Pergamon

Wat. Sci. Tech. Vol. 29, No. 1–2, pp. 1–10, 1994.

0273–1223/94 $7·00 + 0·00

URBAN DRAINAGE: REVIEW OF CONTEMPORARY APPROACHES

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ABSTRACT

Recent developments in urban storm drainage are reviewed starting with rainfall/runoff processes, followed by discussions of combined sewage, drainage impacts on receiving waters, impact mitigation, hydroinformatics, regulatory programs and conclusions. The most promising trends in this field include improvements in spatial definition of rainfall data, runoff modelling with a limited number of model parameters and recognition of modelling uncertainties, analytical statistical modelling of runoff quality, advances in the understanding and modelling of sewer sediment transport, the use of biomonitoring and modelling in assessing drainage impacts on receiving waters, further refinement of best management practices for stormwater management, development of new processes for treatment of stormwater, experience with vortex combined sewer overflow structures and their applications in combination with other treatment devices, real time control of sewer system operation, advances in hydroinformatics leading to improvements in the integrated management and modelling of drainage systems, interfacing of drainage models with geographic information systems, and improved regulation of drainage effluents.

KEYWORDS

Stormwater management; rainfall/runoff processes; modelling; CSO control; best management practices; regulatory programs.

INTRODUCTION

Since 1978, the Joint IAHR/IAWQ Committee on Urban Storm Drainage has sponsored triennial conferences on all aspects of urban storm drainage. The principal aim of these conferences is to promote the exchange of information and technology among researchers, practitioners and urban water managers. The paper that follows is based on the findings of the latest conference in this series - the 6th International Conference on Urban Storm Drainage which was held in Niagara Falls, Canada, in September, 1993. The paper outline follows the conference program, starting with rainfall/runoff processes, followed by combined sewage characterization, drainage impacts on receiving waters, mitigation of impacts, hydroinformatics and regulatory programs.

RAINFALL/RUNOFF PROCESSES AND MODELLING

Studies of rainfall/runoff processes addressed rainfall measurement and analysis, rainfall/runoff modelling, flow routing, and runoff quality characterization and modelling.

Rainfall: Measurement and Analysis

Rainfall, the most important input in runoff calculations, receives a great deal of attention in drainage studies. While many researchers call for an adequate characterization of rainfall spatial and temporal variability in measurements and definition of rainfall data, the actual needs vary depending on the climate, drainage system and study objectives. Non-uniform spatial distribution of rainfall increases uncertainties in sizing storm sewers in cities with no or just one rain gauge station. Uncertainties in spatial rainfall data are generally reduced by increasing the density of gauges, but Lei and Schilling (1993) concluded that it was impossible to guarantee precise rainfall measurements just by increasing the number of rain gauges. However, since the use of a single rain gauge completely ignores spatial variation of rainfall and may lead to errors even in small catchments, at least two rain gauges per catchment should be used. Niemczynowicz and Olsson (1993) suggested that the scale invariant properties of rainfall could be used in conjunction with the fractal theory to develop simulated rainfall data in required spatial and temporal detail.

Further development of radar rainfall measurements continues, even though the precision of these measurements is still not satisfactory and comparisons of radar and ground data show great discrepancies, which could be reduced by applying the Fuzzy theory (Morita *et al.*, 1993). However, radar measurements are useful for identifying bias in rain gauge measurements, particularly in exposed, windy conditions.

In some runoff computations (for specific climates and smaller, highly impervious catchments without much storage) and/or where lack of data prevents other approaches, the use of design storms continues in spite of frequent criticism of the design storm concept. The feasibility of using design storms was demonstrated by Cao *et al.* (1993) by comparisons of continuous and single-event simulations and by Xanthopoulos (1993) for estimations of combined sewer overflow (CSO) loads.

Rainfall/Runoff Modelling

While further development of theoretical concepts in rainfall/runoff modelling is continuing, two other trends may be even more important - the need to compromise between the requirements for model input data and the lack of such data, and the recognition of modelling uncertainties. Demands of complex rainfall/runoff models on input data continue to exceed the data available to practising engineers. Consequently, there is a tendency to remedy this situation by reducing the number of model parameters to a few important ones providing adequate description of rainfall/runoff processes. The selection of such parameters can be guided by sensitivity analyses. In terms of actual parameters, Harremoës *et al.* (1993) suggested that the use of the runoff coefficient, initial loss, and some measure of uncertainty with respect to the individual rain event and the catchment was adequate. The collection of physiographic data for runoff modelling can be done cost-effectively by remote sensing, particularly with respect to land use and surface cover. The propagation of model uncertainty was addressed for several specific models and a correct determination of rainfall spatial and temporal distributions is important for improving modelling results.

Flow Routing

The needs for an appropriate level of hydraulic analysis in drainage studies were discussed by Yen (1993). While the traditional steady flow concept may be adequate in many cases, other applications call for the use of kinematic wave or quasi steady dynamic wave approximation of the Saint-Venant equations. New research was reported on studies of hydraulics of sewer appurtenances - unsteady flows through manholes

(Ball, 1993), calculations of head losses in circular junctions under surcharge by quasi steady-state dynamic equations (Kusuda *et al.*, 1993) and the pressure relaxation effects at manholes (Watanabe and Kurihara, 1993). Among the well-known flow routing models, a major refinement of the U.S. EPA EXTRAN, including the addition of a graphical decision support system, led to the development of a new version named XP-EXTRAN (Goyen *et al.*, 1993). Another proprietary version, ITWH EXTRAN, was developed for applications in real time control (Fuchs and Scheffer, 1993).

Runoff Quality: Characterization and Modelling

Stormwater characterization was addressed in connection with identification of pollutant sources, seasonal variations in concentrations and loads, land use effects, and the effectiveness of control measures. The most frequently monitored pollutants included physical parameters, oxygen consuming constituents, nutrients, heavy metals, and trace organics. A new addition to this list is platinum (released from automobile catalytic converters) which attracts interest because of its increasing occurrences in road sediment and extreme toxicity (Morrison and Wei, 1993).

The data collection for assessing pollutant impacts continues at widely varying spatial scales. Interests in pollutant sources and pathways require detailed studies of chemodynamics of micropollutants running off such surfaces as road and roof experimental plots (Herrmann *et al.*, 1993). In the other extreme, the assessment of impacts of runoff micropollutants on receiving waters in Toronto required a large scale sewer outfall monitoring study focusing on the event-mean concentrations (D'Andrea and Maunder, 1993).

In quality modelling, progress has been made in both physically-based and statistically-based modelling. While the former approach is more common in design/analysis studies, the latter approach is favoured in planning studies. Physically-based improvements focused on improved sediment transport modelling, which is particularly important in combined sewers and is addressed later. Among statistical models, analytical probabilistic models, suitable for long-term pollution control performance prediction, offer a good alternative to planning simulation models (Li and Adams, 1993).

COMBINED SEWAGE: CHARACTERIZATION AND MODELLING

Interests in combined sewer flows focus on flow variations (during both dry and wet weather), flow composition and complex interactions between the discharge and sediment transport. Runoff inflows to combined sewers are superimposed on dry weather flow variation patterns described stochastically e.g. by Scholz (1993). In terms of combined sewer flow modelling, the new German Guideline, A 128, combining model-independent and model-specific steps was described by Schmitt (1993).

Sewer sediment can be found in both storm and combined sewers and affects both the sewer flow capacity and the strength of sewage. Consequently, the Construction Industry Research and Information Association (CIRIA) is developing a standard methodology for the hydraulic design of sewers reflecting a better understanding of the sediment transport processes and the effects of the fluctuating flows (Clark *et al.*, 1993). The areas of uncertainty include the effective bed width, active bed roughness (including bed forms) and, also, lack of field data on sediment movement in sewers. In spite of progress in laboratory studies, field data are needed for verification of theoretical concepts.

Sediment studies in Dundee, UK (Ashley *et al.*, 1993a) and elsewhere suggest that erosion of the bedload layer, characterized by high pollutant strength, seems to be the primary contributor to foul flushes in combined sewers. This sediment layer typically comprised some 12% of total solids transported during dry weather. Such solids transport pollutants in high concentrations and are the main source of materials depositing during dry weather. Shear stress of around 1 N/m^2 was reported to be sufficient to erode the deposited material.

Temporal variations in and vertical distributions of concentrations of suspended solids, volatile solids and chemical oxygen demand (COD) in sewers must be accounted for in the experimental sampling design. Verbanck (1993) noted that suspended solids may be transported in cloudy patches, and hence, instantaneous point samples, which do not integrate spatial and temporal variations, are not representative. To simplify measurements of suspended solids, Delleur and Gyasi-Agyei (1993) suggested a surrogate determination of suspended solids by a transfer-function model using discharge and water temperature which are easily measurable.

The relationships between settling characteristics and concentrations of several polluting substances were studied by Michelbach and Wöhrle (1993), who concluded that grain sizes and assumed densities are not sufficient to describe the settling of sewer sediment particles. In combined sewers, particles contain organic matter, and are fibrous, cohesive and often covered by biofilms. Consequently, settling velocities should be measured directly.

Earlier approaches to sewer sediment transport modelling did not reflect the complexity of sediment movement in sewers and generally assumed a bedload transport of non-cohesive materials over a permanently deposited alluvial bed. For cohesive materials, Ashley *et al.* (1993b) developed a new model predicting the erosion of the bed and the mass of sediments released into the flow.

IMPACTS ON RECEIVING WATERS

Impacts of drainage effluents on receiving waters represent one of the main concerns in the ecosystem approach to urban water management and are demonstrated by the impairment of water uses and ecosystem health. These impacts are determined from field measurements or by modelling. The constituents causing most concerns include indicator bacteria, low dissolved oxygen (DO) and toxic metals. The faecal bacteria pollution of a river receiving CSO discharges was modelled by McCorquodale *et al.* (1993) using a simple bacteria loading model and a detailed river transport model. Impacts of CSOs on DO concentrations were modelled by Schaarup-Jensen *et al.* (1993) using a model belonging to the MOUSE modelling system.

Other studies assessed drainage impacts from observed effluent compositions, or from observations of actual impacts. Speciation studies for drainage effluents in Paris and Bordeaux indicated that metal distributions in solids and the associated toxicity varied greatly among sites. Among the metals studied, cadmium was the most mobile. It was concluded that solids separation has to be implemented in CSO treatment (Flores-Rodrigues *et al.*, 1993). Studies in the Innerste River (Germany) showed impacts of stormwater and CSOs on turbidity, organics and ammonia in the river (Lammersen, 1993). Besides the direct impacts of pollutant discharges, scouring and resuspension of bottom sediment by increased flows also affected the quality of riverine water.

Biomonitoring, using indicator organisms, represents another approach to assessing the ecological impact of urban discharges. For example, bioaccumulation of heavy metals in tissue, by gut ingestion or membrane diffusion, provides a time-integrated measure of contaminant bioavailability rather than its abundance. *Asellus aquaticus* has been used in the assessment of ecotoxicological impacts of both heavy metals (Mulliss *et al.*, 1993) and hydrocarbons (Jones *et al.*, 1993). Borchardt (1993) further suggested that the impacts of drainage discharges produce synergetic effects on aquatic organisms, and ecological evaluation of stormwater runoff should not be based on a single parameter, but on multifactorial matrices considering a number of parameters (varying in time and space) reflecting basic ecological principals of aquatic communities structures (e.g. shear-stress and non-ionized ammonia).

Although the assessment of drainage impacts on receiving waters is normally conducted for surface waters, it should be recognized that urban drainage also contributes to groundwater pollution by leaching from sanitary landfills, exfiltration from leaking sewers, and uncontrolled infiltration of polluted urban runoff. Sewer damage, including cracked or broken sewers and leaky sockets, results in wastewater leakage and groundwater pollution.

IMPACT MITIGATION: STORMWATER MANAGEMENT AND CSO CONTROL

Drainage effluents are discharged into the receiving waters as stormwater discharges and/or CSOs. Mitigation of impacts of such effluents are discussed in this section.

Stormwater Management

Stormwater management measures generally include best management practices (BMPs) applied in urban catchments, and the measures implemented in the collection system or receiving waters.

Best Management Practices. The list of BMPs is extensive and includes such measures as runoff infiltration structures, stormwater ponds, water quality inlets and vegetative practices. BMPs are widely used in many countries and guidelines for their design and implementation have been developed. While in the USA and Canada stormwater detention ponds are particularly popular (Driscoll and Strecker, 1993), in the European practice, stormwater infiltration/percolation and on-site detention/retention are generally preferred (Stahre, 1993).

Runoff source controls, by means of stormwater infiltration, are applicable in areas with both combined and separate sewer systems. Stormwater infiltration has been practised in a number of countries, including the USA, Japan (where it is used as a flood control measure, see e.g. Fujita, 1993) and Sweden. Wider use of stormwater infiltration in many European countries was impeded by lack of design procedures. However, this situation is quickly changing and, for example in Switzerland, stormwater infiltration is now required, where feasible, by the new federal water pollution control law (Krejci *et al.*, 1993). As an alternative solution, stormwater infiltration may also be applied during rehabilitation of significantly overloaded combined sewers.

Infiltration structures include porous pavements, infiltration basins, swales, trenches, perforated tanks and pipes and deep boreholes. Among these, porous pavements and infiltration pits and trenches are particularly common. Porous pavements perform well with respect to both runoff peak reduction and pollution abatement. Removals of suspended solids and metals can be as high as 95% and 98%, respectively (Urbonas, 1993; Balades *et al.*, 1993). To prevent the clogging of the porous pavement surface by dust and sand, these pavements have to be regularly cleaned by high pressure water jet and/or vacuum sweeping. The widespread use of infiltration pits and trenches follows from their ease of construction, low maintenance, efficiency in reducing the load burden on sewer systems, and applicability in areas with no other means of drainage. The main perceived disadvantage is their dependence on soil conditions. Design procedures for soakaway design are now available in the UK (Pratt and Powell, 1993).

The design of infiltration structures has two weak points (Petersen *et al.*, 1993) - uncertainty in the determination of design infiltration parameters and uncertainty in determination of the operational lifetime of infiltration structures. Present design procedures lack rigorous practical evaluation and, therefore, design data on long-term performance and maintenance should be established through comprehensive well documented field studies of infiltration facilities.

Stormwater detention for water quantity and quality control is widely used in North America and Australia. Wet stormwater ponds, particularly with extended detention, are recognized as one of the most effective water quality BMPs. Detention ponds, readily applicable in new developments with available land and suitable sites, are very effective in removal of particulate pollutants, but less effective in removal of dissolved materials (nutrients) through biological action during extended detention periods. The earlier criticism that stormwater ponds alter the timing of hydrographs peaks and thereby contribute to flooding in downstream areas was repudiated by a comprehensive review of case studies (Boyd, 1993). This review found that most facilities examined reduced peaks at the catchment outlet and only a few caused minor increases in downstream peaks.

Wetlands are used in stormwater management either as "stand alone" facilities or in combination with other BMPs, such as stormwater detention ponds. The most widely used are reed bed wetlands which, under favourable conditions, trap sediment, nutrients, bacteria and toxins, and also promote oxygen recovery (Ellis, 1993). Effective removal of nutrients may require regular harvesting. Seasonal variations in removals, caused by temperature changes and the life cycle of reed, are the most obvious disadvantages of wetlands (Cutbill, 1993).

Stormwater treatment. Recent studies of stormwater treatment focused on removal of total suspended solids (TSS) and the associated hydrophobic pollutants. The applicability of solid-liquid separation, by lamellar separation, to stormwater was tested by Dastugue *et al.* (1993) with promising results. Pilot plant studies indicated TSS removals from 50 to 85%, and COD removals from 30 to 55%. However, sludge resuspension problems were encountered and should be addressed in future investigations. In another pilot-scale study, the treatment apparatus comprised a grit chamber, a chemical stage for pre-treatment and a flotation reactor (Pfeifer and Hahn, 1993). Coagulation/flotation resulted in 88% reduction of suspended solids (including particles < 80 μm), 72% reduction in COD and over 70% reduction of particle bound heavy metals, such as Pb, Zn, Cu and Cr. In the last reported case, a swimming beach was protected against faecal bacteria pollution by applying UV disinfection to treat effluent from a stormwater pond discharging upstream from recreational waters. This process reduced the faecal coliform counts to 10 FCU/100 ml, which is well below the Canadian recreational water quality guidelines (Tracy and Craig, 1993).

Controls in the receiving waters. The treatment train applied in stormwater management does not end at the exit from various management/control schemes, but continues into the receiving waters and takes advantage of the self-purification capacity of receiving waters. Such a treatment requires maintenance of the natural character of receiving waters, in which aquatic plants, organisms and microorganisms, and benthic sediment play important roles. Where such elements have been disrupted by stream training or urban impacts, renewal of the natural character and the self-purification capacity of urban streams, by returning them to their pre-development condition, is required.

CSO Control

The need to control CSO pollution ranks high on the list of environmental objectives in many countries. Perhaps the greatest innovation in this field is the integrated management approach to CSO control considering the collection system, sewage treatment plant (STP) and protection of receiving waters.

Temporary in-system storage, created by installing large diameter storage pipes (Yasumoto *et al.*, 1993), is an effective measure designed to utilize the existing capacity in a combined sewer system, reduce CSOs and accommodate future growth. Among overflow structures, vortex type overflows of various designs produced promising reductions in biochemical oxygen demand (BOD) and suspended solids loads discharged in CSOs (Fagan, 1993; Pisano and Brombach, 1993). Furthermore, vortex or swirl separators can be combined with settling in a detention basin (Himmel and Geiger, 1993), chemical precipitation (Helliwell and Harper, 1993) and air flotation and disinfection (Boner *et al.*, 1993) to improve the overall pollutant removal. When locating these schemes, coupled with storage, high rate treatment at the overflow location was found significantly less expensive than central treatment (Weatherbe and Sherbin, 1993).

The use of real time control (RTC) in operation of sewer systems brings about all the possible benefits resulting from a full utilization of storage and conveyance capacities, and contributed to reduce CSO discharges. RTC operations are supported by two types of mathematical models - planning models simulating facility operation, and on-line models for real time operation. The requirements on these two types of tools differ; while the planning models should be accurate and their execution speed is unimportant, the on-line models can be less precise (their errors are corrected by regular updates of the system state) and their execution must be fast. Consequently, simple models with few parameters are selected for these on-line applications (Harremoës *et al.*, 1993).

The general interest in RTC is demonstrated by feasibility studies of RTC implementation in a number of European cities. Difficulties encountered in these studies include unfavourable rainfall patterns (high intensity, short duration rainfalls limiting the time for decision making) and a limited number of points allowing flow transfer among different watersheds. Furthermore, it appears that the control strategy may have to be varied for various system loads. The experience from these studies shows that, at present, the RTC technology is expensive in terms of both hardware and software costs, and the uniqueness of individual designs. Consequently, only a limited number of cities can afford to implement RTC. This situation should be remedied by the EC SPRINT program which strives to provide inexpensive, proven standardized technology for RTC implementation (Lindberg *et al.*, 1993).

HYDROINFORMATICS

Functional, spatial and temporal integration required in comprehensive drainage studies necessitates the use of computer models. International practice continues to be dominated by a limited number of well-supported and continuously updated modelling packages incorporating some aspects of hydroinformatics and merging environmental modelling with information technology. Among such tools, the leading products featured at the conference are, arranged alphabetically, MOUSE, WALLRUS and XP-SWMM. A wide range of options available in some of these tools allow addressing comprehensive drainage/environmental systems, including the collection system, management and control schemes, STPs and receiving waters. Expert system supports are also available.

The collection and processing of physiographical data for drainage modelling and presentations results are greatly simplified by the use of Geographic Information Systems (GIS). Furthermore, GIS systems can be used in conjunction with distributed hydrologic models to compute runoff hydrographs comparing well to those produced by conventional models (Zech *et al.*, 1993).

REGULATORY PROGRAMS

Successful implementation of stormwater management and CSO control is enhanced by supporting environmental programs, regulations and laws. Examples of such measures from several countries are given below.

A new Swiss water pollution control law requires infiltration of unpolluted wastewaters (including stormwater) and where local conditions do not allow this, a permit for discharge to surface waters must be obtained (Krejci *et al.*, 1993). In Ontario, the Interim Stormwater Quality Control Guidelines For New Development adopted the concept that "stormwater is a resource to be managed in support of societal benefits" and stormwater quality control should be considered at all stages of planning and development (Bowen *et al.*, 1993). In the USA, the US EPA's National Pollutant Discharge Elimination System (NPDES) for the regulation of municipal and industrial stormwater discharges requires all cities and urbanized counties with populations over 100,000 to apply for permits to discharge stormwater (Roesner, 1993).

An objective methodology to manage wastewater collection, treatment and disposal under wet-weather conditions, applicable to CSOs, is being developed in UK under the Urban Pollution Management Research Programme (UPM). This program will establish water use related environmental quality objectives (EQOs) and the associated detailed environmental quality standards (EQSs) for receiving waters (Clifford and Tyson, 1993). A recent amendment to the German A 128 Guidelines (1992) strives to prevent receiving water quality deterioration by CSOs (Schmitt, 1993). This amendment relates the permissible COD load, discharged in CSOs, to the load emitting from a separate system. The required storage volume is determined from a standardized design diagram and the rest of design is completed by model simulations.

CONCLUSIONS

Developments in the field of urban drainage continue at a rapid pace. Expansion of drainage goals and objectives to include ecological elements related to the receiving waters greatly broadened the scope and integration of drainage studies. Even though drainage receives various levels of attention in countries with different climatic and economic conditions and environmental expectations, the overall trend is towards integration of consideration of three elements in drainage systems - the collection system, STP and receiving waters. Further development continues in the field of stormwater management and CSO control, where new improvements were made possible by analysis of experience from many earlier facilities. Important trends include the use of runoff source controls by infiltration facilities, recommended for both separate and combined systems, the use of BMPs (particularly stormwater ponds, wetlands) in separate systems, improved combinations of vortex separators with storage and various treatment processes in CSO control, and the use of real time control. The selection of drainage alternatives and evaluation of their impacts on receiving waters is done by modelling. While development of specific model components is further continuing and may be significant in some cases (e.g. assessing the role of sewer sediment in sewage quality), more attention is focused on applications of large modelling packages encompassing drainage, STP, management and control measures, receiving waters and associated costs. These models include elements of expert systems and rapid input data preparation/processing using GIS systems. Finally, successful implementation of recommended schemes requires resources and supporting legislature illustrated by few examples of some regulatory programs.

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