A BIBLIOGRAPHY OF URBAN STORMWATER QUALITY

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CATCHMENT HYDROLOGY

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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 bibliography 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 bibliography forms part of a review of the English language literature on urban stormwater quality research. It summarises the objectives and conclusions of about 700 references, derived mainly from the journal and conference literature. The primary structure of the review is chronological, so that the development of issues, studies, and knowledge with time can be traced. Within each time period references are further divided by subject, and a summary of significant developments is provided.

Subjects used to classify references include general data collection, nutrients, microbiology, heavy metals, hydrocarbons, roads, snow and ice, buildup and washoff, storage, data reviews, process analysis, modelling, model overviews, monitoring, treatment, system management, subject overviews, and literature reviews.

An attempt has been made to identify significant gaps in the documented research. The areas in most need of further work are review of progress to date at the receiving water scale, development of contaminant balances at the whole catchment scale, and further clarification of the real physical processes involved in buildup and washoff on impervious areas.

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A BIBLIOGRAPHY OF URBAN STORMWATER QUALITY

1. INTRODUCTION

This bibliography 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 a review of urban stormwater quality processes (Duncan 1995b), and a database of references set up on the MS-DOS version of the EndNote Plus® bibliography system (Duncan 1995a). Copies of the reports and database are available from the CRC for Catchment Hydrology Office at Monash University, Clayton, 3168, Australia.

The central theme of the review is urban stormwater quality, as seen from an Australian perspective. More precisely, it is concerned with the quality of flow in a separate drainage system resulting from rain falling on urban, suburban, and developing areas, and the effect of this flow on receiving waters. Around this central core are many related topics - atmospheric quality and dustfall, sewage management and treatment, rural water quality, and others - and the distinction between topics is often blurred. These peripheral areas are selectively covered. Intentionally combined stormwater and sanitary sewers are not common in this country, so the extensive North American literature on combined sewer overflows is referenced only when results are also applicable to a separate drainage system. Similarly, urban snow removal in Australia is confined to localised resort areas which are not typical of major urban centres, so papers on this topic are only selectively included. In all the peripheral areas, the line between inclusion and exclusion is necessarily somewhat arbitrary.

The review is extensive but by no means complete, even allowing for the boundary problem noted above. Papers central to another discipline, but also of relevance to urban runoff quality, are difficult to locate reliably. Access can be a problem in some cases. In particular, many reports prepared by or for the United States Environmental Protection Agency are not readily available here, and time and staff resources do not permit access to all of them. We rationalise this limitation by assuming that most significant results from these prime sources will also be published in the journal literature, and will be referenced here from that source. Of course, a reading list on either core or peripheral topics could be extended by reference to the bibliographies of the papers included here, and from the proceedings of conferences noted in the reference list.

2. THE EARLY YEARS: RECOGNITION OF A PROBLEM

The study of urban stormwater quality is a recent development. During the first half of this century, the related areas of stormwater volume and sewerage quality management were advancing rapidly, but stormwater quality was largely ignored. The early years of stormwater quality research are characterised by sparse studies of limited extent, often associated with the issue of combined sewer overflows.

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Interest in water quality in the context of water supply is not new. While describing the sources of water for ancient Rome, Frontinus (97) states: 'New Anio ... is taken from the river, which with cultivated fields of fertile soil round about, and hence less stable banks, even without the adverse effects of rain flows muddy and turbulent.' The translator quotes Vitruvius and Pliny regarding measures of water quality: 'If it did well the work of cooking vegetables, had no sediment on the bottom of the vessel containing it after standing still, or on the sides and bottom by boiling down, nor had taste or odour, it was a good water. If the inhabitants who drank it looked healthy, it was good to drink.' He also describes water filters, settling basins, and upflow clarifiers in the Roman water supply system. Evidently Frontinus and his contemporaries has a practical working knowledge of suspended solids, hardness, taste and odour, biological effects, agricultural runoff, and basic treatment strategies. Unfortunately, neither Frontinus nor his translator comments directly on urban runoff quality.

Over 100 years ago, a text on sewage treatment and disposal (Wardle 1893), quoted by Lindholm and Balmer (1978), stated '... the first storm washings contain quantities of putrescible organic matter ... they are very foul and often contain as much as the sewage itself'. Given such a clear and unequivocal statement, it is interesting that there appears to be little further notice of stormwater quality for nearly sixty years. We could speculate, perhaps, that in an era of horse-drawn transport the pollution of street washoff was much more apparent to casual inspection than it is now.

An extensive and detailed paper (Gregory et al. 1933) describing the design and construction of intercepting sewers at Columbus, Ohio, mentions stormwater quality only in the context of diluting sewage overflows. There is no hint whatsoever that the stormwater itself may be significantly polluted. Stanbridge (1937), reviewed by Kehr (1937), notes increased attention being given to stormwater sewage treatment. He attributes this to more widespread treatment of domestic and industrial wastes which formerly masked the effect of stormwater discharges, and to the fact that in many instances stormwater overflows come into operation before stream flow increases sufficiently to provide the necessary dilution. An initial flush lasting about an hour is noted. Although this seems at first sight to be contradictory, it appears from the context that the stormwater sewage referred to is what we would now call combined sewer overflow, and the rainfall-induced runoff is still assumed to be relatively clean. The common use of combined sewers carrying both sewage and stormwater has masked the separate contribution of stormwater runoff to receiving water quality for many years.

The Buffalo Sewer Authority undertook an extensive program of gauging and sampling of combined sewer flows in 1936 and 1937 (Riis-Carstensen 1955). A strong initial flush of suspended solids was found, and attributed to a combination of dust and dirt washed off streets and scouring of low flow deposits from the combined sewers. The high variability of pollutant loads is noted, and the effect of catchment time of concentration on the load of scoured material is discussed.

One of the earliest reports dealing specifically with urban stormwater quality sampled runoff in Moscow in 1936 (Shigorin 1956) quoted by Weibel et al. (1964). Pollutant levels reported were 186 to 285 mg/L for BOD, and 1,000 to 3,500 mg/L for suspended solids. The same report quotes BOD of 36 mg/L and a suspended solids level of 14,541 mg/L for runoff from cobblestone paved streets in Leningrad between 1948 and 1950. Details of sampling sites and methods, which may help to explain these high values, are not quoted.

A Swedish report (Akerlindh 1950) reviewed by Heukelekian (1951) and quoted by Weibel et al. (1964) studied summer rainfall drainage samples, mainly from streets and parks in Stockholm, from 1945 to 1948. Pollutant levels found were: coliforms - 4,000/100 mL median, 200,000/100 mL peak; COD - 188 mg/L median, 3,100 mg/L peak; total solids - 300 mg/L median, 3,000 mg/L peak; fixed residue - 210 mg/L median, 2,420 mg/L peak; and BOD - 17 mg/L median, 80 mg/L peak. Coliform concentrations from streets and parks were compared. The concentration of organic matter in stormwater is described as being nearly as high as in sewage, but coliform levels are much lower. These results emphasise both the high concentrations and the high variability of urban stormwater pollutants.

A study in Detroit in 1949 (Palmer 1950) compared the merits of combined sewers and separate sewerage and stormwater systems, and strongly advocated the continued use of a combined system since separate stormwater was of such poor quality (and because maintaining the status quo was much cheaper). It appears to be a response to proposals for a separate stormwater system. Samples taken from a catch basin in the business district of Detroit during the initial flush of a single storm gave coliforms up to 930,000, total solids up to 914 mg/L, and BOD up to 234 mg/L. The coliform results, in particular, were felt to be surprisingly high. The author states that the initial flush effect has been previously described, and notes its dependence on catchment time of concentration.

A study of surface runoff from a separately sewered estate at Oxhey, England (Wilkinson 1954) quoted by Weibel et al. (1964) found BOD up to 100 mg/L and suspended solids up to 2,045 mg/L. BOD tended to increase with the length of the antecedent dry weather period for eight to ten days, after which there was little further change. The initial flush was not much more polluting than subsequent flows, except after long antecedent dry periods.

Stormwater samples taken from street gutters in Seattle in 1959 and 1960 (Sylvester 1960) quoted by Weibel et al. (1964) contained turbidity up to 1,290 turbidity units, colour up to 350 colour units, BOD of about 10 mg/L, coliforms up to 16,100 MPN/100mL, organic nitrogen up to 9.0 mg/L, nitrate nitrogen up to 2.80 mg/L, soluble phosphorus up to 0.78 mg/L as P, and total phosphorus up to 1.4 mg/L as P. Details of turbidity and colour units are not quoted. The highest concentrations were usually found when antecedent rainfall had been low.

A paper by Pravoshinsky and Gatillo (1969) quotes a number of references not normally noted in the western literature, including Taplyakova (1956), Blich and Vigilov (1958), and Kvitnitskaja (1959). Although contents are not described in detail, it appears that they present limited data generally comparable to that of their better known counterparts.

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Documented studies of urban runoff quality in this initial period are very sparse, and data sets tend to be small. Even so, the future direction has already been largely determined. The quality parameters most commonly studied are suspended solids, oxygen demand, and sometimes the nutrients nitrogen and phosphorus. Their concentrations are always found to be very high and very variable, and in some cases are as high as in raw sewage. The initial flush effect is well known but not consistently observed, and its dependence on catchment time of concentration has been noted. Antecedent dry conditions are felt to be important, but the relationships involved are unclear. The effects of land use on urban runoff quality have been recognised, but have not yet been studied in any detail. Total storm loadings are the main area of interest. Apart from noting the initial flush effect, there is little emphasis on variation of pollutant loadings with time during a storm.

3. 1961 TO 1970: A DECADE OF GROWTH

A preliminary appraisal of urban runoff quality by the United States Public Health Service in 1964 led to much wider awareness of the problem, greatly increased funding, and rapid expansion of research. The result was a much more comprehensive data base: more sites, more water quality parameters, more frequent sampling, and more detailed analysis. With the expansion in knowledge came a gradual separation into distinct areas of research. The first major distinction is between data collection and analysis, and its application to system management and subject overviews.

3.1 Data Collection and Analysis

3.1.1 General Water Quality Data

A study in Pretoria, South Africa (Stander 1961) quoted by Weibel et al. (1964), sampled stormwater from residential, park, school, and sportsground areas, and from a business and multi-dwelling area. The results appear to be similar from both types of land use, but no statistical analysis is reported. The absence of statistical analysis is very characteristic of the earlier work in this field. Most studies are more exploratory than definitive in style, and in many cases the data sets are too small and diverse to permit any kind of rigorous analysis.

An Austrian study (Kurzweil 1964), quoted in discussion of Weibel et al. (1966), measured the BOD of water from roofs, streets, and stormwater drains. The values found were: roofs, 2.4-12 mg/L; streets in garden suburb, 9-40 mg/L; streets in cities, 9-96 mg/L; and stormwater drain outflow (2 readings only), 26 and 30 mg/L. This appears to be the first attempt to monitor the quality of water as it moves through an urban area. The general increase in BOD downstream suggests that pollutant inputs occur at many places in the urban system.

Flow and stormwater composition were recorded over a number of years at Northampton, England, using automatic samplers (Gameson & Davidson 1963) quoted by Dunbar and Henry (1966), and at two other English sites (Gameson et al. 1965; Davidson & Gameson 1967; Ministry of Housing and Local Government 1970) quoted in discussion to Soderlund et al. (1970). Suspended solids concentration at one site was virtually independent of flow, but at the other sites was higher at higher flows. The concentration of ammonia nitrogen, however, fell progressively with increasing flow at each site, and BOD behaviour lay between these two extremes.

A major project was carried out by the Taft Sanitary Engineering Center in Cincinnati, Ohio. Weibel et al. (1964) provide a concise review of earlier work, and describe the experimental setup at Cincinnati. An 11 hectare residential and light commercial drainage basin with separate stormwater drains was instrumented to provide continuous flow measurement, water samples every ten minutes during storms, and rainfall samples daily. Selected samples were analysed for 20 physical, chemical, and microbiological contaminants. Compared with previous studies, the increased scope and detail of measurement is immediately obvious, and this is reflected in the level of analysis. Annual loadings of total and volatile suspended solids in runoff are very close to the respective annual loadings of dustfall. A clear initial flush effect is present, but a relationship between runoff load and time since last rain is not evident. Using averaged data, a good linear relationship between suspended solids concentration and flow rate is found. Annual BOD load of runoff is nearly as high as that of secondary sewage effluent, and suspended solids load is higher than that of raw sewage.

Weibel et al. (1966) describe further work at Cincinnati, beginning with a literature review of rainfall water quality. Rainfall itself can be significantly polluted. A Canadian study (Matheson 1951) found that nitrogen fall at Hamilton, Ontario, totalled 6.5 kg/ha/yr. Some 61% of it came down on rainfall days, which comprised 25% of all days, and the other 39% dusted down on dry days. McKee (1962) noted that total atmospheric nitrogen reaching the soil tends to increase with annual rainfall, and that much of the atmospheric organic nitrogen is in the form of pollen, spores, bacteria, and dust carried aloft by winds. Several other reports including Chalupa (1960) and Junge (1963) found significant quantities of nitrogen and phosphorus in rainfall. They conclude that, in general, rainfall tends to take on a quality that reflects the character of the land and human activities on it in the surrounding environment. Weibel et al. (1966) found the following averages for rainfall at Cincinnati: pH, 4.8; suspended solids, 13.0 mg/L; volatile suspended solids, 3.8 mg/L; COD, 16.0 mg/L; total nitrogen, 1.3 mg/L; inorganic nitrogen, 0.69 mg/L; hydrolyzable phosphate, 0.24 mg/L; and organic chlorine, 0.28 μg/L. Levels of phosphate and inorganic nitrogen exceed a quoted threshold for algal blooms, as do levels at two rural sites in the same area. Organic chlorine is used as an indicator of the likely presence of pesticides.

Burm et al. (1968) provide detailed tabulations and commentary on 11 physical, chemical, and nutrient parameters in combined sewers at Detroit and separate storm drains at Ann Arbor. All measures of solids, and nitrate nitrogen, were higher in the separate stormwater than in the combined sewers. For organic and ammonia nitrogen, total and soluble phosphates, BOD, and phenols, the reverse was true. Total pollutant loadings were approximated using the rational formula to estimate the volume of runoff.

Eckhoff et al. (1969) and Friedland et al. (1970) present results from a study of five combined sewers and two separate stormwater drains in San Francisco. Hexane extractable materials (greases) and floatable materials are added to the usual measures of solids, oxygen demand, and nutrients. Eckhoff et al. (1969) describe three phases of wet weather flow in combined sewers. 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. Next, if flows are sufficient, there is scour in the sewer and washoff of surface debris, giving pollutant concentrations typically 150 to 200% of dry weather levels. Finally pollutants decrease to a steady state level from 10 to 25% of dry weather concentration. The same three phases could presumably be applied (with different concentration factors) to flow in separate stormwater drains. Friedland et al. (1970) found an inverse relationship between concentration and total storm runoff for each pollutant studied. Catchment characteristics are tabulated in considerable detail, but no correlations were found between pollutant load and land use, antecedent dry period, or rainfall intensity.

A Japanese study (Inaba 1970) measured rainfall, flow, BOD, suspended solids, and volatile suspended solids in a combined sewer and a stormwater drain every two to three minutes during storms. For low intensity storms, peak flow, peak solids, and peak BOD all coincide. At higher intensities the peaks separate, with peak BOD first, then peak solids, then peak flow. The higher the flow, the greater the separation of peaks. The comment on volatile suspended solids is confused - perhaps a translation error - but probably means that suspended solids are mostly organic early in the storm, and mostly inorganic later. This seems to be the most detailed analysis of within storm behaviour to date. It agrees well with Weibel et al. (1966), who found that peak microorganisms occurred earlier than peak suspended solids. The lighter the pollutant, the earlier it peaks.

A study conducted on 15 test areas in Tulsa, Oklahoma, explored the effects of land use on runoff characteristics (Cleveland et al. 1970), quoted by Hergert (1972) and in discussion of Soderlund and Lehtinen (1972). The main result was to highlight again the extreme variability of runoff water quality - many parameters varied between different areas of apparently identical land use. BOD was highest in areas of heavy tree cover or open drainage channels, and suspended solids were highest in an area of housing construction.

A Swedish paper (Soderlund et al. 1970) describes a stormwater sampling program in a newly developed and separately drained area of Stockholm. The area is mainly residential and commercial, but includes some industrial areas and a major highway. The total catchment and three sub-areas were monitored for a typical range of parameters, with the unusual addition of total carbohydrates. There is a strong correlation between pollution load and air temperature when snowmelt is involved. Salt used for deicing roads leads to high chloride levels. Runoff from the highway is the most highly polluted, but industrial areas contribute a significant amount of oil to runoff.

Young et al. (1970) compare the effects of stormwater and sewage inputs to the receiving waters of Kaneohe Bay, Hawaii, and conclude that surface runoff is the main source of pollutants.

3.1.2 Microbiology

Weibel et al. (1966) present long term storm averages of a wide range of pollutants in runoff at Cincinnati, and information on variation with time during a storm. The peak of microorganisms occurs very early in a storm, even at low rainfall intensity. The peak of suspended solids tends to occur later, and at higher rainfall intensities. A physical washoff effect appears to be present here - microorganisms are smaller and more easily transported than suspended solids. Laboratory tests of treatability were not particularly encouraging. Good reduction of suspended solids and BOD required long settling times, and a chlorine dose of nearly 5 mg/L was needed to give a substantial kill of microorganisms.

Geldreich et al. (1968) further extend the work at Cincinnati with a detailed analysis of bacteria. The median bacterial count for rainwater was less than one organism per 100 mL for all parameters. Bacteria in urban runoff showed a marked seasonal effect, with the highest median counts occurring in summer or (more usually) autumn. In contrast, a nearby rural site showed a clear winter maximum. Median bacterial counts from street gutters in autumn were: total coliforms, 290,000/100 mL; faecal coliforms, 47,000/100 mL; and faecal streptococci, 140,000/100 mL. The proportions of species present indicate that the bacteria are largely derived from cats, dogs, and rodents. Evans et al. (1968) describe settling and chlorination tests carried out on Cincinnati water samples. Suspended solids reduced by about 50% after settling for one hour. Organic nitrogen, BOD, and total phosphate showed smaller reductions over the same time. Doses of 2 to 6 mg/L of chlorine for 20 minutes were required to give an effective kill of total coliforms, faecal coliforms, and faecal streptococci.

Two related reports (Benzie & Courchaine 1966; Burm & Vaughan 1966) compare the water quality in a combined sewer at Detroit with that from separate storm drains at Ann Arbor. Rainfall was recorded continuously, and water samples were taken frequently using automatic samplers. There is no mention of any flow measurements, and no flow rates or total loads are reported. Analysis of water quality concentrates on bacteria, but nutrients are also briefly described. The two reports are notable for their extensive plots and tabulations of recorded data. The median bacterial counts in each of a large number of storms appear to be log-normally distributed. The grand medians over all storms in the separate system at Ann Arbor were: total coliforms, 1,200,000/100 mL; faecal coliforms, 82,000/100 mL; and faecal streptococci, 140,000/100 mL. Separate storm runoff at this site is consistently very highly contaminated with microorganisms.

3.1.3 Buildup and Washoff

Pravoshinsky and Gatillo (1969) describe a study of storm runoff, street washing runoff, and snowmelt runoff from built-up but non-industrial areas in Minsk, USSR. Although a statistical analysis is not given, there appears to be little difference in quality between the three types of runoff. The main parameters examined were BOD, suspended solids, and chloride, but oil products, copper, and lead were also detected. They develop a relationship between BOD, storm rainfall, and preceding dry days. BOD is shown increasing linearly with dry days (up to 20 days), and almost linearly with storm rainfall (up to 16mm). The scatter is such that other interpretations would be possible. The bounds are imposed by lack of data rather than any observed change in behaviour.

3.2 Process Analysis and Modelling

The Cincinnati Urban Runoff Model (University of Cincinnati Division of Water Resources 1970), summarised by Hergert (1972), appears to be the first urban runoff model to include a water quality calculation. Washoff of solids is assumed to be proportional to the square of runoff intensity, and proportional to the amount of pollutant on the ground, giving the standard inverse exponential washoff function. Soluble pollutants are routed downstream at the same velocity as the flow.

3.3 System Management and Overviews

In an update of his earlier paper, Palmer (1963) again champions the continued use of combined sewers at Detroit, and presents suspended solids and coliforms data for runoff from four storms in 1960. The debate over combined sewers versus separate systems appears to be continuing with undiminished vigour. The tone of Palmer's papers clearly indicates support for the status quo, rather than for combined sewers as such, since the cost of change to a separate system is very high. Based on the information available, this seems to be a reasonable conclusion on both economic and practical grounds.

A preliminary appraisal of urban runoff quality (United States Public Health Service 1964), quoted by Field and Struzeski (1972), raised widespread awareness of the runoff quality problem, and was largely responsible for the much expanded research program coordinated by the United States Environmental Protection Agency (USEPA) over the following years.

Two papers from Toronto, Ontario, describe a pragmatic upgrade of the overloaded combined sewer system. Dunbar and Henry (1966) discuss the performance of combined sewers and separate storm drains, and review a number of potential methods to alleviate pollution of receiving waters. They present limited stormwater quality data from Toronto and Welland, Ontario. Booth et al. (1967) review the combined sewer overflow problem, tabulate additional stormwater quality data from Toronto, and describe a system of 'road storm sewers' to drain primarily the street and overland flow.

Literature reviews on a wide range of water pollution topics including urban runoff are published annually in the Journal of the Water Pollution Control Federation. These provide an extensive reference list of North American publications, and a brief summary of current issues and research.

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Research in the early years of the 1960's continued the rather episodic pattern of the previous 30 years, but with a tendency towards larger and longer studies. Much of the work appears to be associated with the debate about the relative merits of combined sewers and separate stormwater systems. An attempt has been made to track the quality of stormwater as it moves through an urban system.

The United States Public Health Service appraisal in 1964 led to a rapid expansion of research. Over the next few years the link with dustfall and rainfall quality was established, and rainfall itself was shown to be significantly polluted. Stormwater was analysed for a wider range of pollutants, and sufficient data was accumulated at many sites to show beyond doubt that urban runoff is seriously contaminated.

Time patterns within a storm were investigated, and found to be complex. In general, the lighter the pollutant, the more easily it is mobilised. Thus microorganisms and BOD peak before solids, solids peak before flow, and volatile solids peak before inorganic solids. The more intense the storm, the more distinct the separation between peaks. The interaction between antecedent dry days (buildup) and storm rainfall (washoff) has been observed, but the implications have not been widely recognised. When analysed separately, each is obscured by the scatter of the other.. When analysed together, they are both found to be significant.

A descriptive model of stormflow behaviour has identified three main phases - flushing of existing water from the system, scour of solids from surfaces and pipes, and finally a steady state of moderate water quality. Most elements of urban stormwater behaviour have now been at least partly addresed individually, and a first attempt has been made to combine them into a quantitative urban water quality model. Between them, the developments of the 1960's decade have paved the way for the large scale simulation models of the 1970's.

4. 1971 TO 1975: THE FIRST SIMULATION MODELS

The first half of the 1970's is characterised by another large increase in the research effort, and by further development of distinct areas of research. The majority of papers are still concerned with data collection and analysis, and within this general theme a number of sub-themes can be identified. They include specific investigations of nutrients, lead and other heavy metals, and deicing chemicals. A key study attempts to quantify buildup and washoff processes by direct measurement, rather than by inference from runoff quality. System management and subject overviews form a small but increasing proportion of published papers. But perhaps the most significant new area of research is the development of large scale computer simulation models.

4.1 Data Collection and Analysis

4.1.1 General Water Quality Data

In a large number of studies, a major objective is to measure a broad spectrum of stormwater quality parameters at a site, either as part of a wider data collection program, or for a specific local purpose. DeFilippi and Shih (1971) monitored combined sewers and a separate stormwater system in Washington, DC, and present a large set of graphs of pollutant concentration against time. Separate storm runoff had lower average concentrations of organic matter and nutrients, lower bacterial counts, and higher solids concentrations than combined sewer discharges. Angino et al. (1972) sampled water from a mainly residential catchment in Lawrence, Kansas, to assess its suitability for reuse. They describe changes in quality with time of day, and between rainfall, snowmelt, and dry weather flow. Mische and Dharmadhikari (1971), reviewed by Weiner (1972), gathered data on runoff from three areas with varying characteristics, and presented results of treatment. Chun et al. (1972), abstracted in the Engineering Index, 1973, describe a study of urban runoff, including street litter, and sewage effluent quality on Oahu, to examine their reclamation potential. Soderlund and Lehtinen (1972) investigated a wide range of pollutants in stormwater drains in Stockholm, and found a good relationship between flow rate and pollutant concentration. A first flush of pollutants is evident in the graphs, but is not recognised in the text.

Melbourne and Metropolitan Board of Works (1973) includes a major study of water and pollutant inputs to Port Phillip Bay. Urban sources addressed include sewered and unsewered residential and industrial areas. Much of the urban quality data is based on regular monthly sampling, with stormflow adjustment factors based on very limited data. Total nutrient loads to the bay are tabulated for urban runoff, sullage, trade wastes, agricultural runoff, and sewage treatment plant effluents. Urban runoff is believed to account for about 8% of total nitrogen, and about 1% of total phosphorus.

Runoff quality from an urban catchment and a semi-urban/rural catchment in West Lafayette, Indiana, is compared by McElroy and Bell (1974). The urban catchment produced a stronger initial flush. Multiple flushes were sometimes observed, but never after the flow peak. Whipple et al. (1974)

emphasise the importance of non-point pollution sources, using data from Mile Run and Morristown catchments in New Jersey, and other data from the literature. Gates (1975) studied BOD at three sites in the Susquehanna River at Binghamton, New York. BOD loadings increase downstream through the town, but there is no apparent relationship with river discharge. Hordon (1975) describes the application of factor analysis to water quality data, using data from the Passaic River, New Jersey, as an example. Radziul et al. (1975) describe a study of water quality changes in five streams as they pass through Philadelphia, and note that average pollutant loadings correlate well with catchment characteristics. The non-point load of BOD was about 30% of total point loads from sewage treatment plants.

The water quality response of three adjacent catchments in Milwaukee, Wisconsin, is described by Cherkauer (1975b) and Cherkauer (1975a). Land use on the catchments ranges from suburban to rural. In response to rainfall, the rural catchment produces least runoff and suspended solids, followed by the urban area, with the developing urban area producing most. In response to snowmelt, the rural area produces the highest runoff and suspended solids, as there is no artificial snow removal. Ragan and Dietemann (1975) studied stormwater quality in tributaries of the Potomac River near Washington, DC., and DiGiano et al. (1975) monitored six sites in the Green River through Greenfield, Massachusetts. Both these reports compare the quality of water at several sites as it moves through an urban area, and both use aquatic species diversity as one measure of water quality. Species diversity drops rapidly as urbanisation increases, due to lower water quality, changed flow and channel conditions, or both.

An extensive stormwater monitoring program has been carried out on an urban catchment of 1,067 acres in Durham, North Carolina. The initial experimental setup and early sampling results are described by Peavy (1970), quoted by Bryan (1972), and by Bryan (1970), quoted by Bryan (1974). A summary document (Bryan 1972) presents maximum, minimum, and flow weighted means of a range of parameters, comparative data from several earlier studies, and a detailed analysis of lead and pesticide levels. The report concludes that urban stormwater is a significant source of pollution. The annual contribution of BOD is about the same as that from secondary treated sewage from a similar area, and the contribution of COD is greater than that from raw sewage. Phosphate load is much lower than from typical domestic sewage. The annual yield of lead was 1,190 pounds per square mile per year, and the average pesticide concentration was 0.33 µg/L. Bryan (1974) provides further information on lead concentrations at this site. Colston and Tafuri (1975) update the analysis and extend the range of water quality parameters. They found that pollutant flux within storms could be related to runoff rate and time since the start of the storm, but the elapsed time since the last storm had little apparent effect. Sedimentation for 15 minutes removed over half the COD, suspended solids, and turbidity, and alum dosing increased the removal to well over 80%.

4.1.2 Nutrients

A number of studies have concentrated on sources and loadings of nutrients. Timmons et al. (1970) measured the leaching of nitrogen and phosphorus from a range of crop residues in a series of laboratory tests. The extraction of soluble nutrients from alfalfa (crop) and bluegrass (lawns) was greatly increased by freezing or drying, and is potentially a significant source of nutrients in runoff. Cowen and Lee (1973) measured soluble phosphorus leached from oak and poplar leaves, and found up to 0.65 mg P/g of leaves from finely chopped leaves. Much of this nutrient source will not be detected at a sampling site unless gross pollutants are collected and analysed. Emery et al. (1973) investigated the inputs and effects of nutrients on algal growth in Lake Sammamish, Washington, and concluded that urban runoff had a negligible effect on algal growth at that location.

Kluesener and Lee (1974) describe the behaviour of runoff and nutrient loads from an urban catchment in Madison, Wisconsin, and provide a good discussion of nutrient sources and processes. Leaf and seed fall are a significant source of nutrients in season, and the major source of phosphorus. Rainfall is a major source of inorganic nitrogen. Peak nutrient levels occur on the rising limb of the runoff hydrograph. Fertilisers do not appear to be a significant source of nutrients at this site, as there is little runoff from pervious areas. Sager and Wiersma (1975) studied sources of phosphorus entering Green Bay, Lake Michigan, and found that urban areas made a negligible contribution in this largely rural catchment. Tuffey and Trama (1975) measured phosphorus loads in forested and urbanising catchments, and found that the load during storms is a major part of the total annual load.

4.1.3 Heavy Metals

Several heavy metals can appear in urban runoff, resulting either from human activity in the catchment or from natural sources. The most significant and widespread of these is lead, derived mainly from anti-knock additives in petrol. Crecelius and Piper (1973) measured lead concentration in lake sediments and fir needles at Lake Washington, Seattle. Lead concentration in lake sediments has increased 20-fold over the last 100 years. The distribution of lead in fir needles indicates that highways are a major source of lead in the area. Hallsworth and Adams (1973) measured heavy metal concentrations in rainfall and dustfall at two sites near Nottingham, England, and found substantial air pollution within the area. Fly ash from nearby power stations is one obvious source, but does not fully explain the levels found. The annual fall of lead is about 500 g/ha/yr.

A sampling program to test for lead in snow and snowmelt in Ottawa is described by LaBarre et al. (1973) and Oliver et al. (1974). Lead concentration in snow from disposal sites and along roads was high, but was almost entirely associated with the sample sediment (4,330 ppm max). Soluble lead in filtrates was very low (0.21 ppm max). Dumping of snow away from watercourses instead of into them reduced lead contamination of the water by 30%. Lead levels in snow along city roads was roughly proportional to traffic volume. Newton et al. (1974) estimate an average lead content in runoff from Oklahoma City of 0.23 mg/L, using a simple mass balance method. An experimental value at Tulsa, Oklahoma, was about 0.2 mg/L. The average concentration of lead in snow and ice near roads decreased from 5.5 mg/L beside the road to 0.09 mg/L in an open field.

The sources and concentrations of metals in New York wastewater are described by Klein et al. (1974). The sources considered were electroplaters, other industries, residential, and surface runoff. The concentrations found in surface runoff were: copper, 0.46 mg/L; chromium, 0.16 mg/L; nickel, 0.15 mg/L; zinc, 1.6 mg/L; and cadmium, 0.025 mg/L. Davis and Jacknow (1975) studied heavy metals in wastewater from New York, Pittsburgh, and Muncie, Indiana. A partial separation into residential, industrial, and stormwater contributions is achieved for copper, chromium, nickel, zinc, and cadmium at New York, but not at the other sites. At Durham, North Carolina, Bryan (1974) found lead concentrations in urban stormwater ranging from less than 0.10 mg/L to a maximum of 12.6 mg/L, with a mean concentration of 0.48 mg/L. Wilber and Hunter (1975) describe a study of heavy metals in rainfall and runoff from two small urban catchments at Lodi, New Jersey. Lead and zinc showed the highest concentrations in both rainfall and stormwater. Metal concentration in runoff is typically about 20 times higher than in rainfall at this location.

4.1.4 Hydrocarbons

In one of the first studies directed specifically at hydrocarbons, Hunter et al. (1975) measured petroleum products in storm runoff from a residential catchment in Philadelphia. Total hydrocarbons ranged from 2.2 to 4.0 mg/L, which is higher than in treated oil refinery effluent in the same area. Urban runoff is evidently a major contributor of hydrocarbons to receiving waters.

4.1.5 Snow and Ice

The use of deicing chemicals can be a major source of pollutants in cold climates. Highway deicers include sodium chloride, calcium chloride, and abrasives. Field et al. (1974) provide a comprehensive review of deicing practices and associated environmental effects, including methods of snow and ice removal, chlorides in rainfall and municipal sewage, salt runoff from streets and highways, deicing compounds in surface water and ground water, nutrient or toxic additives, corrosion of vehicles and deterioration of highway structures, and effects on roadside soils and vegetation. Oliver et al. (1974) describe a study of chloride and lead in snow and runoff in Ottawa, Canada. Chloride levels vary widely with time and location, due to changing weather and road salting programs, but total chloride loads are substantial. Schulz and Comerton (1974) measured stormwater pollutants at Montreal

International Airport. They found the major pollutant is glycol-based aircraft deicer, which has a BOD as high as 430,000 mg/L.

4.1.6 Buildup and Washoff

A detailed and definitive survey of street surface contaminants was carried out by Sartor and Boyd (1972), and summarised by Sartor et al. (1974). They measured a wide range of pollutants in runoff from streets in 12 widely separated U.S. cities, and recorded the time since last street sweeping or significant rain. Runoff from streets is generally highly contaminated. The major constituent of contaminants is inorganic mineral matter. The organic fraction is small, but accumulates faster than the inorganic fraction. The quantity of contaminants varies very widely. Industrial areas have the highest loads, and commercial areas have the lowest, due to more frequent street sweeping. Residential areas have intermediate loads. Most pollution is associated with the finest solids fraction. Street sweeping and catch basins are both ineffective for this fine fraction. Most street contaminants are within six inches of the curb. Washoff rate depends on rainfall intensity, street surface type, particle size, and pollutant load on the street.

Their build-up results are widely quoted, but the statistical analysis is rather weak, and their conclusions cannot be supported from the data. Using all data, they found no significant build-up relationships at all. Even using trimmed data 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 claim that build-up reaches equilibrium after about two weeks is an assumption, not a conclusion.

Shaheen (1975) extended the work on buildup and washoff processes by examining samples taken from roadways in Washington, DC. He found that some pollutants were related to traffic load, while others were not. The deposition rate of non-traffic related pollutants is linear with time, but the accumulated total levels off after several days due to displacement of material onto adjacent areas by natural and vehicle-induced winds. Some of this material will be trapped by vegetation or in other ways, and will be removed at least temporarily from the pool of windblown pollutants. Curb height has a significant effect on this process - the lower the curb the more material is carried away to adjacent areas. For traffic related pollutants the net accumulation is of similar form, but is a function of traffic load rather than time. Some traffic related materials originate directly from vehicles (rubber, oil, asbestos, metals), while others do not (BOD, COD, volatile solids, chloride, nitrogen, and phosphorus). Perhaps these latter materials are generated by the physical break up of leaves and other organic matter on the roadway by vehicle movement.

4.1.7 Data Reviews

Loehr (1974) summarises information from the literature on non-point pollutant sources. Extensive tabulations of concentrations and loading rates are presented, with particular emphasis on the nutrients nitrogen and phosphorus. The loading rate of phosphorus in runoff from forest and rangeland is similar to that of rainfall, but the loading rate from urban land is typically 100 times larger. The loading rate of nitrogen in all types of runoff is similar to that of rainfall. In both cases there is considerable scatter.

4.2 Process Analysis and Modelling

The Cincinnati Urban Runoff Model (University of Cincinnati Division of Water Resources 1970), summarised by Hergert (1972) and noted above, appears to be the first urban runoff model to include a water quality calculation. Heaney and Sullivan (1971) estimated the magnitude of a range of solids sources entering combined sewers in Chicago. Sources include dustfall, sanitary wastes discharged to sewers, garbage and refuse, street sweepings, and catch basin contents. Although a complete solids budget was not achieved, some useful estimates were derived, and gaps in the data were identified. Lager et al. (1971), and Metcalf and Eddy Inc et al. (1971), summarised by Hergert (1972), describe the early development of the Storm Water Management Model. Runoff hydrographs are calculated using rainfall intensities, Horton's infiltration equation, allowance for detention storage, Manning's formula, and continuity equations. Quality parameters included at this stage are BOD, suspended solids, total coliforms, and dissolved oxygen. Source material on the ground before the storm is influenced by land use, gutter length, street sweeping practice, and number of preceding dry days. Rates of removal are proportional to runoff intensity, available source material, and time from start of storm. There is some ability to include dry weather flow parameters. In the examples given, goodness of fit is reasonable for dry weather flows, but only moderate for storm flows.

Clark and Malina (1973), abstracted in the Engineering Index, 1973, describe a modelling study of 13 water quality parameters to evaluate the water quality loadings on Corpus Christi Bay. Graham et al. (1974) describe a sensitivity analysis of the Storm Water Management Model, and show that land use and imperviousness parameters have the greatest impact on model output. They relate these parameters to a range of demographic factors, using census data from Washington, DC., and find that households per acre is the best explanatory variable. Heeps and Mein (1974) compare the hydrographs produced by the Road Research Laboratory model (RRL), the Storm Water Management Model (SWMM), and the Cincinnati Urban Runoff Model (CURM), using data from Vine Street in Melbourne and Yarralumla Creek in Canberra. They provide a good comparative table of functions simulated and procedures used by the three models. Water quality routines are not tested.

Hergert (1972) and Nebraska University (1974) describe a data collection program and modelling study on three residential catchments in Lincoln, Nebraska. They find an approximate log-log relationship between suspended solids and rainfall, and between COD and rainfall. An initial flush effect is observed. BOD and COD increase with tree cover and housing density, and construction activity leads to high suspended solids. Water quality modelling is confined to solids, BOD, and COD, and uses the same formula as the SWMM model. A copy of the computer program is included. Roesner et al. (1974) describe the initial structure and philosophy of the Storage, Treatment, Overflow, and Runoff Model (STORM). It is intended to be used as a screening tool in preliminary master planning for water pollution control. Warren and Bewtra (1974) use a simple deterministic model of combined sewer drainage areas to compare different combinations of storage capacity and treatment capacity for a typical Ontario community. Calibration of the model is not discussed.

4.3 System Management and Overviews

A number of papers in this period discuss management issues, problems, and potential solutions, without necessarily presenting new data or analysis. Field and Struzeski (1972) provide an overview of the history and significance of combined sewer overflows. Stormwater is discussed in the context of evaluating the separation of stormwater and sanitary sewers, and its poor quality is emphasised. Otto (1972), abstracted in Water Pollution Abstracts, 1973, compares the effects of combined and separate sewer systems on receiving waters, and outlines West German design standards of the time. Field (1973) gives a non-technical overview of several methods being developed by the United States Environmental Protection Agency (USEPA) to manage combined sewer overflows. Methods applicable to separate stormflow management include street sweeping, porous pavements, swirl concentrators, upstream storage and flow reduction, integrated system operation, fluidic flow regulators, storage of overflows, microstraining, high rate filtration, high rate disinfection, and combined storage and treatment options. Gangopadhyay and Brylinski (1973), quoted by Field and Knowles (1975) and abstracted in the Engineering Index, 1974, emphasise the importance of integrated system operation.

Lager and Smith (1974) assess a range of current and completed stormwater projects. They include extensive data summaries, and a description of sources and movement of pollutants. McPherson and Schneider (1974) provide a rather negative overview of social, management, and generic issues related to urban runoff, concentrating more on problems than on solutions. Preul (1974) presents an overview of runoff and washoff processes on an urban catchment, and Singh (1974) demonstrates the calculation of urban runoff pollutographs for a hypothetical city of 100,000 people. An investigation San Francisco's combined sewer system and a master plan to reduce pollution of receiving waters are described by Giessner et al. (1974) and Feuerstein and Friedland (1975). Contributions from dry weather sewage flow and wet weather runoff are estimated and tabulated. The master plan is an integrated system of transport, storage, treatment, control, and disposal facilities. Field (1975) and

Field and Lager (1975) both provide a positive overview of urban runoff pollution and control. They emphasise the poor water quality of urban runoff - solids concentration equal to or greater than that of raw sewage, and BOD concentration about the same as that of secondary treated effluent - and discuss a wide range of potential solutions.

Urban stormwater design and research in Australia are reviewed by Aitken (1973) and Aitken (1975). While dealing mainly with water quantity, the reports note the almost complete absence of local water quality information, and recommend upgraded data collection, analysis, and modelling.

Annual literature reviews of urban runoff and combined sewer overflows have been carried out by Weiner (1971), Weiner (1972), Field and Weigel (1973), Field and Szeeley (1974), and Field and Knowles (1975).

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Studies during this period confirm beyond doubt that urban stormwater is always a significant source of pollution, and is often the major source. Areas of urban development and construction produce much higher levels of suspended solids than stable urban areas. Several projects investigated treatment and the potential for reuse, and found that a useful improvement in quality can be achieved by settling.

Other developments include the use of aquatic species diversity as an integrated measure of water quality degradation, and more frequent investigation of whole town effects rather than small plot studies. It is consistently found that species diversity in urban streams drops as urbanisation increases, due to lower water quality, increased flow, and changed channel conditions.

The dominant source of nitrogen in urban runoff is rainfall. So strong is this effect that some urban catchments appear to be a sink for nitrogen, rather than a source. Gross pollutants such as autumn leaves, seeds, and grass clippings are shown in laboratory studies to be the major source of phosphorus in urban runoff. But the practical significance of this appears to go unnoticed. Since breakdown is slow, much of this phosphorus will not be detected by stream sampling unless gross pollutants are collected and analysed, but it will be released over time in receiving waters. Thus the major source of what is often the limiting nutrient is almost totally unrecorded by conventional water quality measurements!

A number of heavy metals have been investigated, with lead receiving the most attention. Trends with both time and location show that lead is related to highway use. Lead in urban runoff is almost entirely associated with the sample sediment. The effects of highway deicing salts have been reviewed, and are found to be significant.

Buildup and washoff on impervious areas, and the effect of street sweeping, have been assessed in considerable detail. Buildup is best described as a bounded function made up of constant or traffic related deposition, minus wind-induced displacement proportional to the load already present. Washoff is assumed to be an exponential function of initial catchment load, although this assumption will be revisited in later years. Street sweeping is effective for large particles, but not for fine dust and dirt. Most pollution is associated with the finest solids fraction, for which sweeping is ineffective. But the delayed effect of leaves and grass clippings on phosphorus load is not yet recognised, and may well change the conclusion that street sweeping is of limited value.

An increasing number of papers discuss management issues, problems, and solutions, showing that there is a practical value and need for the research effort. A review of urban stormwater design and research in Australia notes the almost complete absence of local water quality information, and recommends upgraded data collection, analysis, and modelling.

The early development of water quality simulation models is perhaps the most significant feature of this five year period. The earliest water quality models were a very bold step into the unknown. Data was sparse, processes were not well understood, and accuracy of fit was moderate, at best. Their value lay in their ability to test and develop theories and processes, in a field where highly nonlinear processes make standard statistical techniques very difficult to apply. Quality models initiated during *this time include the Cincinnati Urban Runoff Model (CURM), the Storage, Treatment, Overflow, and Runoff Model (STORM), and the Storm Water Management Model (SWMM).*

5. 1976 TO 1980: MODELS, MODELS EVERYWHERE

Research in this period is characterised by further growth in all areas, but most of all in the area of simulation modelling. A review paper in 1980 compares fourteen operational and documented stormwater quality models, many of which can be applied in the urban situation. Data collection and basic analysis is still the largest major category of study, but reviews of data, models, and urban runoff quality generally, are necessarily becoming more common. There is now a significant contribution of Australian research.

5.1 Data Collection and Analysis

A very large number of papers in this period are concerned with data collection and analysis. More specific themes, such as microbiology and hydrocarbons, continue to appear, but many studies collect a range of general water quality parameters. To maintain manageable blocks of text, these have been further subdivided by geographic location.

5.1.1 General Water Quality Data

5.1.1.1 North America

Ragan et al. (1977) studied the impact of urbanisation on stream quality in suburban Washington, DC, using satellite data to distinguish urban and rural land use categories. There was a sharp reduction in fish species diversity in the urban areas, probably due more to habitat destruction than to water quality degradation. Wanielista et al. (1977) describe the development of an automatic water sampler with refrigeration facilities, and its subsequent use on two drainage basins near Orlando, Florida. They found linear relationships for total organic carbon, orthophosphate, and total phosphorus versus flow.

Betson (1978) found that rainfall was a significant source of runoff pollutants at Knoxville, Tennessee. The pollutant input from rainfall ranges from only 2% (for iron) to over 2000% (for arsenic) of the output in runoff. Meadows et al. (1978) investigated pollutant profiles along Brush Creek, Tennessee, and developed a mathematical model for dissolved oxygen and BOD. Lateral inflow from the heavily urbanised areas is high in BOD and low in dissolved oxygen. Inflow from nonurban areas is low in BOD and high in dissolved oxygen. Bedient (1980), in discussion of the previous paper, notes the extreme shortage of data, and hence the tentative nature of the results.

Rimer et al. (1978) describe a study of stormwater runoff quality at 11 automatic sampling stations in North Carolina. Pollutographs are plotted for COD, suspended solids, and total phosphorus, for rural, residential, and commercial areas. Peak concentrations of these parameters tend to increase with the percent impervious area, except in the central business district where street sweeping gives lower peaks. Impacts on receiving waters are monitored and discussed. Whipple et al. (1978) describe a study of urban runoff quality from an area of cluster townhouse development at Twin Rivers, New Jersey. Loadings per unit area of BOD, ammonia, and phosphorus are much higher than expected, but the increase in suspended solids with flow is less than expected. It appears that erosion has been almost eliminated at this site.

Klein (1979) studied stream quality and urbanisation on 27 small catchments in Maryland, using species diversity as a measure of stream quality and percent impervious area as a measure of urbanisation. Diversity decreases significantly as urbanisation increases, but stream quality impairment can probably be prevented if percent impervious area does not exceed 15%, or 10% for more sensitive stream ecosystems. Pisano et al. (1979) carried out an extensive and detailed study of deposition and flushing of solids and dissolved pollutants in combined sewers in Boston, Massachusetts. A significant quantity of settled sediment and pollutants can be artificially flushed from the combined sewer system during dry periods, when the capacity of the treatment plant will not be exceeded. The flushing principle could be applied to separate stormwater provided some form of treatment, settlement, or other assimilative capacity is available.

Singh et al. (1979) studied BOD and dissolved oxygen at nine urban sites in the United States, and developed a lumped areawide water quality index, based on the BOD removal required to achieve a minimum dissolved oxygen level of 5 mg/L in a specific design storm. The index can be used for screening and ranking treatment requirements at different locations. Adamowski et al. (1980) demonstrates the technique of cross spectral analysis to analyse leading and lagging relationships between time series, using data from Wasatch Canyon, Utah.

Collins and Ridgway (1980) investigated relationships between suspended solids and other pollutants in urban runoff in southeast Michigan. Organic nitrogen, total phosphorus, lead, and iron correlate well with suspended solids. Ammonia and BOD show a fair correlation with suspended solids. Chloride correlates well with total dissolved solids. The other parameters correlated better with runoff volume than with suspended solids. Polls and Lanyon (1980) studied runoff water quality from 16 small catchments in and around Chicago, Illinois, with 7 different types of uniform land use. There was a tendency for commercial land use to have the highest pollutant concentrations, and forest the lowest, but few differences between land uses were significant. Urbonas and Tucker (1980) describe the establishment of a stormwater quality data collection program at three sites in Denver, Colorado, with different proportions of land use. The data collected did not indicate a significant first flush effect. More intense land use produced greater pollution loads, but variations between catchments were less than expected. Volume of runoff had a greater effect.

Sonzogni et al. (1980) describe a study of non point source pollution by the International Reference Group on Great Lakes Pollution from Land Use Activities (PLUARG). They conclude that land form is more important than land use as the cause of non point source problems. Land form includes soil texture, soil type (mineral or organic), surficial geology, slope, drainage density, and soil chemistry, with soil texture being the single most important characteristic. Land use intensity has a major effect on water quality. Widely spaced row crops and urban construction sites generate high pollution levels. In urban areas, the degree of impervious cover, degree of industrialisation, tree density, and animal population can also affect pollutant contributions.

A substantial data collection and analysis program centred on the development of The Woodlands, a large integrated urban and suburban development near Houston, Texas. Zogorski et al. (1975) describe a cross-sectional comparison of water quality data from Durham, North Carolina, West Lafayette, Indiana, and Houston and The Woodlands, Texas. A log-log relationship is found between pollutant loads and peak flow in depth of rainfall units, for a number of storms. Davis et al. (1977) compared the bacterial characteristics of rural runoff at The Woodlands and urban runoff in Houston, and found that faecal coliforms and faecal streptococci increased with increasing urbanisation.

Bedient et al. (1978) describe further analysis at the same sites. Direct linear relationships were found between pollutant mass loading rates and total storm runoff volume. The highest nutrient loads came from the more urbanised areas, while the highest suspended solids came from urban and developing sites. They define initial flush in this way: plot accumulated pollutant load (as a fraction of total load) against accumulated runoff volume on linear scales for an event. If the resulting curve lies above a 45 degree line from the origin, an initial flush is present, since the pollutant is passing the measuring point faster than the water early in the storm. Characklis et al. (1978) conclude that rainfall is a significant source of COD and nutrients. Pollutant concentration in runoff increases as percent impervious area increases, and storage in two artificial lakes is very effective in controlling sediment discharge.

Characklis et al. (1979a) provide the most comprehensive report of the Woodlands project. At The Woodlands, nutrient concentrations in rainwater were higher than in runoff water, while the reverse was true in the urban areas. Quite good linear relationships were found between total pollutant load and total runoff depth for a number of storms. A simplified washoff model is described, and a unit loadograph is developed. Urban catchments are clearly the greatest producers of total suspended solids and nutrient loads. Two artificial lakes reduce suspended solids concentration greatly, and reduce turbidity and COD to about half, but have only an averaging effect on other parameters. Characklis et al. (1979b) provide a short note on COD, ammonia, nitrate, and phosphate in rainfall and runoff.

Concentration of nitrate in runoff is less than that in rainfall at both rural and urban sites. Rainfall is a major source of COD at both sites. Concentrations of ammonia and phosphate in runoff are less than in rainfall at The Woodlands, but are much greater at the urban site.

Bedient et al. (1980b) present results from a comprehensive stormwater monitoring program in Houston. Total suspended solids and total phosphorus plotted against total storm runoff for a number of storms gave a moderately good straight line fit. Peak concentration and total storm load for three pollutants showed no significant relationship with antecedent dry days when rainfall intensity was ignored. The effect of sampling frequency was assessed. A minimum of four samples on the rise and six on the recession is usually needed to give an accurate storm load from developed areas. Amandes and Bedient (1980) develop a stormwater detention storage methodology for urbanising areas, and apply it to suspended solids and nutrients in Keegans Bayou in Houston. Jennings (1980) uses the STORM model to study stormwater quality in Houston, and tabulates daily load accumulation rates for a range of quality parameters and land uses.

Another major project from this period studied the catchment of the Occoquan Reservoir in northern Virginia, which was experiencing eutrophication due to development in the catchment. Randall et al. (1975) describe a water quality study on three sub-catchments of the Occoquan watershed. Organic matter and suspended solids loadings from runoff are greater than those from secondary effluent, while nitrogen and phosphorus contributions are less. Randall et al. (1977) estimate total annual pollutant loadings from urban runoff, and show that they are a substantial proportion of all inputs to receiving waters (up to 40% of total phosphorus, and 64% of total organic carbon). They conclude that runoff management is more important than further sewage treatment in this catchment. Grizzard et al. (1978) monitored plant nutrients during dry weather and storm flow, and found that urban land produced twice as much nitrogen and phosphorus per unit area as rural land. An intermediate storage effectively reduced nutrient transport into the reservoir.

Randall et al. (1978) describe a study of atmospheric contaminants in rainfall over the Occoquan catchment. Pollutant loads were found to be significant, and relatively uniform in space throughout the test area. Contaminants are washed out quickly, so that total load is almost independent of rainfall total or intensity. There is a tendency for washout to increase with increasing antecedent dry period, but the correlations are generally poor. Dustfall contributes less at these sites than washout by rainfall. Helsel et al. (1979) describe a study of metals in runoff, while Griffin et al. (1980) investigated suspended solids and nutrient using nonparametric tests, and found strong relationships for suspended solids and nutrients versus fraction of impervious area. As a result of these studies, Biggers et al. (1980) review the best management practices proposed for the catchment. Areas covered include nonpoint pollution loading factors, sedimentation in detention basins, volume control practices, estimates of cost effectiveness, porous pavements, street sweeping, and physical-chemical treatment measures.

5.1.1.2 Europe

Malmquist and Svensson (1977a) studied air, rainfall, and stormwater quality in Goteborg, Sweden, and found that a number of pollutants in stormwater could be attributed to specific sources or processes - zinc and copper to atmospheric fallout and corrosion rate, lead to traffic volume and street sweeping behaviour, phosphorus to atmospheric fallout and population density, and so on. The contribution of dustfall to stormwater pollutants is much less than that of rainfall at this site. Malmquist and Svensson (1977b) calculated a water budget for a residential suburb of Goteborg with the existing separate system, and for a number of alternatives.

Roberts et al. (1977) investigated rainfall and runoff pollutants in Zurich, Switzerland. Loads are often substantially lower than elsewhere, which is attributed mainly to the absence of heavy traffic in the study area. Most pollutants measured correlate well with suspended solids. Van den Berg et al. (1977) carried out a study of water quantity and quality at the new town of Lelystad, the Netherlands, built on land recently reclaimed from the sea. Quality was measured at a number of points in the surface drains, subsurface drains, town drains, and polder canals. Rainfall and treated sewage effluent were also measured for water quality. There is considerable removal of nitrogen and phosphorus from water in the town drains, which is due at least partly to annual removal of vegetation growing in the drains. Goettle (1978) tabulates sources and quantities of atmospheric pollutants, and concentrations and loads of pollutants in rainfall and stormwater in Munich. Atmospheric pollutant loads vary widely, but can be of great importance to stormwater quality.

A study of suspended solids in urban runoff at Nottingham, UK, is described by Tucker and Mortimer (1978). A log-log relationship between total solids load and total storm flow over many storms was found. The load of the first flush is proportional to the antecedent dry period up to at least 16 days. Major factors affecting total solids load are impervious area and volume of runoff. Minor factors are antecedent dry period and rainfall intensity.

Lindholm and Balmer (1978) studied annual pollutant loads in stormwater drains and combined sewers in Norway, and tabulated the annual pollutant loads found. The proportion of load from each source is very variable from one catchment to another, and from one pollutant to another. Melanen (1978) summarises the objectives and methodology of the Finnish Urban Stormwater Project. Measurements include air temperature and humidity, rainfall, dustfall, rainwater quality, stormwater quality, and groundwater level. Preliminary results are presented, tabulated by city and by land use.

5.1.1.3 Australia

Cordery (1977) studied dry weather and wet weather water quality in Musgrave Avenue Drain, Powells Creek, and Bunnerong Storm Water Channel, all separate stormwater drains in Sydney. He found that urban stormwater is highly polluted, particularly during the first flush, with flood flow pollution levels higher than in secondary sewage effluent for many parameters, and that leaves and grass clippings are a major source of nutrients.

Cullen et al. (1978) and Cullen and Rosich (1979) describe an extensive and detailed study of phosphorus sources in the urban and rural environs of Lake Burley Griffin in Canberra. Urban runoff is a significant source of phosphorus per unit area, but not in total for this largely rural catchment. Sedimentation is the major removal process, but phosphorus in sediments is still potentially available to plants and algae. Bell et al. (1979) studied stormwater flow and quality in the urbanised catchment of the Lane Cove River in Sydney. They were concerned mainly with the effect of sewer overflows from the Northern Suburbs Ocean Outfall Sewer into the river, and the subsequent movement of pollutants in the river and estuary. They conclude that the BOD load of stormwater is much greater than that from the sewer overflow.

Bliss et al. (1979) present results of investigations into stormwater quality in runoff from residential catchments in Melbourne and Sydney, and in motorway runoff in England. They discuss the sources, types, and effects of pollutants in urban runoff, and factors affecting stormwater quality. They quote pollutant loads from dry weather urban runoff calculated for the Port Phillip Bay Study in Melbourne, and present data from Tarban Creek and Musgrave Avenue Drain in Sydney. Urban storm runoff has the potential to degrade the quality of surface waters. Walker (1979) describes a study of urban stormwater runoff quality in Melbourne and its relationship to catchment land use and rainfall parameters. Twelve urban or urbanising catchments have been instrumented to provide streamflow and water quality measurements. He provides a general description of urban stormwater pollution, and presents a small amount of data from the Moorabbin main drain. An initial flush of pollutants appears to be present.

National Capital Development Commission (1980) describes the initial setup and early data collection program of the Giralang and Gungahlin catchments near Canberra, Australia. Giralang in a largely urban catchment of 94 hectares, developed between 1974 and 1976. Gungahlin is an adjacent rural catchment of 112 hectares. Rainfall, runoff, and baseflow and stormflow water quality have been recorded from both catchments since late 1973.

5.1.2 Nutrients

Cowen and Lee (1976) describe a study of the availability of different forms of phosphorus in urban runoff in Madison, Wisconsin. They conclude that for this location, a probable upper bound would be all soluble phosphorus plus 0.3 times particulate phosphorus. In further work at the same site, Cowen et al. (1976) assess the extent to which nitrogen loads in urban runoff are biologically available. Algal-available nitrogen ranged from 4 to 66% of total nitrogen in fresh samples, and from 57 to 82% (with a mean of 70%) after incubation for about 100 days.

Cullen et al. (1978) describe an extensive and detailed study of phosphorus sources in the urban and rural environs of Lake Burley Griffin in Canberra. They develop a budget for five forms of phosphorus: total, dissolved reactive, particulate, dissolved organic, and total dissolved phosphorus, and three flow conditions: drought, flood, and typical years. Biological surveys of phytoplankton, zooplankton, algae, macrophytes, fish, and birds are reported. They find that most phosphorus input is associated with flood events. Urban runoff is a significant source of phosphorus per unit area - 3% of catchment urbanised delivers 3.5% of phosphorus - but not in total at this largely rural site. Sedimentation was the major removal process, but phosphorus in sediment is potentially available to promote algal and plant growth. Cullen and Rosich (1979) summarise the results and conclusions of the study.

Grizzard et al. (1978) monitored plant nutrients during dry weather and storm flow conditions in seven sub-basins of the Occoquan reservoir watershed, Virginia. Good log-log relationships were found between total nitrogen load and runoff depth, and between total phosphorus load and runoff depth. Nearly 90% of nitrogen and phosphorus load to the reservoir came from storm runoff events. Urban land produced twice as much nitrogen and phosphorus per unit area as rural land. An intermediate storage effectively reduced nutrient transport into the reservoir.

Nicholls and Cox (1978) measured nitrogen and phosphorus in precipitation and dry fallout and the pH of rainfall over Harp Lake in Ontario, Canada. Weighted mean concentrations of total nitrogen and total phosphorus during the ice-free period were 1.91 mg N/L and 0.105 mg P/L. Winter concentrations of total nitrogen were similar, but total phosphorus concentrations were much lower, averaging 0.013 mg P/L in fresh snow. Total atmospheric loading on the lake was estimated to be 74.4 mg/sq.m/yr of phosphorus, and 1600 mg/sq.m/yr of nitrogen. Rolfe et al. (1978) describe a study of nutrient flux in southern Illinois forests, including analysis of nutrients in rainfall. Measured nutrient fluxes in rainfall were: nitrogen, 17.7 kg/ha/yr; potassium, 12.1 kg/ha/yr; calcium, 11.1 kg/ha/yr; magnesium, 1.7 kg/ha/yr; and phosphorus, 1.3 kg/ha/yr. Nutrient concentrations were higher in summer than in winter.

Simpson and Hemens (1978) measured nitrogen and phosphorus in rainfall and urban runoff in Durban, South Africa. Atmospheric deposition of total nitrogen (23 kg/ha/yr) was greater than the amount exported in runoff (20 kg/ha/yr). Deposition of total phosphorus (0.5 kg/ha/yr) and suspended solids (215 kg/ha/yr) was less than the amount exported in runoff (2.9 kg/ha/yr and 988 kg/ha/yr respectively). Verworn (1978) studied nutrients in baseflow and stormflow on a mixed land use catchment near Hannover, Germany, using the concept of characteristic pollutograph, which is the water quality equivalent of a unit hydrograph.

Amandes and Bedient (1980) developed a stormwater detention storage methodology for urbanising areas, and applied it to Keegans Bayou in Houston, Texas. Quality parameters are total suspended solids, total nitrogen, and total phosphorus. Although concerned mainly with peak flow and attenuation, the paper contains some incidental data on water quality and sediment removal in detention basins. Freund and Johnson (1980) used regression analysis to investigate the relationships between rainfall, discharge, sediment, and nutrients on three separately sewered urban catchments in Madison, Wisconsin. The parameters are regressed against each other and against discharge.

Griffin et al. (1980) investigated water quality in 16 small catchments in the Occoquan and Four Mile Run basins, using nonparametric Kruskal-Wallis and Jonckheere tests since the data is not normally distributed. Pollutant loads per unit area and per unit rainfall depth increase with increasing impervious area fraction at the 0.001 significance level for suspended solids and a wide range of nutrient measures. The fraction of impervious area may be acting as a surrogate for urbanisation level, and hence for the presence of more pollutant sources. They define initial flush in the same way as Bedient et al. (1978). By this criterion, suspended solids shows an initial flush for this data, while soluble phosphorus does not.

Prasad et al. (1980) describe a study in Toronto, Canada, to estimate the pollution potential of autumn leaves in urban runoff. Total litter from 120,000 trees was estimated to be 3,400,000 kg, including 3,000,000 kg organic matter, 37,400 kg nitrogen, and 6,500 kg phosphorus. Soaking for two days could release 722,000 kg COD, 5,900 kg N, and 1,600 kg P in soluble form. Thus annual organic loadings from autumn leaves can be significant, and shock loading from a storm which washes out leachate can be very high.

5.1.3 Heavy metals

Horkeby and Malmquist (1977) describe a study of 17 heavy metals and 4 organic compounds in stormwater and atmospheric fallout at Goteborg, Sweden. Tables of known effects, permissible levels, ambient concentrations, and uses are given. For As, Cd, Cr, Hg, Sb, V, Pb, and polychlorinated biphenyls, atmospheric fallout can explain most of the stormwater content. The main sources of other pollutants are vehicle exhausts, wear of tyres and asphalt, and corrosion of vehicles and building materials.

Solomon et al. (1977) studied lead solubility in water, using gutter dust samples from heavily travelled streets in Champaign-Urbana, Illinois. They found lead contents of 5.8 to 12.3 mg Pb per gram of dust, and 1 to 24 g Pb per square metre of street surface, in the <0.6mm sieved fraction of the gutter dust. Lead solubility ranged from about 0.5 mg/L at pH 5.5 to 5 mg/L at pH 4. Christensen et al. (1978) measured heavy metals in sediment cores taken from Upper Newport Bay, California. Sediment deposition rate was found to be about 1.8 cm/yr. Zinc and lead showed clearly increased levels in the upper layers, deposited since about 1955 when urban development in the catchment began. Association with grain size shows that the highest metal concentrations in the sediment are produced by large storms. The highest lead concentration (132 ppm) was found in sediment near the mouth of the channel draining an urban area. Murphy and Carleo (1978) describe a study of mercury and chlorinated organics in combined sewer overflows from a predominantly residential area in Rochester, New York. Annual loading of mercury was 0.034 kg/ha, and annual loading of chlorinated organics was 0.011 kg/ha. Concentrations of both parameters correlated moderately well with suspended solids concentration, and with rainfall intensity, rainfall duration, and antecedent dry days.

Helsel et al. (1979) describe a study of metals in runoff from 19 small catchments in the Occoquan watershed, Virginia, and the Four Mile Run watershed, Washington, DC. Catchments with iron and manganese average concentrations significantly greater than those of the forested site were agricultural land uses. Catchments with lead, zinc, and copper average concentrations significantly higher than those of the forested sites were urban land uses. Iron showed a negative correlation with impervious cover. Variations were large within a given land use. Significant nonlinear correlations were found between lead, zinc, and copper, versus traffic and percent impervious cover. A definition of pollutant flush is proposed: flush occurs when the incremental load exceeds the incremental flow during any time interval, where flow and load are expressed as a fraction of the event total. Commercial sites usually showed a first flush of metals, agricultural sites sometimes, and forested sites never. The average incidence of first flush increases with urbanisation.

A study of heavy metals in the Saddle River catchment, New Jersey, is introduced by Wilber and Hunter (1977), who investigated heavy metals in rainfall, urban runoff, and receiving waters. A first flush of metals in stormwater was usually observed. Metals in rainfall accounted for a substantial proportion of metals in the receiving water of the Saddle River (18% Ni to 116% Zn), but only a small proportion of metals in urban stormwater (4% Cu to 9% Zn). Metal concentrations in the river were very variable during baseflow periods, and were usually substantially higher during wet periods. Wilber and Hunter (1979a) analysed street sweepings for lead, zinc, copper, nickel, chromium, manganese, iron, and COD. Most metal concentrations in street sweepings were highest for an industrial area, followed by a road junction, and lowest for a residential area. Lead was highest for the road junction. Metal concentrations generally increase with distance downstream through the urban area, and with decreasing particle size. On average, less than 1% of the total metals was soluble in river water.

Wilber and Hunter (1979b) measured heavy metals in bottom sediments of a 4.6 mile stretch of the Saddle River. Heavy metals are nondegradable and persist in the environment, and may undergo biological magnification in the food chain. Concentrations of all metals and COD were higher in the lower river and, with the exception of iron and manganese, metal concentrations are significantly greater than in soils from the same area. Metal concentrations in sediments were found to be strongly dependent on particle size. Although heavy metals were most concentrated in the smaller particle fractions, by far the greatest total quantity occurred in the fractions greater than 125 microns, because these fractions comprise most of the total sediment.

5.1.4 Microbiology

Davis et al. (1977) studied the bacterial characteristics of runoff from rural and urban catchments in two small lakes at The Woodlands, Texas. Bacterial densities are compared, and the effect of disinfectants on lake water was investigated. Chlorine demand varied from 8 to 16 mg/L, and ozone demand always exceeded 32 mg/L. Initial reductions in bacterial density were followed by recovery in about four days, sometimes rebounding to levels higher than in untreated controls (perhaps due to reduction of competing populations of bacteria). A strong first flush effect was present, with all types of bacteria peaking at or well before the flow peak. Faecal coliforms and faecal streptococci increased with increasing urbanisation.

Olivieri et al. (1978) studied pathogens and indicator organisms in urban runoff from Baltimore, Maryland, and found positive correlations between the levels of indicator and pathogenic bacteria. Geometric mean densities (MPM/100 mL) in stormwater at this site were: total coliforms, faecal coliforms, and faecal streptococci, 10,000 to 1,000,000; pseudomonas aeruginosa, 1,000 to 10,000; staphylococcus aureus, 10 to 100; and salmonella, 0.1 to 1. Olivieri (1980) covers much the same ground in considerably more detail.

Qureshi and Dutka (1979) describe a study of the microbiological quality of urban stormwater runoff from three locations in southern Ontario, Canada. Discharges from all three catchments contained significant quantities of indicator bacteria. Pseudomonas aeruginosa was the most numerous and most frequently isolated pathogen, and salmonella species were also frequently detected. Baseflow from infiltration appears to be a source of low level but continuous microbial pollution. There was little relationship between rainfall intensity or volume and incidence of indicators or pathogens, and no apparent initial flush. Microbial populations in stormwater were high at all sites throughout the sampling period, and often approached densities found in dilute raw wastewater.

5.1.5 Hydrocarbons

Wakeham (1977) sampled sources suspected of contributing hydrocarbons to Lake Washington, Seattle, and identified hydrocarbons by gas chromatography. Urban stormwater including bridge runoff contains the highest concentrations of petroleum hydrocarbons. River waters contain the lowest concentrations, but provide most of the water input. These two sources contribute almost equal quantities of hydrocarbons to the lake, while rainfall and dustfall are less important.

A study of hydrocarbons in urban runoff was carried out on four catchments in Trenton and Philadelphia, Pennsylvania. Hunter et al. (1979) found that most petroleum hydrocarbons are associated with particulate matter, and are apparently adsorbed on to it. Total hydrocarbons were about 70% aliphatic and 30% aromatic, and had an average concentration over five storms of 3.69 mg/L. Number of antecedent dry days has only a small effect. MacKenzie and Hunter (1979) found that about 95% of total aromatic hydrocarbons were associated with particulates. Hydrocarbons in stormwater samples and Delaware River mud sediments both resemble used crankcase oil in gas chromatograph analysis. Whipple and Hunter (1979) covers much the same ground. A number of toxic polynuclear aromatics were detected, including napthalene, anthracene, pyrene, fluoranthene, chrysene, and benzo(a)pyrene.

5.1.6 Roads

The quality of water trapped in road drain catchpits, or gully pots, was measured by Fletcher et al. (1978) at Clifton Grove, near Nottingham. Water quality in the gully pots deteriorates rapidly in dry summer conditions, and can be an important source of runoff pollution. A pollutant whose principal origin is in the gully pot itself (e.g. ammonia) will have the earliest runoff peak. Highly mobile pollutants (e.g. soluble material) from the road surface or atmosphere will peak later, and less mobile material from these sources (e.g. suspended solids) will have the latest peak. Mance and Harman

(1978) also concluded that road drain catchpits are an important source of pollution, particularly in the first flush. They monitored atmospheric deposition, roof runoff, road drain catchpits, and total catchment runoff at Stevenage New Town, Hertfordshire, and have tabulated summary data for each pollutant. They found discharge volume to be a better predictor of pollutant mass discharge than antecedent dry period.

Pope et al. (1978) report preliminary results of an investigation of motorway runoff quality in the UK. There is a definite first flush of total solids and total metals, but total oil, lead, and zinc have a later peak. Total oil appears to be related to the antecedent traffic count since the last storm, and to the peak runoff.

Black (1980) measured water quality during a summer thunderstorm on a suburban parking lot in central New York. Most parameters showed a definite initial flush, followed by dilution to less than pre-storm levels. Trace quantities of numerous substances from vehicles, pavement, and marking paint were found in aquatic vegetation and channel sediments. Clark et al. (1980) developed a proportional sampler to measure stormwater runoff from highways, and field tested it on a portion of Interstate-5 in Seattle, Washington. The sampler uses a simple flow splitter to isolate a sample of about 1% of the total flow. The design appears to need very careful setup and levelling to yield accurate results.

Gburek and Urban (1980) measured the perfomance of a porous asphalt test plot set up near Willow Grove, Pennsylvania. The plot appears to withstand freezing weather well, and has produced no surface runoff in three years. Percolate concentrations are often higher than rainfall concentrations, but are well within local drinking water standards.

5.1.7 Snow and Ice

Pierstorff and Bishop (1980) studied pollutants in snow removed from the streets of Durham, New Hampshire, and dumped on the banks of the Oyster River. Quality parameters are pH, chloride, suspended solids, dissolved solids, BOD, COD, coliforms, and lead. Lead was isolated separately from suspended solids, settled solids, and filtrate. Samples of freshly fallen snow were analysed for the same constituents. Pollutant levels were much higher in the dumped snow than in the fresh snow. Of the pollutants considered, total solids, chloride, COD, and lead appear to be the most important. The impact on the Oyster River near the dump sites did not appear to be significant.

5.1.8 Buildup and Washoff

Ellis (1977) studied dust and dirt washoff behaviour on the Grahame Park catchment in northwest London, UK. Solids typically show a strong initial flush and a double peak. It is proposed that the first peak is derived from sediment in the drain, and the second longer peak comes from sediment on the catchment. Most pollutants are associated with particles of less than 0.2 mm, with nutrients and organics being particularly concentrated in the fine fraction. About 85% of solids by weight occurred within one metre of the kerb. Street sweeping was found to be ineffective for removing the finest particles.

Ellis (1979) describes the same study in more detail. He notes an interesting mechanism of pollution: the drowning and containment of sewage or runoff flows through increase in stage of the receiving stream means that slugs of pollutants can be 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 can occur. Rainfall contributes 1 - 2% of total solids loading in storm runoff, while roof runoff contributes 10 - 30%. Street surface materials from a range of locations were subdivided into inorganic, vegetation, wood, paper, metal, and glass fractions. Organic material can be up to one third of the total pollutant weight, and is mostly rubber and bitumen. Low curbs cause less accumulation, as passing traffic blows the dust off the road. BOD and COD, as a fraction of total solids, both increase with increasing antecedent dry period.

Whipple et al. (1977) set out to challenge the assumption of the SWMM Model that pollution loading in runoff from impervious surfaces in a given storm is an almost linear function of time since last rainfall, using data from the Saddle River, New Jersey. They present data on washoff versus storm runoff in a number of events, and conclude that there is little relationship between washoff and time since rainfall.

Which in hindsight is true enough, but it doesn't address the hypothesis about a 'given' storm (i.e. *only* the antecedent dry period changes), since their approach does not include other modelled variables such as runoff flow rate. There seems to be a reluctance here to accept the increasing complexity of the processes as revealed, or at any rate proposed, by the modellers. Harremoes (1981) will later address this issue more directly by recommending that the level of detail not exceed that of the ultimate study objective - usually receiving water quality - while Jewell and Adrian (1982), Driver and Troutman (1989), and others will continue to develop the simpler lumped statistical models.

Malmquist (1978) describes a study of factors affecting build-up of pollutants in Goteborg on the west coast of Sweden. Dry deposition was small compared with washout by rain. Both sources together contribute about 7% of copper, 20% of COD, 25% of total phosphorus, 30% of zinc, 40% of lead, and 70% of total nitrogen to stormwater. Urban snow was tested at several locations, and was found to be heavily polluted compared with fresh snow. Street cleaning effectiveness was studied by repeated flushing of a pair of swept and unswept streets. The wash water from the unswept street contained on average 2.3 times more suspended solids and heavy metals than that from the swept street. Concentrations in subsequent flushings decreased less than expected - even in the fourth flushing, concentrations were similar to those from heavy rainfall - which implies that initial catchment loads are large compared with typical storm washoff. He concluded that street sweeping removes about half the suspended solids and heavy metals, which matches the results of Sartor and Boyd (1972).

Pitt (1979) carried out a comprehensive study of street cleaning machinery and methods in San Jose, California, and tabulates accumulation rates, particle size, effectiveness of removal, distribution across the street, runoff water quality, and estimated control costs. Large particles are picked up much more effectively than small particles. Accumulation rate is found to decrease with time after cleaning or washoff (but only very gradually). Heavy rain can increase street loadings by erosion from adjacent areas. Higher accumulation rates for poor quality asphalt inply a contribution from breakup of the road surface. Removal efficiency of mechanical or vacuum sweepers is typically only 30 to 50% for one pass. Urban runoff may have more important short term effects on receiving waters than secondary treated effluent.

Freund and Johnson (1980) measured buildup on street surfaces in 12 test areas, using heavy duty vacuum cleaners. It was divided into seven size classes, plus leaves and grass, and other material. The load of leaves and grass was substantial. Solids loads were much higher from asphalt streets than from concrete, and had a different distribution of size classes. No relationships between solids buildup and traffic volume were found. Samples were analysed for total phosphorus, cadmium, nickel, lead, zinc, copper, chromium, and iron, and compared with the results of Sartor and Boyd (1972) and others. Lead concentrations were significantly related to traffic volume, and all pollutants tended to be associated with the finer particles.

Terstriep et al. (1980) describe an extensive water quality sampling program and model simulation conducted by the Illinois State Water Survey in eight urban areas. Dry accumulation on roads was measured by dry sweeping with a vacuum cleaner, followed by wet sweeping with a carpet steam cleaner. In one test area, a curve of accumulated total solids with time, up to six days, was produced by sequential sampling of adjacent street segments. Buildup was much higher in the commercial area than in the residential areas. Ratios of various pollutants to total solids by weight are tabulated. The data is used to calibrate the QUAL-ILLUDAS model. Calibrated loading rates are broadly compatible with the buildup curves.

5.1.9 Storage

Cherkauer (1977b) looks at the effect of Northridge Lakes on the quantity and quality of total streamflow in Beaver Creek, Wisconsin, while Cherkauer (1977a) concentrates on baseflow changes at the same site. The lakes cause a substantial reduction in peak outflow, and have a strong averaging effect on water quality throughout the year. In particular, concentration and load of deicing chemicals are decreased in winter and increased in summer. Averaging of water temperature reduces ice cover downstream in winter.

Characklis et al. (1978) found storage in two artificial lakes at The Woodlands, Texas, to be very effective in controlling sediment discharge. In the same area, Amandes and Bedient (1980) developed a stormwater detention storage methodology for urbanising areas, and applied it to suspended solids and nutrients in Keegans Bayou in Houston. Grizzard et al. (1978) found that an intermediate storage effectively reduced nutrient transport into the Occoquan Reservoir.

Cordery (1976a) investigated the quality improvement that can be achieved by settling of stormwater. Grab samples from Musgrave Avenue Drain and Powells Creek in Sydney were allowed to settle in Imhoff cones for times ranging from 4 minutes to 24 hours. Average removal after one hour was 24% for ammonia, 41% for BOD, 71% for total phosphate, and 90% for suspended solids. Settling had little effect on nitrate concentration. Comparison with sewage from an equivalent area suggests that settling of stormwater for a few minutes would be as effective as upgrading sewage treatment from secondary to tertiary level, for overall pollution abatement.

5.1.10 Data Reviews

Bradford (1977) describes the statistical analysis of urban runoff quality data collected from a number of U.S. locations by various studies. Five groups of explanatory variables were used - land use, climate, average daily traffic, type of landscaping, and street surface. Commercial areas had dust and dirt loading rates below average despite heavy traffic, perhaps because they were swept more often, but BOD, organic nitrogen, and lead were well above average. Residential areas produced below average organic nitrogen, although use of garden fertilisers was expected to give above average results. Tree-landscaped areas showed below average loads of dust and dirt, an unexpected result since it was thought that leaves would be a major source of street-borne material. It is, however, consistent with the explanation of Shaheen (1975), who found that windblown dust and dirt could be trapped by vegetation and removed from the pool of available material. Total coliform counts were below average in heavy industry and heavily trafficked areas, perhaps because there were fewer birds and animals, but significantly higher in tree covered areas. Dust and dirt was below average in grass covered areas, which is again consistent with Shaheen (1975).

Huber and Heaney (1978) list a large number of sources of good quality urban rainfall-runoff-quality data, and provide catchment descriptions for studies in the United States. Huber et al. (1979) update, expand, and summarise the list. They see a need for more rainfall-runoff-quality data, better documentation of parameters and processes, basic statistical analysis, continuous rainfall-runoff-quality data, and sampling and analysis of receiving water quality. Whipple et al. (1978) provide an overview of urban runoff quality studies in New Jersey, Massachusetts, New York, Maryland, and Virginia. Loadings of BOD, phosphate, lead, zinc, copper, nickel, and chromium, and species diversity are tabulated. Species diversity decreases as the stream passes through an urban area. Pollution from urban runoff can be estimated accurately only by sampling at frequent intervals.

McMahon and Denison (1979) tabulate information on atmospheric deposition parameters, based on an extensive literature search. Parameters include deposition velocity of particles, deposition velocity of gases, surface resistance to gaseous deposition, scavenging coefficient of particles, scavenging ratio, and scavenging coefficient of gases.

5.2 Process Analysis and Modelling

The Federal Water Pollution Control Act of 1972 (Public Law No. 92-500) declared that the waters of the United States should be 'fishable and swimmable' by 1983. Section 208 authorised the preparation of regional water quality management plans to achieve this goal, and required that all sources of water pollution - point, intermittent point, and non-point - be evaluated during the planning process. A number of modelling studies were generated or influenced by this requirement.

5.2.1 Process Analysis

Waller (1977) developed a model of phosphorus movement through undisturbed and urbanised ecosystems, and applied it to a residential catchment in Halifax, Nova Scotia, Canada. Phosphorus in urban runoff originates from animal droppings, dustfall and precipitation, vehicles, and vegetation, with vegetation being the largest source. Price and Mance (1978) describe the development and testing of a suspended solids washoff model for urban runoff, using data from Stevenage New Town, UK. SWMM and STORM assume that washoff of a pollutant from a given area is directly related to the instantaneous discharge from the area and the amount of pollutant available. In this model, washoff is developed by considering disturbance of particles by raindrop impact, entrainment into flowing water, and deposition from the flow. Raindrop impact seems to be the major influence. Model fit is good during a calibration event, and satisfactory during a test event.

Alley (1980) presents a methodology to find the optimal value of the exponential washoff decay coefficient K. The exponential washoff equation assumes that the rate of washoff is proportional to the amount remaining on the land surface. K is often assumed to be 4.6, based on the assumption of Sartor and Boyd (1972) that 0.5 inches of runoff will wash off 90% of a constituent from the land surface. Most optimised K values for the site used were less than 4.6, implying a less rapid decrease in concentration. Allowing for pollutant input in rainfall can make a significant difference to the optimum K value.

5.2.2 Modelling

Diniz (1978) and Diniz et al. (1979) document a number of changes made to the Stormwater Management Model (SWMM), to more accurately model the processes occurring at The Woodlands, Texas. The changes include modification of the infiltration routine, and new subroutines to model natural channels, baseflow, and runoff from porous pavements. Good log-log relationships between cumulative pollutant and cumulative flow volume were found. The modified model was able to fit observed quality data fairly well during the calibration period.

Jewell et al. (1978) describe a procedure for calibrating quantity-quality stormwater models, using the Stormwater Management Model (SWMM) and data from Maple Brook, Greenfield, Massachusetts. Quantity and quality portions of a model should be calibrated separately, and may be done using different data sets. The standard error of estimate is used to measure the goodness of fit of the calibration. Good quantity calibration can be achieved by adjustment of a few basin parameters, and quality calibration involves only the adjustment of pollutant buildup rates for most cases. Calibration based on a single storm varies substantially from one storm to another, so several storms should be used for calibration. Jewell and Adrian (1978) look at the mathematical development of the exponential pollutant washoff functions used in SWMM and many other models, and conclude that it is satisfactory. Jewell et al. (1980) further investigate pollutant washoff algorithms. They find that the parameters of the conventional exponential washoff equation optimise to unrealistic values, using a large US data set, and that nonlinear buildup equations degenerate to straight line buildup when parameters are optimised. They therefore suggest that the assumption of exponential washoff is invalid, and propose a number of alternative algorithms. Whichever fits best should be used on a given catchment and data set.

Hajas et al. (1978) describe a field program to characterise urban runoff flows and loads at four locations in southwestern Pennsylvania, and the projection of flows and loads for all urban areas in the region. The Corps of Engineers Storage Treatment Overflow Runoff Model (STORM) was fitted to the measured catchments, then used to estimate the flows and pollutant loads from 30 urban areas in the region. Jennings et al. (1978) scaled up short term water quality data from eight subcatchments in Houston, Texas, to long term estimates using the STORM runoff model and linear relationships between water quality parameters and flow data. Accumulation rates were assumed to be the same for all types of land use.

Hartigan et al. (1978) describe calibration of the USEPA's NPS Model to 16 small catchments in the Occoquan River Basin and the Four Mile Run Watershed. A linear relationship between loading rate and runoff volume from each runoff event was found. For nutrients, increased impervious area gave decreased concentration but increased load. For heavy metals, increased impervious area gave increased concentration and increased load. Washoff from impervious areas used an exponential relationship, while washoff from pervious areas was given by a power function. Buildup on impervious areas is modelled as the sum of a linear increase with time and a dry weather decay rate of four to six percent. A substantial proportion of nutrients can come from the pervious area.

Novotny and Goodrich-Mahoney (1978) studied of non-point pollution loads on the Menomonee River watershed near Milwaukee, Wisconsin, using the deterministic watershed model LANDRUN. Atmospheric fallout and litter accumulation rates are quoted, and the effects of land use and soil types are investigated. They conclude that most non-point urban pollution originates from impervious areas, except in developing urban areas. Schultz and Wilmarth (1978) describe the calibration and verification of the Hydrocomp Simulation Programming (HSP) model on three basins in southwestern Illinois, and its use in analysing and comparing potential water quality control measures. Model calibration is only moderate, for both quantity and quality parameters.

Sutherland and McCuen (1978) propose the Management of Urban Non-point Pollution (MUNP) model as a tool for evaluating non-point sources. Buildup is derived from a bounded exponential function of traffic volume, land use, and pavement condition. Washoff is modelled by a gutter flow routine, since most dust and dirt is likely to be close to the gutter. The model is used to assess sensitivity of runoff quality to street sweeping methods. The model does not appear to be calibrated in the usual sense, but isolated checks against real data show that results are more or less plausible. Medina (1979) describes the development of a simplified continuous receiving water quality model, to be used as a planning guide to permit preliminary screening of areawide wastewater treatment strategies. Standard exponential washoff of pollutants is assumed. A minimum inter-event time is calculated statistically, and used to distinguish independent wet weather events. The model is applied to the Des Moines River at Des Moines, Iowa.

One of the first Australian modelling studies was carried out by Moodie (1979), who modelled the hydrology and water quality of Gardiners Creek in Melbourne. A model based on the Streeter-Phelps equations gave a satisfactory fit to BOD and dissolved oxygen data, and was used to predict the effect of alternative future options. A model describing conservative water quality parameters gave a less satisfactory fit. Dissolved oxygen in Gardiners Creek is high, particularly under low flow conditions, presumably due to photosynthetic activity of weeds attached to the concrete channel. Henley et al. (1980) studied the effects of nutrients on algal growth in Lake Burrinjuck and the upper Murrumbidgee River, to guide the operation of the Lower Molonglo Water Quality Control Centre (LMWQCC). They developed a river water quality model, and used it to estimate the effect of the LMWQCC on nutrient concentrations and algal growth in the Murrumbidgee River.

Alley et al. (1980) developed a continuous model of buildup and washoff behaviour, called the Particulate Transport Model (PTM). The model considers bed load, suspended load, particle size fractions, and bed armouring. It is claimed to be more versatile than exponential washoff modelling, which can only simulate advanced-type load characteristic curves where the pollutant comes off relatively faster than the runoff early in the event. Buildup is modelled as the sum of deposition (a linear function of time) and removal (a linear function of current load). Washoff is based on both sediment availability and transport capacity of the flow. Bedient et al. (1980a) describe an investigation of water quality variation in concrete lined urban channels in Houston, using the steady state model QUAL II to simulate the low flow dissolved oxygen profile. A strong diurnal pattern is present in the DO of low flows, mainly due to attached algae on the bottom of the concrete channel. The diurnal pattern is suppressed during storm flows, due to the higher turbidity in the channel.

5.2.3 Model Overviews

Overton and Meadows (1976) provide a comprehensive overview of stormwater modelling. Chapters on water quality include an overview of stormwater quality, a description of pollutograph and loadograph simulation, and a summary of stormwater quality indices. Wu and Ahlert (1978) summarise a range of methods for computing storm runoff loads. They recognise three levels of detail - annual average, event average, and pattern within events, and describe four methods of estimation - transfer from literature, from estimates or measurements of flow and concentration, from correlation with catchment and storm characteristics, and from a consideration of actual processes involved. Data from West Lafayette, Indiana, is used in an example.

Sutherland (1980) discusses various aspects of stormwater quality modelling. The stages of model development are formulation, calibration, and verification. A model may be deterministic or stochastic, continuous, quasi-continuous, or single event, time-variant or time-invariant, and lumped or distributed. Accumulation or buildup of particulates is a function of time since last rain or street cleaning, type of land use, traffic volume, pavement type and condition, and curb height. Street surface accumulation is less than deposition due to fugitive particles lost to other parts of the catchment or lost from the catchment. Washoff is a function of rainfall characteristics, catchment characteristics, and physical and chemical characteristics of the accumulated sediment. Impact of urban runoff on receiving waters depends on quantity and quality of the urban runoff, upstream flow, and point sources. Biological monitoring may be an effective means of assessment. Urban runoff controls may be at the source, along the line, or downstream. Models covering a wide range of complexity are reviewed and discussed. There are two main types of pollutant washoff models, based on exponential decay and sediment transport respectively.

Huber and Heaney (1980) present a detailed summary of fourteen operational stormwater models with water quality capability. The models are ACTMO, AGRUN, ARM, CAREDAS, EPARRB, HSP, Hydroscience Simplified Model, MRI, NPS, QQS, Simplified Stormwater Management Model, STORM, SWMM, and SWMM Level I. The models are not ranked in any way. The best model to use depends on the particular problem. They recommend that the simplest model that will accomplish the task at hand should almost always be used. Torno (1980) attempts to predict some likely future trends in urban drainage modeling, and notes among other things that the capability of current models exceeds the ability of the data base to support them.

5.3 System Management and Overviews

5.3.1 Monitoring

Pratt and Coler (1976) document a stepwise procedure for the biological evaluation of urban runoff in small rivers. The procedure is based on the observed diversity of benthic macroinvertebrates on artificial substrates. The authors argue that biological evaluation is necessary if aesthetic, recreational, and ecological issues are to be considered. Young (1976) describes a technique for ranking the severity of urban runoff pollution problems, for first level screening of priorities. It is a semi-analytical approach, which estimates the ultimate BOD of large runoff events from a range of catchment characteristics, without using simulation models. The main drawback seems to be its neglect of variation with time, particularly the first flush of scouring in combined sewers.

Jalal (1977) shows how the Storage Treatment Overflow Runoff Model (STORM) can be used to assess the impacts of urbanisation and compare development alternatives. A 'Pollutant Loading Index' based on model output is defined, and is used to assess the relative merits of changing storage or treatment capacity. Model accuracy and calibration do not appear to be addressed. Tupper and Waller (1978) describe the layout and setup of a system to measure the quality and quantity of urban runoff from two small catchments within a combined sewer area in Halifax, Nova Scotia, Canada. They note that only directly connected impervious areas contribute to runoff at this location, except in the largest storms.

5.3.2 Treatment and Management

Higgins et al. (1976) provide a brief review of eutrophication in inland waters, and the effects and sources of the nutrients total nitrogen and total phosphorus. They use typical data values from the literature to estimate inputs to the upper Murrumbidgee Basin, and conclude that urban runoff contributes about 30% of nutrient load to the basin, after the introduction of advanced sewage treatment. Recommended control measures include artificial lakes, erosion control during urban development, and other non-structural measures.

Homer et al. (1977) describe the partly separate stormwater system of London, and discuss options for reducing the effect of storm runoff. Oxygen demand decreases rapidly with storage - typically 50% reduction after ten minutes. Improvement options include simulation modelling, increased treatment capacity, short term settling, and artificial aeration of the receiving waters to combat low dissolved oxygen levels.

Barfield et al. (1978) studied sediment production from urban construction areas, and methods of control. Soil erosion from urbanising catchments is typically 100 times greater than from natural catchments. Methods of control include procedures which stabilise the soil surface, stabilise drainage channels, prevent sediment from entering drainage ways, and trap sediment which has entered drainage ways. They claim that soil loss in an urban construction area is not seen as a problem at the erosion site, in contrast to the rural situation.

Guy (1978) proposes that an urban drainage system designed to address sediment problems will minimise most flow and pollution problems at the same time, and presents diagrams of relevant time and space scales for a range of water quality issues. Factors that can reduce sediment problems during construction include planning to minimise earthworks and provide adequate green belts, construction which minimises the area of soil exposed, and use of temporary drains, ponds, and soil stabilisation. Factors for the post construction phase include planning coordinated between neighbouring communities, integrated use of drains, floodways, and storage components, minimal use of impervious areas, and use of small on-site storage.

Biggers et al. (1980) review the best management practices proposed for the Occoquan River Basin, in Virginia and Washington, D.C. Areas covered include nonpoint pollution loading factors, sedimentation in detention basins, volume control practices, estimates of cost effectiveness, porous pavements, street sweeping, and physical-chemical treatment measures. They include extensive tabulations of cost effectiveness factors for a range of management practices, land uses, and water quality parameters. Browne and Williams (1980) claim that erosion from developing areas is largely an educational problem, and that good watershed management requires public participation and cooperation.

5.3.3 Subject Overviews

Cordery (1976b) describes the typical effects of urbanisation on streams, and notes the lack of local data for Australia. He discusses the changes in flood flows, catchment yield, sediment yield, and water quality, based mainly on US research. He notes that the quality of urban runoff is usually no better than secondary treated sewage, and is often much worse. Cullen (1976) provides a brief literature review of nutrients in urban runoff. He comments that records of total phosphorus from Canberra '... are an underestimate, since vegetation floating in the water was not sampled.' Pisano (1976) provides an overview of erosion rates for a range of land uses, including construction and urbanising areas, and discusses the proposed management of nonpoint sources under Public Law 92-500. The erosion rate of construction and urbanising areas is typically extremely high.

De Ruiter (1977) discusses the changes in water quality in the Netherlands over the last 100 years. On the higher land to the south and east there has been little apparent change. There may have been a slight increase of nutrients in rainfall, but lakes not affected by sewage effluents are still very low in nutrients. The lower land to the north and west is influenced by the quality of the Rhine River, which has declined greatly over the last 100 years. Falkovskaya-Chernysheva (1977) gives a general overview of factors affecting sources of urban water pollution from a USSR perspective. The report covers a wide range of issues, including some not commonly encountered, such as percentage of houses with plumbing, and the effect of livestock farms in suburban areas. Skakalski (1977) provides some general comments on water quality in sewage, urban runoff, and receiving waters, also from a USSR perspective.

Whipple and Hunter (1977) discuss the significant contribution of nonpoint sources to pollution loading of receiving waters. They note the flashiness of urban runoff events, and discuss sampling methodology. They provide a brief summary of urban runoff pollution control, and note that costs tend to be high. Jeung (1978) provides a detailed yet readable review of urban stormwater pollution issues and state of the art in the 1970's. The report assumes that communities are generally unaware of the problem, and sets out to inform them about it. Areas covered include types and sources of pollutants, a wide range of potential control measures, and management and policy implications.

Cullen (1980) discusses the sources and movements of nitrogen and phosphorus in a catchment, and summarises a number of basin studies in both urban and rural catchments. The main mechanism of phosphorus transport is movement of soil or plant particles. It will not move substantially in subsurface flow except in sands. Nitrogen may travel in either dissolved or particulate forms, and can be transported by sub-surface flow. Typical nitrogen and phosphorus export rates for pasture, forest, cropped land, and urban areas are tabulated, using Australian data where available.

Sonnen (1980) provides a critical and sometimes cynical summary of urban runoff quality issues, and attempts to identify areas with major data and knowledge deficiencies. Political expediency is viewed as a major driver of perceptions and priorities. The significance of urban runoff pollution can be determined only in the context of local conditions, and cannot be generalised. He gives a laconic but perceptive review of washoff processes, pointing out that common assumptions are not necessarily correct, and concludes that the current models do not adequately address fundamental processes. In response, Field states 'Theoretically, all models become a black box at some point in the breakdown. The key is, at what point should that occur?' This question will arise repeatedly, in various forms, throughout the 1980's.

Whipple (1980) provides an overview of urban water pollution issues and planning processes. Urban runoff is highly intermittent, so storm based sampling rather than periodic sampling is necessary. Illegal dumping may cause unexpected peaks in pollutant loads. Heavy metals may occur largely in particulate form, and settle out quickly in slow moving larger streams. If so, taking samples of water only may not record the pollutants. Yu et al. (1980) summarise results from two studies of runoff pollution in Trenton, New Jersey, and Philadelphia, Pennsylvania. Urban and industrial areas along the Delaware River are the main sources of pollution. They discuss the various methods of estimating urban runoff pollution, and proposes a stepwise methodology of increasing level of detail for evaluating pollution.

5.3.4 Literature Reviews

Annual literature reviews of urban runoff and combined sewer overflows have been carried out by Field et al. (1976), Field et al. (1977), Field and Gardner (1978), Field et al. (1979), and Field and Cibic (1980).

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Developments in this period are characterised by further growth in data collection and basic analysis, a proliferation of increasingly complex simulation models, and a growing number of review papers.

The buildup and washoff processes remain a subject of much interest, with several studies measuring buildup directly rather than by inference from runoff quality. Measurements of washoff loads from impervious surfaces in repeated flushings show that typical washoff is only a small fraction of the initial load, and emphasises the important distinction between the buildup and washoff processes.

Several studies use impervious area as a measure of urbanisation. But is it the state of urbanisation (impervious area) or the rate of urbanisation (construction area) that is more important? There seems to be some evidence each way, and it may well depend on the quality parameter in question.

A small number of papers deal specifically with microbiology. Total coliforms, faecal coliforms, and faecal streptococci consistently occur at high levels in urban runoff, appear to increase with increasing urbanisation, and typically show a strong first flush. Effective disinfection of raw stormwater requires very high doses of chlorine or ozone.

Sedimentation in detention basins has emerged as a useful and effective treatment technique, and significant removal of nutrients in wetlands has been noted. Control of sediment will minimise many other flow and contamination problems at the same time.

A great deal of effort has been directed towards simulation modelling. Many models have been described, and there is a strong tendency to add more detail in an attempt to improve the goodness of fit. Even so, modelling accuracy is much lower for water quality than it is for quantity. The increasing complexity of modelling is occasionally viewed with concern. There is a suggestion that the SWMM model is over-parameterised, and a claim that the capability of current models exceeds the ability of the data base to support them.

Continuing expansion of the field has led to an increasing number of review and overview papers. Data sets have been summarised, models have been compared, and many overviews of issues and solutions have been prepared. It is gratifying to see this stage of development. Urban runoff quality is now a rapidly maturing discipline providing practical solutions to recognised problems in the real world.

6. 1981 TO 1985: THE NURP PROJECT

Early in this period, the United States Environmental Protection Agency instituted the Nationwide Urban Runoff Project, or NURP, to assess the nature, causes, and severity of urban runoff problems, and methods for controlling them. Comprehensive results and conclusions were published in 1984. The conclusions are more incremental than radical, and contain few surprises compared with earlier work. Even so, this definitive review is a major milestone in the growth and dissemination of knowledge about urban runoff quality and treatment.

6.1 Data Collection and Analysis

6.1.1 General Water Quality Data

6.1.1.1 North America

Novotny and Kincaid (1981) investigated rainwater and stormwater quality from five locations around Milwaukee, Wisconsin, and concluded that local conditions substantially affect rainfall water quality. Nitrogen and phosphorus levels in rainwater were found to be high. Randall et al. (1981) looked at the concentration of a range of nutrients and heavy metals in both rainfall and runoff, using data from the Four Mile Run and Occoquan Watersheds, Virginia. Washout of atmospheric contaminants occurred early in the rainfall events. For all land uses other than tilled agricultural land and highly impervious commercial areas, the runoff loads were less than the rainfall loads. Dry dustfall was considerably less than wet washout. Meister and Kefer (1981) studied stormwater quality on adjacent areas of 'urban' (university campus) and forested/rural land use at Carbondale, Illinois. The 'urban' area showed a first flush for all parameters except faecal coliforms. In the rural area, only total and suspended solids showed a first flush.

Duda et al. (1982) describe a study of benthic macroinvertebrates in streams affected by urban runoff in North Carolina. Species numbers were reduced by up to 80% as the streams flowed through the urban area, even though all local water quality standards except for faecal coliforms were met. Leaking sanitary sewers and illegal intermittent waste discharges to the drainage system were found to be potentially important sources of pollution. Miller and Mattraw (1982) studied the quality of stormwater and rainfall plus dry fallout in three small basins near Fort Lauderdale, Florida. Storm loads were correlated with rainfall volume, peak discharge, and antecedent dry period. On a unit area basis, the residential area yielded the largest loads of nitrogen, phosphorus, and dissolved solids. The commercial area yielded the largest loads of lead, zinc, and COD. Atmospheric deposition provides a substantial part of all pollutants measured in urban runoff - at least half in every case, and sometimes more than measured in runoff.

Halverson et al. (1984) measured rainfall and runoff quality in a non-industrial urban area in Pennsylvania. Rainfall was sampled only during rain - dry deposition was excluded. Runoff was sampled from throughfall and stemflow, a residential roof, and a range of street surfaces. Quality of precipitation was highly variable, and was not significantly related to storm size, antecedent dry period, or minor precipitation events. Nitrogen was increased by tree surfaces, but not by roofs or paved surfaces. Precipitation also contributed some sulphate and phosphorus to runoff, but very little potassium and calcium. All surfaces significantly increased pH. Mikalsen (1984) used correlation and principal components analysis to analyse a large water quality data set from five clusters of streams in Georgia, USA. Urban areas had the highest faecal coliforms, nutrients, hardness, alkalinity, and conductivity. Agricultural areas had the highest colour, suspended solids, and total organic carbon. Forestry areas were not significantly different from control areas. Metal concentrations were highest in urban areas. Organic compounds were detected in fish flesh in small amounts, and occasionally in sediments, but not in the water column.

Waller and Novak (1981) estimated the components of pollution from various sources from Ontario into the Great Lakes. They concluded that for phosphorus, which is of greatest concern, storm generated discharges account for 4% of loads discharged to Lake Ontario from all Ontario sources, and 15% of loads discharged to the lake from municipal sources in Ontario. Ostry (1982) studied water quality in two adjacent catchments in southern Ontario as part of the Pollution from Land Use Activities Reference Group (PLUARG) study. Major pollutant sources are trace elements from urban runoff and point source discharges, phosphorus from agricultural and urban runoff and private waste disposal, chloride from transportation corridors, and sediment and nitrogen from agricultural sources.

Ng and Marsalek (1984) studied rainfall and runoff quality in Burlington, Ontario. Rainwater supplies practically all the dissolved nitrogen in the observed runoff, and significant portions of copper and zinc. The contribution in rainfall of suspended solids, phosphorus, organic carbon, and lead was insignificant. Concentration in rain can vary by a factor of 10 between storms, and this variation is reflected in runoff for those parameters supplied mainly by rainfall. Grimard (1984) describes the Quebec precipitation sampling network, which comprises 46 automatic samplers distributed throughout Quebec, and is intended primarily to assess acid rain. Cumulative frequency curves are presented for pH, calcium, magnesium, sulphate, and nitrate.

6.1.1.2 Europe

Ellis et al. (1981) describe a study of the size, elemental composition, and mineralogy of suspended solids from an urban catchment in northwest London. They found a bimodal size distribution, with peaks at about 2 and 20 microns. Silicon was associated with larger particles, and calcium with smaller particles. A titanium peak, presumably from road marking paint, occured late in the hydrograph.

Niemczynowicz and Falk (1981) calculated a water and pollutant budget for the city of Lund, Sweden. Annual mean pollutant concentrations in stormwater and treated waste water are of the same order of magnitude. Combined sewer overflows are the major source of pollution in the stormwater. Malmquist and Hard (1981) monitored groundwater quality changes in single property infiltration systems in Sweden. They concluded that infiltration of stormwater does affect groundwater quality, but the effect is relatively small in these sandy soils. Melanen (1984) describes the Finnish Urban Stormwater Project, in which rainfall, atmospheric deposition, and runoff quantity and quality were measured at seven urban test catchments. Aerial deposition was found to contribute a substantial proportion of runoff pollutant load. Concludes that under Finnish conditions, the load of organic matter and nutrients in urban runoff is relatively minor compared to that of treated sewage effluent, in contrast to most other studies.

Deutsch and Hemain (1984) summarise data measured on four catchments as part of the French National Program of Urban Runoff Quality Measurement, and conclude that pollution levels of urban runoff can be as high as for secondary treated sewage effluent. Desbordes and Servat (1984) used multiple regression, principal components analysis, and Kalman filtering to relate total suspended solids to rainfall event characteristics on the same four catchments. Suspended solids concentration depends mainly on mean maximum 5-minute rainfall intensity, and number of antecedent dry days.

Uunk and Van de Ven (1984) calculate monthly and annual water and nutrient budgets for part of the the new town of Lelystad, built on land recently reclaimed from the IJsselmeer, Netherlands. More than half the nitrogen and phosphorus are removed from the canals, presumably by settling and chemical reactions. Van de Ven and Uunk (1985) summarise the project at Lelystad, and describe the computerised measurement system for precipitation, storm runoff, subsurface drains, and receiving water quality.

6.1.1.3 Australia

Gutteridge Haskins and Davey et al. (1981) describe a major study of 13 stormwater catchments in Melbourne, and provide a brief review of buildup and washoff processes. They conclude that urban stormwater runoff is an important source of pollution of receiving waters. Weeks (1981) presents water quality data from the same study, and describes the effects of urbanisation. The majority of pollutants showed some degree of initial flush. Duration of initial flush should be related to catchment time of concentration. Pollutant exports were directly related to runoff volume, but antecedent rainfall had little effect. Exports from the mainly industrial catchment were about twice those from mainly residential catchments. Weeks (1982), quoted by Loh (1988), used data from the same 13 catchments to calculate order of magnitude estimates of likely pollutant loads from urban development at Tuggeranong, south of Canberra.

Arthington et al. (1982) describe the effects of treated sewage effluent discharged into Bulimba Creek, Brisbane. While concerned mainly with sewage effluent rather than storm runoff, the report contains extensive information on species diversity studies, and the effects of water pollutants on stream biota. A number of measures of species diversity are discussed, including heterogeneity indices, species richness indices, equitability indices, and similarity indices. Physico-chemical monitoring and biological monitoring are evaluated and compared.

Harris and Meredith (1982) compare the water quality in two branches of Cockle Creek, Newcastle, one 45% urbanised and the other only 6% urbanised. Samples were collected over a four day period in August 1981, under very low flow conditions. Both branches were very polluted, and most concentrations were substantially higher in the more urbanised branch.

6.1.1.4 Other Areas

Bruwer (1981) monitored three successive runoff events from a catchment of 100 sq km in Pretoria, South Africa. Most pollutant loading was associated with storm events, but little relationship was found between flow rate and pollutant concentration.

Konno and Nonomura (1981) studied sediment yield from areas graded for urban development, and concluded that the suspended sediment rate varies as the square of the flow rate, in any one development phase. If sediment production is taken as 1 before grading, it increases to 100 - 10,000 during grading, then decreases to 1 - 10 after completion of work. The initial value depends on the geology of the area.

Yamada (1981) describes a study aiming to relate pollutant content to particle size distribution. Correlation coefficients for iron, manganese, and cadmium vs size index are typically 0.7 to 0.8. The smaller the size index, the higher the metal content. For these parameters at least, size distribution indices appear to be a potentially useful measure.

6.1.2 Nutrients

Ahern et al. (1981) describe a study of nutrient and sediment loadings from a separate storm sewer system in a residential catchment in Madison, Wisconsin. The highest loadings for most constituents occurred during seed fall in late spring and early summer. Dugan (1981) presents water quality data for routine and storm-induced flows from Kamooalii Stream, an urbanising catchment in the Kaneohe Bay watershed, Oahu, Hawaii. Storm flows contribute a disproportionate amount of nitrogen and phosphorus load, with much of the increase due to increased suspended solids in storm flows.

Glandon et al. (1981) studied nitrogen and phosphorus in runoff from urban, wetland, and agricultural areas in Michigan and Indiana. Nitrogen loading per hectare was highest for agricultural use, lower for urban use, and lowest for wetlands. Phosphorus loading per hectare was highest for urban use, lower for agricultural use, and lowest for wetlands. Since phosphorus is the limiting nutrient in this area, urban use has the highest impact per unit area on algal growth in the receiving waters. Yousef et al. (1981) measured water quality in Lake Eola, a small, shallow, landlocked lake in downtown Orlando, Florida, receiving runoff from local street drains. The lake appears to be phosphorus limited when total phosphorus is less than 60 μg/L, which is most of the time. Most input nitrogen and phosphorus were retained in the lake, and only small fractions were discharged through drainage. Anaerobic conditions released phosphorus from the bottom sediments.

Brimblecombe and Stedman (1982) show that there is a marked increase in the atmospheric deposition of nitrate ion between 1880 and 1980. English and European data shows a clear trend, and a fourfold increase over the 100 years. North American data is more scattered, but the increase is possibly even larger. There is little or no change in ammonium deposition from either location over the same period.

Baca et al. (1982) describe a comparison of water quality in two tributaries of Lake Houston, Texas, one in a rapidly developing urban area and the other in a mostly forested watershed. Good relationships between Secchi depth and turbidity and photic zone were found. Lower water quality was observed in the flow from urban areas. Most of the solids that come into the lake remain there, while most of the nitrates and about half the total phosphorus are lost over the spillway.

Brown (1984) used data from eight large urbanising catchments and six small urbanising catchments in Minnesota, to find the land use and catchment characteristics which best explain suspended solids and nutrient levels in runoff. Stormwater quality is correlated to the amount of wetland, the amount of agricultural land use, and the drainage density of the catchment. Hvitved-Jacobsen et al. (1984) measured phosphorus and nitrogen in a detention pond receiving highway runoff near Orlando, Florida. Samples of highway runoff, pond water, and pond sediments were analysed. About 99% of total input phosphorus accumulated in the sediment. About 85 to 90% of total nitrogen input has been removed from the system, probably by denitrification.

6.1.3 Microbiology

Schillinger and Gannon (1985) investigate the adsorption of bacteria on suspended particles in stormwater from Allen Drain, Ann Arbor, Michigan. Adsorption of bacteria onto particles results in higher settling velocities (of the bacteria), and higher concentrations in bottom sediments. Bacteria are removed from water by this process, but can become resuspended by disturbance or high flow velocities.

6.1.4 Heavy Metals

Revitt et al. (1981) compared the distribution of heavy metals with variations in suspended solids during stormflow on an urban catchment in northwest London. No marked first flush of suspended solids was noted for any of the three storms monitored. Copper, iron, lead, and zinc concentrations behaved similarly, and correlated well with Saturation Isothermal Remanent Magnetization (SIRM), but not with suspended solids. Cadmium variations were different, suggesting that the sources or transport processes were also different. SIRM values might feasibly be used as a measure of metals in stormflow. Morrison et al. (1984) describe a study of zinc, cadmium, lead, and copper in urban stormwater from Oxhey in northwest London, and Goteborg in Sweden. Each metal was analysed into three dissolved fractions and three suspended fractions. Zinc and cadmium are mainly in the dissolved phase, while lead is mainly in the suspended solid phase. Copper is distributed equally between both phases. Potentially toxic forms account for 63% of total zinc, 77% of cadmium, 66% of lead, and 32% of copper.

Palmgren and Bennerstedt (1984) studied heavy metals in stormwater by analysing sludge produced by a combined sewer treatment plant in Stockholm, Sweden. A large part of the cadmium and lead in stormwater comes from dry and wet fallout. Only a small part of the copper and zinc comes from fallout. Between 1976 and 1982, loads of lead, zinc, and cadmium reduced to less than half. Reduction of lead in petrol, and decreased use of cadmium plating are likely causes of the change for these metals.

Wigington et al. (1983) studied the accumulation of lead, zinc, cadmium, and copper in the soils of three detention basins in Washington, DC. All metals increased significantly in basin soils on the roadway and commercial catchments, and lead was significantly greater on the residential catchment. There was little downward movement of metals through the soils, and the leachable fraction was very small. Yousef et al. (1984) summarise two studies of heavy metals in stormwater runoff from highway bridges near Orlando, Florida. Most of the heavy metals in highway runoff are in particulate form, and tend to settle out close to their point of release. Retention ponds can significantly reduce the release of pollutants to adjacent water bodies.

Ashawa et al. (1985) describe the use of Differential Pulse Anodic Stripping Voltammetry (DPASV) to measure cadmium, lead, and copper in rainwater at Bombay, and develop log-log relationships between deposition and rainfall. The correlation is good for cadmium, quite good for lead, and moderate for copper.

6.1.5 Hydrocarbons

Gavens et al. (1981) describe a study of aliphatic hydrocarbons in stormwater and sediments deposited by the Silk Stream, which drains an urbanised catchment in northwest London. In the sediment samples, aliphatic hydrocarbons are found in both high and low molecular weight hexane fractions. Total n-alkane levels are up to 0.69 mg/g in sediments, and up to 1.1 mg/L in stormwater. Sources are both natural and artificial. Natural sources include organic detritus and windblown leaves.

Hoffman et al. (1982) studied hydrocarbon load and its relationship to rainfall and land use, to calculate the hydrocarbon loading in runoff into the Pawtuxet River, Rhode Island. Most hydrocarbons are associated with particulate material. Peak particulate hydrocarbons follow the flow peak by about 10 minutes, which suggests that oilier particles are mobilised or transported more slowly than less contaminated particles. Concentration was apparently not affected by antecedent dry days. Hydrocarbons in this runoff resemble used crankcase oil. Hoffman et al. (1984) measured polycyclic aromatic hydrocarbons (PAH's) in runoff from four urban catchments in the same area. PAH's are mostly associated with particles. The particles associated with PAH's have two size peaks - large (probably asphalt particles), and small (associated with atmospheric fallout). The larger particles could be removed from the flow by settling. Urban runoff contributes about 36% of total PAH's to Narragansett Bay, and over 70% of high molecular weight PAH's.

Herrmann (1984) measured polyaromatic hydrocarbons, and 3.4-benzopyrene in particular, in rainfall, urban street dust, and runoff from two nested catchments in Bayreuth, Germany. High to very high concentrations of 3.4-benzopyrene were found in street dust in densely populated areas and along main roads. Concentration in rainfall is generally low compared with that in storm runoff. A strong initial flush is observed.

Stenstrom et al. (1984) studied oil and grease in urban stormwater from a small catchment in Richmond, California. Concentrations from commercial areas and parking lots is about three times higher than from residential areas, and runoff coefficients are also higher from these areas, leading to a much higher total load. Mass of oil and grease is proportional to total rainfall. The oil and grease collected resembled used crankcase oil.

6.1.6 Roads

Clark et al. (1981) describe the development and use of a proportional flow sampler on runoff from interstate highway I-5 near Seattle, Washington, and provide some data on suspended solids, COD, and lead. Owe et al. (1982) measured water quality in precipitation and runoff during a series of storm events on the parking lot of a large suburban shopping mall in Syracuse, New York. Dry deposition accumulation correlated well with antecedent dry period, but precipitation and runoff contaminant concentrations did not. Hoffman et al. (1985) tested storm runoff from Interstate Highway 95 near Cranston, Rhode Island, for a wide range of metals and hydrocarbons. A first flush effect was observed for most parameters, including litter. Antecedent conditions appear to affect the concentration of metals in runoff. They estimate that highways contribute over 50% of total input to receiving waters for suspended solids, PAH's, lead, and zinc.

Pratt and Adams (1981) collected and analysed sediment washed into roadside gullys on the Clifton Grove catchment in Nottingham. Mean 14-day sediment washoff correlated well with catchment characteristics - impervious area, maximum drainage path length, the slope along this path, and the number of houses served. Organic debris showed clear seasonal effects of leaf fall, grass cutting, and blossom shedding. Fletcher and Pratt (1981) describe the retention of pollutants in gully pots on the same catchment. A maximum of only 0.2% of the bottom pot sediment was removed by the highest flow rate. Removal of dissolved pollutants had a greater effect on outflow quality. A rainfall-runoff model which allows for the effect of gully pots on quantity and quality of runoff is briefly described.

Dussart (1984) describes a study of algae on rocks sampled from seven streams bisected by the M6 motorway in Cumbria and Lancashire, UK. With the exception of one stream, there was an increase in the number of species downstream of the motorway, and a decrease in the sample variance. This is attributed to the motorway acting as a source of nutrients to the otherwise nutrient-poor upland streams. Beckwith et al. (1984) describe the use of magnetic parameters to identify the sources of pollutants in storm runoff from a small separately sewered highway catchment in northwest London. Sediment samples from different sources do tend to show different magnetic characteristics, suggesting that the method is feasible, but the process is not carried through to any conclusions about sources in this paper.

Balades et al. (1984) analysed runoff from the A4 and A61 motorways in France, to assess the long term mean runoff pollution. Relationships between pollutant loads and catchment and storm characteristics were developed, and used to estimate total annual loads.

6.1.7 Snow and Ice

Bennett et al. (1981) investigated urban rainfall and snowmelt quality on two residential catchments in Boulder, Colorado. An initial flush was observed for both rain and snow, but was more pronounced for rainfall. Pollutant loadings are generally lower for snowmelt than for rainfall. Both concentrations and mass loadings of pollutants were greater in the catchment with higher housing density and higher traffic volumes. Treatability by filtration, settling, and chemical clarification was assessed. Snowmelt tends to carry finer particles than runoff from rainfall, and so is more difficult to treat effectively.

Couillard (1982) describes a study of snowmelt quality in runoff from two urbanised areas with combined sewers in Montreal. Composite toxicity was assessed by means of bioassays on the green algae selenastrum capricornutum. Snowmelt without rain had a greater potential chronic toxicity than combined sewage during a dry period, due mainly to the presence of inorganic compounds. Toxicity of snowmelt with rain is reduced, presumably due to a dilution effect.

6.1.8 Buildup and Washoff

Reinertsen (1981) investigated surface concentrations and runoff of suspended solids, lead, and COD from small areas of streets, car parks, and footpaths, presumably in Trondheim, Norway. Washoff is affected by initial surface concentration, rainfall intensity and volume, increasing or decreasing discharge, antecedent dry period, and traffic intensity. Single rain events alone did not reduce the surface concentrations dramatically, but many high intensity rain events in succession caused a reduction of about 80% over six weeks.

Bellinger et al. (1982) monitored runoff from the M55 motorway into Woodplumpton Brook, England. An initial flush of pollutants was frequently but not always observed. Removal rates were pollutant-specific, and were a function of total runoff and only slightly affected by runoff intensity. Volume lost by spray from vehicle wheels is linearly related to rainfall. Rain within the last 24 hours leads to higher spray loss, presumably because the road is still wet.

Bender and Terstriep (1984) studied the effects of street sweeping on urban storm runoff quality, using two pairs of separately sewered urban drainage basins in Champaign, Illinois. Samples of rainfall, fallout, street dirt load, and runoff were collected. Sweeping effectively reduced the total street dirt load measured by sampling on the street. The reduction varied widely, but was typically about 50%. Washoff loads of each constituent in stormwater were found to be log-normally distributed. Washoff loads for swept and unswept periods were compared by checking for overlap of 95% confidence limits at the median. Few parameters were found to be significantly reduced according to this approximate test, and the stated conclusion is that sweeping is not effective in reducing washoff. In view of the consistent direction of change over many parameters, the approximate nature of the test used, and the fact that some changes were judged significant, this seems to be an unduly pessimistic conclusion.

Sartor and Gaboury (1984) provide a review of street sweeping practice and effectiveness, and tabulate typical street loadings and pollutant concentrations for several land uses at a number of locations in North America. Most contaminants are associated with the finer particle sizes. Street sweepers typically remove nearly 80% of particles 2000 microns or greater, but only about 15% of particles less than 43 microns. The finer particles associated with most contamination are not effectively removed. To achieve moderate efficiency, the street sweeping interval must be less than the average time between storms. Street sweeping is most effective for areas with long dry periods, for removal of chemicals and grit after snowmelt, and for small urban catchments which dominate a specific receiving water body of high local interest. Street sweeping is effective for removing gross pollutants such as leaves and litter.

6.1.9 Storage

Oliver and Grigoropoulos (1981) measured the water quality of rainfall, inflow, and outflow at a small urban lake in Rolla, Missouri, with an average residence time of about 28 days. Ammonia increased by about 30% in the lake, but all other parameters decreased. The decrease ranged from 22% for organic nitrogen to 90% for suspended solids. The improvement is attributed to sedimentation, dilution with baseflow, and biological utilisation. Whipple and Hunter (1981) tested the settleability of urban runoff from five sites in New Jersey. Settlement for 32 hours in indisturbed water removed substantial quantities of common pollutants - about 70% of suspended solids, 65% of hydrocarbons, and 50% of BOD.

Hey (1982) describes the effect of detention on stormwater quality at Lake Ellyn in suburban Chicago, Illinois. About 90% of suspended sediments and 80% of heavy metals are removed from the flow, but ammonia and dissolved lead are increased. The increase in ammonia is attributed to anoxic conditions on the lake bed, while the increase in dissolved lead appears to be associated with high concentrations of chloride from road deicing salts. Randall et al. (1982) review the use of sedimentation for removal of pollutants from urban runoff, and describe a laboratory study of stormwater runoff from three shopping centre parking lots near Manassas, Virginia. Substantial reductions were obtained by gravity sedimentation for all detectable pollutants measured except soluble nitrogen forms.

Ferrara and Witkowski (1983) investigated the effect of a wet detention basin on stormwater quality in Hillsborough, New Jersey, and concluded that effluent quality is modified by sedimentation and by an averaging process. Removal of solids, COD, and total phosphorus was typically 25 to 50%, although there was wide variation between storms, but Kjeldahl nitrogen increased by up to one third.

Dally (1984) assessed the use of detention basins for water quality and quantity control at two basins in Seattle, designed to reduce peak flows rather than pollutant loads. Suspended solids removal was often negative (that is, existing sediment was washed out of the basins). One of only two exceptions occurred after a long dry period, when grass had stabilised the basin sediments. Soluble metals were washed out of the basins more easily than particulate forms. Synthetic runoff events, created by opening fire hydrants, carried high loads, suggesting that pipe (and gutter) flush may be a dominant source of pollutants during larger events. She concludes that small detention basins not designed for the purpose may not be very effective at pollutant removal.

Gjessing et al. (1984) analysed snow, water, and sediment at Lake Padderudvann, a small lake close to a four lane highway near Oslo, Norway. Pollutants are concentrated in the banks of snow on the road shoulders, and decrease rapidly with distance. Runoff from the highway is highly polluted, but lake outflow is hardly affected. Heavy metals in the lake sediments are highest in the top two centimetres, and in the middle of the lake (presumably due to the association with finer particles). Polyaromatic hydrocarbons are effectively adsorbed and retained by all soil types tested, with highly organic soils the most effective.

6.1.10 Data Reviews

Hemain (1981) analyses a large amount of solids and COD data from catchments in France, Seattle, and Florida. The influence of rainfall and runoff characteristics on runoff quality is generally significant for a given catchment, but there is great dissimilarity between catchments. A linear function is usually satisfactory, and log transforms rarely help. The effect of antecedent dry days, when significant at all, appears to be bounded at about 15 days.

6.2 Process Analysis and Modelling

6.2.1 Process Analysis

Alley (1981) discusses the formulation of exponential buildup and washoff processes, and describes a method of estimating pollutant accumulation parameters for impervious urban areas. The parameter estimation procedure is demonstrated on a small urban catchment near Miami, using suspended solids, total nitrogen, and total lead. The exponential parameters fitted effectively gave a straight line buildup on top of the load already present. Alley (1981) investigates the exponential washoff equation using data from the same catchment. The fitted decay coefficient was generally lower than the default value derived originally from Sartor and Boyd. In other words, the concentration tends to drop off more slowly than is often assumed.

Shivalingaiah and James (1984a) and Shivalingaiah and James (1984b) review the processes of pollutant buildup, washoff, erosion, and transport in urban runoff. Buildup is affected by atmospheric dustfall, vehicles, vegetation, population, activities in the catchment, wind, decomposition, and deliberate removal. Buildup decreases with time and eventualy reaches a steady state. Washoff is affected by rain energy, overland flow rate, and moving vehicles. Algorithms are proposed for each process, and tested using data from Chedoke Creek catchment in Hamilton, Ontario. The work is developed into a model of buildup and washoff on impervious surfaces (James & Shivalingaiah 1985). Modelled curves of accumulation versus antecedent dry days are presented. A full range of observed curve shapes can be produced, from severely bounded (high vehicle speed and/or high wind speed) to almost linear buildup (low vehicle speed and/or low wind speed). The fit between modelled and observed suspended solids in runoff is moderately good.

Ichikawa (1981) proposes a washoff relationship of the form $Q_s = KQP^m$, where Q_s is pollutant load, Q is flow rate, P is the mass of pollutant in the catchment, K is a coefficient, and m is either 1 or 2. Nakamura (1984) investigated washoff of pollutants using an artificial rainfall generator and field experiments in urban Tokyo, and developed equations relating washoff to rainfall intensity, rainfall volume, and surface roughness. The exponential washoff decay coefficient shows a good linear relationship on a log-log plot with cumulative runoff volume (higher volume -> lower coefficient). This smooth change in the exponential decay coefficient seems to suggest that the process is not fundamentally exponential at all.

Gburek (1983) developed a technique to define the area of a catchment contributing surface runoff directly to a stream as the result of any rain, which is the area of potential non point source pollution. Although applied here to a pervious agricultural area, the principle is perhaps also applicable to urban areas.

Shen (1981) provides an overview of sediment transport in pipes and channels. Where sediment supply exceeds transport capacity (low flow and/or large particles), deposition will occur. Where transport capacity exceeds supply (high flow and/or small particles), erosion may occur. The crossover point is the critical runoff rate, which normally decreases with time through a storm. Medina et al. (1981a) present a detailed theoretical analysis of the effects of storage and mixing on pollutant mass transfer and stormwater quality.

Loganathan and Delleur (1984) derive theoretical distributions for overflow volume and quality of receiving river water as a result of stormwater inflow. The methodology is applied to data from West Lafayette, Indiana, and compared with the simulation model STORM. Di Toro (1984) presents a probabilistic approach to the analysis of the water quality response of a stream receiving intermittent storm runoff. Runoff, streamflow, and concentrations are assumed to be log-normally distributed. An exact solution is derived, and an approximate method is proposed. The equations are tested using data from Rapid Creek at Rapid City, South Dakota.

6.2.2 Modelling

Jewell and Adrian (1981a) and Jewell and Adrian (1981b) describe the use of multiple linear regression with optional log transforms for water quality modelling. They emphasise the variation between catchments, and hence the need for local data. No one model (linear, log, etc.) is consistently better, so several forms should be tested and the best fit used for each parameter. Atmospheric deposition can be important, and should be modelled where possible. Jewell and Adrian (1982) applied their techniques to a large set of stormwater quality data. They found that log-log models fitted best in most cases, and semi-log models fitted best in fewest cases. Average runoff intensity and total runoff volume were the most important explanatory variables.

Pisano et al. (1981) develop an empirical model relating pollutant deposition loadings to drainage system characteristics, using data from 75 collection subsystems in eastern Massachusetts. The model uses multiple regression and log transforms to estimate dry weather solids deposition, and explains 85% of the variation compared with a detailed simulation model. The accuracy of the detailed simulation model itself does not appear to be addressed.

Chui et al. (1982) develop a model to simulate pollutants in highway runoff, using data from nine sites in Washington state. Cumulative suspended solids appears to correlate well with cumulative vehicles during storms, after highway sanding and episodes of ashfall from Mount St Helens are omitted. Prediction based on vehicles during storms works well over extended periods, but not for individual storms.

Glenne (1984) used computer simulation and calibration of three urbanising catchments in the Wasatch Canyons near Salt Lake City, Utah, to assess the causes and sources of runoff pollution. A very good log-log correlation was achieved between total coliforms and equivalent population density. Human and domestic animal activities close to streams cause a large share of stream pollution, but buffer strips provide a significant improvement. Septic tank drainfields generate a relatively small pollution load at this location. Most suspended sediments come from dirt roads and construction sites.

Medina et al. (1981b) develop a simplified river quality model named Level III-Receiving for preliminary screening of areawide urban wastewater treatment alternatives, in terms of frequency of violations and more traditional approaches such as dissolved oxygen profiles. The model is applied to dissolved oxygen data from the Des Moines River, Iowa. The fit appears to be good in the example given.

Schlossnagle et al. (1981) describe the Air Force Runoff Model (AFRUM), and record water quality in three drains at Grissom Air Force Base, Indiana. AFRUM is based on the TVA Double Triangle Model. It appears to produce rather equivocal results on these catchments. Sueishi et al. (1981) describe a modelling study of sediment production from an urbanising rural area on Osaka Bay, Japan. Poor report format and syntax reduce the value of this paper.

Hartigan et al. (1983) derived non point pollution loading factors by calibration of the NPS continuous simulation model to 11 small single use test watersheds in the Chesapeake Bay catchment. Simulated nitrogen washoff loads in an average year are 6 pounds/acre/year for single family residential, and 10.7 pounds/acre/year for commercial use. Simulated phosphorus loads in an average year are 0.86 pounds/acre/year for single family residential, and 1.29 pounds/acre/year for commercial use. Forest and pasture have lower loadings of both nutrients, and high tillage cropland has higher loadings.

Barnwell and Kittle (1984) summarise the Hydrologic Simulation Program - FORTRAN (HSPF), which is designed to simulate the hydrological cycle in a river basin. They include a brief history of water quality model development, explaining the relationship between the Stanford Watershed Model, ARM, NPS, HSP, SERATRA, EXAMS, and HSPF. Maalel and Huber (1984) illustrate the calibration of SWMM to multiple separate events using data from four catchments in south Florida. In this technique, several storm events are simulated simultaneously using the same set of parameters. This is shown to be more robust than single event calibration, and is often better suited to available data than full continuous calibration.

Qing (1984) describes a simple mathematical model to monitor pollutant flows and their impacts on receiving waters, and its application to runoff data from Beijing in China. A strong first flush effect is observed. Point and non point source loadings are tabulated. Wada and Miura (1984b) investigated stormwater quality in separately sewered urban areas in Japan. Pollutant loads of stormwater were substantial, and a strong initial flush effect was observed. Simulation models based on storm and catchment characteristics are proposed, and are found to be moderately accurate. Wada and Miura (1984a) modelled buildup and washoff on roads in the same area. The buildup function uses linear deposition, together with decay proportional to the total load, and the washoff function is exponential. The calibrated model appears to fit observed data quite well.

Novotny et al. (1985) describe modelling of pollutant accumulation on street surfaces, and the quantity and quality of runoff, at four pairs of sites in Madison, Wisconsin. Sources considered are dry atmospheric deposition, street refuse, traffic, vegetation, and urban erosion. Both positive and negative 'accumulations' are observed at one site, with an equilibrium load of 20 to 30 g/m of curb. The model fit is very good for dust and dirt accumulation, and moderate for suspended solids in runoff. Modelling of street sweeping efficiency confirms that it is only moderately effective, because the sweeper itself is not very efficient, and because the cleaner the road, the faster the short term buildup by influx from surrounding areas.

6.2.3 Model Overviews

Dendrou (1982) reviews the role of urban stormwater models, their data requirements, and the need for calibration, validation, and verification. Models summarised include STORM, SEMSTORM (a variant of STORM developed for a study in southeast Michigan), Lager's EPA model, the Penn State runoff model, ILLUDAS, SWMM, RUNQUAL, MITCAT, the Urban Wastewater Management Model, HEC-1, SSARR, WQRRS, SCS-TR20, HSPF (successor to the Stanford Watershed Model), NPS, CAREDAS, and HVM-QQS. Many of these models include water quality routines.

Barnwell (1984a) describes the Center for Water Quality Modeling, set up by the USEPA to provide a focal point for water quality modelling activities, and provides a very brief summary of several water quality models. The models are Water Quality Assessment - A Screening Procedure for Toxic and Conventional Pollutants, Exposure Analysis Modeling System (EXAMS), Stream Quality Model QUAL-II, Storm Water Management Model (SWMM), Agricultural Runoff Management model (ARM), Non Point Source model (NPS), Hydrological Simulation Program - FORTRAN (HSPF), and the Water Analysis Simulation Program (WASP). Barnwell (1984b) summarises the same models in slightly more detail.

Geiger (1984) applied four stormwater runoff models to the same combined sewer catchment in Munich, Germany. The models are ILLUDAS, STORM, HYBAG, and SWMM. The simplest models performed almost as well as the most detailed in the great majority of events. Only severe backwater problems or flow reversal required the detailed modelling approach. Sueishi et al. (1984) compare the performance of two volume models and two quality models, using data from Kusatsu, Suita, and Kobe, Japan. The quality models are SWMM and STORM. They conclude that STORM is most applicable to small urban areas, and SWMM is best suited to non-urban and larger areas. DeCoursey (1985) provides a general discussion of the nature and capabilities of mathematical water quality models, concentrating mainly on non-urban areas. SWMM, STORM, CE-QUAL-R1 and QUAL II are briefly mentioned and described.

Reckhow et al. (1985) review pollutant runoff models, selection criteria, and objectives. The wide range in level of detail in available models is noted. They propose a form of model based on the annual frequency distribution of input phenomena, rather than event by event simulation. They discuss a number of possible approaches, and explore the concept of a dynamic, variable source area for overland flow generation.

6.3 System Management and Overviews

6.3.1 Monitoring

Bedient et al. (1981) present a methodology for the design of a comprehensive stormwater quality monitoring program, using projects at The Woodlands and Lake Houston as examples. A modelling effort of some sort, no matter how simple, should be used to guide the field monitoring program, so that predictive relations can be developed and extrapolated for management purposes.

Deutsch and Desbordes (1981) describe the establishment of the French urban water quality study. Four catchments have been established, at Maurepas and Plaisir la Boissiere in Paris, and Aix-Z.U.P and Aix-Nord in Aix en Provence. Land uses are single family housing and multi family housing, and all catchments have separate stormwater drains and sanitary sewers.

Duda et al. (1982) describe the establishment of the Nationwide Urban Runoff Program (NURP), and discuss sources of urban pollutants, monitoring problems, and water quality goals. Lee and Jones (1981) query the usefulness of the Nationwide Urban Runoff Program, claiming that a pollution abatement program should be based on receiving water quality criteria, not just lists of parameters. We need to know the availability of a pollutant, not just its concentration. For example, only a small part of the phosphorus in urban drainage is available to affect water quality in receiving waters, since most is bound up in sediments. Bioassays are valuable, but are not required under current NURP policy. In response, Myers et al. (1982) claim that the NURP will produce useful results, and attempt to refute the claims made by Lee and Jones.

Rossmiller (1985) describes a program to monitor and manage the quantity and quality of runoff from an urbanising agricultural catchment in Ames, Iowa. As land use changes from agricultural to urban, chlorophyll-a concentration is predicted to more than double due to increased phosphorus export from the watershed.

6.3.2 Treatment and Management

Howells and Grigg (1981) discuss the role of State and Local Government in four main areas of urban stormwater management - drainage and detention, flood plain management, erosion and sedimentation, and stormwater quality. They describe Section 208 of the Federal Water Pollution Control Act, which calls for the development and implementation of areawide waste treatment management plans, and note that integrated stormwater quantity and quality management is likely to be the most effective solution.

Clark (1983) looks at the role of legislation in the management of non-point sources of pollution in Australia, concentrating on rural areas. He notes the difficulty of applying traditional legislative techniques to actions which are dispersed in space, gradual or cumulative in time, and hard to quantify exactly. He queries the effectiveness and uptake rate of voluntary action and education programs, and supports greater use of land use controls where necessary.

Field (1982) summarises the USEPA's Storm and Combined Sewer Program collection system research on management alternatives for wet and dry weather wastewater transport and interception. Areas covered include maintenance, catchbasins, new sewer design, sewer flushing, polymer injection, infiltration/inflow controls including inflow reduction, insitu lining, impregnated concrete pipe and trenchless sewer, upstream storage and attenuation, flow routing and in-pipe storage, flow regulators including swirl and helical bend regulator concentrators, fluidic regulators, and hydrobrake, and a rubber 'duckbill' tide gate. The emphasis is on optimal use of the existing sewerage system for the dual purpose of combined sewer drainage and overflow pollution control. Field and Fan (1981) discuss the issue of urban stormwater reuse. They tabulate urban runoff water quality at a number of locations, and the effectiveness of sedimentation for removing a range of pollutants. They conclude that conjunctive use of stormwater and reticulated supply may be cost effective under some conditions.

Finnemore (1982a) describes non-structural and elementary structural stormwater pollution control measures, also called best management practices. Non-structural control measures include preserving natural land conditions, controlling development, limiting embankment slope, modifying neighbourhood cleaning, changing chemical use, and upgrading drainage system maintenance. Elementary structural control measures include soil protection and stabilisation, berms and protective dikes, temporary storage basins, detention ponds, percolation ponds and other pervious areas, and porous pavements. Most measures will need institutional support, such as finance, education, and ordinances. Finnemore (1982b) reviews structural measures to reduce stormwater pollution. The examples discussed are in-line storage control at Seattle, Washington; integrated use of storage and treatment at Saginaw, Michigan; and physical and biological wet-weather treatment processes at Mount Clemens, Michigan. Integrated use of storage and treatment will generally provide cost effective control of stormwater pollution. Finnemore and Lynard (1982) cover much the same ground as the two previous reports, in a more abbreviated form.

A conference on stormwater detention facilities was held in New Hampshire in 1982, covering both quantity and quality aspects of storage design. Papers by Driscoll (1982), Kropp (1982), Randall (1982), Smith (1982), and Stahre (1982) present various design and management aspects of stormwater detention for quality control. Hey (1982) describes the effect of detention on stormwater quality at Lake Ellyn in suburban Chicago, Illinois, while Randall et al. (1982) describe a laboratory study of stormwater runoff from three shopping centre parking lots near Manassas, Virginia. Substantial reductions during storage were obtained for most pollutants by both studies.

Weeks and Crockett (1983) describe a very simple model for estimating pollutants exported by stormwater runoff, based on Australian data, and discuss a range of abatement options. For new areas, the most attractive methods are grass swales instead of concrete kerbs, porous pavements, and soil stabilisation. For existing urban areas, detention, sedimentation, and reed beds are the most attractive options.

Field (1984) overviews the USEPA's Storm and Combined Sewer Overflow Pollution Control Research and Development Program, emphasising the combined sewer overflow aspects. Many possible management alternatives are briefly described, including porous pavements, street sweeping, catchbasins, sewer design, sewer flushing, polymer injection, in-sewer storage and flow routing, regulators and tide gates, storage, treatment, and integrated systems. Novotny (1984) discusses a range of low cost and non structural measures to control urban runoff pollution. Measures include control of atmospheric deposition, street sweeping, litter control, traffic emission control, porous pavements, enhanced infiltration, grass filters, environmental corridors, natural drainage, urban erosion control, and low cost detention and retention schemes including wetlands.

Torno (1984) summarises the objectives and conclusions of the USEPA's Nationwide Urban Runoff Program (NURP). The conclusions are grouped in three main categories, covering pollutant loads, receiving waters, and control effectiveness. **Pollutant loads:** Urban runoff flows and contaminant concentrations are generally log-normally distributed. Heavy metals, especially copper, lead, and zinc, are by far the most prevalent priority pollutants in urban runoff. Organic priority pollutants were detected less frequently and at lower concentrations than the heavy metals. Coliform bacteria are present at high levels in urban runoff. Nutrients are generally present in urban runoff but, with a few individual site exceptions, concentrations do not appear to be high in comparison with other possible discharges to receiving waters. Oxygen demanding substances are present in urban runoff at concentrations approximating those in secondary treatment plant discharges. Total suspended solids are fairly high compared with treatment plant discharges. **Receiving waters:** Frequent exceedences of heavy metals criteria for freshwater aquatic life are produced by urban runoff. Levels of impairment of freshwater aquatic life suggested by the magnitude and frequency of exceedences were not observed. Lead, zinc, and particularly copper appear to pose a significant threat to aquatic life uses in some areas of the US. Organic priority pollutants in urban runoff do not appear to pose a general threat to freshwater aquatic life. Erosion and scour can be a significant cause of habitat disruption. Urban runoff may cause buildup of priority pollutants in sediments. Domestic water supply systems affected by urban runoff should check for priority pollutants. Nutrients in urban runoff may accelerate eutrophication problems in lakes. Coliforms in urban runoff can affect the recreational use of lakes. Coliforms are the primary pollutant of concern for estuaries and bays, but are not believed to be a major threat in most areas. Aquifers that receive deliberate recharge of urban runoff do not appear to be imminently threatened by this practice, based on a small sample. **Control effectiveness:** Detention, street sweeping, recharge, grass swales, and wetlands were the most frequently used control measures. Detention basins can provide very effective pollutant removal. Wet basins perform best for both particulates and dissolved pollutants. Dry basins with extended detention times work well for particulates. Conventional dry basins are not very effective. Recharge devices can effectively control discharges to surface waters. Available evidence does not suggest that groundwater will be contaminated. Street sweeping is generally ineffective for improving urban runoff quality. Grass swales can provide moderate improvement to urban runoff quality. Wetlands are a promising technique for runoff quality control.

Urbonas (1984) reviews the design of detention basin outlets, with regard to hydraulic function, public safety, maintenance, and aesthetic factors. He notes the NURP conclusion that wet retention basins with a permanent pool of water are more effective, and suggests design based on settling analysis. Field (1985) again reviews progress on urban stormwater management and pollution control, with emphasis on non-structural and low-structural techniques, and the total system approach including both control and treatment.

Goyen et al. (1985) describe a number of constructed or proposed projects for the enhancement of urban runoff quality in Australia. Sullivans Creek Ponds in Canberra use sedimentation and a vertical trash rack to reduce gross pollutants. The Tuggeranong Creek and Stranger Creek Ponds in Canberra are expected to remove about 40% of phosphorus, and significant amounts of sediment, organic material, bacteria, and nitrogen from urban runoff. Storage lagoons and reed beds have been proposed for Eight Mile Creek at Albury-Wodonga, to improve urban runoff quality. They discuss the biological aspects of urban runoff quality improvement by ponding, and conclude that urban runoff quality enhancement by detention storage is a cost-effective measure.

6.3.3 Subject Overviews

Ammon and Field (1981) reviewed urban runoff and concluded that stormwater discharges and combined sewer overflows contribute large quantities of oxygen consuming materials, heavy metals, and petroleum hydrocarbons to receiving waters. Major receiving water impacts from heavy metals tend to occur in the sediments. Urban stormwater and wastewater effluents together account for at least 10% of petroleum hydrocarbons entering the ocean.

Field and Turkeltaub (1981b) and Field and Turkeltaub (1981a) present a brief history of the USEPA's Storm and Combined Sewer Program's receiving water impact projects, and a summary of significant results. Up to 80% of the total annual organic loading entering receiving waters from a city is caused by sources other than the sewage treatment plant. Runoff of toxic pollutants, particularly heavy metals, and petroleum hydrocarbons is high. Many toxic substances are associated with particulates. Resuspension of sediments can cause dissolved oxygen depletion after combined sewer overflow events. Species diversity of fish and macroinvertebrates can be greatly reduced in urbanised reaches. Control methodologies should be based on receiving water impacts.

Harremoes (1981) provides an overview of urban storm drainage issues. He proposes that we need to address water quality in terms of the ultimate problem (usually receiving water quality) rather than by arbitrary rules. We need to use an appropriate time scale - short for bacteria and oxygen depletion, but longer for accumulating pollutants such as heavy metals. Standards need to address less common events, as they may be the main problem. Nutrient contributions from urban runoff become important after sewage has been diverted or treated. Rain and dry deposition contribute significantly to pollutant load of runoff - almost all nitrogen, but much less phosphorus. Monitoring of pollutants seems to be out of proportion with knowledge of their effects. Many significant pollutants are associated with sediment, and can be removed with suspended solids, so are treatable in principle. The extent of urban runoff pollution reduces the advantage of separate storm and sanitary sewers.

Brush (1981) gives a brief historical overview of urban sediment issues, and a summary of six conference papers related to urban sediment. Wanielista (1981) summarises eight conference papers on pollutant loadings. He notes, among other things, the importance of measurement location, and the distinction between experimentally recovered buildup and as-discharged washoff. Randtke (1981) summarises seven conference papers on stormwater pollutant loadings. The Federal Water Pollution Control Act, Public Law 92-500, in 1972 established a national goal of fishable and swimmable waters by 1983, and a national policy to develop and implement planning processes to assure adequate control of sources of pollutants. Most effort and funding has been directed at point sources. Urban stormwater is a significant non-point source of pollution, and data is still inadequate. Colyer and Yen (1983) present a general review of the Second International Conference on Urban Storm Drainage held at Urbana-Champaign in 1981. They claim that not enough is known about urban hydrology and hydraulics, and note the opposing trends in modelling, towards greater detail on one hand, and towards simplification on the other. Simplification is a response to data availability, computer power, user friendliness, and level of understanding of ecological implications.

Stephenson (1981) provides an overview of urban stormwater quality. Topics covered include representative pollution parameters, oxygen balance in streams, eutrophication of receiving waters, sediment erosion and transport, and planning and management. Eckhoff and Liu (1983) review urban runoff quality research up to about 1972, and summarise water quality results from combined sewer overflows, storm flows, and rainfall. The issue of treatment versus storage is discussed, and the available control technology is assessed. Roesner (1982) provides a good, readable overview of the history and development of urban runoff quality studies, picking up the story where Field and Struzeski (1972) left off. Extensive tables of typical stormwater quality, combined sewer overflow quality, loading rates, and quality guidelines for drinking water, recreational use, and aquatic life are included. The need for environmental assessment of receiving waters is noted.

Librach et al. (1982) present an overview of the evolution of water quality management philosophy for the Potomac River, and describe an emerging approach to comprehensive water quality management. Future investigations will involve an assessment of the costs of achieving desired water quality levels, and a study of possible mixes of point source, non point source, and combined sewer overflow controls. Weatherbe et al. (1982) review ongoing research in the characterisation of urban runoff quality, design storm analysis, modelling of urban runoff processes, and urban runoff control technology, and quote typical pollutant concentrations in Ontario storm sewers. An initial flush effect is usually observed. The effect of urban runoff on pollutant loads to the Great Lakes is believed to be small. Runoff quality control usually takes the form of storage ponds and/or street sweeping.

Boughton (1983) provides an overview of non-point source pollution in Australia, in both urban and rural areas. The main problems are claimed to be with salt, sediment, and sewage. Urban non-point sources include sediment from building activities, sewage effluents, road surfaces, litter, accidental spills, and deliberate dumping. Garman (1983) and Garman and Sutherland (1983) review water quality issues in Australia, with emphasis on rural non point sources of pollution. Topics include pesticides, salinity, heavy metals, and nutrients.

Thompson (1983) provides a clear and well structured review of non point source pollution from an Australian perspective. Issues covered include definitions, costs, benefits, and justification of an abatement program, the need for catchment based boundaries, and the range of possible elements of an abatement program in both rural and urban areas. O'Brien et al. (1983) include a brief description of the deterioration of waterways in urban areas, concentrating more on the broader ecological and management issues rather than specific water quality parameters.

Hogland and Berndtsson (1983) describe a study of urban runoff from Lund, Sweden. They provide a general discussion of urban runoff features, including storm runoff, combined sewer overflows, snowmelt, industrial discharges, initial flush, and the effect of low natural flows in receiving streams.

Heaney and Huber (1984) summarise results of the NURP program to date. Urban stormwater runoff has been recognised as a potential major contributor of pollution to receiving waters, but the projected high cost of control has prompted a review of impacts. They address the definition of receiving waters, and define the dilution ratio for an urban area. Problem areas are defined as those with combined sewer systems, fish kills, beach closings, or low dissolved oxygen levels. Ellis (1984) summarises nine conference papers on pollutant loads in separate stormwater systems. Vigon (1985) discusses the nature and significance of nonpoint sources of pollution, and claims that the administrative structure to address nonpoint pollution sources in the U.S. has been slow and ineffective.

6.3.4 Literature Reviews

Annual literature reviews of urban runoff and combined sewer overflows have been carried out by Moffa et al. (1981), Moffa et al. (1982), Moffa et al. (1983), Moffa et al. (1984), and Moffa et al. (1985).

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The conclusions of the Nationwide Urban Runoff Project (NURP), published by the United States Environmental Protection Agency in 1984, represent a major milestone in the growth and dissemination of knowledge about urban runoff quality and treatment. Detention basins, recharge basins, grass swales, and wetlands appear to be the best management techniques. Street sweeping, although often used, is claimed to be less effective for improving runoff quality. Treatment usually centres around storage and sedimentation. Removal of suspended solids and associated contaminants can be very high in basins specifically designed for quality improvement, but ammonia and Kjeldahl nitrogen tend to increase.

The importance of rainfall as a source of contaminants in stormwater appears to be widely recognised. Many studies of stormwater quality now measure rainfall quality as a matter of course, and dry deposition may also be recorded. Taken together with the emphasis on receiving water effects which already exists, this shows urban runoff being viewed more and more as an integrated part of the full water cycle.

A rare study of trends with time concluded that loads of lead, zinc, and cadmium in Stockholm had reduced substantially over several years. It would be interesting to see more work of this type, to document any improvements (or otherwise) which may have occurred for other pollutants and other areas.

Interest in hydrocarbons in runoff increased during this period. Hydrocarbons are strongly associated with particulate material, and tend to resemble used crankcase oil. Eroded asphalt particles are another source of hydrocarbons in urban runoff.

The continuing interest in buildup and washoff leads to more data collection studies, and to theoretical analysis of processes. A detailed model of buildup can explain why accumulation appears to be almost linear in some cases, and heavily bounded in others. The concept of a pool of dust and dirt in dynamic equilibrium between pervious and impervious areas is reinforced by further work. Washoff concentrations drop off more slowly than often assumed, and many intense storms in succession are needed to really clean a catchment. Washoff is generally assumed to be an exponential decay process, but a study using an artificial rainfall generator suggests that this may not be so.

There is a distinct trend towards simplification and generalisation in modelling. Statistical models, based on multiple regression with optional log transforms, remain prominent. Larger data sets are used to calibrate both statistical and deterministic models, in an attempt to obtain both more general results and more robust calibrations. A comparison of four models concluded that the simplest models performed almost as well as the most detailed in the great majority of events.

The need to address water quality issues in terms of the ultimate problem (usually receiving water quality), and at appropriate time scales, is promoted. It is claimed that the monitoring of pollutants is out of proportion with our knowledge of their effects. The need for environmental assessment of receiving waters is noted.

7. 1986 TO 1990: PRACTICAL APPLICATION

The emphasis in this period shifts towards the practical application of existing knowledge to improve the quality of urban storm runoff. A number of techniques are used and reviewed, but the most important of these is sedimentation by storage. There is a further increase in review and overview papers, and a growing number of Australian contributions to both data collection and system management.

7.1 Data Collection and Analysis

7.1.1 General Water Quality Data

7.1.1.1 North America

Schmidt and Spencer (1986) surveyed connections to Allen Creek Drain in Ann Arbor, Michigan, and claim that direct connection of individual, commercial, and industrial pollutant discharges to the storm drain system is a major contributor to urban nonpoint pollution. Most of these old connections were approved at the time they were built. Ebbert and Wagner (1987) tabulate the contribution of rainfall to runoff for 12 constituents from 31 urban and suburban catchments in the United States, and the contribution of combined rainfall and dryfall in some cases. Contributions from rainfall alone range from 2% for suspended solids to 74% for nitrite plus nitrate. Contributions from combined rainfall and dryfall range from 50% for total phosphorus to 114% for nitrite plus nitrate.

Fanchiang et al. (1987) correlated dissolved oxygen in the Passaic River, New Jersey, with flow rate and water temperature. Fairly reliable estimates of dissolved oxygen can be obtained using both explanatory variables together, except in midsummer when algal effects are significant. The use of either explanatory variable alone is generally inadequate. German (1987) tabulates the quality of storm runoff and other water injected into the upper Floridan aquifer through drainage wells in Orlando, Florida, for a wide range of water quality parameters.

Garie and McIntosh (1986) studied benthic macroinvertebrates at eight sites along Shabakunk Creek near Trenton, New Jersey. Population density and number of taxa both consistently decreased downstream through the urban area. Heavy metal concentrations in substrates were higher downstream, and may have been the cause of the reduction in benthic macroinvertebrates. Jones and Clark (1987) determined the impact of urbanisation on stream insect communities by sampling 22 separately sewered sites in northern Virginia, representing a range of human population densities. Development had little effect on total insect numbers, but did have a marked effect on relative abundance. Genus diversity and richness were significantly higher in less urbanised streams. Possible causes include increased scour and erosion, decreased base flow, alterations in trophic relationships, and toxic chemicals such as heavy metals, organics, and road salts.

Hall and Anderson (1988) studied the effects of land use on the chemical composition of urban stormwater runoff, and its toxicity to the aquatic invertebrate Daphnia pulex, in the Brunette drainage basin, British Columbia. Runoff from commercial land use was the most toxic to Daphnia, followed by industrial, then residential, then open space. Copper and zinc showed the highest correlation with toxicity. Residential areas had the highest loading rate of COD, which is attributed to the combination of high vegetation level and high impervious area. Suspended solids and pH both affect the toxicity of trace metals to Daphnia.

Irvine et al. (1987) investigated the effect of pervious land on urban stormwater runoff quality from Chedoke Creek catchment in Hamilton, Ontario. Concentrations of most metals increase progressively from sand to clay fraction, although some exceptions do occur. But since the larger grain sizes make up a large part of the sediment washed off, all grain sizes need to be analysed. Industrial sites and those near major transportation routes have higher metal concentrations in eroded sediment. Erosion from pervious land may provide significant inputs of particulates, metals, and organic compounds. Ng (1987) investigated the relationship between the dissolved chemistry of rainwater and urban storm runoff, in an urban test catchment with industrial land use in Burlington, Ontario. Rainwater is a major source of various forms of nitrogen, copper, and nickel, but a relatively minor source of the other pollutants studied.

Pitt (1988) describes a study of asbestos fibres in urban stormwater, and soils and surfaces in Castro Valley, California. Fibre counts, asbestos mass, and fibre size and aspect ratio distributions are tabulated for a wide range of surfaces in the catchment, and for stormwater samples above and below the urban area. About 10% of the monitored runoff flows and 80% of street surface samples had detectable asbestos fibres. Tremolieres (1988) studied the toxicity and oxygen demand of deciduous leaves and conifer needles at Kananaskis, Alberta. Tree species were trembling aspen, western balsam poplar, lodgepole pine, two species of spruce, douglas fir, subalpine fir, white fir, and three species of larch. Oxygen consumption, chemical characteristics, and toxicity are tabulated.

7.1.1.2 Europe

Duysings et al. (1986) used cluster analysis to investigate rainfall water quality and identify likely sources of contamination at a forested site in the Netherlands. Sodium, magnesium, and chloride are associated with seaspray. Sulphate, ammonia, and additional chloride are associated with industrial activity. Potassium, calcium, and additional sodium and magnesium appear to be derived from local dust. Nitrate may be associated with rural activities, and hydrogen ions appear to be associated with sulphur dioxide emissions. Harrop et al. (1987) describe the effect of urban stormwater runoff from a separately sewered area on the quality of the receiving stream, for a catchment northwest of London. Pollutant concentrations downstream of the drain were on average greater than upstream, but lower than in the drain itself. All pollutants except suspended solids showed a strong first flush effect. Peak pollutant concentrations were too high for potable water extraction. Krejci et al. (1987) investigated different sources of pollutants to combined sewers in a fully developed area in Zurich, Switzerland. Contribution of surface runoff to total combined sewer load ranged from 35% for suspended solids down to 7% for total phosphorus.

Roberts et al. (1988) describe the progressive change of size and surface texture of suspended sediment transported along a drain in storm discharge. The study catchment is separately sewered, and covers 420 ha of mixed urban land use in north west London. Particle size distributions and micrographs at five points along the drain are presented. The observed pattern is explained as due to cementation into larger particles by the precipitation of silica, together with abrasion of particles. A settling pond in the drain allows substantial settling of larger particles and aggregates.

Aalderink et al. (1990) review the hydrological research project at Lelystad, the Netherlands. They tabulate pollutant loads and event mean concentrations for a large number of runoff constituents, and recognise three types of response. For parameters associated with suspended solids, such as COD, event mean concentration increases with runoff intensity, but shows only a vague increasing relationship with antecedent dry period. The occurrence or absence of a first flush depends on the dynamics of the runoff intensity. For soluble parameters such as chloride, there is a tendency towards lower event mean concentration with increasing runoff intensity, and no apparent relationship with antecedent dry period. Soluble substances almost always show a first flush. Bacteria behave similarly to the dissolved parameters, except that the first flush is much more pronounced.

Forster (1990) studied the quality and characteristics of rainfall and runoff from various roof types in Bayreuth, Germany. The pH increases in all cases during flow over the roof. All heavy metals show a first flush, and increase with the duration of the antecedent dry period. High molecular weight PAH's are strongly associated with particles. Copper and zinc roof fittings increase the concentration of these metals in roof runoff. Mancici et al. (1990) describe initial data collection from the Malvaccaro experimental catchment in Potenza, Italy. The catchment is separately sewered and 85% urbanised. High initial COD values in a storm seem to be associated with longer antecedent dry periods.

7.1.1.3 Australia

McNamara and Cowell (1987) summarise water quality data from Jamison Park catchment, a fully residential catchment near Penrith, NSW. All measured parameters except oxidised nitrogen showed a first flush. In some events there is a significant second flush due to runoff from pervious areas. For some catchments, quality control measures directed at the second flush may be appropriate, either alone or combined with controls directed at the first flush.

Sinclair et al. (1989) studied trace elements in suspended particulate matter from the Yarra River near Melbourne. Sampling sites were at Warrandyte where the catchment is largely rural, and at Heidelberg where the catchment also includes a substantial urban area. The flow weighted mean concentration of suspended particulate matter increased fivefold between Warrandyte and Heidelberg, and the load increased sevenfold. The annual load passing Heidelberg was estimated to be 170,000 tonnes, with about 80% occurring during high flows. Total phosphorus load increased about 2.5 times between the sampling sites. Lead and zinc concentrations in suspended particulate matter increased 15 to 16-fold between the sites, but iron, copper, and chromium showed little change, and manganese concentration was approximately halved. Heavy metal content of suspended particulate matter in the Yarra is broadly comparable to that in the Gironde, but much less than that in the Scheldt, Meuse, and Rhine Rivers.

7.1.1.4 Other Areas

Ishaq and Khararjian (1988) monitored stormwater quantity and quality in Dhahran, Saudi Arabia, to assess its suitability for reuse. The As-Salamah catchment comprises 182 hectares of university campus and industrial area. A strong first flush was observed. Suspended solids were very high after an extended dry period (up to 6,000 mg/L), but much lower after consecutive storms. Dissolved solids showed a similar but less pronounced effect, with a long term average of about 1,000 mg/L. Reuse of the runoff water is technically feasible, but economic feasibility needs to be checked. The proposed scheme uses inflatable weirs within the box culvert drainage system to store the water and permit settling. Ishaq and Khararjian (1990) investigated the quantity and quality of urban storm runoff from Abha, Dhahran, Jeddah, and Riyadh, all in Saudi Arabia. Urban runoff quality at Dhahran and Riyadh appears to be adequate for reuse other than for potable water. Five treatment alternatives are proposed, depending on the quality requirements of the intended use.

Yaziz et al. (1989) studied the quality of rainwater and runoff from a tile roof and a galvanised iron roof in Serdang, Malaysia. A strong first flush of pollutants was observed, which should be discarded to improve the quality of collected rainwater. All constituents of roof runoff increased with increasing antecedent dry period up to four days (the longest dry period tabulated). Sampling of sequential litres of roof runoff provides valuable washoff data. Washoff occurs fastest under high intensity rainfall.

Ebise (1990) estimated changes in pollutant loading in the River Sanno at Ishioka, Japan, due to urbanisation and expansion of the sewer system. Pollutant loading increased with increased annual rainfall and annual streamflow. Expansion of the sewer system decreased pollutant loads in the river. Increased urbanisation increased the pollutant loads. Pollutant loads during storm events is estimated to account for more than 70% of total pollutant load to receiving waters.

7.1.2 Nutrients

Dorney (1986) measured the phosphorus content of urban street tree leaves in Milwaukee, Wisconsin. Total phosphorus content of leaves ranged from 0.08 to 0.44%, and averaged 0.22% of air-dry weight over several species. Only about 9% of total leaf phosphorus was leachable in two hours. Tree species had a large effect on both total and leachable phosphorus. Total phosphorus content of seeds is similar (0.29%) to that of leaves, but only about 2% is leachable in two hours. Thus the load of phosphorus released over time in a receiving water is likely to be many times that measured in runoff during an event.

Yassini and Clarke (1986) review a detailed study of nutrients in Lake Illawarra, near Wollongong in New South Wales. They summarise the nature and effects of urban and non urban stormwater, describe the lake and its catchment, and investigate algal growth in the lake. A survey of the nutrient load of stormwater drains entering the lake indicates high plant nutrient input from urban and commercial areas. An increase in phosphorus and nitrogen levels of the lake water during the last 15 years correlates with urban development and population growth in the catchment. The surplus of nutrients and increasing siltation has encouraged excessive growth of algae. Possible management options and strategies are briefly reviewed.

Smalls (1987) reviews the sources, availability, and effects of phosphorus in urban runoff, using examples from around Sydney, Australia. The effect of phosphorus on algal growth, and its interaction with turbidity and suspended solids, is discussed. Sekine et al. (1990) studied the behaviour of nutrients in runoff from a range of urban and rural land uses in Japan, and developed a mathematical model of nutrient movement. For farm and forest land uses, dust in runoff is less than in wet and dry deposition. For urban areas, and grassed and bare rural areas, dust in runoff is greater than in wet and dry deposition.

7.1.3 *Microbiology*

Gannon and Busse (1989) measured coliforms, faecal streptococci, and enterococci in urban stormwater from the Allen Drain and other tributaries of the Huron River at Ann Arbor, Michigan, to assess the safety of body contact water sports downstream. Wet weather bacterial densities are significantly higher than dry weather levels for all indicators at nearly all measuring sites. Downstream bacterial densities were significantly higher than upstream levels. Faecal coliform to faecal streptococci ratios suggest animal rather than human origin. They include extensive tabulations of data summary statistics.

7.1.4 *Heavy Metals*

Wigington et al. (1986) investigated the accumulation of cadmium, copper, lead, and zinc in the soils of roadside grassed swale drains receiving stormwater runoff from residential and highway areas in Virginia and Maryland. Lead and copper concentrations decreased with increasing distance from the road. Zinc and cadmium accumulated at the residential sites, presumably derived from galvanised culvert pipes. All significant increases were confined to the top 5 cm of soil. The leachable fraction was low - less than 25% for zinc and cadmium, less than 5% for copper, and less than 1% for lead.

Morrison et al. (1987) measured the concentrations of heavy metals in runoff from residential catchments at Oxhey in London and Goteborg in Sweden, and compared them with proposed EPA 'early warning' and 'significant mortality' levels. Zinc and lead occasionally exceed early warning levels in snowmelt at Goteborg, but not in rainfall runoff. The bioavailable forms of cadmium and copper regularly exceed both early warning and significant mortality levels in storm runoff from both catchments. Morrison (1989) develops a new method for measuring bioavailable metals in urban stormwater, and in the process presents some data on metals in stormwater at three sites near Goteborg, Sweden. Morrison (1990) studied the complexation capacity of water in four lakes near Goteborg, Sweden. Complexation capacity of a receiving water is a measure of the metal concentration that can be discharged to the receiving water before toxic ionic metal appears. Results suggest that zinc and copper are most likely to overload the complexation capacity. Lead and cadmium, although highly toxic, can be complexed by organic ligands and rendered relatively innocuous.

Latimer et al. (1988) describe a study of cadmium, chromium, copper, lead, and nickel at a number of sites along the Pawtuxet River, Rhode Island. Metal concentrations generally increased from the headwaters to the mouth, and stations near industrial and municipal point source discharges showed increased levels of metals. Dastugue et al. (1990) studied metals in suspended solids in the first flush of urban runoff from urban, semi-urban, and motorway sites in Toulouse, France. Composition of suspended solids does not vary from site to site, except in the case of lead and zinc. Total loads to the Garonne and Hers Rivers are calculated and tabulated.

Ellis et al. (1990) assessed the effect of increased copper, lead, and zinc loadings due to storm sewer overflows on three species of macroinvertebrate in an urban river in north east London, UK. The dose-response behaviour of the three species suggested that they were suitable as biomonitors of acute intermittent events. Murakami and Nakamura (1990) measured heavy metals in urban runoff from two separately sewered catchments, and in roof runoff and atmospheric fallout in Kobe city, Japan. Commercial land use generated higher heavy metal loadings than residential land use.

7.1.5 *Hydrocarbons*

Fam et al. (1987) sampled runoff from 15 catchments in the San Francisco Bay area, and analysed them for hydrocarbons using gravimetric analysis and gas chromatography. Hydrocarbons are further divided into particulate and soluble parts, and into aliphatic, aromatic, polar, and nonelutable components. Methods for testing hydrocarbons, and for distinguishing between natural and manmade hydrocarbons are discussed. Relationships between land use and hydrocarbon ratios are developed.

Marsalek (1990) measured fourteen specific polycyclic aromatic hydrocarbons in atmospheric deposition, runoff, and sediment at Sault Sainte Marie, Ontario. Atmospheric deposition was studied by surveying PAH accumulation in the urban snowpack. Equal loading contours were centred over the urban area, but concentrations were highly variable in both time and space, and did not appear to depend on detailed land use. PAH's in runoff are strongly associated with particles, and concentrations closely follow a lognormal distribution.

Saito et al. (1990) studied precursors of organic halogens in urban runoff in the Yodo River basin, Japan. The precursors comprise organic matter such as humic substances and organic sewage effluents, which react with chlorine to produce organic halogens. They estimate the deposition rate, runoff coefficient, and annual load of organic halogen precursors from urban areas.

7.1.6 Roads

Shelley and Gaboury (1986) describe the statistical analysis of highway runoff quality at a number of U.S. sites. Site medians and coefficients of variation are tabulated for a number of quality parameters at each site. Yousef et al. (1986a) and Yousef et al. (1986b) measured the quality of highway runoff, and investigated its treatment in retention and detention ponds in Orange County, Florida. High removal rates of nitrogen, phosphorus, and heavy metals were achieved. Grottker and Hurlebusch (1987) describe the results of laboratory experiments on the accumulation and removal of sediment in gully pots. Both dry and wet gully pots remove large particles more efficiently than small particles. Overall efficiency of removal is quite good for flows up to one litre per second.

Strecker et al. (1987) summarise and consolidate the information on highway runoff water quality, collected in the USA for the Federal Highway Administration. Data affected by Mt. St. Helens has been omitted, and data affected by snowfall has been analysed separately. Almost all the data sets at a single site can be described by a log-normal distribution. Site medians are also log-normally distributed. Results are tabulated for 24 locations, for suspended solids, total Kjeldahl nitrogen, lead, and zinc. Average traffic density correlates with suspended solids concentration.

7.1.7 Snow and Ice

Altwicker et al. (1986a) and Altwicker et al. (1986b) measured the chemical composition of rainfall and snowfall at a network of sites in Adirondack Park, New York, and carried out a statistical analysis of the data. Median concentrations in micro-equivalents per litre are sulphate 43, nitrate 33, chloride 4.8, ammonium 15, calcium 12, magnesium 2.0, sodium 4.7, and potassium 1.6. Median pH was 4.2. Distributions of concentration appear to be log-normal. Differences between sites, seasons, and type of precipitation (rain or snow) are noted.

Oberts (1986) investigated the effects of sand and salt applied to roads near Twin Cities, Minnesota, using laboratory studies and measurements on 17 urban, urbanising, and rural catchments. The quality of snowmelt runoff is tabulated for a number of sites. Sand and salt can contribute to suspended solids, phosphorus, lead, and zinc in snowmelt from roads.

Westerstrom (1990) measured the chemical composition of snowmelt from a small urban study plot in Lulea, Sweden. Under thaw conditions, frozen ground behaves as an impervious surface. Concentrations of all four parameters in meltwater were initially very high, but declined rapidly as the thaw proceeded. pH reached 3.3 early in the runoff, then increased almost continuously to about 5.5 during the peak snowmelt. As much as 65% of the hydrogen ions are washed out from the snowpack with the first 25% of runoff. Because dissolved salts depress the freezing point of water, the highest concentrations are likely to be on the outside of snow crystals during their formation, and also melt first during the thaw.

7.1.8 Buildup and Washoff

Prych and Ebbert (1987) describe the effect of street sweeping on urban runoff quality from two residential catchments in Bellevue, Washington. One catchment was swept three times a week, while the other was unswept, then the treatments were swapped. Swept/unswept ratios of concentration are tabulated for a wide range of quality parameters. Sweeping had little effect on pollutant concentration in runoff - only one parameter (suspended ammonia plus organic nitrogen) showed a significant reduction (33%).

7.1.9 Storage

Grizzard et al. (1986) conducted field and laboratory studies to assess the removal of selected pollutants from urban stormwater in detention basins in Maryland. A retrofitted basin with a median detention time of about six hours removed about 60% of suspended solids, 40% of COD, 15% of total phosphorus, 30% of total Kjeldahl nitrogen, negligible oxidised nitrogen, 60% of zinc, and 80% of lead. Laboratory tests show that ultimate removals are almost achieved in about six hours. A higher initial load typically leads to a substantially higher percentage removal and a slightly higher outlet concentration.

Yousef et al. (1986a) studied the behaviour of phosphorus and nitrogen in retention and detention ponds in Orange County, Florida. Under an areal loading of 5.5 grams per square metre, 99% of total phosphorus was removed from the water into the sediments. Under an areal loading of 35 grams per square metre, 85 to 90% of total nitrogen was removed, probably by denitrification. Yousef et al. (1986b) summarise existing design considerations and report removal efficiencies of a wider range of pollutants at the same site. Heavy metals are concentrated in the top layer of sediment, and within 60 to 90 metres of the stormwater inlet. Peak concentration of lead and zinc was only 15 metres from the stormwater inlet. Most effective pollution control is achieved with a permanent water pool, relatively long mean residence time (i.e. days to weeks), and shallow depth (4 to 6 feet). Aerobic conditions at the sediment-water interface are believed to be important.

Martin and Miller (1987) measured pollutant removal in an in-line detention pond and wetlands system at another site in Orlando, Florida. Load of lead was reduced by 83%, zinc 70%, total solids 55%, phosphorus 43%, and nitrogen 36%. Martin (1988) describes the same system in more detail. The catchment comprises about 17 ha of four lane concrete roadway and adjacent areas in Orlando, Florida. Pond live storage is about 5 mm of runoff, and wetland live storage is about 16 mm. The removal efficiency is tabulated for each parameter for the pond, the wetland, and the total system, and the likely removal processes are discussed. Removal efficiencies for the total system were suspended solids 88%, TOC 22%, and COD 17%. Removal of dissolved ions was negligible.

Hvitved-Jacobsen et al. (1987) describe a study of pollutant removal in a wet stormwater detention pond in Viborg, Denmark. Inflows, outflows, and sediment cores were sampled. Mass removal of suspended solids, phosphorus, zinc, cadmium, lead, and copper in the pond varied between 43 and 90%. Time of year may have an effect on removal efficiency. Residence time appears to be an important parameter, and ideally the pond volume should be more than twice the volume of the design storm. Analysis of core samples showed that long term accumulation of heavy metals occurred in the pond sediments.

Nightingale (1987b) measured a wide range of water quality parameters in and beneath retention and recharge basins constructed between 1962 and 1980 in Fresno, California. Samples of percolating soil water were analysed for 80 specific organic compounds, but only one (diazinon) was found, occasionally, at very low levels. There was some downward movement of copper and iron in sandy and loamy soils, and possible downward movement of lead in very sandy soil. There was no significant contamination of soil water or ground water under any of the basins, for any of the constituents monitored in this study. Nightingale (1987a) summarises results of the same study for arsenic, nickel, copper, and lead. Concentrations under each basin were compared with concentrations at a nearby site. These metals accumulate in the top few centimetres of soil in the basins, and are almost totally confined to the top 20 centimetres of soil.

Striegl (1987) describes a study of suspended sediment and metals removal from urban runoff in Lake Ellyn, Illinois. The lake has a surface area of 4.1 ha and a mainly residential catchment of 216 ha. Trap efficiency was about 93% for suspended solids, 82% for copper, 90% for iron, 88% for lead, and 77% for zinc. The average rate of sediment deposition was about 20 millimetres per year. The finest sediments have the highest metal concentrations. Brown (1988) studied the effects of land use on the quantity and quality of storm runoff from three catchments near St. Paul, Minnesota. The catchment with the lowest ratio of urban area to surface water (wetland plus lake) area had the lowest yield per area of all parameters, and vice versa. Suspended solids and phosphorus are physically trapped in lakes and wetlands, while nitrogen is removed by nitrification and denitrification, and by incorporation into plants.

Wu et al. (1988) summarise the results of a monitoring program on three urban wet detention ponds in Charlotte, North Carolina. The ponds were initially designed for storm runoff control only. The pond with the largest area ratio achieved very good removal of suspended solids (91%), iron (82%), and zinc (79%), but lower and inconsistent nutrient removal, perhaps due to the effect of water birds. Holler (1989) measured the nutrient removal efficiency of a combination grassed swale and wet detention pond stormwater management system at Lake Worth, Florida. The catchment is 15 ha in area, including the pond (1 ha), and is all single family residential land use. Nutrient removal efficiencies are total phosphorus 64%, orthophosphate 98%, nitrite plus nitrate 98%, and total Kjeldahl nitrogen 77%. Ammonia increased in the basin, which is attributed in this case to groundwater infiltration. Suspended solids did not decrease, but were very low (2.6 mg/L) in the inflow.

7.1.10 Data Reviews

Noel (1987) advertises the availability of information from the USEPA's Nationwide Urban Runoff Program (NURP). Information includes bibliographies, project data summaries, basin maps, and data. Data includes atmospheric deposition, water quality, rainfall/runoff, surface loading, and 'best management practice' observations. Hemain et al. (1990) summarise the existing urban stormwater quality data from catchments in France, and propose the establishment of a national data base. Possible uses of the proposed data base are briefly reviewed.

7.2 Process Analysis and Modelling

7.2.1 Process Analysis

James and Shivalingaiah (1986) discuss buildup and washoff processes as a continuum of redistribution processes acting between contributing and non-contributing areas, and list a range of natural and artificial pollutant sources. They quote the work of Shaheen, who distinguished between deposition on roads, which is linear, and accumulation, which levels out due to redistribution into surrounding areas which may not be directly connected to the drainage system. Factors individually modelled include atmospheric dustfall, pollutants from vehicles, pollutants from construction and demolition, pollutants from population related activities (lawn mowing, pesticides, fertilisers, etc.), pollutants from vegetation, removal by vehicle induced eddies, removal by decomposition, removal by wind, intentional removal by street sweeping and snow removal, scavenging by rainfall, and canopy washoff. The model was tested on data from Chedoke Creek, Ontario. Validation results are claimed to be good with respect to time to peak and peak concentration, but no data is presented. Data requirements and model calibration appear to be very demanding.

Shivalingaiah and James (1986) describe the physical processes of atmospheric fallout that are relevant to water quality modelling, and show that fallout contributes significantly to dust and dirt buildup. Monthly accumulated wet and dry deposition is measured at several stations in Hamilton, Ontario, and statistical dustfall models are developed using monthly mean dustfall, wind data, and precipitation data. Shivalingaiah and James (1987) develop equations for the processes of aerosol and gaseous scavenging from the atmosphere, leaf canopy washoff, dry weather baseflow, and local deposition and erosion due to obstructions such as measuring weirs. The equations are coded into the CHGQUAL version of SWMM3, and tested on data from Chedoke Creek, Ontario. Based on this data, they appear to improve the predicted pollutographs.

Akan (1987) describes a physically based mathematical model for pollutant washoff by overland flow on impervious surfaces, based on the kinematic overland flow and convective pollutant transport equations. The model is tested using the rainfall simulator data of Nakamura (1984). The fit is quite good, but it may be significant that only rainfall simulator data appears to have the rigour and detail to adequately test the model. Akan (1988) derived a frequency distribution for suspended solids in storm runoff, assuming Michaelis-Menton buildup and exponential washoff functions. For a given catchment, three parameters need to be fitted from observed data. The derived equations can be applied to a single event, or to an annual total pollutant load.

Driscoll (1986) presents a set of probability plots for water quality data from a number of different applications, and concludes that a log-normal distribution can be assumed both for event mean concentrations at a site, and for mean or median concentrations from a number of different sites in the same category. Hall et al. (1990) studied the statistical distribution of event mean concentrations of pollutants in stormwater runoff, using a large set of data from four catchments in France and five in Denmark. They conclude that a mixture of two normal distributions provides at least as good a description of pollutant event mean concentrations as the log-normal distribution. This agrees well with the finding by Ellis et al. (1981) that particle size distributions tend to be bimodal.

Desbordes and Servat (1987) present two pollutant washoff formulations for total suspended solids, BOD, and COD. The simpler model relates pollutant mass transfer to five minute peak rainfall intensity and runoff volume. The other model also uses mass of pollutant initially available on the catchment. Both models give results within 10% for annual totals, and within 30% for individual events, when applied to data from the French national program. Osuch-Pajdzinska (1987) discusses the forecasting of pollutant load and its concentration in stormwater, and uses a laboratory model to investigate the exponential washoff equation. It is concluded that the washoff exponent k is not constant, but decreases steadily with time through a storm. Patry and Kennedy (1989) investigated the effect of a noise component in the input data on the standard exponential washoff equation, and conclude that a bias may be introduced into the estimate of pollutant load.

Wada et al. (1987a) develop both mathematical and physical hydraulic models of sediment removal from gully pots. The physical model is described, and the characteristics of the sample sediment used are tabulated. The mathematical model is developed from the work of Fletcher and Pratt (1981). The models are compared using suspended solids, BOD, and COD. Agreement is good for a constant flow rate, but only moderate under varied flow.

Etoh et al. (1987) describe a theoretical study of the performance of storage-treatment systems. Assuming a compound Poisson process for runoff time series, exact expressions for the ratio of treated load are theoretically derived for some special conditions. From this, a simplified approximate expression is developed. Preul and Ruszkowski (1987) present the basic continuity equations applicable to sedimentation in a small completely mixed basin. Many urban stormwater pollutants are associated with sediment, so sediment removal is an effective means of improving water quality. McCuen and Moglen (1988) note that a detention basin which limits peak flow to pre development levels may still permit increased bank erosion downstream, since the duration of near-peak flows is greatly increased. They present a detention basin design method based on erosion control, and another based on flow volume control. They recommend that detention basins should be designed to control peaks, erosion, and flow volumes, not just peaks alone.

7.2.2 Modelling

7.2.2.1 Deterministic Models

Najarian et al. (1986) use the STORM model to assess the water quality impacts of a proposed large scale residential development in a New Jersey coastal community. Haith and Shoemaker (1987) developed a set of loading functions for nutrients in runoff, including ground water and sediment transport components, using a monthly time step. The model was tested using data from the largely rural West Branch Delaware River at Walton, New York. Over 90% of the observed variation was explained, even using default parameter values. Kuo and Zhu (1987b) describe a simple model of pollutant removal in detention basins, based on pollutant detention time. Rowney and Wisner (1987) describe the continuous water quality simulation model QUALHYMO, a continuous model which minimises the number of parameters to be calibrated, and provides channel and pond routing routines not available in STORM. Wada et al. (1987b) describe a simple model of pollutant loads in urban runoff. Runoff load is a function of flow rate, flow squared, and remaining load on the catchment. The model is tested using data from Kobe, Chiba, Yamagata, and Kitakyusyu, in Japan, and the fit appears to be reasonable.

Yu and Das (1987) summarise the Virginia Storm Model (VAST), a microcomputer model written in PASCAL. Modelling techniques are claimed to be similar to those found in HEC-1, STORM, and

SWMM. Kuo (1987) and Kuo et al. (1988) describe a computer program developed for the preliminary design and evaluation of various measures to control stormwater quantity and quality. The program is written in BASIC for personal computers. It generates pollutographs using a first order washoff equation, and accounts for the effect of detention ponds, infiltration trenches, and porous pavements. Walker et al. (1989) describe a nonpoint pollution model (WATERSHED) modified to run in a spreadsheet format, and demonstrate its use to assess options to improve the quality of highly eutrophic Delavan Lake in Wisconsin by managing phosphorus inputs. The model was developed from a manual pollutant accounting system, and comprises seven linked worksheets.

Huber and Dickinson (1988) describe the SWMM model in detail, and include an extensive review and discussion of literature relevant to the processes modelled. Huber et al. (1987) describe a calibration method for SWMM which compares the frequency characteristics of the monitored and simulated event mean concentrations, to aid in specifying buildup and washoff parameters. Event mean concentrations are consistently log-normally distributed, both for all EMCs at one site and for site median EMCs over all sites. Simulations of buildup with no upper limit generally produced better results than those with an upper limit. The size of the upper limit is important, but buildup rate and shape have little effect.

Codner et al. (1988) studied the effects of urbanisation on the hydrology and water quality of runoff from the Giralang and Gungahlin catchments in Canberra. The average runoff from the urban Giralang catchment is almost six times that from the rural Gungahlin catchment. The average concentrations of filterable orthophosphate, ammonia, and nitrate are about 50% higher on the urban catchment. When combined with the increased flow, this gives a total flux about ten times higher on the urban catchment than on the rural catchment. Event loads of total phosphorus and oxidised nitrogen are related to event runoff on the urban catchment by log-log relationships. SWMM was calibrated on four events for these parameters, and achieved a very satisfactory fit. Codner (1988) describes calibration of the continuous Storm Water Management Model for water quality modelling on small urban catchments, using data from the Giralang urban catchment in Canberra. He presents washoff frequency distributions for total phosphorus and oxidised nitrogen, and notes that event calibration and continuous calibration give quite different results.

Baffaut and Delleur (1990) and Delleur and Baffaut (1990) describe the use of an expert system to assist in the calibration of the Storm Water Management Model (SWMM) to simulate runoff quality. The expert system amounts to a coded formulation of the steps an experienced modeller would carry out in fitting the model to a measured loadograph. Sample calibration and verification are carried out using data from Denver, Colorado, and Broward County, Florida. The expert system appears to speed up and simplify the calibration process, but it cannot change or improve the structure built into the model.

White (1989) describes modelling of urban stormwater quality at Jamison Park, a mainly residential catchment in Sydney, using the SWMM and ILSAX models. ILSAX is a modification of the ILLUDAS program. Buildup was assumed to be exponential, but a very rapid buildup to the limiting value was found to best fit the available data. Modelling of flow quantity is reasonable, but modelling of quality is poor. Goyen et al. (1988) review the Australian Capital Territory Water Quality Strategy, and describe the water quality control structures in Canberra which resulted from the strategy. Structures include lakes, water quality control ponds, and major and minor gross pollutant traps. The POLLUTE model is briefly described. It simulates daily runoff using a modified Boughton model, estimates daily export of a number of pollutants, and estimates the monthly retention of pollutants in control ponds.

Arnold et al. (1987) describe a modelling study of inflow and sediment input to White Rock Lake at Dallas, Texas. Catchment land use has changed from all rural in 1910 to 77% urban in 1984, and further urbanisation is expected. The Simulator for Water Resources in Rural Basins (SWRRB Model), a modification of the CREAMS model, was fitted to the catchment and used to estimate the effects of past development and a range of future options. Simulation showed that annual surface runoff increased from 135 mm/year to 151 mm/year, and sediment yield reduced from 4.4 t/ha to 4.1 t/ha as a result of urbanisation. Butkus et al. (1988) investigated the relationship between biologically available phosphorus from increased urban runoff and chlorophyll-a and transparency in Lake

Sammamish, Washington. A model to estimate biologically available phosphorus (BAP) was developed, and chlorophyll-a was related to BAP by linear and nonlinear regression analysis.

Singh and Scholl (1989) developed two linked computer models of urban water quality. The Continuous Stormwater Pollution Simulation System (CSPSS) model provides continuous simulation of an urban area and its receiving water. The Computer Optimised Stormwater Treatment (COST) program identifies the least costly combination of pollution control alternatives needed to maintain the desired water quality in the receiving water. The pollution control alternatives modelled are street sweeping, combined sewer flushing, and a range of storage/treatment options including storage, microscreening, flocculation, sedimentation, dissolved air flotation, and high rate filtration.

Osborne and Hutchings (1990) and Osborne and Payne (1990) describe the structure of the MOSQITO urban water quality model, and its calibration and testing using data from Clifton Grove near Nottingham. MOSQITO is a deterministic water quality model incorporated within the WALLRUS flow simulation program. It comprises four sub-models which simulate washoff from catchment surfaces, foul water inflow, pollutant and sediment routing in pipes and channels, and pollutant and sediment behaviour in ancillary structures. Data needs include input describing the sources of the pollutants, and verification data to check the behaviour of the model.

Ha (1990) describes the development and improvement of the KISNPS non point source pollutant runoff routing model. The model calculates pollutant contributions from both overland and channel flow, using a numerical approximation technique. Grottker (1990) used simulation of synthetic catchment areas to compare the effectiveness of various combinations of stormwater treatment techniques for removing suspended solids. The most effective single technique is the sedimentation basin, followed by the swirl separator, wet gully pots, street sweeping, and dry gully pots. Combinations of wet or dry gully pots with each of the other techniques added little extra value.

Kawara et al. (1990) modelled water quality in the Hino River, Japan, which flows into Lake Biwa, and assessed the effects of development on water quality. The model consists of four sub-models - runoff, point sources, non point sources, and in-stream behaviour. Modelled results show relatively good agreement with observed data. The model suggests that urban development has no adverse effect in this case, since the pollutant loads from forests and rice agriculture are greater than from households. Wen and Liu (1990) describe water quality modelling in an area of interconnected waterways in Suzhou, China, using a model derived from the kinematic wave equations. Land use is derived from Landsat images. Pollution is more severe in commercial and mixed land use areas than in agricultural areas.

7.2.2.2 *Statistical Models*

Driver and Lystrom (1986) and Tasker and Driver (1988) develop a method for estimating water quality parameters on unmonitored sites in urban areas. Model parameters are estimated by a generalised least squares regression method, using USGS and USEPA data. Mean storm load is defined and tabulated at a large number of US sites for a range of water quality parameters. Typically about half the variance is explained by this method.

Driver and Lystrom (1987) and Driver and Troutman (1989) present regional regression models relating storm runoff loads and volumes to land use and climatic factors. For this study the United States was divided into three regions, with rainfall less than 20 inches, 20 to 40 inches, and more than 40 inches. Log transforms were used for all variables. Regression coefficients and several measures of error are tabulated for each quality parameter and each region. Total storm rainfall and total contributing drainage area were the most significant explanatory variables. Impervious area, land use, and mean annual climatic characteristics were also significant in some models. The most accurate models were those for the low rainfall region.

Driver (1990) summarises the work on regional regression models, and notes that the regressions are limited by the availability of explanatory variables on a regional basis. Possible explanatory variables with insufficient data include antecedent conditions, detailed land use categories, best management practices, and indicators of urbanisation (other than impervious area). The effects of antecedent rainfall were investigated where data permitted. Antecedent dry period improved the regressions in the high rainfall region, but had little effect in low rainfall areas.

Hemain (1987) compared annual pollutant load estimated using calibrated regression equations with measured pollutant load from the Maurepas catchment, France. Relationships between pollutant mass load and rainfall depth seem to give consistent results, but accuracy is no better than + or - 50%. Novotny et al. (1990) used ARMA modelling techniques to separate wet weather and dry weather flow and quality components in a drainage or sewerage system, using data from Fusina in Italy and Green Bay in Wisconsin.

7.2.2.3 Comparison and Discussion

Patry (1987) developed urban water quality forecasting models for real time control of combined sewer systems, and applied them to a small system in Hamilton, Ontario. Two types of model were used - an autoregressive moving average (ARMA) model, and a deterministic/stochastic model. The differences and limitations of the two types of approach are summarised. The ARMA model performed better at all lead times up to one hour for COD, but the deterministic/stochastic model performed better at short lead times for suspended solids.

Harremoes (1988) notes that deterministic modelling of pollutant transport has been less successful than that of flow volumes and peaks, due to the high level of random variability in the pollutant runoff processes, and proposes a modelling approach which uses both deterministic and stochastic elements. He recognises two categories of pollution problems - acute or short term effects (which may still have long term consequences), and cumulative or long term effects. He proposes that standards and compliance be specified as a plot of parameter level versus return period, and states that this approach is now an accepted standard in Denmark. The time period must be chosen to match the specific pollutant.

7.2.3 Model Overviews

Ellis and Linder-Lunsford (1986) compared the performance of a number of conceptually based and regression based runoff models, using quantity and quality data from four small urban catchments in Denver, Colorado. The conceptual models studied are DR_3M-II for quantity and DR_3M-QUAL for quality. Multiple linear regression models are developed for both quantity and quality. The estimates obtained from the conceptual models are generally no more accurate than those of the regression models within the range of the calibration data. The conceptual models performed better outside the range of the calibration data. Neither type of model could accurately estimate individual storm runoff loads.

Huber (1986) summarises a range of analysis approaches and provides an extensive literature review. The need to suit the analysis method and level of detail to the task, and the need for calibration and verification, are both emphasised. Wittenberg et al. (1990) review the types of water quality models applicable to receiving waters affected by point and non-point pollutant sources, and emphasise the importance of biological measures of pollution.

7.3 System Management and Overviews

7.3.1 Monitoring

Ellis (1986) describes the monitoring of effluent from an urban landfill site near Sydney, and outlines the origins of dissolved compounds in the leachate. Water may come from rainfall, runoff, and groundwater, or from the organic material in the landfill. Leachates from sanitary landfills are typically high in BOD, COD, Kjeldahl nitrogen, suspended solids, dissolved solids, and soluble iron. Cowell et al. (1987) outline the selection, setup, operation, and data analysis of three water quantity and quality gauging stations at Penrith and one at Hornsby in New South Wales. Problems encountered at each site are discussed.

Anderson and Hammerschmid (1987) describe an urban runoff study carried out in the Hawkesbury-Nepean catchment near Sydney. Automatic sampling stations were installed on a developing residential catchment, an established residential catchment, and a rural catchment. Sampling methods and frequencies are described, and quantity and quality models are discussed. The MITCAT model was chosen for quantity, and CDM-STORM for quality. Hammerschmid and Harvey (1987) note a number of problems encountered in the selection of suitable sites. Issues covered include homogeneous land use, point source pollution, flow monitoring dificulties, uniform geology and soils, power supply for refrigeration, physical and legal accessibility, vandalism and stock damage, and natural and artificial storages.

Smith et al. (1988) discuss the design of an urban water quality monitoring system. They emphasise the importance of high flows for pollutant loads and concentrations. The aims of a particular monitoring program need to be understood and reflected in the system design. There is a need to obtain and consider public input to the planning and monitoring process. Hahn and Xanthopoulos (1990) discuss sampling methodologies and the likely effects of unrepresentative sampling procedures. If the sample collected is not typical of the total flow, the calculated loads will be incorrect. This is particularly so for pollutants such as heavy metals which tend to associate with particles of a given size range.

7.3.2 Treatment

7.3.2.1 General Treatment Methods

A number of papers discuss or compare a range of stormwater treatment methods. The options covered include planning and land use controls, construction stage controls, infiltration pits, porous pavements, grass swales, temporary on-site ponding, street sweeping, litter control, drainage controls, public education, sedimentation ponds, dry retarding basins, wet and dry stormwater ponds, wetlands, gross sediment pits, litter booms, trash racks, and control of miscellaneous urban pollutant sources. Wanielista and Yousef (1986) review best management practices for urban runoff, concentrating on infiltration basins and vegetated swales. Best management practices are techniques which achieve satisfactory water quantity and quality control at minimum cost. Woodward (1986) reviews the sources and effects of urban runoff pollutants, and summarises a range of control measures. Interim guidelines for urban pollution controls in New South Wales are proposed, and typical costs are tabulated. Brown and Molinari (1987) outline the contents of the Pollution Control Manual for Urban Stormwater in New South Wales, produced by the State Pollution Control Commission. Desirable stream quality is tabulated for a number of parameters, and a wide range of control techniques are discussed.

Goyen et al. (1987) and Lawrence and Goyen (1987) describe urban water quality management measures in Canberra. Measures include no direct discharge of runoff from future urban development to lakes or rivers, urban lakes, water quality control ponds and wetlands upstream of urban lakes, gross pollutant traps, off-stream sediment retention ponds, retention of natural creeks augmented with retarding basins, and temporary control measures during construction. Water quality modelling concentrates on three main processes: source generation, instream transfer, and response of biota in receiving waters. Correlations between pollutant reduction and hydraulic retention time have been developed. Modelling and monitoring both indicate that quality similar to rural conditions is achieved where the strategy is in place. Phillips and Goyen (1987) cover much the same ground, and present retention curves for suspended solids, total phosphorus, and e.coli against hydraulic residence time, and for sediment against area ratio and grain size. Of the several references on the Canberra water quality control program, this paper provides the most information on design parameters and requirements.

Tonkin-Hill and Crooks (1987) propose a multi-disciplinary approach to urban stormwater management. After a brief history of stormwater management, they break down the management approach into a tree structure of objectives, solution elements, and constraints, which includes at the most detailed level a very large number of potential options. Australian Environment Council (1988) summarises sources, types, and concentrations of pollutants, and their impacts on receiving waters, and describes a range of control measures to improve the quality of urban runoff.

7.3.2.2 Treatment by Storage

Walesh (1986) describes three nonpoint source pollution control projects. They include two sedimentation basins in series with a detention basin at Madison, Wisconsin, a sedimentation basin in series with a restored wetland at Roseville, Minnesota, and a system of flow regulators, surface storage on streets, detention basins, and underground tanks to control flooding and improve water quality at

Stokie, Illinois. He concludes that useful quality improvement can be added on to quantity control facilities at relatively small incremental expense.

Kuo and Zhu (1987a) and Kuo and Zhu (1989) describe the use of a diversion box and a small detention basin to treat only the first flush of urban runoff. A software package to carry out the analysis and design is illustrated by example. Ormsbee et al. (1987) illustrate the design of stormwater detention basins for control of both quantity and quality of urban runoff, using dynamic programming. The method is applied to the Glen Ellyn catchment above Lake Ellyn, Illinois. Whipple et al. (1987) discuss the principles and practice of dual purpose stormwater detention and retention basins. Their design method is based on the concept of a settleability design storm, and separate flood control design storms. The settleability detention storage should empty slowly, and the flood control storage should hold 2 year, 10 year, and 100 year floods at the site to their respective pre-development peaks. Nix et al. (1988) demonstrate an approach for estimating the long term performance of detention basins for removal of suspended solids, by applying the storage/treatment block of the SWMM model to a notional detention storage.

Cullen et al. (1988) investigated various approaches to the design of retention ponds to improve the water quality of urban runoff, with emphasis on the biological systems that will develop in them. Mechanisms for urban water quality improvement in ponds are sedimentation, filtering by macrophytes, coagulation and flocculation, gas loss, uptake of nutrients and metals by plants, disinfection by sunlight, decomposition and grazing of organic matter, complexing of metals in sediments, and biodegradation of organic toxicants. Issues covered include retention time, pond shape, trash racks, flow distribution, algae, macrophytes, shoreline trees, fish management, and mosquitoes and insect pests. Recommended design includes open areas of water for sedimentation, 10 to 30% of surface area for emergent macrophytes, baffled inflows, water level control, trash racks and bedload traps upstream, and use of side slopes and depth to limit macrophyte encroachment.

Strecker et al. (1990) review the ability of wetlands to control urban stormwater runoff pollution. Pollutant removal mechanisms in wetlands include sedimentation, adsorption, precipitation and dissolution, filtration, and biochemical interactions. Average removal efficiency over the eleven studies reviewed is suspended solids 87%, ammonia 17%, total phosphorus 54%, dissolved phosphorus 40%, total lead 85%, dissolved lead 63%, total zinc 56%, dissolved zinc 61%, total copper 40%, and dissolved copper 29%. Constructed wetlands tend to be more consistent than natural wetlands in their removal of pollutants.

7.3.2.3 *Treatment by Porous Pavements*

Niemczynowicz (1989) presents a general discussion of stormwater management by source control in Sweden, with particular emphasis on porous pavements. The quality of drainwater from porous pavements at four sites in Sweden is tabulated. High pressure sprays seem to be effective for restoring the infiltration capacity of clogged porous pavements.

Pratt (1989) provides an extensive review of porous pavements, and their use for stormwater quality management. Issues covered include types of porous pavement, quality of leachate, time trends in quality, mechanisms of pollutant removal, laboratory studies, blockage and remedial works, and attenuation of flow peaks and volumes. Pratt et al. (1989) and Pratt et al. (1990) measured water quantity and quality from a porous car park of concrete blocks and gravel in Nottingham. For monitoring purposes the construction was underlain by an impermeable membrane and drained, but even so, both peak and total flow were substantially reduced. The system greatly reduces suspended solids, and other pollutants which tend to be attached to solids. Effluent quality was affected by the type of stone used for the sub-base. Blockage of the permeable surface and remedial works to reinstate surface infiltration are discussed.

Hogland et al. (1990) describe laboratory and field studies of porous asphalt pavements in Lund, Sweden. Concentrations of most pollutants were significantly reduced during transport through the porous asphalt construction, and acid rain became almost neutral, but chloride and the various forms of nitrogen increased. Drainage water from the construction usually achieved drinking water quality for most parameters.

7.3.2.4 Other Specific Treatment Methods

MacNeill et al. (1988) investigated erosion and sedimentation control measures at urban development sites in Halifax, Nova Scotia. The effectiveness of surface stabilisation techniques depended on the proportion of exposed area stabilised. Sodding and paving worked best. Gravel tended to wash away, and seeding took time to take effect. Ditching of storm runoff was ineffective, because the ditches themselves were unstable. Straw and crushed aggregate filters, and sedimentation ponds were both found to be ineffective. Silt fences were partially effective, depending on installation standard and flow conditions.

Brouwer (1987) outlines the erosion and sediment control measures implemented in the Tuggeranong Valley, Canberra, to reduce the impact on the Murrumbidgee River of works associated with the new Tuggeranong Town Centre. Permanent control measures include Lake Tuggeranong, three water quality control ponds, and a number of gross pollutant traps as described by Phillips and Goyen (1987). Temporary control measures include perimeter banks, catch drains, level spreaders, sediment traps, and sediment retention ponds.

Hanrahan and Fagen (1987) describe an investigation of water pollution incidents at Lake Ginninderra in Canberra. The pollution incidents involved odours, garbage, and oil contamination in an ornamental pond at the inlet of a major stormwater drain. A sediment trap upstream was found to be full, and hence ineffective, but trash racks were apparently working well. Odours were attributed to general eutrophication of the ornamental pond. Much of the litter appears to originate from the shores of the lake. The oil source was located and installation of interceptor traps was recommended.

Molinari and Carleton (1987) review the design and operation of a number of installations to intercept litter in urban waterways. Locations include the River Tame in England, the Yarra River in Melbourne, urban streams in the Australian Capital Territory, and several locations in Sydney. All use either floating booms or fixed trash racks. Floating booms appear to be preferable, particularly in a retrofit situation, but trash racks may be suitable in a new development where they are incorporated at the design stage.

Silverman and Stenstrom (1988) explored a variety of techniques to remove oil and grease from urban stormwater runoff at or near the source. Several traditional control technologies are briefly described but are felt to have little potential for stormwater. They propose four alternative measures - porous pavements, greenbelts, adsorbents in storm drain inlets, and surface cleaning using wet scrubbing - directed at commercial land use and parking areas only. Greenbelts are vegetated areas on a constructed pervious soil profile - a porous lawn or garden, analogous to a porous pavement. Adsorbents could be hung in a mesh bag in the stormwater inlet, and removed annually for regeneration. Wet scrubbing would use a purpose built sweeper to remove concentrated deposits of oil and grease.

7.3.3 Management

Das (1987) lists a step by step approach to a water quality control strategy, while Hawley and McCuen (1987) discuss the regulatory elements that should be considered for inclusion in a comprehensive stormwater management program. Kaiser and Burby (1987) document the delay between available technology for stormwater management and its application in new urban development, and note the potential for state programs to influence the practical application of stormwater management. Korpics (1988) discusses the legislative aspects of the regulation of stormwater point source discharges in the United States, and reviews the history of the National Pollutant Discharge Elimination System (NPDES).

Woodward (1987) summarises the work described in more detail by Yassini and Clarke (1986) at Lake Illawarra near Wollongong, New South Wales. Sedimentation rates and nutrient concentrations in the lake have increased, and regular algal blooms have occurred. Increased urbanisation in the catchment is one of the major factors causing deterioration of lake water quality.

Gannon (1988) notes that faecal coliform concentrations at Gallup Park lake in Ann Arbor, Michigan, correlate well with precipitation. A sign warning of high coliform levels is displayed or covered based on recorded precipitation, rather than direct measurement of faecal coliforms. Murray (1988) looks at the impact of illegal connections to stormwater drains. Connections which should be to sewer are a significant source of stormwater pollution in Allen Creek, Michigan, particularly by petroleum products. Schmidt and Spencer (1986) describe the same study in more detail.

Awad (1990) studied the effect of stormwater in Lattakia, Syria, by transposition of data from Stuttgart and Munich in Germany. The objective is apparently to design the combined sewer overflow storage needed to control pollution of the Mediterranean Sea along the Syrian coast. The details of the scheme, and the justification for transposing the German data, are not entirely clear.

Clifforde et al. (1990) describe the UK River Basin Management Programme, and promote the concept of Environmental Quality Objectives and Standards, rather than emission standards. They note the distinction between continuous discharges, for which present emission standards may be adequate, and intermittent discharges such as those associated with stormwater runoff, for which duration, magnitude, and return period need to be considered.

Payne and Hedges (1990) developed of a set of simple guidelines for predicting the water quality effects of discharges from urban drainage systems. Biological monitoring using benthic macroinvertebrates was used to evaluate discharge impacts. Largest adverse impacts occurred for large catchments, highway catchments, catchments with industrial areas, and outfalls discharging to good quality streams. A decision tree based on these results is developed and presented.

7.3.4 Subject Overviews

Terstriep et al. (1986) summarises projects, data, and conclusions from the Nationwide Urban Runoff Program (NURP). Street sweeping had little effect of storm runoff quality, but does reduce gross pollutants. Wet fallout is a significant source of nutrients, and dry fallout is a significant source of copper, zinc, lead, and mercury. Detention basins and percolation pits can reduce pollutant loads, while grassed swales are good for removing COD, inorganic nitrogen, total residue, and metals. Wetlands can reduce concentration of metals and solids. Heaney (1986) presents the results of an analysis of research needs in urban stormwater pollution control, and summarises the findings of the NURP program. Tables of event mean concentrations by land use and pollutant, and detention basin performance by pollutant are included.

Jennings and Miller (1986) summarise urban stormwater quality investigations by the United States Geological Survey (USGS). Relevant areas include instrumentation, urban stormwater data bases, and the effect of detention on water quality. Marsalek (1986) reviews the 1985 NATO advanced research workshop on urban runoff quality at Montpellier, and provides a clear itemised summary of urban runoff quality issues.

Jones (1986) provides an extensive review of issues related to urban runoff impacts on receiving waters. Issues include the uses of receiving waters, forms of contaminants, mechanisms used by life forms to cope with pollution, and sampling and statistical methods. The paper concludes with a list of key questions for assessing the impacts of urban stormwater runoff on receiving water uses. Mancini and Plummer (1986) present a general discussion of water quality criteria, with respect to the intermittent and highly variable nature of urban runoff. They claim that quality criteria do not properly apply to intermittent pollution, and propose that less stringent criteria be developed, based on exposure times and intervals between exposures. Event mean concentration is defined and used as a key measure of pollutant at a site. Use of such a measure implies the importance of averaging pollutant levels when considering effects on receiving waters.

Gujer and Krejci (1987) summarise a range of urban storm drainage issues, based on experience in Switzerland, and champion the concept of ecological overview. They describe the historical background of wastewater treatment, and the gradual separation of wastewater treatment and urban drainage into separate disciplines. They claim that our understanding of ecological impacts has lagged behind the mechanistic aspects of the problem, and that ecological issues should receive more emphasis. They discuss the kind of ecological issues that need to be addressed, and the kind of information required to address them. There is a need to understand the entire sewerage and drainage system, before during and after a rainfall event. It may be better to cover more aspects of a system at less detail, rather than specific aspects at a level of accuracy which exceeds our ability to interpret them ecologically. Cost effective management of wet weather flows is likely to take the form of many small scale improvements at the source of the problem.

Roesner (1986) summarises three conference papers on pollution sources and potential impacts, and concludes that we still have much to learn about pollutant loads in urban runoff. He comments on the history of urban runoff quality research, and recommends among other things the development of a manual of design criteria for urban runoff quality control devices. Sonnen (1986) reviews three conference papers on data needs and collection technology for urban runoff quality and claims acerbically that not much has happened over the last eighteen years. He claims that 'the pollutional effect of urban runoff has not attained a societal level of importance sufficient to support understanding it, much less controlling it'.

Lawrence (1986) outlines the approach to describing and modelling urban runoff adopted in the Australian Capital Territory. Pollutant concentrations correlate poorly with flow, but correlations between pollutant load and storm volume are more satisfactory. Relationships between pollutant retention and hydraulic residence time are plotted for suspended solids and phosphorus, and for sedimentation and macrophyte systems. Planning and development policies for Canberra include no direct discharge of urban runoff to lakes and streams, the use of online water pollution control ponds, and a shift away from pipes and drains towards natural streams and retarding basins.

Smalls (1986) reviews the impacts of stormwater on the ecology and utility of receiving waters, with emphasis on the Australian situation. He tabulates the likely effects of a range of quality parameters on a number of in-stream and extractive water uses, and discusses the sources, fates, and consequences of nutrients in stormwater in the Sydney area. Apitz (1989) summarises drainage and water quality issues for Sydney, in the context of the Metropolitan Strategy for Sydney, released for public comment during 1988. The draft plan supports the control of urban and rural runoff. Methods include the retention of natural features of tributaries and floodplains, and the use of retarding basins to accommodate the first flush of stormwater runoff.

Carleton (1987) and Carleton (1990) examine the relative contributions of separate sewer overflows and stormwater to pollution of receiving waters in Sydney. Sewer overflows typically occur after five to ten millimetres of rainfall, giving 20 to 50 separate overflow events per year, each lasting about 12 hours on average. Dissolved oxygen deficits persist in receiving waters for up to ten days after an overflow event, so the water quality may be adversely affected for a large part of the year. Sewer overflows have higher concentrations of BOD, COD, and suspended solids than stormwater, but due to their smaller volume they generate a lower annual load - about one quarter of the total pollutant load. Possible control measures include detention storage, improved hydraulic performance of the overflow, pollution reducing structures, and computer control of the whole system.

Loh (1988) provides a comprehensive review of water quality monitoring and modelling in Australia up to 1987, and an extensive reference list. Most research has been on rural issues, particularly salinity, and this is reflected in the balance of the paper, but the research on urban water quality is also reported. O'Loughlin (1990) discusses the history and relative merits of separate and combined sewer systems. He notes that most separate systems are really only partly separate, due to illegal connections of stormwater to sewers, and overflows from sewers to watercourses. From about 1890, separate systems were favoured where population density was relatively low, and are almost universal in Australia. He concludes that separate systems are preferable, with conventional treatment of sewage, and stormwater treated using detention ponds, trash collectors, sediment traps, and vegetation filters. Where cities are locked into combined systems, a combination of storage and treatment appears to be the best short and medium term solution.

Ullah et al. (1988) summarise the elements of the Waterford River Basin urban hydrology study in Newfoundland. Study components included an urban runoff study, an urbanising watersheds study, and a general water quality study of surface water and groundwater. Urbanisation caused a pronounced increase in dissolved ions, nutrients, trace metals, and bacteria. Walesh (1989) reviews the subject of urban surface water management, in a comprehensive textbook format. Sections dealing with water quality include a review of the impact of urbanisation on the quality of runoff, and a review of non point source pollution load techniques. Stahre and Urbonas (1990) provide an extensive review of stormwater detention for management of both quantity and quality. The three chapters on quality management include a review of the National Urban Runoff Program (NURP) findings, discussion of suspended solids in stormwater, theoretical and observed aspects of sedimentation, and a chapter on the practical design of wet ponds and dry basins for water quality management.

7.3.5 Literature Reviews

Annual literature reviews of urban runoff and combined sewer overflows have been carried out by DeGuida and Clarkson (1986), DeGuida and Clarkson (1987), DeGuida (1988), DeGuida and Walker (1989), and DeGuida and Walker (1990).

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The most notable feature of this period has been a substantial shift away from basic data collection and analysis, towards the practical application of existing knowledge to improve the quality of urban storm runoff. This appears to be associated with the publication of the NURP conclusions in 1984, either as a direct result of publication or as a parallel development.

Quality improvement methods include planning and land use controls, construction stage controls, infiltration pits, porous pavements, grass swales, temporary on-site ponding, street sweeping, litter control, drainage controls, public education, sedimentation ponds, dry retarding basins, wet and dry stormwater ponds, wetlands, gross sediment pits, litter booms, trash racks, and control of miscellaneous urban pollutant sources.

Most attention has been directed towards storage and sedimentation processes. Pollutant removal in practice covers a wide range, but typically lies between 50% and 90% for a wide range of parameters including the nutrient phosphorus. The notable exception is ammonia, which is not reliably removed and may even increase.

The bioavailability of heavy metals and other pollutants has been investigated, and is found to have more effect on toxicity to aquatic life than total concentration as determined in the laboratory. Bioavailability is reduced by adsorption onto particles and complexation into unavailable forms. This again emphasises the need to consider urban runoff quality in the context of the total water cycle.

A steadily increasing body of evidence suggests that almost all urban water quality data can be adequately described by a log-normal distribution, both for data at a single site and between multiple sites.

Australian studies of urban water quality become increasingly frequent during this period, particularly in the areas of water treatment and system management. A substantial body of design and performance data is now available for local conditions. Much of the Australian work is centred around Sydney and Canberra.

8. 1991 TO 1994: AN AUSTRALIAN EMPHASIS

The growth in Australian urban water quality studies noted previously continues through this most recent period. Local work covers many aspects of the field, with a tendency to concentrate on practical applications and the whole catchment scale.

8.1 Data Collection and Analysis

8.1.1 General Water Quality Data

8.1.1.1 North America

Wright et al. (1991) characterised the pollutant loadings to the Providence River, Rhode Island, and tabulated wet weather pollutant loadings from a number of tributaries and point sources. Bannerman et al. (1993) collected water samples from streets, parking lots, roofs, driveways, and lawns, in residential, commercial, and industrial areas in Madison, Wisconsin, and identified critical source areas for each quality parameter in each land use area. Typically streets were critical in residential areas, streets and parking lots in commercial areas, and parking lots, streets, and sometimes lawns in industrial areas. Roofs were a critical source area for zinc in industrial and commercial areas.

Pirrone and Keeler (1993) measured the deposition of trace elements in urban Chicago and rural Kankakee, and found that deposition fluxes were typically two to four times higher at the urban site. Deposition fluxes and total load of each trace element after a seven day dry period are presented. Poissant et al. (1994) measured the spatial variability of urban rainwater quality on Montreal Island, Canada and found that rainfall quality was relatively uniform over the area of observation. The only exception was pH, which was higher in the city centre than in suburban areas.

D'Andrea and Maunder (1993) studied urban runoff quality in Toronto, and found that event mean concentrations were independent of runoff volume in most cases. With the exception of higher dieldrin concentrations and lower copper and zinc concentrations in residential areas, most quality parameters were not sensitive to land use. Therefore they suggest that transfer of data to ungauged catchments may be acceptable. Green (1993) describes the stormwater component of the Municipal Industrial Strategy for Abatement (MISA) program in Ontario, and includes stormwater concentration information for a wide range of quality parameters. Under the Strategy, key industrial premises are required to monitor effluent discharges, and in some cases stormwater runoff as well.

Whiteley et al (1993) sampled stormwater quality from two low density residential areas and one small commercial development in Guelph, Canada, and present results for suspended solids and faecal coliforms. Sampling sites in residential areas were at roof downpipes, street gutters, detention pond inlets, and detention pond outlets. Residential suspended solids concentrations were highest in the gutter, then the pond inlet, then the roof, and were lowest at the pond outlet, both in the first flush and averaged over the whole storm. Dissolved solids tended to increase downstream to a maximum at the pond outlet. Faecal coliforms increased downstream as far as the pond inlet, then decreased at the outlet. Both dry and wet detention ponds gave effective quality improvement, with the average removal being 90% for suspended solids, 70% for phosphorus, and 50% for BOD.

Dempsey et al. (1993) examined the partitioning of contaminants in urban dust and dirt between runoff water and particles of various sizes, and the effect of pH and contaminant/sorbent concentrations. Contaminants are primarily associated with particles, even after suspension in runoff water for several hours, but acidification or extensive dilution may cause desorption of contaminants from particles. Contaminants associated with small particles will be transported as if dissolved, but will react as if immobilised on particles. They conclude that to remove contaminants effectively, it is necessary to remove small particles from the runoff.

8.1.1.2 Europe

Forster (1993) studied roof runoff water quality in Bayreuth, and concluded that concentrations and loads of pollutants in roof runoff depend on the roof material and on the rainfall event. There was a tendency for washoff to increase with antecedent dry period. Prada-Sanchez et al. (1993) used principal components analysis to assess the quality of rainwater at three sites near a power station at As Pontes in Spain. They identified three main sources of pollution: a marine source characterised by chloride, sodium and magnesium, a rural source characterised by ammonium and nitrate, and an acid source related to the power station and characterised by sulphate, nitrate and hydrogen ions.

Xanthopoulos and Augustin (1992) measured particulate pollution in street runoff and sewers in Karlsruhe-Waldstadt, Germany. About 90% of the total solids entering the sewer system during rain came from street runoff, with the remainder coming from roof runoff. Many important pollutants were associated with sediments. Heavy metals and hydrocarbons show higher concentrations in the finer sediment fractions, which tend to remain in suspension while larger mineral particles settle out. Traffic density is the most important factor affecting the degree of contamination. Xanthopoulos and Hahn (1993) compared the results with those from a number of similar studies, and tabulated cross correlation coefficients between the water quality parameters. The correlations between heavy metals and fine sediment were particularly high. Lammersen (1993) assessed the effects of separate storm runoff, combined sewer overflows, and treatment plant effluents on the River Innerste at Hildesheim, Germany. Urban storm runoff has a major effect on river water quality. Ammonia is generated in anaerobic sediments by biological degradation of organic matter, and is released when the sediments are eroded by higher flows.

Morrison et al. (1993) assessed water and sediment deterioration in an urban river in Goteborg, during and after stormwater runoff and sewer overflow. Stormwater runoff typically caused dissolved oxygen sag, increased conductivity, and increased turbidity, the latter effects being attributed to salt and grit applied to roads. Copper and lead concentrations in sediments exceeded sediment quality criteria. Mouchel and Simon (1993) measured the impact of wet weather discharges on dissolved oxygen, ammonia nitrogen, and organic nitrogen in the River Seine. Combined sewer overflows cause a pronounced short term oxygen sag in the river. More prolonged oxygen sags are probably due to reduced photosynthesis during cloudy weather. Ammonia nitrogen appears to be produced within a reach by degradation of organic matter.

8.1.1.3 Australia

Duncan and Wight (1991) discuss the quantity and quality of rainwater tank water in Melbourne, summarise potential sources of pollution, and tabulate the results of five Australian studies of tank water quality. Dissolved solids and pH were slightly higher in summer than in winter, and temperature was substantially higher. Dissolved solids were higher in residential and industrial areas than in agricultural areas. Tank water usually met drinking water guidelines for all physical parameters except zinc, but often failed to meet microbiological guidelines.

Thomas and Greene (1993) analysed the quality of rainwater and runoff from different roof catchments in rural, urban, and industrial areas around Armidale, Australia. Measured concentrations are plotted for concrete tile and galvanised iron roofs in each land use area. Suspended solids, turbidity, conductivity and lead increased with antecedent dry period, while the other parameters did not. Cheung (1994) measured water quality at seven sites along Werriberri Creek in New South Wales. Most parameters show a substantial increase as the creek passes The Oaks, a township of 2000 people, but subside again with dilution and assimilation downstream. Concentrations are generally (and often significantly) higher in wet weather flows than in dry weather.

A comprehensive pollution measurement and abatement program in Sydney, New South Wales, generated a number of papers on both data collection and management issues. The socio-economic and political factors associated with the program are discussed by O'Loughlin (1994). Ngo et al. (1992) sampled water quality on two tributaries of the Georges River, to determine the relative contributions of stormwater runoff and sanitary sewer overflows. Pollutant contributions from sewer overflows at these sites were significant, typically as much as doubling total loads in the creeks during runoff events.

O'Brien et al. (1992) studied water quality in five coastal catchments in the Sydney region. The five catchments cover residential and industrial land use, and sewered and unsewered areas. Median daily loads and percent exceedences of guidelines are tabulated for selected parameters under dry weather conditions. Very high variability was observed both between days and within days, and no significant correlations were found between the quality of dry weather discharge and bathing water quality at nearby beaches. Preston et al. (1992) describe two short term sampling programs undertaken to assess spatial and temporal variability of river water quality, as part of a water quality monitoring program for the Lane Cove River. The spatial study used 36 sampling sites on tributaries and the main stream, while the temporal study used frequent sampling at two sites. Dry weather water quality varied significantly over the catchment, and distributions were found to be either normal or log-normal. Hourly and daily variations were not critical factors in determining water quality.

Sim et al. (1993) review the stormwater pollution investigations on Cup and Saucer Creek in Sydney. The catchment is mainly residential, and has separate storm drains and sanitary sewers, but is subject to sewer overflows in larger storm events. Litter caught in the trash rack comprised 60% vegetation (by volume), 15% plastics, 10% paper, 5% glass, 5% metals, and 5% rags. Sediment was analysed for nitrogen, phosphorus, and a range of metals.

Linforth et al. (1994) describe a comprehensive monitoring program of stormwater runoff and sewer overflows from urbanised catchments in the Upper Parramatta River catchment in Sydney. The contribution from each source to nutrient and bacterial contamination of waterways is calculated for one summer storm event, and the accuracy of the calculation is discussed. Urban runoff contributes 57% of total nitrogen load, 34% of total phosphorus load, and 5% of faecal coliform load. Vorreiter and Hickey (1994) investigate the incidence and significance of the initial flush effect on six catchments in Sydney. A first flush occurred for most insoluble determinands in stormwater drains. Up to 60% of the pollutant load of suspended solids, faecal coliforms, and total phosphorus was contained in less than 25% of the event volume. Capture and treatment of the first flush may be a feasible management option in these cases. The first flush effect was less prominent in natural channels and for soluble pollutants.

Allison et al. (1994) describe studies of gross pollutants in urban runoff in Sydney and Melbourne. The Sydney monitoring program has investigated discharges from ten urban catchments from 0.5 to 54 square kilometres, over the full range of flows. The Melbourne program is investigating discharges from a set of five nested sites, concentrating on storm event loads. Based on preliminary data, it appears that organic material (mainly leaf litter) makes up most of the gross pollutant load, and is washed off very early in the storm. Human-derived material is a minor component by mass, and is washed off later in the event.

8.1.1.4 Other Areas

Wright (1993) measured the quality of runoff from a new high density residential area in Cape Town, South Africa, including areas of squatter housing. Samples were taken during storm events and other specific weather conditions. Sandy soils cause low surface runoff but high interflow and baseflow, and as a result, the first flush is of little significance. Pollution levels were high, and were linked to population density rather than land use or infrastructure.

Chui (1993) investigated the time variation of runoff quality during single storm events, and factors affecting the pollution load and mean concentration of storm runoff, on a separately sewered urban catchment in Singapore. Most parameters showed a first flush, but peak colour and turbidity coincided with peak discharge. Event mean concentrations of TSS and COD increase with increasing antecedent dry period.

Yamada et al. (1993) investigated urban runoff quality in Kyoto, Japan. Analysis covered a range of quality parameters, grain sizes, land uses, and runoff stages. Total matter on the road surface is highest for industrial areas, and lowest for residential areas. Load per unit area on road surfaces correlated significantly with antecedent continuous days with less than 30 mm rain, but concentration in runoff correlated poorly with antecedent days. Load remaining after a storm was typically 2 to 3 days buildup for nutrients, and 10 days buildup for organic matter. Separate sewering decreases concentrations of organic matter and cadmium in storm runoff, but does not prevent an increase in lead concentration. Ebise (1993) measured storm runoff pollutant loadings and river sediments in the River Sanno at Ishioka City, Japan, and found that annual pollutant load increased with annual rainfall and annual runoff.

Zhen-Ren et al. (1993) used an artificial rainfall generator to assess runoff water quality from urban areas in Jiangmen, Shenzhen, and Zhuhai, in south China, and present curves of washoff versus accumulated runoff. Ammonia and nitrate levels in artificial runoff are similar to those in the tap water used in the rainfall generator. Commercial areas tend to generate the highest concentrations, followed by industrial areas, then residential areas. In these tests, about half the total solids were washed off by the first 10 mm of rain, and pollutant concentrations were lower in repeated storm events.

8.1.2 Nutrients

Sharpin (1992) investigated non point source nutrient behaviour from urban and rural catchments near Canberra. Event volumes and event mean concentrations are log-normally distributed. Seven distinct pollutograph types are distinguished, similar to those of Characklis et al. (1979a). Simple and multiple regressions in the linear and log domains are used to estimate pollutant load from a range of storm characteristics. Tan (1992) describes a small sampling study of nitrogen and phosphorus in urban stormwater in Perth, Western Australia. One runoff event was sampled in winter, spring, and autumn, at ten sites covering a range of soil types and groundwater depths, in sewered and unsewered areas. High nutrient export is associated with clay catchments, high groundwater, and presence of septic tanks. Steeper slopes and industrial land produced larger nutrient loads due to higher runoff. No correlation between nutrient load and prior road sweeping was found.

Ichiki et al. (1993) describe the changes in urban runoff which accompany sewer construction in the catchments of the Tenjin and Yamashina Rivers, Japan. River discharges and contaminant loads both reduced greatly after sewer construction in baseflow and small events, but not during large events. The first flush load has continued to increase as urbanisation continues, so storage or treatment of the first flush would improve runoff quality.

Jassby et al. (1994) studied atmospheric deposition of nitrogen and phosphorus at Lake Tahoe, on the California-Nevada border. Atmospheric deposition provides most of the dissolved inorganic nitrogen and total nitrogen input to the lake, and a significant amount of soluble reactive phosphorus and total phosphorus. Schultz (1994) describes monitoring of wet deposition for nitrate and pH at two urban locations in Cincinnati, and a non-urban site near Oxford, Ohio. Urban wet deposition nitrate differs from non-urban deposition when compared on a monthly and seasonal basis, but not on an annual basis. Nitrogen oxides are a significant contributor to acid rain.

8.1.3 *Microbiology*

Jacobs and Ellis (1991) investigated bacterial loadings and the associated public health risk in the Silk Stream catchment in London. Quality parameters were total coliforms, faecal coliforms, faecal streptococci, salmonella species, pseudomonas aeruginosa, staphylococci, and enterococci. EEC guidelines were frequently exceeded throughout the study area during storm events. A consistent first flush was not observed. A downstream storage basin greatly improved the microbiological quality. They propose that bacteria settle out during low flow periods, and are resuspended during storms.

8.1.4 *Heavy Metals*

Akhter and Madany (1993) measured concentrations of lead, zinc, cadmium, nickel, and chromium in street and house dust at a number of sites in Bahrain. All metals measured in street dust showed elevated concentrations, compared with remote control sites, but there were few significant differences between sites. Concentrations in house dust tended to be higher than controls but lower than in street dust, which suggests that vehicles on roads are a major source of these heavy metals. Chandra et al. (1993) measured trace metal concentrations in water and a range of aquatic plants at Koraput and Unnao, India. Variations in concentration are observed between species, locations, and seasons. Aquatic plants appear to have potential for both monitoring and amelioration of metals in runoff.

Estebe et al. (1993) assessed the effects of urban storm runoff on the heavy metal content of suspended solids in the River Seine. Floating suspended solids traps were used to collect samples upstream of Paris, downstream of Paris but upstream of two major CSO's, and downstream of the CSO's. There was little variation in iron and manganese levels with either location or time, but cadmium, copper, lead, and zinc concentrations increased substantially through the urban area, and increased further downstream of the CSO's. Flores-Rodriguez et al. (1993) studied the mobility of lead, zinc, and cadmium in separate storm drains and combined sewers in Paris and Bordeaux. Five fractions were identified - ion-exchangeable, acid-soluble, oxidisable, reducible, and residual. Mobility of lead is lower than that of cadmium, and is lower in downstream sites. Lebreton et al. (1993) evaluated the secondary impact of cadmium, zinc, copper, and lead, by studying their release under laboratory conditions. Samples of suspended solids were obtained from gully pots and settling basins in Paris. More dissolved metals are released under anaerobic conditions than under aerobic conditions.

Quek and Forster (1993) measured the concentration of heavy metals and other parameters in runoff from a range of roof types in Bayreuth, Germany. Metal concentrations varied greatly depending on roof type, with the flat gravel roof and the sloping asbestos cement roof having the lowest concentrations. Lead comes mainly from dry deposition. Zinc, copper, and cadmium come mainly from rainfall and the roofing material. Zinc and copper levels can be high, and zinc in particular can exceed guideline levels for wastewater. But in most cases the average concentrations of heavy metals in roof runoff were lower than those in rainfall.

Good (1993) measured metal concentrations in roof runoff from a range of roof materials at a sawmill in Washington state, and tested the toxicity of runoff to rainbow trout. USEPA water quality criteria for marine waters were exceeded for copper, lead, and particularly zinc. Survival of rainbow trout in undiluted roof water was zero for most roof types. Concentrations decreased with time after the first flush. Ball et al. (1994) describe the establishment of a field gauging station to measure stormwater runoff and the load of heavy metals from a road surface in Sydney, and present preliminary data for lead, copper, zinc, iron, manganese, and cadmium concentrations. Their results are broadly similar to USA data.

Morrison and Wei (1993) measured the concentration of platinum in sediments from roads, gully pots, and streams in Goteborg, Sweden, and found that concentrations increased markedly between 1984 and 1991. The main source of platinum is from catalytic converters on car exhausts. Like other road sediments, platinum accumulates mainly near the kerb. Although concentrations are low, platinum salts are more toxic than copper, for example, and further increases could potentially pose a threat to receiving water quality.

Steinnes et al. (1994) used the concentration of trace elements in moss samples as a measure of atmospheric deposition at 500 sites in Norway. The deposition patterns of vanadium, zinc, arsenic, selenium, cadmium, antimony, and lead are substantially influenced by long range transport from other parts of Europe, but a general decline is evident from 1977 to 1985, most strongly for lead. For chromium, iron, cobalt, nickel, and copper, the deposition patterns are largely determined by contributions from more localised point sources. Data for bromine and iodine reflect airborne supply from the sea, while aluminium and scandium indicate contributions from soil dust.

8.1.5 Hydrocarbons

Jones et al. (1993) investigated the extent and ecological impacts of hydrocarbon contamination in the waters and sediments of the Silk Stream in London. Total alkane and polyaromatic hydrocarbon concentrations in the water and the sediment were higher at the downstream urbanised sites than at a background site. An oil boom decreases concentrations by up to 25% in the water downstream, but not in the sediment. A lake reduces concentrations in both water and sediment downstream by 50 to 80%. Hydrocarbons in sediment tend to have higher molecular weights than those in water. Composition suggests that combustion products are the main source of hydrocarbons. Mortality of asellus aquaticus increases with distance downstream, but drops again downstream of the lake.

Herrmann et al. (1993) used sections of road and experimental roofs at Bayreuth, Germany, to investigate the behaviour of polycyclic aromatic hydrocarbons and other trace organics during runoff. Sorption processes, transport, and photochemical reactions are discussed, and sample data is presented.

Maldonato and Uchrin (1994) examined petroleum hydrocarbons in the sediments of a dry stormwater detention basin in New Jersey. Catchment land use is a high density, moderate income residential community. The basin removes about 99% of petroleum hydrocarbons from runoff, which become concentrated in the sediments. Concentrations are highest near the basin inlets and near the sediment surface. At 150 mm depth, concentration of hydrocarbons has reduced to background levels.

8.1.6 Snow and Ice

Daub et al. (1994) studied the concentration and behaviour of organic pollutants and heavy metals in snowmelt from a street surface and four roof surfaces in Bayreuth, Germany. Freeze and thaw cycles concentrate both dissolved and particulate contaminants in the liquid phase and the surface of ice crystals, leading to a strong initial flush on melting. Suspended solids concentrations in meltwater are two to five times higher than in rain runoff, and concentrations of dissolved PAH's are also high. Conductivity decreases smoothly with time, and depends on the roughness and type of roofing material. Akan (1994) has developed a physically based mathematical model to simulate the enrichment process.

8.1.7 *Buildup and Washoff*

Butler et al. (1992) describe a study of dust and dirt buildup on street surfaces at six sites in London. Sediment is collected from 25 square metres of surface every six weeks, using a process of manual brushing and dry vacuuming. A hazardous dust cleaner was used, because of its efficiency in retaining the finest dust particles. Results show a large variation between sites, and a steady reduction with time over repeated measurements. Non particulate material, volatile material, and sediment grading curves are presented for each site.

Spangberg and Niemczynowicz (1992) and Spangberg and Niemczynowicz (1993) measured rainfall, runoff, turbidity, pH, conductivity, and temperature of flow from an asphalt car park in Lund, Sweden, at ten second intervals during rainfall. Wet and dry atmospheric fallout was measured weekly two metres above the ground, and dry accumulation on the surface was measured twice weekly by vacuum cleaning marked squares. Correlation coefficients between rainfall intensity and the other variables are plotted versus lag time for a sample storm. The best correlation of turbidity with rainfall intensity occurred at a lag of about 30 seconds, and that of flow with rainfall intensity at about 90 to 120 seconds, indicating the presence of a strong first flush. Since peak turbidity consistently precedes peak flow, it seems unlikely that turbidity is caused directly by flow. It could, however, be caused by rainfall. Dust collected from the surface is very much greater than atmospheric dust at two metres height, and there is little correlation between them.

8.2 Process Analysis and Modelling

8.2.1 *Process Analysis*

Hatfield (1993) presents a model for estimating stormwater quality affected by rate limited pollution transfer from contaminated impermeable surfaces, based on diffusive and first order mass transfer relations. Parameter sensitivity is investigated, but the model is not demonstrated on real data. Several simplifying assumptions are made, including that rainfall intensity is constant during an event.

8.2.2 *Modelling*

8.2.2.1 *Deterministic Models*

Sear and Bays (1991) document an environmental assessment of Lake Maggiore, a hypereutrophic urban lake in St. Petersburg, Florida. The SWMM model was fitted to the catchment under current conditions, and used to assess alternative management options. They conclude that phosphorus is the limiting nutrient at this site, and propose solutions based on construction of wet detention ponds. Reckhow and Qian (1994) modelled phosphorus removal in wetlands, using data from a large cross sectional study and from a single wetland in the Florida Everglades over time. The form of the adopted model suggests that outlet phosphorus concentration is constant as long as input phosphorus loading is below a long term accumulation rate associated with peat and sediment buildup rates. Higher loadings will lead to an increase in outlet concentration.

Meyer et al. (1993) discuss the use of Graphic Information Systems in urban stormwater management, and demonstrate their use on a study area in in Fort Collins, Colorado. The model used is similar to the RUNOFF block in SWMM. Haster and James (1994) describe a model of sediment washoff from small urban catchments during storm events, using data from Houston and Austin, Texas. Washoff from commercial, multi-family residential, single family residential, and bare soil areas is modelled separately. Sediment load on impervious areas increases with antecedent dry period, but the shape of the curve cannot be determined with any accuracy. The exponential washoff coefficient increases linearly with antecedent dry period.

Rowney and Wisner (1993) summarise the history and features of QUALHYMO, a Canadian continuous runoff quantity and quality model which can simulate a variety of best management practices. Buildup uses a power function or exponential relationship. Washoff is a function of flow only, or of flow and pollutant remaining on the catchment.

Bertrand-Krajewski (1992) outlines an initial version of the HYPOCRAS model for solids production and transfer in small urban catchments with combined sewer systems. Bertrand-Krajewski et al. (1993) describe the model in more detail. It uses exponential buildup, and washoff proportional to the available mass of solids and the net rainfall intensity. It distinguishes between small particles which are transported as suspended load, and larger particles which may form either bed load or suspended load. Simulation of suspended solids on catchments at Mantes-la-Ville and Entzheim in France is very good for the examples shown.

Bujon et al. (1992) describe the FLUPOL model, an urban runoff quality model developed to supplement water quality measurements in Paris. FLUPOL calculates the flow rates and discharges of suspended solids, BOD, COD, and Kjeldahl nitrogen downstream from an urban catchment, using limited data. Buildup is modelled as the sum of linear deposition and removal proportional to the mass present. Washoff rate depends on the mass present and the rainfall intensity. Pollutants are routed through the drainage network at the same speed as the flow. Goodness of fit is very good in the examples shown, for both calibration and verification data.

Perrens et al. (1991a) describe a study of water quality in the Nepean-Hawkesbury River near Sydney. An integrated modelling system is being developed, using the Wallingford TIDEWAY system for river hydraulics and quality, and the HSPF model for catchment hydrology and quality. The structure, data needs, and calibration procedures of the two models are described. White and Cattell (1992) describe AUSQUAL, an Australian water quality management model developed to obtain useful results from limited data. The model can be run at different levels of complexity, and hence data needs. It is demonstrated using data from urban catchments in Sydney. Goodness of fit appears to be satisfactory for flow, but is not shown for quality parameters.

Phillips et al. (1992) and Phillips et al. (1993) summarise the XP-AQUALM water quality package, which incorporates a number of water quality models with limited data requirements. Features of XP-AQUALM include a rainfall-runoff model based on Boughton's Model, a non-point source export model which uses a power function of daily runoff, models of sediment traps, gross pollutant traps, water pollution control ponds and wetlands, a lake loading model, a river quality and loading model, and a graphical user interface which links the separate models into the total package. The model is illustrated using data from Canberra.

Srinanthakumar and Codner (1992a) illustrate a method for evaluating urban runoff quality data prior to modelling, using data from the Giralang urban catchment in Canberra, Australia. The method uses scatter plots to check for obvious outliers, hydrographs, pollutographs, and loadographs to check for consistent trends in behaviour, and plots of cumulative washoff versus cumulative runoff to provide information on processes. Srinanthakumar and Codner (1992b) use the edited data to develop a modification to the SWMM washoff algorithm which improves washoff prediction. The modified washoff method accounts for the effect of cumulative runoff volume on washoff decay coefficient. Low runoff events and high runoff events need to be calibrated separately, and high runoff events require a larger initial catchment load. Pervious areas may be contributing to high runoff events, or the assumption that the previous storm removes all pollutants may not be correct.

Srinanthakumar and Codner (1993a) tested the washoff model of Nakamura (1984) using nitrogen and phosphorus data from the Giralang catchment. The model assumes that the pollutant washoff rate is proportional to the overland flow shear stress and the amount of pollutant available for washoff, and has only one calibration parameter. The model gives better results than the washoff routine in SWMM for both calibration and verification, and there is no need to calibrate low and high runoff events separately. Srinanthakumar and Codner (1993b) demonstrate a methodology for selecting calibration events for urban runoff quality modelling, so that the selected events reflect the average conditions of the catchment and the storm events under consideration. A representative selection is made with the aid of plots of cumulative washoff versus cumulative runoff.

Kuo et al. (1993) describe an urban non-point source pollution model written for personal computers. The model was calibrated and verified using data from Shan-Hsia, near Taipei in northern Taiwan. It uses Michaelis-Menton buildup and exponential washoff from surfaces and channels. The washoff rate coefficient is a function of rainfall rate for surfaces, and a function of scouring velocity for channels. Goodness of fit is good for calibration events and moderate for verification events.

Hasegawa et al. (1993) present a simulation of urban runoff pollutographs using the so-called water quality tank model. The model achieves a moderate fit, using data from the Yodo River, Japan. Noguchi et al. (1993) describe the extension of the runoff volume model NUMEROUS (Nagasaki University Model for Estimating the Rates Of Urban Stormwater) to estimate pollutant runoff. The model appears to be designed for combined sewer overflows rather than urban runoff. It is demonstrated using data from the Honmyo River at Isahaya, Japan.

Stephenson and Wimberley (1993) modelled stormwater quality in runoff from a high density informal urban area near Alexandra, South Africa. Interception, infiltration, percolation, evaporation, transpiration, groundwater, and stormwater flow were linked in a spreadsheet format, and a water balance calculated. Nutrient pollution in the stormwater runoff is comparable to that of raw sewage, and is predominantly of human origin. A first flush was observed in many storm events.

8.2.2.2 Statistical Models

Chow and Marsalek (1993) describe the development of Model P, a planning level model for estimating urban pollutant loadings. Model P includes a data base of mean, upper and lower EMC values, and coefficient of variation for more than 60 pollutants, which are accessed by the user in a menu format. The model is applied to the urban areas of Fort Erie, Niagara Falls, and Welland, Canada. Xu et al. (1993) describe the PMSQ water quality model, developed to estimate long term and large scale pollutant loads using data which is below the detection limit in a proportion of samples (censored data). Three possible methods of handling the censored data are discussed - extrapolation of a regression equation, replacing censored data with half the detection limit, and the maximum likelihood estimation method.

Li and Adams (1993) present a statistical approach to the modelling of urban runoff quality control. The approach is coded into a program called Extended Statistical Urban Drainage Simulator (Extended SUDS). Prediction of long term pollution control performance of storage-treatment systems is claimed to compare favourably with the STORM simulation model.

Horn and Grayman (1993) outline the Reach File, a spatially referenced geographic data base of surface water features of the United States, with graphical and tabulation routines. The system includes information on flows and industrial discharges, and can be used for modelling and routing of water quality parameters.

Hiratsuka et al. (1993) describe an autoregressive model using rainfall and runoff to predict stormwater runoff up to one hour ahead, and apply it to data from the Nabetagawa River, Japan. There appears to be a moderate correlation of total nitrogen and total phosphorus with runoff, and hence some potential to predict water quality for a short time into the future.

8.2.2.3 Comparison and Discussion

Codner (1991) reviewed two catchment water quality models - The Storm Water Management Model (SWMM) and the Hydrocomp Simulation Program Fortran (HSPF). SWMM was chosen because of its widespread publicity, and HSPF because of its extensive technical capabilities. Both models are described, and reviewed in terms of model structure, modelling capability, user friendliness, computing facility requirements, and local and overseas applications. HSPF is probably the most physically based and best tested catchment quality model. Many options are available, but because of this it is complex and difficult to use. SWMM is claimed to be reasonably user friendly, although the quality calibration is difficult.

Coleman (1993) compared the performance of two deterministic suspended solids washoff models using data from the Pinetown and Alexandra catchments, South Africa. One model is based on the buildup and washoff algorithms in SWMM3, while the other is based on sediment transport theory. The second model assumes buildup is not limiting, and assumes particle detachment is proportional to the square of the rainfall intensity. The sediment transport model performed about as well as the empirical SWMM model.

8.3 System Management and Overviews

8.3.1 Monitoring

Winton and Linforth (1992) summarise the sampling strategy developed to obtain water quality data for the Sydney Water Board's Clean Waterways Program. Studies within the overall strategy include intensive pilot studies of spatial and temporal variations, short term event studies of diurnal and tidal effects and short term rainfall events, long term monitoring based on the results of the pilot studies, and studies of algae, estuarine sediments, and bioindicators of nutrient loads.

Vindimian and Garric (1993) describe two types of ecological effect caused by stormwater drainage into receiving waters - short term reversible effects and chronic effects - and outline three tests which can be used to estimate their impacts. The tests are based on toxicity to trout, toxicity to *Daphnia magna,* and induction of the enzyme ethoxyresorufin-O-deethylase (EROD).

Argue et al. (1994) present details of a nested catchment urban drainage monitoring network recently established at Noarlunga in the southwestern suburbs of Adelaide. Flow proportional sampling will generally be employed for water quality purposes. Kachka et al. (1994) discuss water quality sampling methodology and frequency, using data from Sheas Creek and Orphan School Creek in Sydney. To minimise storage effects, automatic samplers were refrigerated and the period between sample collection and delivery to the laboratory was limited to eighteen hours. The effect of sampling frequency is assessed by simulated compositing of frequent samples into less frequent samples, and by simulated discarding of a proportion of the samples. Discarding samples introduced larger errors than compositing samples.

8.3.2 Treatment

8.3.2.1 General Treatment Methods

Perrens et al. (1991b) describe pollution by floating litter, bacteria, and heavy metals at Bondi Beach, Sydney, caused by a nearby sewage outfall and compounded by polluted stormwater flows. A range of possible source control measures and stormwater treatment options are discussed, and an overall pollution control strategy is developed.

Lawrence and Phillips (1993) review best management practices for urban stormwater pollution control in Australia. They note the unacceptable impacts of urban stormwater pollution on receiving waters, and list the range of best management practices most commonly used in Australian urban areas. BMP's are divided into three main categories: at source controls, controls integrated into drainage systems, and management of receiving waters. The prevalence of pollution control measures in an area depends on population and the nature and sustainability of receiving waters. Since BMP's have cost and equity implications, they foresee that control strategies will increasingly be developed by means of community participation.

Urbonas (1991) summarises the most effective stormwater quality management practices. Controls that reduce runoff peak and volume are best, followed by those that mainly reduce runoff peak. To minimise erosion, small storm peaks after urbanisation should not exceed the two-year peak before urbanisation. Most obnoxious pollutants in urban runoff are settleable. The best management practices generally involve some form of infiltration - swales, filter strips, porous pavements, infiltration basins and trenches, and absence of directly connected impervious areas. Storage practices tend to be less effective, but remain a useful practical alternative.

Urbonas (1993) provides an assessment of current BMP use and technology. Non structural BMP's include public education and citizen involvement programs, street sweeping, leaf pickup, and deicing programs, local government rules and regulations, and elimination of illicit discharges. Structural BMP's include minimising directly connected impervious areas, grass swales, grass buffer strips, porous pavements, percolation trenches, infiltration basins, sand filter basins and filter inlets, water quality inlets, extended detention basins, retention ponds, and wetland basins. Pollutant removal ranges for some of the structural BMP's are tabulated.

Driscoll and Strecker (1993) review the best management practices being used for urban runoff control in the United States and Canada. BMP's covered include source controls, detention basins, infiltration, filters, catch basin separators, and wetlands. The severe lack of hard data on the performance of specific designs is noted. Pitt et al. (1993) summarise some results of the USEPA's Storm and Combined Sewer Research Program. Most beneficial treatments include settling for at least 24 hours (40 to 90% reduction), screening through 0.040 mm screens (20 to 70% reduction), and aeration and/or photo degradation for at least 24 hours (up to 80% reduction).

Scholze et al. (1993) discuss methods of controlling priority pollutants in urban runoff. Priority pollutants defined by the USEPA are 14 inorganic chemicals - antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, zinc, and cyanide - and 115 organic compounds. The major processes for removal of pollutants are adsorption, precipitation and complexation, volatilisation, biodegradation, and photolysis. Best management practices are based on infiltration, sedimentation, wetlands, and other processes. Adsorbed pollutants are mostly biologically unavailable, so their removal may not have much effect on toxicity. The effectiveness of a number of BMP's is discussed.

Stahre (1993) reviews the best management practices being used for urban drainage in Scandinavia. Non-structural BMP's include organised collection of household chemicals, proper disposal of pet droppings, controlled transport of chemicals and hazardous waste, use of swales in street drainage, and active contact with industrial dischargers. Structural BMP's include local disposal by infiltration or percolation, and onsite detention or retention in a park environment. Three variations of structural BMP's from Sweden are illustrated and discussed.

8.3.2.2 Treatment by Storage

Akan (1992) presents a series of design charts to aid design of detention basins for the removal of pollutants from storm runoff. The method is based on reservoir routing techniques, and uses a single design event approach. Basins will detain runoff for a specified period to achieve a desired level of treatment, then empty within a specified period. Ellis (1993) reviews wetland best management practice design for urban runoff pollution control in Europe and Australia, and summarises pollutant removal mechanisms, design criteria, and typical designs. Loganathan et al. (1994) present a statistical formulation for estimating the average detention time within a pond for a captured runoff volume. Computer experiments with the SWMM model support the use of detention time for assessing the pollutant settling efficiency within the pond. The methodology provides estimates of pond volume and withdrawal rate for a required efficiency.

Tilley et al. (1994) discuss the operation of the Sydenham Stormwater Storage Pit in Sydney, with a view to optimising both flood mitigation and stormwater pollution control. Although built for flood control, the pit also acts as a pollution control structure, capturing both sediment and litter. Keeping the basin empty gives best flood control, but keeping it full gives best quality control. Increased storage capacity is limited by surrounding development and embankment stability. The recommended scheme comprises a sedimentation pond in the floor of the pit, litter traps on drainage outlets into the pit, and separate works on an adjacent channel.

8.3.2.3 Other Specific Treatment Methods

Senior (1992) outlines a study of litter in Merri Creek, Melbourne. Litter traps were installed on three sub-catchments and on the main stream, and the litter collected was analysed. First level breakdown of litter items was: plastics 66%, paper 21%, cans 1%, glass 1%, and miscellaneous items 11%. The effectiveness of the various litter traps used is tabulated. Recommendations for litter management include further use of litter traps, volunteer clean-up days, a public education campaign, an evaluation of street sweeping and flushing operations, and a study of litter movement using tagged litter items.

Sim and Webster (1992) describe the performance of a prototype trash rack constructed in Cup and Saucer Creek in Sydney. Most litter is transported during the first few minutes of a storm event. Components of trapped litter are: organic matter and vegetation 60%, plastics 15%, paper 10%, glass 5%, metals 5%, and rags 5%. The trap also collected a substantial volume of sediment, mainly sand and gravel.

Fujita (1994) summarises a range of stormwater infiltration structures in Tokyo, for runoff volume control, groundwater recharge, and receiving water quality management. Porous asphalt paving is claimed to be used for all footpaths in Tokyo, and other areas with limited traffic, to help provide water to street trees. A cleaning machine using high pressure water sprays is used to remove dust and dirt and prevent clogging. Pavements of porous concrete blocks are also used. An Experimental Sewer System (ESS) is described, in which the stormwater component is intercepted by a range of infiltration techniques before it reaches the combined sewer.

Guibelin et al. (1994) describe the Actiflo® process, a compact, high rate water treatment process which is claimed to be suitable for stormwater treatment.

8.3.3 Management

Hahn (1993) subdivides urban runoff into three categories, and looks at the management options most appropriate for each. The categories are roof runoff (less polluted), paved area runoff (polluted), and combined sewer flows (highly polluted). Less polluted runoff should be returned to the natural water cycle as quickly as possible. Polluted runoff should be treated to remove suspended solids and associated pollutants, and highly polluted runoff should also receive a biological treatment step to remove organic material.

National Capital Planning Authority (1993) discusses urban stormwater in the context of total urban water management and water sensitive urban design. A large number of techniques are described to manage the volume and quality of urban runoff at scales ranging from single house lot to neighbourhoods and regions. Relevant techniques include infiltration trenches and wells, aquifer recharge, stormwater reuse, swales, porous pavements, reduced road area, zoned garden watering, turf management, infiltration and retention basins, gross pollutant traps, water pollution control ponds, wetlands, and urban lakes.

Robinson and Waldman (1993) review the nature of stormwater management from an Australian perspective, and claim that it needs to be treated like a business with identifiable customers. They propose a strategy based on market research, community consultation, appropriate pricing structures, information and education, monitoring and feedback, and supportive regulatory framework. Sharpin (1993) discusses hydrological variability, urbanisation, and water quality in Australia, using streamflow and water quality data from Canberra for illustration. Streamflow variability is very high, but is reduced by urbanisation. Australian event mean concentrations are similar to NURP data, and tend to be log-normally distributed. High variability leads to difficulties in formulating water quality criteria, and in designing management measures.

Hicks et al. (1993) discuss methods for estimating and describing wet and dry deposition under various scenarios. They propose that the sum of wet and dry deposition is the most relevant, and that it will vary greatly with location, season, and characteristics of individual subregions. Wet deposition depends on atmospheric contaminants at several kilometres altitude, while dry deposition depends on contaminants near the surface.

Lee and Jones-Lee (1993) claim that stormwater quality criteria for many contaminants may be too stringent since exposure is episodic, substantial proportions of many contaminants are associated with particulates and so are largely unavailable to aquatic organisms, and evidence of beneficial use impairment has not been forthcoming. At the same time, they claim that nutrients and microorganisms cause real problems, but are not being reliably addressed. They propose that quality management should concentrate more on observable receiving water effects, and less on numeric exceedences of water quality criteria.

Westerling (1993) discusses the hazardous waste aspects of stormwater management. Stormwater runoff is a possible pathway for hazardous waste to achieve human exposure. Hazardous wastes may include trace metals (toxic hazard) and petroleum products (explosion hazard). Urbonas (1995) discusses the need for reporting a variety of physical, climatic, geological, biological, and meteorological parameters along with data on the performance of structural best management practices. He proposes that a standard list of parameters be developed, to facilitate comparison between studies, and presents a first attempt at such a standardised list.

Zahorcak and Detweiler (1991) used a range of models to evaluate the impact of stormwater and combined sewer overflows on the Columbia Slough, an urban drainageway in Portland, Oregon. Possible abatement measures include reduction of combined sewer overflows, and dry season flow augmentation using water from the Columbia River. Cohn-Lee and Cameron (1992) describe an inventory and assessment of urban storm runoff quality and management facilities in the Chesapeake Bay catchment. Contamination of the Bay from runoff is equal to or greater than that from point sources, and stormwater controls are being outstripped by the effects of development. Downstream treatment by detention or infiltration may not be adequate to meet proposed guidelines unless source controls are also implemented.

Hart and Waller (1993) investigated sources of faecal coliforms into First Lake in Nova Scotia. Most high faecal coliform concentrations in the lake were associated with storm events. Sources considered were catchbasins, birds, swimmers, resuspension of bottom sediments, and stormwater runoff. Stormwater runoff is the main source of faecal coliforms, and dog droppings are the most likely means of stormwater contamination. Hipp et al. (1993) measured the runoff and output of nutrients from four levels of landscape management. Resource efficient plants grown without irrigation or fertiliser produced the least runoff, and the lowest export of nitrate. Phosphorus loss was significabtly higher from the landscapes receiving phosphorus, although only a small fraction of the applied load was exported.

Pratt (1993) reviews drainage practice in the UK, and claims that development of best management practices in the UK lags behind other parts of the world. The reasons relate partly to the historical development of the drainage and sewerage systems, but mainly to the structure of the water industry. He queries the fast runoff philosophy, and notes the drying out of natural watercourses and the potential for greater groundwater recharge.

Saget et al. (1992) used data from four catchments in France to estimate the volume of urban stormwater which must be captured and treated to achieve a given level of pollutant retention. On these catchments, a first flush of suspended solids occurs sometimes but by no means always, so capturing a small initial volume will not be adequate. They conclude that storage of about 100 KL per impervious hectare is needed to intercept 80% of the contaminants.

McKay and Marshall (1993) describe a study of tagged litter released into drainage pits in Melbourne and Geelong, to help establish the sources and destinations of urban litter. They estimate that four to five million items of floatable litter enter the urban waterways via the underground drainage system each year. Natural, highly vegetated waterways trap and retain most of their litter. Constructed drains and watercourses transport litter very efficiently into receiving waters. Litter booms can be quite effective, typically removing 20 to 50% of floating litter. They recommend a management strategy based on the reduction of litter entering drains during street cleaning and rubbish collection, reduction of litter entering watercourses from drains, and removal of litter from waterways using litter traps or booms.

Turner and Ruffio (1993) describe the use of geographic information systems (GIS) to characterise nonpoint source pollution in rural areas, and present a case study using data from part of the Lachlan River catchment. O'Loughlin (1994) describes the socio-economic and political factors associated with the pollution abatement program in Sydney. He provides a brief history of the sewerage and stormwater systems in Sydney, and discusses in more detail the political, administrative, and public attitude issues of the last few years.

Argue (1994) describes an alternative street drainage philosophy developed in Adelaide, South Australia, which offers reduced peak outflows and greatly improved effluent quality from minor suburban streets. The essential features of the scheme are a grassed swale and a gravel filled trench running along one side of the street, which receives all runoff from high side properties and the road, and roof runoff from low side properties. Bores set at regular intervals along the trench convey part of the stormwater into underlying sand aquifers. Calculations indicate satisfactory behaviour for runoff events up to 100 years return period.

8.3.4 *Subject Overviews*

Huber (1992) discusses a wide range of methods for prediction of urban non point water quality. Matching the level of detail to the ultimate objective (which is often related to receiving water quality) is emphasised, and a table of appropriate detail is provided. Modelling options covered include the assumption of constant concentration and unit loads, the USEPA's statistical method, regression and rating curve approaches, spreadsheet implementation methods, and models based on buildup and washoff of dust and dirt. Data needs and potential sources for each method are tabulated. Four of the more detailed urban runoff quality models (USGS, HSPF, STORM, and SWMM) and two models developed for PC use (MOUSE and the Wallingford suite) are discussed and compared, and a number of modelling case studies are briefly described.

Marsalek (1992) presents a detailed review of sediment issues in urban drainage. The three main topics are sediment impacts, sources, and controls. Physical impacts centre around pipe and inlet blockage, and excessive sludge production in combined systems. Water quality impacts are mainly related to transport of pollutants associated with the sediment, and with the effects of erosion. Sources of urban sediment are soil erosion, attrition of pavement surfaces, vehicular traffic, atmospheric deposition, vegetation, litter, spills, street sanding, and municipal sewage in combined systems. Sediment control can take the form of source controls or later removal. Source controls include limiting of surface exposure, surface stabilisation by seeding, mulching, sodding, rip-rap, etc., and runoff control by grading and shaping, benches, berms, diversion ditches, and energy dissipators. Sediment removal methods include street cleaning, sewer cleaning, and treatment of stormwater and combined sewer overflows by storage, sedimentation, and other processes. An extensive reference list is included.

Field et al. (1993) discuss the microbiological characteristics of stormwater, and claim that current bacterial indicators are a poor measure of the water's illness producing capacity. On the one hand many indicators are not specific to human faecal contamination, and on the other hand they do not assess the risk from non-enteric pathogens. Studies of illness caused by contaminated bathing water are discussed, and the origins of guideline levels are described. The intermittent and highly variable nature of stormwater runoff present problems for disinfection.

House et al. (1993) present a comprehensive review of the impact of urban runoff on receiving water quality. Average urban runoff quality is tabulated for a number of parameters, and the impacts on receiving waters are discussed in detail. Water quality criteria and standards are discussed, and the value of biological monitoring is emphasised. The significance of magnitude-frequency-duration curves for intermittent discharges is noted. Modelling of stormwater impacts on receiving waters may be deterministic or stochastic, and event-based or continuous.

Lijklema et al. (1993) provide a summary of the Interurba '92 Workshop conclusions. The Interurba Workshop looked at the interactions between urban drainage systems and sewage treatment plants, and the influence of contaminants from different sources on receiving waters. They summarise and tabulate the impacts of key contaminants on receiving waters, and the resulting monitoring needs. Modelling of sewers and sewage treatment plants, and integration of urban drainage planning, design, and management are discussed, and an 8-stage integrated planning process for urban drainage improvements is proposed. More detailed reviews of the Interurba '92 Workshop are provided by House et al. (1993), Marsalek et al. (1993), and Tyson et al. (1993), all of which include extensive reference lists.

Marsalek et al. (1993) address the design and operation of urban drainage systems as part of the larger system comprising drainage, sewage, and receiving waters. The basic elements and interactions between the drainage, sewage, and receiving water components are succinctly described. Past and present design practices are discussed, covering both quantity and quality issues, and the significance of receiving water effects is noted. A large number of control measures are briefly discussed. Real time operation of sewer systems is discussed, and modelling tools and procedures are described. Models discussed and tabulated include HSPF, ILLUDAS, and AUTO QI, STORM, SWMM, MOUSE, and the Wallingford procedure.

Melbourne Water and Melbourne Parks and Waterways (1993) describe a comprehensive review of water quality in the waterways and bays of Melbourne. Feral and domestic animals and ineffective septic tanks appear to be the main contributors of bacteria during dry weather, but sewage overflows add to bacterial levels in wet weather. The major point source of nutrients to the bays is treated sewage effluent. A major source of nutrients to waterways is faecal matter from agricultural and domestic animals. Urban runoff and atmospheric fallout are significant and increasing sources of nitrogen. Urban runoff contributes most of the toxicant loads to the bays. The vast majority of all litter is conveyed to waterways and the bays via the stormwater system, with most probably coming from high generation areas such as shopping centres. Sediments are the principal repository of heavy metals. Higher concentrations and loads of sediment and heavy metals occur in stormwater than in treated effluent. Land disturbance in the catchment has a major effect. The behaviour of many classes of contaminants mirrors the behaviour of sediments in waterways. Further improvement in water quality will come more from stormwater management than from sewage effluent control.

Tyson et al. (1993) address the worldwide progressive increase in urban pollution and the significance of policy, regulation, and institutional development. They claim that society has not learnt from early European experience, but has continued to make the same mistakes as urbanisation has spread around the world. They note that the wastewater system and the receiving water need to be treated as one integrated system, and that this is often not the case in practice. Relevant environmental policies are discussed, concentrating on Europe but with shorter discussions on USA, Japan, and South Africa.

8.3.5 Literature Reviews

Annual literature reviews of urban runoff and combined sewer overflows have been carried out by Walker (1992), Walker (1993), and Walker (1994).

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New issues that stand out during this period include the measurement and management of waterborne litter, the significance of anaerobic conditions for the accumulation of ammonia and the release of heavy metals, and the problem of urban drainage from areas of high density informal housing. This latter problem emphasises the need to view urban drainage issues in a broad hydrological, social, and political context.

A study of washoff from impervious areas at very short time intervals is notable for the light it sheds on the buildup and washoff process generally. Even so, our understanding of the real physical processes of buildup and washoff remains incomplete.

Despite these new issues, the distinctive feature of this most recent period could be best described as the incremental expansion of knowledge. The main impression is that many previously known factors have been confirmed or reinforced on a broader scale.

The most significant feature from a local point of view is the very large increase in Australian contributions to the urban water quality literature. Areas covered include basic data collection, modelling, treatment, and management, with a tendency towards whole catchment and large area studies.

The subject overviews reviewed in this period provide a particularly good coverage of most aspects of urban runoff quality - modelling, sediment, microbiology, receiving waters, planning, design and operation, practical application, and institutional issues. The reader is referred to these publications for a comprehensive state of the art review of urban stormwater quality.

9. INTO THE FUTURE: FILLING THE GAPS

What, then, does the future hold for urban stormwater quality research? It is obviously impossible, or at any rate extremely risky, to try and give a categorical answer to the question, since the subject is inextricably linked to so many other environmental, social, and political issues. Tyson et al. (1993) claim that society has not learnt from experience, but it is arguably not ignorance, but rather pressure from competing priorities which leads to the situation they describe. In any case, it is clear that future research will depend for the most part on future needs, as perceived by society at that time.

Rather than trying to predict future priorities and long term directions, it is perhaps more appropriate to identify and record the loose ends of the current effort in the shorter term. Based on this review, the following areas appear to be in most need of further work.

9.1 Review of Progress to Date

Techniques which can be used to review progress include literature review, time trend analysis within data sets, and the comparison and meta-analysis of multiple data sets. All these techniques have been used to some extent, but they are not common. This study provides a draft literature review, but coverage is incomplete and level of detail is limited. Perhaps the most useful sequel from a local perspective would be the expansion and maintenance of the Australian component of this review.

Studies of long term time trends are rare, particularly at the space scale of receiving waters. We know that well designed individual management components 'work', in the sense that litter booms intercept litter, sedimentation ponds collect sediment, and so on, but how effective are they in the longer, larger scale? Are we even keeping up with the expansion of urban areas? The information available is sparse and equivocal.

Comparisons of performance between locations, climatic zones, and management philosophies provide valuable technical information, while comparisons between performance, community expectations, and legislated standards provide an additional social dimension to the problem. As well as providing checks on current performance, such comparisons may also show where data and conclusions can be safely transferred from one location to another. At present, studies of this type appear to be almost totally confined to North America, and could usefully be extended to other areas.

9.2 Broad Scale Contaminant Balance

Many studies measure contaminant flux or content at a few sites or a few stages of the water cycle, and the sum of available information is substantial. But a complete contaminant balance over a catchment is rarely attempted, even for major contaminants such as total solids. Where does a particular contaminant come from, where does it go, and what damage does it do on the way? Can a new equilibrium be achieved, or are unstable trends occurring (such as net urban soil loss, or pollutant buildup in groundwater)? If control is necessary, where is the contaminant most easily intercepted? A broad scale contaminant balance is surely as important to quality studies as a water balance is to hydrology.

An area of particular interest concerns the behaviour of gross pollutants - plant debris and litter. Gross pollutants by definition comprise larger particles, and are not measured by conventional automated sampling techniques, yet their total nutrient and organic load can be substantial. There appears to be a real risk of underestimating their contribution to receiving waters.

9.3 Buildup and Washoff Processes

Buildup and washoff are key processes in the generation of urban runoff pollution. Both processes have been studied extensively, and are discussed in more detail by Duncan (1995b). A comprehensive descriptive view is available for buildup, but not yet for washoff.

Two relevant points about buildup arise from this review. Firstly, buildup on small test areas cleaned for experimental purposes will be unnaturally fast, due to redistribution from surrounding areas. Secondly, washoff from large test areas cleaned by natural rainfall is typically only a small part of the total surface load, so buildup will not start again from zero. The existing experimental data needs to be reviewed with these points in mind, to ensure that current interpretations and conclusions are correct.

Current descriptive views of washoff are inadequate. Where surface loads are measured directly, washoff is consistently found to be only a small fraction of total load, which strongly implies that washoff, not buildup, is the limiting process. Yet washoff is almost universally modelled by an exponential decay function, with initial surface load the limiting factor, despite the various documented problems of this approach (Duncan 1995b). Certainly, the modellers do not claim that their algorithms describe real physical processes in any detail, but in the absence of a direct disclaimer it is an easy assumption to make. In any case, alternatives have rarely been proposed. The possible influence of rainfall impact energy on particle detachment and transport in overland flow is occasionally mentioned, but has rarely been followed up in the urban context, although it can explain many observed phenomena. This process (among others) needs to be investigated further, with a view to developing a descriptive view of real physical processes, and more robust models based on the physical processes.

10. SUMMARY

This bibliography has reviewed about 700 references on the subject of urban stormwater quality, derived mainly from the journal and conference literature. The primary structure of the review is chronological, so that the development of issues, studies, and knowledge with time can be traced. Within each time period references are further divided by subject, and a summary of significant developments is provided.

An attempt has been made to identify significant gaps in the documented research. The areas in most need of further work are review of progress to date at the receiving water scale, development of contaminant balances at the whole catchment scale, and further clarification of the real physical processes involved in buildup and washoff on impervious areas. The physical processes of urban runoff contamination are reviewed in more detail in a companion document derived from this review (Duncan 1995b).

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