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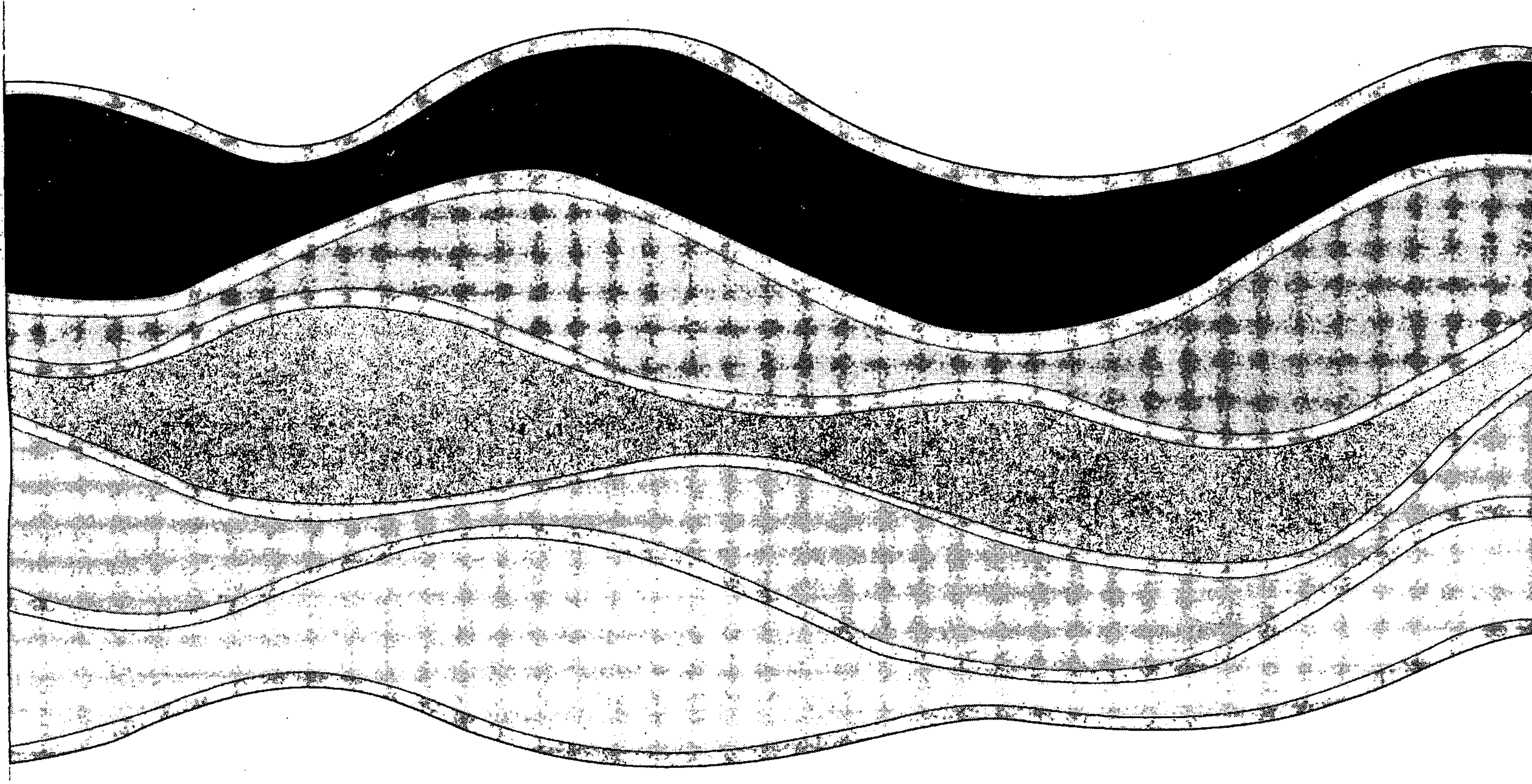

OPERATION OF SEWER SYSTEMS

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NWRI Contribution No. 98-013

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Management Perspective

Traditional provision of sewerage in urban areas relied on ever-continuing expansion of sewer infrastructures, without much regard for the resulting impacts on the receiving waters. Recently, environmental concerns and lack of funding for construction of new sewers forced a new approach to sewerage services, focusing on enhancing their effectiveness in wastewater collection and treatment by improved operation. The potential for adopting such an approach is examined, recognizing that the existing systems are not optimally operated and that significant benefits can be gained without large investments in sewer infrastructures. This approach is based on inventories of the physical assets, improved sewer inspection and maintenance, a progressive system control strategy, and proper administrative and financial controls. The most promising system control is based on real time control (RTC) of sewer operation. RTC is particularly efficient in reducing the frequencies of combined sewer overflows.

This report should be of interest to researchers, managers, environmental planners and municipal engineers dealing with operation of sewer systems.

Sommaire à l'intention de la direction

En milieu urbain, la façon classique de répondre à la demande a été d'étendre sans cesse les réseaux d'égout, sans beaucoup d'égard pour les répercussions sur les masses d'eau réceptrices. Récemment, des préoccupations d'ordre environnemental et le tarissement des sources de financement pour la construction de nouveaux égouts ont conduit à envisager de nouvelles façons d'offrir les services d'assainissement, avec l'accent mis sur des gains en efficacité de la collecte et du traitement des eaux usées, obtenus en améliorant l'exploitation. Sachant que les réseaux existants ne sont pas exploités de manière optimale et que des gains importants sont à notre portée sans investissement important dans de nouvelles infrastructures, les auteurs examinent les possibilités d'appliquer cette approche. Celle-ci est fondée sur l'inventaire des actifs matériels, sur l'inspection et l'entretien plus serrés des égouts, sur une stratégie de contrôle progressif des réseaux ainsi que sur des mesures appropriées de contrôle financier et administratif. Le contrôle en temps réel de l'exploitation des réseaux d'égout est la solution la plus prometteuse. Il est particulièrement efficace pour réduire la fréquence des déversements de trop-plein d'orage.

Le présent rapport s'adresse aux chercheurs, aux gestionnaires, aux planificateurs et aux ingénieurs municipaux concernés par l'exploitation des réseaux d'égout.

Abstract

Urban drainage infrastructures represent large investments which have to be properly operated and maintained. The development of an operational plan starts with defining the system performance parameters with reference to discharges, the degree of treatment, and acceptable frequencies and durations of service interruptions. To meet and sustain this performance, day-to-day operation rules are developed as well as a maintenance plan. Maintenance is based on regular inspections, which are used to plan both corrective and preventative maintenance. Modern operation of sewer systems uses real-time control to minimize the drainage business risk, which is defined as the cost of system operation and damages. Both operation and maintenance are conducted by a single department providing administrative and financial control.

Résumé

Les réseaux d'égout urbains nécessitent des investissements importants; il faut donc les exploiter et les entretenir de façon efficace. Dans un plan opérationnel, on doit commencer par déterminer, en termes de performance des réseaux, les paramètres de rejet, de degré de traitement et de fréquence et de durée acceptables des interruptions de service. Pour atteindre ce degré de performance et s'y maintenir, on développe des règles d'exploitation au jour le jour ainsi qu'un plan d'entretien. Les inspections régulières, à la base de cet entretien, permettent de planifier l'application de mesures correctives et de prévention. Les formes modernes d'exploitation des réseaux d'égout appliquent des contrôles en temps réel afin de réduire le plus possible le risque d'entreprise, défini comme étant le coût d'exploitation du réseau plus les dommages. L'exploitation et l'entretien sont assurés par un même service qui assure le contrôle financier et administratif.

1. Introduction

Urban sewerage and drainage systems are important infrastructures which require large financial investments. To protect these investments and ensure delivery of sewerage services, such systems have to be properly operated and maintained, with adequate financing and administrative control. Thus, the operation of sewer systems can be defined as a set of procedures designed to provide a service by collecting, transporting, and managing the quality of, urban wastewater in a cost-effective, environmentally responsible and sustainable way. More specifically, the process of operation comprises all activities conducted after placing the sewer system into operation - including the specification of system performance parameters, day-to-day operation rules, inspection procedures, short-term and long-term maintenance, financial aspects, and administrative control. Further explanations of these issues follow.

The system performance parameters need to be defined with respect to the conveyance flow rates/capacities, acceptable frequency/duration of service interruptions or damages, and the level of treatment/dilution provided. These service parameters generally evolve in time, usually as a result of increasing regulatory demands on control of stormwater and combined sewer overflow pollution. The older systems were typically designed for single objective controls (flow conveyance), but in recent years, the demands on them were increased to reflect much broader ecosystem health objectives. Consequently, the original sewer systems, which may have been fully functional for the old objectives, have to be upgraded.

Day-to-day operation rules describe the procedures followed to deliver the prescribed service. The complexity of such procedures varies with the sophistication of the operated system; for example, in gravity storm sewers there are hardly any needs for operational intervention under normal operating conditions. The other extreme is represented by a combined sewer system subject to real time control, with sophisticated sensor networks (rainfall, sewer flow and quality, receiving water conditions, including water quality), a data gathering module, a central control module and the implementation of operation strategies involving variable flow control at many points in the system. Most sewer systems fall somewhere between these two extremes, with some requirements on operation of pumps and gates, to control flows and their quality.

Many failures of sewer elements are not sudden incidents, but rather represent a qualitative change preceded by a gradual build-up of conditions leading to the problem. For example, the clogging of sewers generally results from a gradual build-up of sediment, or from structural failures that are usually preceded by the appearance of sewer cracks or partial collapse. Indications of the deteriorating condition of the system can be detected through inspection, which benefits from modern technology including in-sewer inspection by video cameras, or ultrasonic techniques.

Sewer system maintenance is usually classified into two categories, corrective or short-term maintenance dealing with remediation of the immediately pressing problems (i.e., trouble shooting, cleaning out a blocked sewer or an ice-blocked sewer inlet), and preventive, long-term maintenance aimed at avoiding anticipated problems. The latter category includes sewer system rehabilitation and renovations, which are fully discussed in the next paper in this Chapter.

Sewer system operation requires financial resources, and these have to secured through allocated budgets. Normal procedures of financial operation and control are applied, including the collection of funds and proper accounting. The sewer systems represent very large capital investments and as discussed later, operation of such systems appears to be generally underfunded (Lehmann 1994).

Finally, sewer system operation has to be organised administratively, usually by concentrating operation activities in a single department, which has to be properly set up, funded and empowered to deliver the expected services.

The issue of funding of sewer system operation is gaining in importance and has received much attention in recent years, particularly in connection with the privatisation of water services. Typically, public water infrastructures represent very large capital investments, as documented by two examples from Switzerland and Norway. In Switzerland, the replacement value of the public infrastructure was estimated at 250 billion SF (approximately 200 billion U.S.$); wastewater systems represent approximately 30% of this amount (60 billion U.S.$), and water supply systems represent 25% (50 billion U.S.$). However, municipalities typically budget only 3% for wastewater and the same amount (3%) for water supply systems in their operation budgets. In Norway, the replacement value of the wastewater systems is 70 billion NOK (approximately 11 billion U.S.$), but annual expenditures are just 1.5 billion NOK (240 million U.S.$). Similar examples could be found in other countries as well and indicate under-funding of sewer system operations.

Thus, the sewer systems are capital intensive systems, which are still operated in many jurisdictions under the myth of "maintenance-free" policies. Long service lives of some structural components of these systems (particularly concrete pipes) disguise the overall system ageing and deterioration. In fact, it would be hard to find another service industry that would operate such expensive systems while spending so little on their operation and maintenance. Catastrophic failures are generally handled by special financing or fund allocations from general budgets. Some changes in this attitude should be noted, for example, some municipalities in Germany are collecting annually 2% of the replacement sewer value in a special fund that can be used only for rehabilitation activities.

The discussion presented in this chapter is restricted to sewer systems only, recognising that the operation of wastewater treatment plants is rather complex and the proper treatment of that subject is beyond the scope of these proceedings. Also it should be recognised that sewer system operation is discussed here only in connection with applications of hydroinformatics to sewer systems, and no attempts are made to provide a detailed treatment of operational procedures.

2. Tasks and Challenges of Urban Drainage Operation

The main challenges in providing urban drainage by means of combined and storm sewers can be summarised in the following five points: (a) increased regulatory demands on stormwater and CSO control, (b) reduced capacities of receiving waters to accept wastewater effluents, (c) poor utilisation of existing system capacities, (d) ageing/ deterioration of sewer systems requiring rehabilitation/replacement, and (e) the rate of sewer replacement outpaced by the rate of sewer deterioration. Further discussion of these points follows.

2.1. INCREASING REGULATORY DEMANDS ON STORMWATER AND CSO CONTROL

When the first combined sewers were built (100 years ago), wet-weather flows were considered unpolluted and the small fraction of sanitary sewage escaping from sewers through CSOs was considered sufficiently diluted. However, increasing demands on sewer systems have evolved from the original single objective (prevention of flooding or water ponding in the case of storm sewers, and the protection of public health in the case of combined sewers) to much broader objectives, namely ecosystem health protection. Consequently, the older systems, designed for simple objectives, have become obsolete and require both functional and structural renovation. In fact, it is prudent to combine any rehabilitation projects addressing structural rehabilitation/renovation with a critical analysis of functional renovation and harmonise both requirements.

The objective of ecosystem health protection is not well defined, but quite often it may be replaced by effective mitigation of wet-weather discharge impacts, which depend on both the characteristics of the catchment producing such effluents and the characteristics of the receiving waters (Ellis and Marsalek 1996). The actual impacts need to be evaluated for individual sites and the issues of interest include habitat changes (particularly changes in morphology), water quality changes (dissolved oxygen depletion, eutrophication), sediment and toxic impacts, impairment of public health (by discharge of fecal bacteria), impacts on biological communities, and groundwater impacts (Ellis and Hvitved-Jacobsen 1996). In general, the complexity of processes in receiving waters and the time-varying nature of these impacts necessitates the assessment of receiving water conditions by computer modelling. In current modelling practice, there is a major knowledge gap with reference to ecotoxicological modelling, particularly when reconciling laboratory and in-situ field dose-response relationships as well as in relating biotic uptake rates to target pollutant concentrations and exposure durations and frequencies (Ellis and Hvitved-Jacobsen 1996).

2.2. REDUCED CAPACITIES OF RECEIVING WATERS TO ACCEPT WASTEWATER EFFLUENTS

Progressing urbanisation increases the total loads of pollutants on receiving waters and leads to the exceedance of self-purification capacities of such water bodies. This is further exacerbated by the cumulative nature of some runoff impacts (e.g., gradual morphological changes resulting in the loss of habitat), or synergistic action of contaminants released from various sources. Consequently, the capacities of streams and reservoirs to accept new wet-weather discharges have greatly diminished over the years, and much more rigorous regulations have to be imposed on more recent developments. In this connection, it should be realised that the urban development of even as little as 10% of the total catchment creates detectable impacts on the receiving waters (Horner *et al.* 1994) and, consequently, there are relatively few ecosystems in the world that are not impacted by civilisation. Thus, in environmental protection or remediation, the goal should be to strive for attaining a desirable quality of the ecosystem, which will, however, fall short of the pristine “natural” state.

2.3. POOR USE OF THE EXISTING SEWER SYSTEM CAPACITIES

It has been demonstrated in the literature (Schilling *et al.* 1989; Schilling 1995, 1996) that gravity controlled and operated sewer systems are generally inefficient in utilising available sewer capacities and their collection efficiency falls short of the potential of the same system equipped for and subject to real-time control operation. Low collection efficiency translates into sewage overflows and leads to the pollution of receiving waters. A gravity only (static) control cannot account for non-uniform distribution of flows and storage in the system, or ensure that system capacities (particularly storage capacity) can be utilised in response to a given storm and system loading pattern. Such benefits can be realised only by implementation of real-time control (RTC), which is particularly beneficial in systems with large static storage, uneven distribution of storage volume, and long times of travel in sewers (Jorgensen *et al.* 1995). Under such circumstances, the volume of overflows can be reduced by as much as 25%, without increasing the system's physical capacity.

2.4. REHABILITATION/REPLACEMENT OF AGEING SEWER SYSTEMS

Sewerage rehabilitation deals with three types of sewer system failures - structural, hydraulic and environmental. To manage this task effectively, Grigg (1988) recommended the use of a computerised Maintenance Management System (MMS), which should include programs for inventory control, condition assessment, rehabilitation and replacement, preventive maintenance, budgeting and decision support. The inventory can be stored in a GIS system that should include the condition assessment data consisting of such categories as capacity, safety, structural integrity, quality of service, role and age. The needs assessment should include an analysis of projected needs, alternatives, rates of deterioration and obsolescence, cost-benefits and impact studies as well as sensitivity analysis. The use of MMS must be accompanied by a long-term commitment of personnel and budget. Descriptions of failures, methods of diagnosis and rehabilitation are given in the next paper in this Chapter.

2.5. THE RATE OF REPLACEMENT OF AGEING SEWERS IS OUTPACED BY THE RATE OF DETERIORATION OF SEWERS

Opinions on sewer design life differ widely and reflect the variation observed in actual sewer systems. While some older sewers can serve, in optimal conditions, as long as 100 years, some younger sewers built just 30-40 years ago, but exposed to adverse conditions (e.g., in landfills, or areas with corrosive ground water) already require rehabilitation. For simplicity, a fixed design life is considered, usually 50 years. On the average, this design life would require annual renewal of about 2% of all sewers, but the actual rates of rehabilitation typically range between 0.25 and 1%. Thus, the gap between the rehabilitation needs and the actual rehabilitation is increasing and contributes to growing liabilities.

The above discussion points to two obvious solutions – (a) increased expenditure on sewer rehabilitation and renewal, and/or (b) optimisation of operation of existing systems for better performance and longer service life. Recognising the ever-increasing competition for dwindling public funds and the overall aims of this ASI, only the second solution is discussed in this Chapter.

3. Potential for Improving Sewer System Operation

The existing sewer systems in Europe and North America suffer from a number of operational problems, including poor sewage collection efficiency, identified by dry weather bypassing, CSOs or sewage back up into basements, and general problems of underutilisation of the sewer system capacity.

Sewage overflows or bypasses in dry weather, when the system operates below its design capacity, have been reported in many jurisdictions. Generally, they are caused by flow obstructions in sewer systems or by malfunctioning dynamic overflow regulators. For example, it was estimated that in Trondheim (Norway) about 20% of the sewage volume bypasses the sewage treatment plant via CSOs, and one half of this volume occurs in dry weather.

Sewer blockage may cause pressurisation of the sewer system and sewage may enter basements through basement drains, with concomitant large damages and public health risks. These problems are common in older combined sewer systems and are reported in many countries. Data from Trondheim indicate that in 1980, a total of 506 sewer blockages resulted in damage of private property due to backing up of sewage. After implementing improved maintenance and regular sewer flushing, this number was reduced to 66 cases in 1993.

Some components of sewer systems are clearly under-utilised. Primary examples of such structures are CSO storage tanks, which are used widely in Canada, Denmark, Germany, Switzerland, UK and USA. In typical conditions, these tanks are designed to reduce the frequency of overflows from 50-100 to about 10 per year. A simple calculation can be used to demonstrate the poor cost effectiveness of these tanks when not equipped and operated to provide system-wide benefits. For an assumed service life of 50 years, a typical tank will overflow 500 times during this period. Since one cubic metre of tank storage costs about $1,500 U.S., the capture of the last cubic metre of sewage costs $1500/500 = $3, which is an enormous cost to prevent diluted sewage from reaching the receiving waters. Obviously, these costs could be significantly reduced if the tank would be used more frequently, especially when some tanks are under-utilised while overflows occur at other sites.

Thus, there is ample evidence that most of the existing sewer systems are not operated at their optimum, and that significant pollution control benefits can be gained just by improving system operation, without large investments in the sewer infrastructure.

4. Operation - Definition Revisited

Efficient operation of any system requires the fulfillment of two conditions, which can be illustrated by an analogy with driving a car. Firstly, the car has to be in such a technical state that all vital components function properly (e.g., engine, transmission, steering, brakes, fuel supply, and ignition). This car can run, but cannot be driven until the second condition has been met. The driver must know how to drive and where to go. In other words, he has to have a driver's license, driving experience, and knowledge where to go and how to get there. Only then the car can reach its destination.

It is obvious that fulfilling the first condition but not the second results in a poor investment strategy. With reference to sewer operation, it is necessary to fulfill both conditions and define operation as a two stage process. Stage 1 includes all the measures that bring the sewer system to, or keep it in, a proper state as originally designed. These measures include regular inspections, flushing, catch basin cleansing, grease removal, root cutting, infiltration control, rat control, etc. In a conventional approach, these measures are summarily referred to as "operation and maintenance".

However, even a sewer system which is well maintained does not necessarily perform well. This is caused by temporal and spatial variations in system's loading with sewage, stormwater and pollutants. Performance shortcomings can be observed in the form of local water/sewage ponding/flooding, CSOs, or shock loading of treatment plants, occurring while there is unused storage or flow capacity in other parts of the system. All these phenomena indicate poor performance of an otherwise perfectly maintained sewer system. Hence, it is necessary to implement the second stage, by manipulating the system continuously in such a way that its capacity is optimally used in all operational situations and no damage occurs unless the system capacity is completely exhausted. This type of operation is usually referred to as "real-time control" (RTC), because the system is manipulated during the ongoing flow process. Thus, RTC increases the collection efficiency and pollution control effectiveness of the sewer system.

5. Operation and Maintenance

Public demands to improve the performance of existing sewer systems, coinciding with a general restraint on public spending, force municipal managers and politicians to look for innovative non-capital intensive solutions. Such solutions generally involve the development of an improved operation plan. In this process, the existing sewer system and treatment facilities are analysed to determine the changes in system operation which would improve system performance, as described by the collection efficiency and reduction in total pollution loads discharged to receiving waters. This approach differs from facilities planning, which simply addresses the planning of the facilities needed to meet a performance standard.

Such an operational plan determines the capabilities of existing facilities to maximise the reduction of all municipal effluent discharges into the receiving waters. To achieve this goal, some limited new facilities may be needed, but in principle, environmental impacts can be reduced in this approach without embarking on a major capital improvements program. The operational plan comprises three major elements - examination of major system components of the collection and treatment system, the administration of the system, and system maintenance. In each element, opportunities for reducing inflow, temporal storage of wet-weather flows, or increasing treatment capabilities are explored.

5.1. INVENTORIES AND CONDITION ASSESSMENT

The foundation for rational operation, maintenance and needs assessment of a sewer system and treatment facilities is a good documentation of the entire system. Where such documentation is missing or is outdated, a new inventory needs to be developed. The types of information needed include the physical features of the collection and treatment system, its administration and the maintenance program. Inventories of physical facilities are done through a process of measuring the physical condition of system components using objective criteria. The parameters include safety, structural integrity, capacity, quality of service, role and age (O'Day and Neumann 1984). This information is entered into and stored in computer databases with a geographic base file holding the system geometry as well as all other operational aspects. The inventorised physical system is then analysed, generally by computer modelling, to determine the system's strengths and weaknesses. Positive findings include spare flow conveyance, storage and treatment capacities, and documentation of good structural integrity of the system. Weak points include overloading of system components, lack of storage in critical components, excessive infiltration and inflow, and poor structural conditions (Grigg 1988).

5.2. ADMINISTRATIVE CONTROLS

An operation plan must include administrative controls specifying basic rules for system operation. Such controls start with municipal sewer ordinances, including procedures for making connections to the system, construction requirements, limits on materials discharged to the system, pretreatment, monitoring structures/programs, and rate schedules. Additional controls are introduced at higher jurisdictional levels, e.g., at the territorial or national government levels. Such controls may prescribe the quality of system effluents. For example, the Canada Fisheries Act specifies that no matter deleterious to fish may be discharged into open waters frequented by fish (Chambers *et al.* 1997). Administrative controls may be changed to improve system performance, e.g., reducing inflows to the system by forcing disconnection of roof runoff and other sources, or by enhancing pretreatment specifications and establishing administrative bodies for improved control over the system.

5.3. SEWER SYSTEM MAINTENANCE

Operational management consists of operations and maintenance. Thus, sewer system maintenance is part of the overall operational plan, and both operation and maintenance should be under a common management. The main goal of maintenance is to keep equipment and systems ready to go at any time. A maintenance program comprises three elements: maintenance tasks, schedule, and manpower needs (Grigg 1988).

Maintenance tasks can be classified into four activities: condition assessment, inventory, preventive maintenance, and corrective maintenance. Inventory of physical facilities and system functions is a continuous determination of whether the system is working properly. If it is, then operations and surveillance continue. If not, corrective or major maintenance activities must be initiated. Corrective maintenance requires a decision: is the deficiency serious enough to warrant entering the planning, programming and budgeting activity (i.e., capital requests), or is it minor enough to go ahead and fix it or even postpone the corrective action (Grigg 1988)?

Sewer system maintenance tasks are rather varied, depending on the sewer system and its components under consideration. Typical tasks deal with street sweeping, catch basin cleaning, sewer cleansing, sewer repairs and emergency response, upkeep of stormwater management systems, inspection/cleaning of siphon and overflow regulators, and maintenance of pumping stations. Further details of such tasks follow.

Street sweeping is used not only for aesthetic reasons, but also for reducing pollutant (particularly solids) entry into sewers. The frequency of sweeping varies depending on land use (typically from daily to monthly). Catch basins are designed to control the entry of coarse street sediment into sewers and thereby to reduce sedimentation in sewers. Catch basins are cleaned regularly in most jurisdictions; inspection is used to record structure conditions and schedule any repairs required.

Sewer cleansing is particularly important in those system sections that are susceptible to sedimentation. Such areas are regularly inspected, their condition recorded, and records entered into a data base (GIS based). The areas subject to sedimentation are usually further characterised with reference to the frequency of cleansing required, varying from once a week to once a month (or even longer intervals), but most sewers are cleansed at least once every five years. The most common and cheapest method of sewer cleansing is flushing; other methods used include mechanical cleansing (dragging) or use of high-pressure nozzles.

Among the methods for repairs of sewers (cracks and joints) and manholes, injections of synthetic concrete mortar and relining with plastic liners are most common. The latter option is more costly, but may be necessary in deteriorated systems.

Maintenance of storm drainage systems somewhat differs from that of the conventional sewer systems. In particular, the stormwater systems consist of concrete, earth, grass and miscellaneous structures, without much machinery or exposure to biochemical processes. Relatively few checks are performed in such systems, generally in response to public complaints usually dealing with short-duration flooding. Consequently, the general attitude toward inventory, maintenance, and upkeep of storm drainage systems is different from that for other municipal utilities (Grigg 1988).

Storm drainage maintenance is sometimes done by contracts involving three types of tasks: routine, restoration and rehabilitative. Routine tasks include vegetation mowing, trash and debris cleanup, weed control, and revegetation. Restoration tasks are more demanding and include stormwater pond mucking, trash rack cleaning, rebuilding steep rundowns, tree thinning and clearing, extending trickle channels, repairing local erosion problems, and local grading and shaping. Finally, the most demanding are rehabilitative tasks, including reconstruction of drop structures, trickle channels, reshaping channels, installing riprap and maintenance access structures, and protecting existing drainage features.

Some experience with maintaining stormwater management systems was reported by the Denver Urban Drainage and Flood Control District: (a) there was a gap between what was designed and what was actually built; (b) hardly any communities within the District had systematic maintenance programs; and, (c) stormwater management facilities degrade rapidly without proper maintenance (Hunter and Tucker 1982).

Special structures in combined systems, such as overflows and siphons, require frequent inspections, because they are critical for satisfactory operation of sewer systems. In the case of overflows, it is customary to inspect each structure regularly (the frequency varies from daily to several times a year; on average, weekly) and during rain events, when inflow to the treatment plant exceeds some threshold. Maintenance crews are typically on call to make such inspections. In general, inspections have two goals : to correct operational failures, and prevent or reduce their recurrence. Common causes of failures include clogging, silting, sticking of movable parts, parts failure, corrosion, power failure, and hydraulic pressure failure, in the case of hydraulically operated structures. The most common problem, clogging, cannot be eliminated completely. Experience indicates which structures require more attention (U.S. EPA 1990).

Recommended maintenance schedules include cleaning out regulator chambers after every storm, and during each visit, the crew should visually inspect the regulator, remove debris, operate gates to prevent seizing, lubricate and clean chains and gears, examine for corrosion and wear, check bearings and frozen parts, and verify operation of water level sensors.

Many sewer systems employ pumping stations for drainage of low-lying areas. These stations require special attention, because of the nature of mechanical and electrical equipment used at these installations. Major factors in deterioration include wear on moving parts, mechanical damage, corrosion of metal components, and physical deterioration by ageing. The functional deterioration of pumping stations usually manifests itself through reduced pumping capacities (fouling or wear of pumps) or decreased pump efficiency. The latter may lead to overloading the pump drive. The average life-time of mechanical installations of pumping stations can be estimated from 25 to 30 years for sewage stations, and 40 to 50 years for stormwater drainage stations. The average life of the electrical installations is just 15 to 20 years, but the average life-time of the station structural elements is 100 years or more. In general, the need for station alterations may reduce this life (Hissink 1995).

Many problems with sewer systems are identified during maintenance activities or through citizen complaints. This fragmented information about the state of the sewer system is systematically complemented by sewer inspections, which are conducted at least once a year, preferably at the end of the wet season, using remotely controlled TV cameras. Results of inspections are filed, and three types of files recognised; the structure files reflecting the "as built" conditions, inspection files reflecting the actual state, and the failure files. By comparing the structure "as built' and actual files, deviations can be identified and the need for action assessed. The system or structure failures are recorded separately in failure files. If failures of a structure are too frequent, the reliability of that structure is endangered.

The observed defects must exceed certain threshold criteria to warrant immediate action; minor defects are rejected for immediate attention. In these decisions, the input of field crews is invaluable. Typical examples of conditions requiring immediate attention include (Hissink 1995):

- severely cracked and leaking concrete sewers (as determined by TV inspection)
- internally corroded sewers, with gravel or reinforcement steel showing
- permanent loss of storage capacity, due to stagnant water, exceeding 80%
- bank revetments of drainage channels are so damaged that the embankments sag out into the drain, blocking its hydraulic profile
- drainage channels are silted up to 0.4 m or less below the mean water level
- pumping stations are damaged or the manufacturers criteria are exceeded
- pump discharge capacity or efficiency was lowered by 10%.

Good record keeping is essential for development of effective sewer maintenance programs. This is done in computerised databases (GIS based) which are used for data storage and problem documentation. Typically, the following repair needs or activities are recorded: (a) manhole repairs (major repairs, cleaning, height adjustments, minor repairs), (b) sewer lines to be televised, (c) sewer repairs (urgent, major, minor), (d) problems of intruding roots, and (e) sewer complaints. Using this information, monthly summaries are prepared and used to issue work orders. Sewer related complaints, such as sewage back-up, point to problems of sewer blockage and the need for cleaning.

The maintenance program requires sufficient personnel, which is typically organised into a number of crews that perform routine and special tasks. Crews consist of 3-5 men, one of whom always stays on the street surface. Safety concerns are of paramount importance and dictate the needs for special training, proper equipment, and development of safety manuals with descriptions of specific safety measures. The municipal area is divided into regular maintenance sub-areas, which are regularly inspected and maintained. For all these activities, the associated costs have to be established and complete records kept of all inspection and maintenance work.

It is obvious from the preceding discussion, that in large urban areas, sewerage maintenance represents a large business activity that should be rationalised by introducing a maintenance management system (MMS). MMS brings together disparate maintenance activities through a holistic approach of caring for the system, and ensures that the overall maintenance is done properly. It involves all essential management tasks, including planning, organising, and controlling, and requires an effective decision support system. With respect to maintenance functions, MMS deals with the condition assessment, corrective maintenance and preventive maintenance, and the decision support system will provide the information and data needed for these activities (Grigg 1988).

The MMS support system is used to develop and formulate effective maintenance strategies, including the following approaches or their mixtures (Grigg 1988):

- crisis maintenance only
- maintaining the most deteriorated facilities first
- performing opportunistic maintenance, when related work is scheduled
- using pre-specified maintenance cycles
- repairing the components with the highest risk of failure
- using preventive maintenance
- reducing the causes of wear and tear on the facility
- comparing the economic advantages of maintenance strategies.

The MMS should be an integral part of the overall organisation management control system. As a minimum, it should have an inventory control component, and a record system for maintenance work scheduling and completion. The records kept should include equipment data, the preventive maintenance record, the repair record and spare parts stock cards. The use of MMS is particularly advantageous when dealing with needs assessment, which links maintenance management and capital improvement processes. Maintenance decisions and strategies require proper planning. The needs assessment process involves an inventory, a condition assessment, and identification of the desired level of improvement and maintenance; all viewed in the light of present and future conditions (Grigg 1988).

Sewer maintenance helps implement quality control in sewer operations. In this respect, quality control provides assurance that the quality of a product (i.e., delivery of sewerage services) is within the acceptable limits of quality, as defined for that product. Basic elements of the quality control process, such as inspection, administration and record keeping, quality control engineering, and performance gauging, can all be well related to the earlier discussed tasks of sewer operation and maintenance (O'Day and Neumann 1984). The performance could be assessed by the absence of complaints, or the physical and functional state of the sewer system.

In a proactive approach, sewer maintenance and rehabilitation can be improved through early diagnosis and treatment of structural and geotechnical anomalies. Methods and computer tools have been developed to carry out the tasks involved in sewer rehabilitation. These include an expert system for the structural and geotechnical diagnosis of the sewer network as well as a decision aid tool for choosing the most appropriate rehabilitation technique. The geotechnical conditions addressed include steep slopes (>5%) and hydrological conditions causing earth slides. Some of these systems have been validated in actual sewer systems and have been found useful in improving the system analysed and identifying the shortcomings of the current state of knowledge and the type of information collected (MacGilchrist 1989).

5.4. SEWER SYSTEM CONTROL STRATEGY

Even without sophisticated real-time control, it is advantageous to look for improvements in the operational strategy that would reduce discharge of pollution from the sewer system, and particularly from combined sewers. Two sources of improvement are obvious : reducing incoming flows, e.g., by disconnecting roof leaders, or enhancing infiltration in the catchment; and, improving utilisation of storage in the system, e.g., by installing flow throttles in critical sections of the system. The use of such controls has to be thoroughly tested by computer simulations. The implementation of this strategy should improve the overall system efficiency, in terms of both collection efficiency and pollution loads discharge into the environment (U.S. EPA 1990).

The connection of operations and maintenance can be illustrated by a general operation model, involving data collection, operator decision, and control command sequence. Operations connect to maintenance through the condition assessment activity. In modern approaches, an expert system and computer control are incorporated into this process, as discussed in next section.

6. Real Time Control (RTC)

6.1. WHAT IS RTC ?

An urban drainage system (UDS) is controlled in **real time** if process data that are concurrently monitored in the system are used to operate flow regulators during the actual flow process. Typically, this task involves activating a number of pumps, sluice gates, weirs, etc. to allow the occurrence of adverse effects (e.g., flooding, combined sewer overflow CSO) only if the system is at capacity and only at those locations where the least damage is caused. In **static** systems this can only be achieved in the rare case when the UDS is receiving its design load. If, for example, the outflow of a detention pond is controlled by an orifice, the optimal outflow rate is reached when the pond is full. During other periods the outflow rate is smaller than the optimum and, consequently, the emptying time is longer. To activate excess storage in a large sewer a (static) high-side weir overflow regulator can be used. The overflow opening has to be large enough to allow passage of the design overflow rate. Thus, much of the available storage cannot be used in most situations.

Operational concepts of real time control systems (RTCS) are concerned with logical ways of using process information. Since the deficiencies of static systems are well known, moveable (self-operating) regulators have been introduced to maintain a pre-set flow or water level. Many of these regulators use process measurements taken directly at the regulator site (e.g., by a float, counterweight, etc.). Therefore, such a system is termed a **local control** system. Under local control, regulators are not remotely manipulated from a control centre, even if operational data are centrally acquired. This type of setting makes the system supervision easier.

If a RTCS is more complex or if all regulators need to be operated in a coordinated manner, **global** or **systems control** is applied. Here, all regulators are operated with respect to process measurements throughout the entire system. Global control in drainage systems is required under the following conditions:

- many regulators exist that affect each other, or
- the actual loading differs substantially from the design loading (e.g., as a result of temporally and spatially varying rainfall).

6.2. EQUIPMENT AND HARDWARE REQUIREMENTS

In an RTCS there are **control loops** consisting of:

- **sensors** (e.g., water level gauges) that monitor the ongoing process,
- **regulators** (e.g., pumps or gates) that manipulate the process,
- **controllers** that activate the regulator to bring the process to its desired value (**set point**), and
- **data transmission systems** that carry the measured data from the sensor to the controller and the signals from the controller back to the regulator.

From the large variety of available **sensors** only very few fulfill the requirements for RTC in UDS. Such requirements include, among many others, the sensor suitability for continuous recording and remote data transmission (**monitoring**). The following sensors are widely used:

- **rain** gauges (weighing gauges, tipping bucket, drop counters, and radar devices),
- **water level** gauges (bubbler, air pressure, water pressure, and sonic principles),
- **flow** gauges (level-to-flow conversion, ultrasound velocity measurement, electromagnetic induction meters), and
- **limit switches** (e.g., mercury float, diaphragm).
- Rainfall intensity data can be used to provide short term **runoff forecasts**. The forecasting horizon can be extended if rainfall forecasts are included (particularly using the radar technology).

Level measurements are the backbone of every sewer monitoring system. They are indispensable for determining the state of storage devices or converting levels to flow rates (large sewers, overflow weirs, flumes, gates). Water **quality** sensors still play a very minor role in RTC of UDS because of their deficiencies.

Regulators for sewer flows include axial **pumps** (constant or variable speed) or screw pumps. **Weirs** (perpendicular, side-spill, or leaping) are used to create storage in ponds or sewers. Self-operating weirs use a counter-weight or buoyancy of a float to adjust the height of the crest. A special design is an air regulated **siphon** which functions as a weir or a siphon depending on the air supply in its crest. **Inflatable dams** are broad-crested weirs used to activate storage in large trunk sewers. **Gates** (e.g., sluice, radial, sliding) are movable plates that constrict the flow in a sewer or in the outlet structure of a tank. **Valves** are devices used to throttle pipe flows (i.e., plug, knife, butterfly). In a **vortex valve,** the fluid rotation increases head losses with increasing flow rates. It operates without external power supply or any moving parts. Other regulators used in RTCS include air regulated **inverted siphons**, movable **tidal (backwater) gates**, and **flow splitters** which separate incoming flow into two outgoing paths.

Flow or water level regulators in urban drainage systems are often very large, custom-designed devices. However, some basic design principles are common to all successful designs.

1. Regulators should be **fail-safe** designed, so that malfunction of vital parts results in an acceptable functional decline of the system. For example, sluice gates should have bypasses, and dynamic weirs should move into a safe position in case of a power failure, etc.
2. All parts exposed to sewage and the corrosive sewer atmosphere should be drastically simplified and made corrosion resistant. The material of choice for their manufacturing is stainless steel.
3. Sensitive parts should be located in an appropriate environment, i.e., a dehumidified vault for hydraulic and electric machinery, dehumidified and heated vaults for programmable logic controllers, telemetry equipment, etc.
4. All components of a regulator station (including gates, sensors, motors, etc.) should be accessible, maintainable, and exchangeable.
5. It should be possible to supervise the vital regulator functions from the control centre.

In a centralised RTCS, a data transmission system is required; both transmission by wire (e.g., public telephone) or wireless transmission are used. **Digital** data transmission is becoming more and more common. Compared to analog transmission, its main advantages include high suitability of digital data to be fed directly into digital computers, improved transmission reliability (eliminates noise), and high information transmission rates (measured in bits per second, bps).

With the development of digital computers, many analog controllers could be replaced by a single central computer. This allows more flexibility in controller calibration, interconnection of control loops, and adjustment of set points. With the advent of inexpensive microprocessors, the vulnerability of such a system could be overcome by implementing a central minicomputer and several local **programmable logic controllers (PLC)**. Typically, the PLCs control and coordinate all functions of outstations, including the acquisition of measured data; data pre-processing (smoothing, filtering, etc.); checking the status, function, and limits; temporary data storage; local controls; and, receiving data from, and reporting to, the central station. As computers become more powerful, fewer tasks remain to be done by the central **process computer**, i.e., system-wide data acquisition, long-term storage and data management, operator interfacing, interactive simulation / optimisation (decision support software), and automatic execution of control strategies.

6.3. PLANNING, DESIGN AND IMPLEMENTATION OF RTC SYSTEMS

The planning, design and implementation of RTC systems typically include the following stages:

1. Define the operational **objectives** of UDS (e.g., minimise flooding, minimise CSOs, etc.)
2. **Simplify** the UDS, but simultaneously highlight its “hot spots” (e.g., hydraulic bottlenecks, CSO sites, regulator stations, etc.)
3. Evaluate the **potential** for RTC through simulation or monitoring (i.e., do idle capacities exist during the periods when environmental damage occurs?)
4. Determine the **current** performance of the UDS (i.e., analyse historic events during which damage was observed and/or determine the statistics of damages through long-term simulation)

5. Select **locally** controlled regulators and determine the performance of locally controlled UDS (e.g., is the capacity better utilised in comparison to current operation ?)
6. Optimise control strategy and determine the maximum performance of UDS under **global** control (i.e., how large is the improvement in reaching the operational objectives as compared to local control ?)
7. Compare RTC operation with **conventional** (i.e., static) remedial measures (e.g., larger sewers and tanks)
8. Evaluate **cost/effectiveness** of alternatives and chose the best alternative
9. Develop a **control strategy** including a sensitivity analysis and the assessment of fail-safe precautions
10. Test the **automation** concept (e.g., requirements for information processing, presentation functions, operator functions, communication system, hardware specifications, etc.)
11. Develop **software** (i.e., application software, user interfaces, control software)
12. Evaluate the UDS hydraulics, controller behaviour, pollution discharges, etc. with **detailed** models
13. Define factory and site acceptance **tests**
14. **Undertake personnel resources** planning (education requirements, training, maintenance, etc.)
15. Produce a preliminary **operations manual**.

6.4. DEVELOPMENT AND ANALYSIS OF CONTROL STRATEGIES

Controllers adjust regulators to achieve minimum deviations of the regulated flow discharge or level from the **set points**. A **control strategy** is defined as the time sequence of all regulator set points in a RTCS. In almost all cases with multiple control loops it can be shown that the optimum strategy requires time-varying set points.

A control strategy has to be physically executable (feasible), i.e., flows and levels cannot exceed the physically possible rates (**static constraints**). Additionally, the control strategy has to be in harmony with the physical laws of flow in a drainage system, including continuity and energy balances (**dynamic constraints**). The dynamic constraint of a storage device is its mass balance and, for a sewer pipe, a mathematical description of flow.

Since the RTCS depends on the loading of the system (i.e., storm inflows, pollutant loads, etc.), it is obvious that a **loading forecast** represents an extremely important information for decisions on controlling flows. The further these forecasts reach into the near future, the better control strategy can be achieved. The options which help determine the inputs to a drainage system include:

- flow and level measurements in upstream sewers, which would allow to react within the time of sewage travel,
- rain measurements and applications of rainfall/runoff models which extend the available reaction time by the concentration time of the overland flow on the catchment surface, and
- rainfall forecasts to gain additional time depending on the forecast time horizon.

If none of the above listed information is available only a local control strategy (i.e., reactive strategy) can be applied.

Since measurements include **errors**, it is important to check control strategies with respect to measurement errors or failures of sensors. From a practical point of view, control strategies have to be "cautious" to avoid "surprises", which could be caused by unexpected storm developments, inflows from unmonitored tributary sewers, etc. Control strategies are usually based only on measurements. However, it might be useful to develop a better strategy by using **off-line simulation** of drainage processes or even by including an **on-line simulation** model to "interpolate" process data that cannot be measured.

The most rigorous approach to find a control strategy is based on mathematical **optimisation**. This technique allows the evaluation of the control performance on an absolute ("the best") rather than a relative ("a better") scale. Here, the problem is translated to the minimisation of an **objective function** subject to **constraints**. The objective function is usually of a mixed integer/continuous, nonlinear, and non-monotonous type. Since powerful analytical optimisation techniques are not available for this type of objectives, the function has to be further simplified (e.g., by linear programming).

Heuristic methods for finding a control strategy can be directly derived from the experience of the operation personnel. This is usually done by specifying an initial control strategy (e.g., the default, fixed set point strategy) and using multiple simulation runs to improve the initial strategy by a trial-and-error procedure. When no further improvement appears possible, it is assumed that an optimum strategy has been found.

Optimisation or search results can be translated into **decision matrices** (DMs). Each element of the matrix represents the control decision which has to be executed for a given combination of state and loading variables. DMs allow for very fast on-line execution of control strategies. Simplifications of DMs take the form of **decision trees** that are sets of "if-then-else" statements. Recent research in this field focuses on the use of expert systems and neural networks; however, no implementation of these tools in practice has been as yet reported.

6.5. ANALYSIS OF CONTROLLER BEHAVIOUR

The **control loop** defined above is a basic element of any RTCS. In a **feedback** loop, control commands are actuated depending on the measured deviation of the controlled process from the **set point**. Unless there is a deviation, the feedback controller is not actuated. A **feedforward** controller anticipates the immediate future values of these deviations using a model of the process controlled and activates controls ahead of the time to avoid these deviations. A **feedback / feedforward** controller is a combination of the two.

A standard controller used for **continuously** variable regulator settings is the proportional-integral-derivative **PID-controller** and its simplified versions (P, PI, PD). Its signal sent to the regulator is in the form of a function of the difference between the measured variable and the set point. The parameters of that function have to be calibrated unless the controller has an **auto-tuning** capability. Calibration is performed through analysis of the underlying differential equations, or through real or simulated experiments.

Two point or on/off control is the simplest and most frequently applied method of **discrete** control. It has only two positions: on/off or open/closed. An example is the two-point control of a pump used to fill a reservoir. The pump switches on at a low level and off at a high level. The difference between the two switching levels is called the **dead band**. **Three point** controllers are typically used for such regulators as sluice gates, weirs, etc. In the middle position of the controller, the output signal is indifferent, and in the other positions, it reaches either a maximum or minimum.

Once the control system has been implemented, the behaviour of a controller has to be tested. Especially the interactions of neighbouring controllers require rather involved analyses featuring a detailed hydrodynamic model with the controller functions built-in. Full-scale experiments over the whole range of control variables have to be carried out to ensure that operational malfunction such as overshoot, instability, etc. cannot occur. During start-up operation, the initially selected control parameters can be fine-tuned to ensure that the optimum controller behaviour is eventually attained.

6.6. PLANNING TOOLS

In the early planning stages, a conceptual model of the UDS system is developed and has to be able to simulate the key process variables such as flow rates in hydraulic bottlenecks, storage contents, overflow rates, times of flow travel, pollutant concentrations, etc. The model should be calibrated and verified with process data. Furthermore, the model must allow for input of control strategies, e.g., a set of if-then-else rules, a control matrix, or an optimisation routine. Examples of simulation programs used in this stage of RTC planning are FITASIM (Wolf-Schumann *et al.* 1991) or SAMBA-CONTROL (Triton 1991).

For comparison of control alternatives, the model is first used to simulate the current system's behaviour. Inputs to the model are the events of interest, for example all rainfall events of a representative period, a set of dry weather flow scenarios, etc. The performance of the system is thus analysed under the current operation conditions. If flooding and/or CSO occurs and, at the same time, spare storage, transport, or treatment capacities can be identified, a new control strategy that activates these spare capacities could be defined.

For the same set of events the system is simulated once again, this time including the new control strategy involving such structural modifications as weir and throttle adjustments, or storage, transport and treatment capacity expansions. A different performance is obtained, i.e., different flooding volumes or CSO discharges.

Each of the alternatives can be characterised by its specific performance and costs. A cost-benefit analysis is carried out to determine the optimal solution. With this step, the conceptual analysis is finished and a decision must be made whether to implement the RTC system. Whichever alternative is chosen the risk of failure should not, of course, exceed the risk level in the existing system.

If decision to implement a RTC is made, the behaviour of the proposed system is simulated in full detail with a more detailed model. These simulations involve the hydrodynamic modelling of sewer flows and flow levels, including transients; pollutant transport modelling; treatment plant simulation; and, dynamic modelling of controller behaviour. Simulation programs used in this stage of the project are for example HydroWorks (Wallingford 1994) and MOUSE (Bo-Nielsen 1993).

6.7. MAN-MACHINE INTERFACES AND OPERATIONAL TOOLS

Any RTCS that is not operated in the fully automatic mode needs a well-defined operator (user) interface. Historically, such an interface comprised analogue displays, strip chart recorders, and control switches using relays. Today, active wall panels and colour screens are used to display standard features common in a variety of application fields. Currently under development are

UDS specific **simulators** that allow an animated display of the current state of the UDS, its loading, and a dynamic evolution of the UDS state.

Such RTC simulators can be used to evaluate control strategies before they are actually executed. The simulator can be run in two ways: it can be used as an on-line tool, which has to be fed with process measurements to update the state variables, or as an off-line tool, when it can be used to train operators and to analyse past events. The successful development of these systems requires extensive joint efforts of the software development engineer and the operating personnel to guarantee that the necessary information (and only that) is available and displayed.

6.8. OPERATION OF RTC SYSTEMS

Introduction of RTC requires a number of organisational changes within the urban drainage department. For smooth implementation of such changes, the key activities are communication and documentation.

Operation of a RTC system requires intensive communications among all divisions and levels of an urban drainage department. This is a management task that is extremely difficult to achieve, especially in large organisations. For adoption of RTC in larger agencies, it seems almost impossible to imbed the RTC planning and operation in either of the traditional planning and operations divisions. Often it is advisable to create a new **operational control** division instead, originating from a UDS performance monitoring group (i.e., the group operating a measurement network), and have this division to report directly to the department's management. Thus, "traditional rivalries" can be avoided and well-educated personnel can be hired according to the needs. In small agencies, creation of a new division is not affordable. Instead, it is preferable to choose such a RTC technology that can be operated with the existing operating personnel (usually the treatment plant operators).

In any RTCS under supervisory control, the operating personnel has to be advised on how to proceed in all possible operational situations (i.e., both routine and emergency). Naturally, this should be done before critical situations arise. For example, the operator has to know and understand the operational objectives and their priorities (e.g., first allow an overflow at location x, then at y, etc.). Extreme situations such as the decision which district to flood first have to be included! Operational advice should be **documented** because it reflects a consensus of all involved parties (i.e., the public, supervising agency, management, staff). Without such an **operations manual,** operators might be afraid to take any steps to avoid being blamed in cases of mismanagement. Since it is almost impossible to foresee all possible operational states of the system, the operators need to have some freedom to make "reasonable control decisions" and their adoption of such decisions has to be backed by the management.

The general purpose of RTC is to understand drainage processes, and to monitor and manipulate them, in order to achieve **maximum performance** of the existing UDS. The information gathered during RTC operation is valuable for the whole operating agency, including both the traditional planning and O&M divisions. It is an important management aspect that the new operational division will not be regarded as "big brother" but as the source of information that allows the documentation of successes. **Success** is then defined as a close match between the envisioned and actual problem solutions. Success should result in **benefits**, and the staff's successful operation be positively acknowledged by the management and / or the supervising agency.

6.9. BENEFITS OF RTC

General performance estimates of RTC systems cannot be given because of the multi-objective character of the approach and the large variety of existing systems. However, if CSOs are the problem of concern, an analysis of the current behaviour of the system can reveal whether RTC might be beneficial.

It can be shown that during wet weather approximately one half of the total system capacity (i.e., storage, transport and treatment capacities) remains unused (Almeida 1993). The potential reduction of CSOs can be obtained by comparing the "no control" scenario with a RTC scenario, for which the control strategies are optimised (Papageorgiou 1983; Schilling and Petersen 1987; Nelen 1992). Based on case studies for a variety of sewer systems, it can be concluded that with optimum RTC the CSO volume per event can be reduced by approximately 25% of the total available storage, taking all physical constraints into account (Schilling 1996).

In terms of CSO abatement, the typical RTC benefits include drastic reductions in overflows at the most sensitive locations, reduced frequencies of overflows (about by 50%), and reduced annual CSO volumes (by 10-20%). Secondary benefits include lower energy costs (less pumping), improved wastewater treatment, control of sediment in sewers, and better supervision, understanding and record keeping.

7. Sewer System Operation in the Future

There is a trend in many countries to privatise urban drainage operations, or at least to provide urban drainage departments with more freedom and independence to act. This trend is likely to lead to a more holistic way of operation in the sense that the urban drainage system will be operated to minimise total costs or, more generally, minimise the "business risk" (Price 1996). In urban drainage the business risk comprises the continuous costs of operations (e.g., energy, maintenance, repair, reporting, etc.) plus the damages caused by adverse events and the respective probability of their occurrence (e.g., flooding, sewer collapses, pollution, etc.). Both, daily operation and adverse events cause direct, indirect or social costs that must be minimised.

In terms of the physical system and its operation in real time, the trend is to include the states of both the wastewater treatment plant and the receiving water in the operation of the urban drainage system. For example, there is no good reason for "wasting" precious storage or treatment capacity on weak sewage. If the available capacity would primarily be used to capture the most polluted sewage, the potential for pollutant discharge reduction can be increased ("pollution based RTC"). If the treatment plant and the CSOs discharge into the same receiving water, it is obvious that overall pollutant discharges should be minimised, because it is not rational to reduce CSOs at the expense of a much lower efficiency of the treatment plant.

This argument can be expanded, if adverse effects on the receiving waters are considered: the whole drainage system contains numerous elements that can be utilised with respect to the prevention of water pollution. This includes not only the hydraulic storage volume in tanks and pipes, but also the time lag of processes in the wastewater treatment plant and the receiving water. For example, in the case of an acute-effect pollution (e.g., oxygen depletion in a water course), a time delay of the failure of the secondary clarifier under hydraulic loading introduces a time shift in the occurrence of the acute effect that can be assessed and used as extra capacity. The direct focus on minimising the detrimental impact to the receiving water allows the identification of the optimal control strategy for the operation of the total system under dynamic loading. Future research is focusing on such a kind of water quality-oriented aspects of "integrated" RTC.

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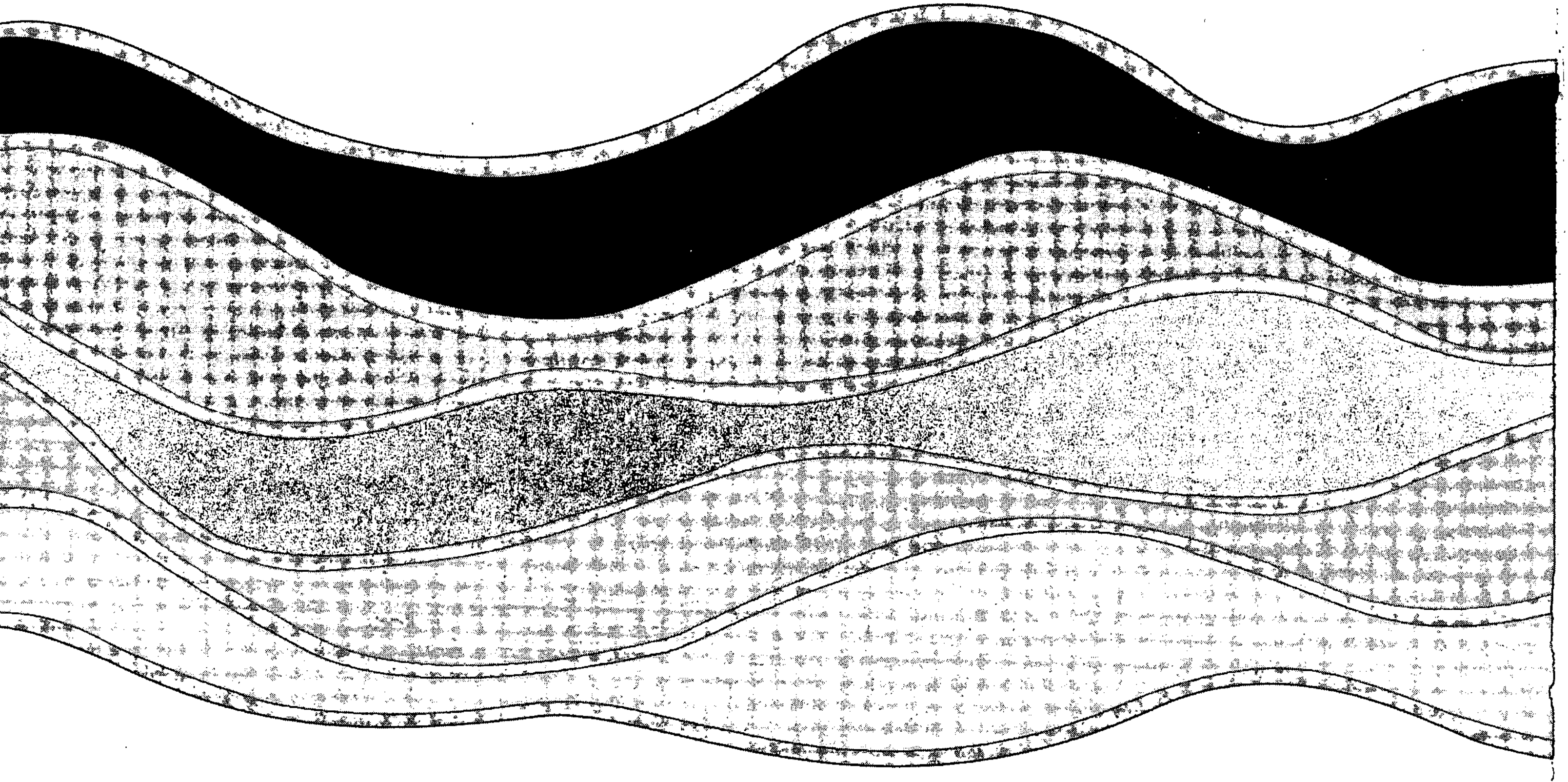

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