacity downstream (either actively in a treatment plant, or passively in detention or wetland) was exceeded by the peak flow. Algorithms for pollutant transport based on flow routing principles are developed by Shivalingaiah and James (1984a), while Alley et al. (1980) address the effects of particle size and bed armouring on sediment transport.

Several papers have assessed the value and performance of gully pots or catch basins - sediment traps associated with gutter entries into the piped drainage system. They may act as either sink or source of pollutants in a given runoff event, depending on storm characteristics and maintenance history. Sediment removal efficiency of both wet and dry gully pots is quite good for low flow rates and larger particle sizes, but is less satisfactory for finer particles (Sartor & Boyd 1972; Grottker & Hurlebusch 1987; Driscoll & Strecker 1993). Control of suspended solids is less effective at higher flow rates, due to reduced removal efficiency (Fletcher & Pratt 1981), resuspension of previously settled matter (Heaney & Sullivan 1971), or both. A model based on the work of Fletcher and Pratt (1981) fitted well under constant flow conditions (Wada et al. 1987). Dissolved pollutants are washed out of catch basins more readily than solids (Fletcher & Pratt 1981). Disadvantages include a significant maintenance requirement, and increased loads of ammonia and dissolved metals, resulting from bacterial action under anaerobic conditions (Fletcher et al. 1978; Mance & Harman 1978; Lebreton et al. 1993).

## 6.2 Leaves and Grass

Deciduous trees in the urban landscape drop a large mass of leaves over a relatively short period each year. The gradual leaching of nutrients from fallen leaves has been discussed previously. Alternatively, whole leaves and other plant debris may be carried away by the flow. The total phosphorus content of leaves is typically about 0.2% of dry weight and total nitrogen is about 1% of dry weight (Cowen & Lee 1973; Prasad et al. 1980; Dorney 1986), and higher nutrient contents have been found for bluegrass (Timmons et al. 1970), so total nutrient loads can be substantial.

Conventional water quality measurements record only those contaminants which can physically enter the sample bottle, suction tube, or sensor cavity. By their very nature, indeed almost by definition, gross pollutants such as leaves and litter are not measured, and so their contribution of nutrients and other contaminants to receiving waters is not recorded (Cullen 1976). They are still present, however, and may significantly affect the receiving water quality, particularly if sediments are disturbed by subsequent flood or wave action. The explicit measurement of gross pollutant transport should be considered in any situation where the characteristic time scale is long enough to permit breakdown of leaves and other organic debris.

## 6.3 Litter

Litter presents a distinctive problem for urban drainage systems. It is a highly visible form of waterway pollution (McKay & Marshall 1993), yet community understanding of the problem is low, and its principal origin on streets and urban areas (Perrens et al. 1991) remains largely unrecognised by the general public (Melbourne Water et al. 1993). Litter can be effectively removed by regular street sweeping, and the efficiency of removal is high (Sartor & Boyd 1972).

Senior (1992) and Sim and Webster (1992) describe studies of litter in Melbourne and Sydney respectively. Both find plastics to be the largest component, followed by paper, with smaller quantities of glass, metals, and miscellaneous litter. Sim and Webster (1992) and Allison et al. (1994) find that the mass of artificial litter is less than that of natural litter from vegetation. Litter appears to exhibit a first flush (Hoffman et al. 1985; Sim & Webster 1992), although it tends to wash off later than natural organic matter (Allison et al. 1994). The later washoff could be a result of larger particle size, judging from a more detailed breakdown of components: plastic bags, plastic sheeting, plastic food wrappers, take away food containers, and junk mail comprise nearly two thirds of total litter count (Senior 1992).

McKay and Marshall (1993) describe a study of tagged litter released into drainage pits in Melbourne and Geelong. They estimate that four to five million items of floatable litter enter the urban waterways via the underground drainage system each year, or a little more than one item per resident. Natural, highly vegetated waterways trap and retain most of their litter, whereas constructed drains and watercourses transport litter very efficiently into receiving waters.

Molinari and Carleton (1987) have reviewed a number of litter interception installations comprising floating booms or trash racks, while Goyen et al. (1985) and Hanrahan and Fagen (1987) describe trash racks operating on urban catchments in Canberra. Observation suggests that both floating booms and trash racks are moderately effective, given adequate maintenance to remove accumulated debris (Sim & Webster 1992; McKay & Marshall 1993). Floating booms appear to be preferable for larger streams and in retrofit situations, but trash racks may be suitable in a new development where they are incorporated at the design stage (Molinari & Carleton 1987). Other suggested management techniques include litter traps in drains, review of street cleaning and rubbish collection protocol, volunteer cleanup days, and public education (Australian Environment Council 1988; Senior 1992; McKay & Marshall 1993).

### 6.4 Summary

Transport of pollutants in urban runoff is concerned mainly with suspended solids, natural organic litter, and artificial litter of human origin. Many key pollutants are strongly associated with suspended solids, so the removal of suspended solids will lead to substantial improvement in many water quality parameters.

Natural organic litter - leaves, seeds, flowers, and grass clippings - is a major source of organic matter and nutrients. If the materials are transported in the flow, their contribution to the receiving water will not be fully recorded by conventional water quality measurements until they have completely broken down.

Artificial litter - mainly plastics and paper - is a significant and unsightly contaminant of urban waterways. Removal by trash racks and floating booms is moderately effective, but public awareness of the problem is low, and there is scope for better source control by community education.

## 7. STORAGE

The quality of urban storm runoff can be greatly influenced by storage. The term 'storage' includes natural lakes and artificial basins, deep ponds and shallow wetlands, and typical detention time may range from minutes to months. In all cases processes occur which affect contaminants in the water, and in nearly all cases the result is an improvement in water quality. Storage has been recognised as a quality management option by many authors since at least the early 1970's.

Storage may be used either in conjunction with conventional water treatment technology, or as a treatment process in its own right. When used in conjunction with a treatment plant, the chief function of the storage is to reduce peak plant inflows to a more manageable level (Inaba 1970; Feuerstein & Friedland 1975; Stahre 1982; Field 1984; Etoh et al. 1987). Any improvement in quality during storage is usually seen more as a bonus than as an integral part of the process. Although this is a valid use of storage, it is not considered in any detail here, since it is concerned more with flow volumes than with water quality.

### 7.1 Water Quality Behaviour

Perhaps the most important water quality process occurring in storage is the reduction of suspended solids by sedimentation. In many cases, reductions of 80% or more in suspended solids have been achieved (Characklis et al. 1979a; Oliver & Grigoropoulos 1981; Baca et al. 1982; Striegl 1987; Wu et al. 1988; Urbonas 1993; Whiteley et al. 1993). But smaller reductions have also been observed (Ferrara & Witkowski 1983; Grizzard et al. 1986; Martin 1988), and basins not designed for sedimentation may even increase suspended solids load in some events by scouring of previous deposits (Dally 1984).

Removal efficiency tends to increase with pond surface to catchment area ratio (Wu et al. 1988), and with average residence time (Lawrence 1986; Yousef et al. 1986b; Hvitved-Jacobsen et al. 1987). In the limiting case, a basin which completely contains a runoff event provides complete control during that event (Wu et al. 1988), but probably not when averaged over a longer period. Removal efficiency also depends on the initial load. Higher input concentration of suspended solids typically leads to a substantially higher removal rate and a slightly higher output concentration (Randall et al. 1982; Grizzard et al. 1986). Higher suspended solids loads tend to include larger particles, which therefore settle out more readily (Ferrara & Witkowski 1983). Conversely, where input loads are already low, little further improvement can be expected (Holler 1989).

Laboratory studies of sedimentation tend to support the results achieved in practice. Suspended solids removals are about 70 to 90%, under a range of experimental conditions (Cordery 1976; Whipple & Hunter 1981; Randall et al. 1982). Percentage removal increases with initial concentration and with settling time, but most quality improvement occurs within the first six hours (Randall et al. 1982; Grizzard et al. 1986).

Suspended solids can be a significant pollutant in its own right, but its importance is further increased by its strong association with many other stormwater contaminants. Because of this association, effective reduction of suspended solids will reduce most stormwater pollution problems (Walesh 1986; Preul & Ruszkowski 1987; Urbonas 1991), and if achieved by sedimentation in storage will reduce most flow problems as well (Guy 1978).

Hydrocarbons are strongly associated with particles, and hence tend to behave similarly in storage (Marsalek 1990; Maldonato & Uchrin 1994). About 99% of petroleum hydrocarbons were removed from urban runoff by a dry detention basin, and concentrated near the drain inlets in the top 15 centimetres of sediment (Maldonato & Uchrin 1994). Whipple and Hunter (1981) achieved 65% removal of total hydrocarbons in laboratory tests. Polyaromatic hydrocarbons are effectively adsorbed and retained by many soil types, with highly organic soils being the most effective (Gjessing et al. 1984).

Heavy metals (Yousef et al. 1984; Dempsey et al. 1993) and phosphorus (Cullen 1980; Dempsey et al. 1993) are also associated with particles, and can be effectively reduced by storage. Removals are somewhat lower than for suspended solids because the contaminants are concentrated on the smaller particles which settle out more slowly, and because they can be present in dissolved form as well. Removal in storage is frequently 70% or more for heavy metals (Grizzard et al. 1986; Striegl 1987; Wu et al. 1988), and 60% or more for total phosphorus (Oliver & Grigoropoulos 1981; Baca et al. 1982; Hey 1982; Yousef et al. 1986a; Hvitved-Jacobsen et al. 1987; Whiteley et al. 1993). Heavy metals are concentrated in the deposited sediments (Gjessing et al. 1984; Yousef et al. 1984; Hvitved-Jacobsen et al. 1987). Downward movement appears to be slight in sandy soils (Nightingale 1987) and negligible elsewhere (Wigington et al. 1983).

Moderate reductions in oxygen demand can be achieved by storage. COD is typically reduced by 40 to 60% in practice (Oliver & Grigoropoulos 1981; Hey 1982; Grizzard et al. 1986), while BOD shows the same range of improvement in laboratory studies (Cordery 1976; Whipple & Hunter 1981; Randall et al. 1982). Horner (1977) found that oxygen demand dropped by 40% in as little as 15 minutes. The mechanism of oxygen demand reduction is not discussed in any detail, but in view of the speed of the change it must be mainly due to removal by sedimentation, rather than by oxidation.

The behaviour of bacteria in storage is complicated by their ability to multiply and regenerate, and by the possibility of diurnal concentration patterns (Davis et al. 1977). Nevertheless, Whiteley et al. (1993) found faecal coliform concentrations dropped to less than half in storage, and Jacobs and Ellis (1991) found that the time during which guideline levels for faecal coliforms were exceeded were greatly reduced. Whipple and Hunter (1981) achieved more than 90% removal in settleability columns.

All the contaminants discussed above are at least partly particulate in form, and sedimentation is a major removal process. By contrast, storage has only an averaging effect on dissolved conservative parameters (Characklis et al. 1979a; Hey 1982), with little or no long term removal (Martin 1988). This means that contaminants derived from storm runoff, such as chloride from deicing salts, will be reduced during storm flows but increased at other times. But contaminants derived from natural sources, such as magnesium derived from soil and rock, will be diluted year round by the input of urban stormwater (Cherkauer 1977). Temperature, although not really conservative, also shows an averaging effect. In colder areas, storage may lead to less ice cover downstream in winter (Cherkauer 1977).

Nitrogen exhibits by far the most complex behaviour in storage, since it is by no means a conservative parameter. Removal of total nitrogen ranges from very low (Martin 1988) to as much as 90% (Hvitved-Jacobsen et al. 1984). Ammonia concentration may decrease in storage (Martin 1988), but more commonly increases (Oliver & Grigoropoulos 1981; Hey 1982; Randall et al. 1982; Holler 1989). Total Kjeldahl nitrogen (organic nitrogen plus ammonia) may decrease (Randall et al. 1982) or increase (Ferrara & Witkowski 1983), and nitrate removal covers a wide range (Hey 1982; Randall et al. 1982; Holler 1989). As noted previously, an increase in ammonia is also often observed in roadside catch basins (Fletcher et al. 1978; Mance & Harman 1978; Lebreton et al. 1993).

The processes driving this apparently erratic behaviour are described by Hvitved-Jacobsen et al. (1984) and Yousef et al. (1986a). Ammonia is produced by the gradual degradation of organic matter in sediments (Lammersen 1993; Mouchel & Simon 1993). Under aerobic conditions, ammonia may be converted to nitrate by bacterial action (nitrification). Under anaerobic conditions, nitrate may be converted by further bacterial action to nitrogen gas, which is lost from the system (denitrification). Aerobic and anaerobic conditions may coexist at different depths in the same sediment deposit, so both processes may occur simultaneously. Nitrogen may also be removed from the system by incorporation into plants. Thus the distribution of nitrogen between its several forms depends on many factors, including input levels, oxygen level in sediments, scour and disturbance of sediments, and presence of plants.

The use of typical or average behaviour throughout this section, for review purposes, may imply a greater degree of order and uniformity than is in fact present. While the averaging process does reveal some consistency at the overview level, it should be emphasised that variability remains high at the individual level. Certainly the figures quoted here should not be used for design purposes without reference to the conditions and qualifications described in the various source documents.

## 7.2 Theory and Design

A number of papers have reviewed the more theoretical aspects of storage design for quality improvement (Medina et al. 1981; Kuo & Zhu 1987b; Akan 1992; Loganathan et al. 1994), and for the dual purposes of peak reduction and quality improvement (Ormsbee et al. 1987). Whipple et al. (1987) concentrate more on management and institutional issues of dual use, while Tilley et al. (1994) look at optimising the operation of an existing basin. Best flood control is achieved with the basin empty as often as possible, but best quality control is obtained with long detention time and a substantial permanent pool, hence the need for compromise in any given situation. Kuo and Zhu (1987a; 1989) develop a system to divert only the first flush for quality improvement - a principle which can only be useful where a first flush is reliably present (Saget et al. 1992).

At a more pragmatic level, Randall (1982) lists conditions which encourage settling and infiltration, and so assist water quality improvement: long narrow basins with well separated inlet and outlet; use of baffles, flow retarders, or ponds in series; a permanent wet pool; grass cover on the remainder of the basin floor; and low rate discharge via infiltration to underground tile drains. Yousef et al. (1986b) note the importance of an aerobic sediment layer for nitrogen removal, and conclude that permanently wet ponds of four to six feet in depth are likely to give the best results.

Phillips and Goyen (1987) describe the water quality control ponds and gross pollutant traps used in Canberra in considerable detail, and present design curves of retention versus residence time for suspended solids, total phosphorus, and E. coli, for both sedimentation and macrophyte systems. Cullen et al. (1988) review design and management considerations with emphasis on the biological aspects, and recommend: the use of side slope and depth to control plant growth; 10 to 30% of surface area allocated to emergent macrophytes; full water level control; and trash racks and bedload traps upstream.

### 7.3 Wetlands

Wetlands are a limiting case of water quality control ponds, in which interactions with plants play a major role. Wetlands were recognised by the Nationwide Urban Runoff Program (NURP) as a promising management technique (Torno 1984). Contaminant removal processes are essentially the same as in open ponds, except that sedimentation is improved by the more quiescent conditions (Brown 1988), and uptake by plants is assisted by the greater mass of plants present. Reckhow and Qian (1994) propose a threshold model for phosphorus trapping in wetlands. In this model, phosphorus output is low and constant as long as the input is below some long term acceptance rate, but increases rapidly at higher input rates. Pollutant removal in constructed wetlands tends to be higher and less variable than in natural wetlands (Driscoll & Strecker 1993), which presumably just reflects their suitability for the intended purpose.

Strecker et al. (1990) summarise the characteristics and pollutant removal efficiencies of eleven wetland systems in the United States. Mean removal efficiencies are 87% for suspended solids, 85% for total lead, 56% for total zinc, 54% for total phosphorus, and 40% for total copper. Variability of removal between studies is substantial, to the extent that phosphorus, zinc, and copper all record negative 'removal' in at least one study. Ellis (1993) presents further performance data, broadly similar in both magnitude and variability, and discusses removal processes and design criteria for constructed wetlands. Three areas requiring design attention are recognised: the inlet zone (settling of larger particles), the macrophyte zone (main treatment area), and the open water zone (flocculation and sunlight contact). Martin (1988) achieved similar results using a wet detention pond and wetland in series, showing that different physical layouts can produce similar results.

### 7.4 Summary

The quality of urban storm runoff can be greatly improved by storage in ponds and wetlands. The main processes involved are settling of suspended material, averaging of dissolved material, and conversion of nitrogen between its chemical forms by bacteria. Pollutant removal efficiency tends to increase with average residence time, but in other respects is highly variable, particularly in ponds not originally designed for water quality control.

Although the scatter of results is wide, removal efficiencies of 80%, 70%, 60%, and 50% have frequently been achieved for suspended solids, heavy metals, phosphorus, and oxygen demand respectively. Based on smaller amounts of data, high removals of hydrocarbons and bacteria have also been achieved. Conversion between nitrogen forms frequently leads to an increase in ammonia concentration, although total nitrogen is usually reduced.

## 8. RECEIVING WATERS

Receiving waters are both the beginning and the end of the whole urban runoff quality issue. Physically they are the end of the series of hydrologic processes affected by urban runoff. But in another sense they are also the source of the problem: the adverse effect on receiving waters is always a significant aspect of urban runoff quality, and frequently the only one. No perceived quality problem in receiving waters often equates to no perceived quality problem at all.

Receiving waters for urban runoff are frequently discussed but rarely defined. Heaney and Huber (1984) use a definition based on the naming convention of a standard map series. This has the advantage of objectivity, which is important in a comparative study, but it is not universally applicable and also does not seem to capture the full meaning of the term as used in practice. According to conventional usage, receiving waters must be downstream of the area of interest, but not so far downstream that other areas have a dominant effect. They must have some perceived environmental, aesthetic, or functional value which could potentially be compromised by the urban runoff. And they must have at least some characteristics of natural water systems - a buried pipe is not considered to be a receiving water, but an artificial lake may be. The key features thus appear to be relevant scale, perceived value, and natural characteristics.

Jones (1986) and House et al. (1993) present comprehensive reviews of urban drainage effects on receiving water quality, while further general information is provided by Marsalek (1986), Australian Environment Council (1988), and Lijklema et al. (1993). On more specific topics, Stephenson (1981) summarises eutrophication of receiving waters, Gujer and Krejci (1987) discuss ecological issues, and O'Loughlin (1994) provides an overview of the socio-economic and political issues associated with the pollution abatement program in Sydney.

## 8.1 Scale and Detail

Because of their key position in the urban runoff part of the hydrologic cycle, receiving waters play a major role in both definition and measurement of any potential problem. In particular, the size and nature of receiving waters in a given situation help to define the optimum scale and detail of water quality analysis (Harremoes 1981).

The need to match analysis detail to the ultimate objective has been noted by Huber (1986) and others. Tables of appropriate time and/or space scales for a range of situations are provided by Guy (1978), Marsalek (1986), Huber (1992), and House et al. (1993). Scales vary from local area and time measured in minutes for acute toxicity, to whole catchment area and time measured in decades for accumulation of contaminants in sediments. Gujer and Krejci (1987) suggest that broader coverage of a system may be better than more detailed coverage, and Tyson et al. (1993) emphasise the need to treat wastewater and receiving water as a single integrated system.

The message here seems to be that excessive detail, relative to the time and space scales of the ultimate objective, is not helpful in data analysis. In fact, it could probably be stated even more strongly. By introducing more sources of measurement error, permitting unrealistic or redundant model calibrations, and diverting resources from other priorities, unnecessary detail is likely to be positively detrimental.

Techniques which recognise the possibility of overfitting are available in standard statistical packages, and may well have been used without comment in the more statistically oriented urban runoff studies. But the problem is hard to address in simulation modelling, except by a determination to avoid complexity and eliminate insensitive model parameters wherever possible. It is probably fair to say that this has not always been done. To get the most information from a given data set, we need to understand its limitations (what it does not tell us) as clearly as its content (what it does tell us). The need to match data and analysis detail to the scale of the ultimate objective - usually associated with receiving waters - cannot be overemphasised.

### 8.2 Summary

Receiving waters for urban runoff are frequently discussed but rarely defined. The key features appear to be relevant scale, perceived value, and natural characteristics. The size and nature of receiving waters in a given situation help to define the scale and detail of urban runoff quality analysis required. Detail which is excessive, relative to the time and space scales of the ultimate objective, is not helpful in analysis and may be be positively detrimental.

## 9. SUMMARY AND CONCLUSIONS

This review has drawn on a large data base of urban water quality literature to describe the physical processes of urban runoff contamination. Individual stages addressed are atmospheric deposition, interception, buildup, washoff, transport, storage, and receiving waters. The main conclusions for each stage are summarised below.

### 9.1 Atmospheric Deposition

Atmospheric deposition makes an important contribution to stormwater contamination. It typically supplies as much nitrogen as is washed off in urban runoff, and a smaller proportion of suspended solids, phosphorus, COD, and heavy metals. Spatial variability is high at large to moderate scales, with deposition being generally higher in urban areas and greatly influenced by local sources.

Source control of nitrogen in urban runoff will not be achieved through modification of the urban landscape, as that is not the major source. Effective control will be achieved only when air quality is addressed. The scale of the processes involved suggests that the issue is not confined to urban areas.

### 9.2 Interception

The main pollutant sources accessed by interception processes are accumulated dry deposition on roofs and vegetation, and solution of roof and plant materials. Solution of copper and zinc in roofing materials usually occurs, and undiluted roof runoff may be highly toxic to fish. Fallen leaves and other plant debris are a significant source of nitrogen and organic matter, and may be the major source of phosphorus in urban runoff.

### 9.3 Buildup

Buildup of material on impervious surfaces can be described as an dynamic equilibrium process acting between deposition and removal at a point, and between contributing and non-contributing areas. Buildup is mediated by natural and vehicle-induced winds, and is mainly a dry weather process. Buildup of many contaminants on roads is associated either directly or indirectly with vehicle movement.

Surface load increases with antecedent dry period, but the shape of the curve cannot be determined with any accuracy. The accumulated surface load is typically very high compared with the washoff load in any single event. This strongly suggests that buildup is often not a limiting factor in determining washoff loads.

### 9.4 Washoff

Washoff of material from impervious surfaces is an overland flow phenomenon, and appears to be associated most strongly with rainfall intensity. Its relationship with flow is less satisfactory, particularly at short time intervals, and its association with prior buildup is tenuous, at best. Washoff seems to be the limiting process for urban stormwater pollution in most situations.

Although almost universally used in modelling, the exponential description of washoff is a poor measure of real physical processes. Despite the documented shortcomings of the exponential form, alternatives have only rarely been proposed. An alternative function based on rainfall intensity is presented here.

The first flush phenomenon, in which a disproportionate amount of material is carried away early in the storm, occurs very often but by no means always. First flush, like washoff generally, appears to depend on rainfall intensity, and is by nature and definition a characteristic of small catchments.

## 9.5 Transport

Transport of pollutants in urban runoff is concerned mainly with suspended solids, natural organic litter, and artificial litter of human origin. Many key pollutants are strongly associated with suspended solids, so the removal of suspended solids will lead to substantial improvement in many water quality parameters.

Plant litter - leaves, seeds, flowers, and grass clippings - is a major source of organic matter and nutrients. If the materials are transported in the flow, their contribution to the receiving water will not be fully recorded by conventional water quality measurements until they have completely broken down.

Artificial litter - mainly plastics and paper - is a significant and unsightly contaminant of urban waterways. Removal by trash racks and floating booms is moderately effective, but public awareness of the problem is low, and there is scope for better source control by community education.

## 9.6 Storage

The quality of urban storm runoff can be greatly improved by storage in ponds and wetlands. The main processes involved are settling of suspended material, averaging of dissolved material, and conversion of nitrogen between its chemical forms by bacteria. Pollutant removal efficiency tends to increase with average residence time, but in other respects is highly variable, particularly in ponds not originally designed for water quality control.

Although the scatter of results is wide, removal efficiencies of 80%, 70%, 60%, and 50% have frequently been achieved for suspended solids, heavy metals, phosphorus, and oxygen demand respectively. Based on smaller amounts of data, high removals of hydrocarbons and bacteria have also been achieved. Conversion between nitrogen forms frequently leads to an increase in ammonia concentration, although total nitrogen is usually reduced.

## 9.7 Receiving Waters

Receiving waters for urban runoff are frequently discussed but rarely defined. The key features appear to be relevant scale, perceived value, and natural characteristics. The size and nature of receiving waters in a given situation help to define the optimum scale and detail of urban runoff quality analysis. Detail which is excessive, relative to the time and space scales of the ultimate objective, is not helpful in analysis and may be be positively detrimental.

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**The Cooperative Research Centre for Catchment Hydrology**
**is a cooperative venture formed under the Commonwealth CRC Program between:**

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