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STORMWATER MANAGEMENT TECHNOLOGY: RECENT DEVELOPMENTS AND EXPERIENCE

by

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ABSTRACT

During the last 20 years, urban stormwater management has evolved from fast removal of runoff to comprehensive and cost-effective management approaches providing not only flood protection and drainage convenience, but also minimizing runoff impacts on the receiving waters. Modern stormwater management approaches, which are based on implementation of stormwater quantity and quality controls in various parts of urban catchments and their drainage systems, are reviewed. The presented stormwater controls can be used effectively in the innovative stormwater management which leads to savings on drainage infrastructures and a better protection of the environment.

RÉSUMÉ

Il y a 20 ans, le retrait rapide des eaux de ruissellement constituait le mode de gestion des eaux de pluie dans les villes. Puis progressivement, on en est venu à des approches globales et rentables assurant non seulement uneprotection contre les inondations et un drainage efficace des eaux, mais aussi une réduction des impacts environnementaux sur les cours d'eau qui reçoivent ces eaux. Cette étude passe en revue les approches modernes de gestion des eaux de pluie, lesquelles mettent en oeuvre des mesures de contrôle de la quantité et de la qualité de ces eaux, mesures qui s'appliquent tant au niveau du réseau de captage qu'au niveau des systèmes de drainage. Les mesures relatives au contrôle des eaux de pluie présentées ici peuvent être mises à profit dans le cadre d'une gestion innovatrice des eaux de pluie permettant de réaliser des économies au niveau des infrastructures de drainage et aussi de mieux protéger l'environnement.

MANAGEMENT PERSPECTIVE

In spite of recent progress in control of point source pollution, water quality goals and designated water uses are generally unattainable without control of nonpoint source pollution. In urban areas, control of nonpoint source pollution requires a proper management of stormwater. Recent progress in stormwater management technology is reviewed in the paper that follows. The most successful and cost-effective stormwater management schemes were found to integrate all feasible and economic source controls, collection system controls, off-line storage and stormwater treatment. Implementation of such control measures contributes to savings on drainage infrastructures, better protection of the environment, and attainment of sustainable development in urban areas.

PERSPECTIVE-GESTION

En dépit des progrès récents en matière de contrôle de la pollution provenant de sources ponctuelles, les objectifs en ce qui a trait à la qualité de l'eau et à la gestion des eaux désignées sont généralement hors d'atteinte quand les sources de pollution non ponctuelles ne peuvent être contrôlées. Dans les régions urbaines, le contrôle de la pollution provenant de sources non ponctuelles exige une gestion appropriée des eaux de pluie. Cet article passe en revue les progrès récents en matière de technologie appliquée à la gestion des eaux de pluie. Les méthodes de gestion qui intégrent tous les contrôles réalisables et économiques de sources de pollution, les contrôles de systèmes de captation, l'emmagasinage hors réseau et le traitement des eaux de pluie se sont avérées les plus fructueuses et les plus rentables. La mise en oeuvre de telles mesures de contrôle permet de réaliser des économies en matière d'infrastructures de drainage, de mieux protéger l'environnement et d'assurer le développement durable des régions urbaines.

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ABSTRACT. During the last 20 years, urban stormwater management has evolved from fast removal of runoff to comprehensive and cost-effective management approaches providing not only flood protection and drainage convenience, but also minimizing runoff impacts on the receiving waters. Modern stormwater management approaches, which are based on implementation of stormwater quantity and quality controls in various parts of urban catchments and their drainage systems, are reviewed. The presented stormwater controls can be used effectively in the innovative stormwater management which leads to savings on drainage infrastructures and a better protection of the environment.

1 Introduction

Progressing urbanization leads to increasing concentration of population in relatively small areas and the concomitant stress on the entire urban ecosystem and its water subsystem in particular (Vlachos, 1982). As water resources become depleted, or their quality and utility deteriorate, a comprehensive management of water resources is required to facilitate sustainable development of the society and to preserve its general well-being. The main objectives of water management in urban areas include provision of three important services - water supply, wastewater disposal, and drainage. The discussion in this contribution focuses on urban drainage and stormwater management.

In the management of water resources, recent changes from supply management to demand management were noted (Marsalek, 1988b) and this trend can also be detected in stormwater management. The traditional approach to storm drainage was based on a steady expansion of drainage infrastructures without analysis of the impacts of drainage effluents on the receiving waters. A better understanding of runoff processes and their impacts on receiving waters, as well as economic considerations, led to a new stormwater management approach which strives to manage demands on drainage systems and the receiving waters. This approach represents a conservation approach to stormwater management, where conservation is achieved by reducing both the discharges of and pollutant loadings in drainage effluents. Toward this end, dual drainage systems are used and designed to prevent flooding as well as to reduce inconvenience caused by water ponding, while maintaining stormwater flow volumes, peaks and pollutant fluxes at acceptable levels.

The conservation approach to stormwater management contributes to the achievement of sustainable development in urban water resources and brings about numerous benefits including prevention of flooding, water pollution problems, loss of existing water uses, contamination of water supplies, and loss of habitat; reduced incidence of water ponding, sinking ground water tables, landscape disturbance, soil erosion, and sedimentation (Tjallingii, 1988); improved aesthestics of urban stream environments (Grigg, 1986); and, reduced drainage costs (Province of Ontario, 1983). Savings on drainage costs through advanced stormwater management are particularly important in view of the current concerns about aging drainage infrastructures and high rehabilitation costs (Schilling et al., 1987).

2 Stormwater Management Technology

Stormwater management has evolved from simple removal of runoff to comprehensive management approaches employing various control measures. Such controls can be classified into several categories depending on the location where the controls are implemented (Field et al., 1977). Following the schematic route of stormwater shown in Fig. 1, the following three types of stormwater controls are recognized:

- Source controls
- Collection system controls
- Storage and treatment.

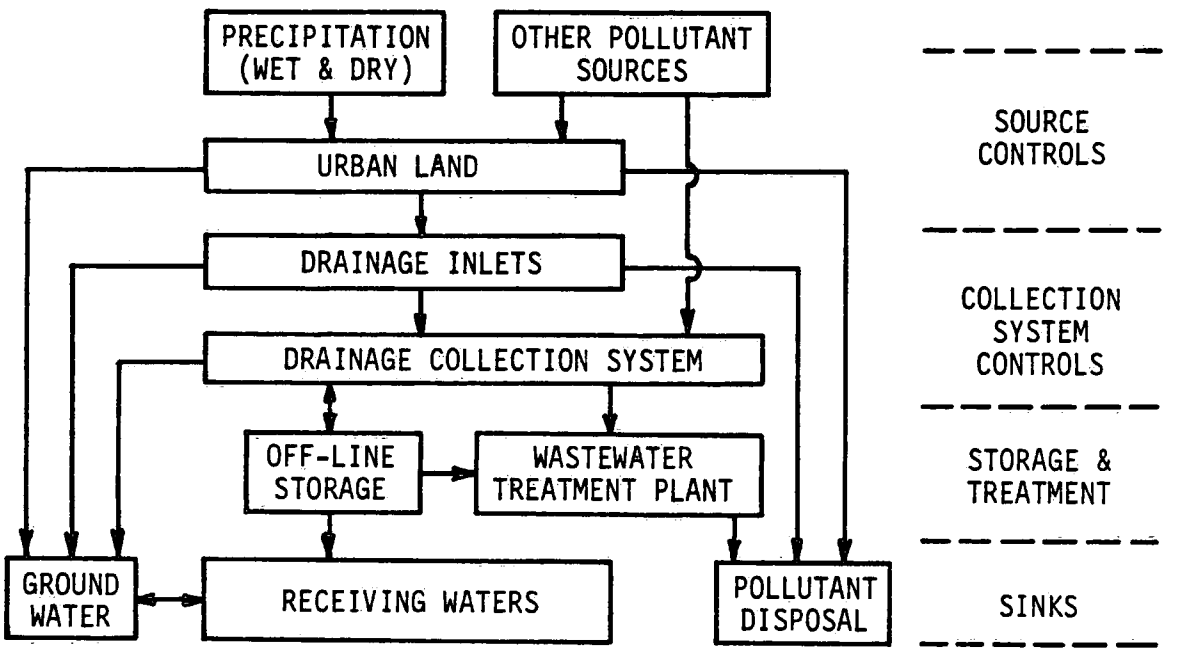

Fig. 1. Runoff Processes and Stormwater Controls in Urban Areas

This classification is introduced just for the discussion of individual controls recognizing that some of them may fit into more than one category and that the actual stormwater management systems are likely to employ combinations of controls from all the above categories. Brief descriptions of individual stormwater controls and recent experiences with their implementation follow.

2.1 Source Controls

Source controls include nonstructural, semi-structural, and structural measures designed to reduce urban runoff flows and pollutant loads before they enter the drainage system. Control measures belonging to this category are listed in Fig. 2.

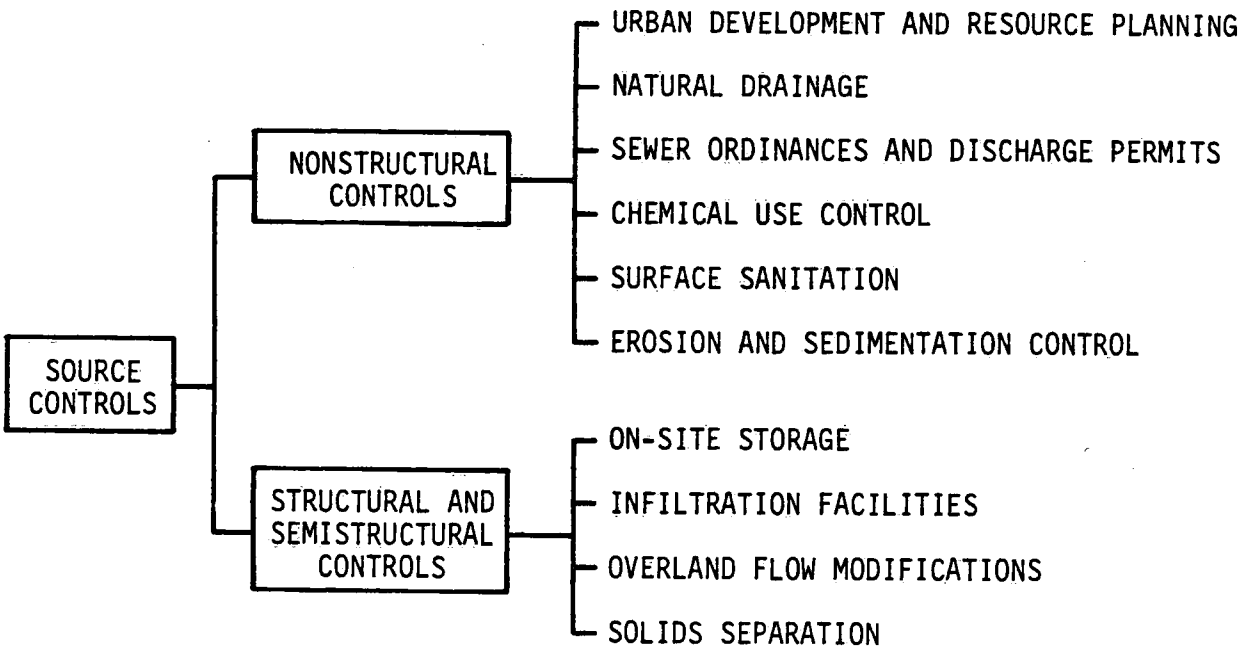

Fig. 2. Urban Stormwater Management: Source Controls

2.1.1 Nonstructural Measures. Nonstructural runoff controls are generally very cost effective and, for that reason, many of them are included among the so-called best management practices for urban runoff control. Typical nonstructural control measures include urban development resource planning, the use of natural drainage, sewer use ordinances and discharge permits, chemical use control, surface sanitation, and erosion and sedimentation control practices.

Urban development resource planning is a planning approach attempting to develop a macroscopic management concept to prevent problems resulting from urbanization. In this approach, new planning variables include population density and total wet and dry pollution controls designed to reduce water pollution (Field et al., 1977; Lawrence and Goyen, 1987).

Integration of natural drainage elements into new urban developments allows runoff to flow through natural channels or low-vegetated swales into a network of wetlands and/or wet-weather ponds, which are strategically located in areas with porous soils. The benefits of runoff retardation and enhanced seepage into the ground include reduced drainage costs; enhanced aesthetics, ground water supplies, and flood protection; and reduced water pollution. Examples of applications of this concept in new developments were reported by Lawrence and Goyen (1987), Martin and Miller (1987) and U.S. EPA (1983).

Properly designed grassed swales, retarding flow and enhancing runoff infiltration, were found to be effective in controlling both runoff quantity and quality (Pitt, 1986). While quantity control is achieved by flow retardation and infiltration, quality control results from reduced flow volumes and sedimentation in swales. The effectiveness of swales in runoff control can be enhanced by using swale blocks which lead to runoff detention/retention (Wanielista and Yousef, 1986).

The passage of runoff through wetlands reduces both suspended and dissolved loads of various pollutants. While the removals of dissolved loads, in the range from 40 to 75%, can be explained by plant uptake and chemical transformations in the sediment and water columns, the suspended load reductions result from sedimentation (Martin and Miller, 1987). This control measure may be unacceptable should the wildlife habitat functions of wetlands be threatened.

Sewer use ordinances and discharge permits are important tools of source controls in both storm and combined sewers. Volumes of stormwater entering sewers can be effectively reduced by ordinances preventing discharges of roof runoff into sewers (Province of Ontario, 1983). Field surveys indicate that commercial and industrial operations are sources of numerous, often illicit, highly polluted discharges which contaminate stormwater and combined sewage (Schmidt and Spencer, 1986). Consequently, standards are being developed and/or implemented for industrial and commercial discharges into municipal sewers with the objective of requesting pretreatment at the source where necessary (Jost, 1987). Programs introducing stormwater discharge permits, with optional enforcement of stormwater controls, should have similar beneficial effects on stormwater composition.

Chemical use control measures include reduction in the indiscriminate use of lawn chemicals; prevention of spills of oil, gasoline and other chemicals in transport; removal of lead from gasoline, and improved storage, handling and applications of deicing chemicals. With the exception of the last two groups, implementation of these controls largely depends on public information and education programs. Significant progress has been achieved in Canada and the U.S.A. in phase-down of lead in gasoline. An extensive research effort attempting to reduce deicing chemical usage was described by Lord (1988). The currently pursued topics include prevention or destruction of the ice-pavement bond, development of improved displacement plows, controls of blowing snow, and management of snow and ice control. These studies should lead to further reductions in the deicing chemical usage (Lord, 1988).

Surface sanitation and general cleanliness of urban areas enhance runoff quality. Toward this end, anti-litter campaigns and good management of solid waste collection were found particularly helpful (U.S. EPA, 1983). Recent studies of street sweeping found it to be much less effective in runoff quality control than initially thought. Reductions in runoff pollutant loads attributed to frequent street sweeping, three times per week, varied between 0 and 50% (Pitt, 1986; Prych, 1987; U.S. EPA, 1983). Considering the associated costs, street sweeping, while beneficial from the aesthetics point of view, does not appear to be a cost effective measure for runoff quality control. In the case of runoff pollutants originating from industrial air emissions (James and Boregowda, 1986), air pollution control may be the only feasible control measure.

Controls of erosion/sedimentation in urban areas, particularly during land development, are required to avoid large economic and environmental damages (Lord, 1986). Consequently, many jurisdictions developed standards and specifications for erosion and sediment control before and during construction. Typical measures include management options reducing soil loss, cropping by seeding and sodding, mulching, chemical soil stabilization, the use of fabric filters and protective riprap, and structural measures for retardation of flow and retention of sediment - detention and retention ponds, diversion ditches, sediment basins, silt fences and filter berms (Lord, 1986). The protection of urban stream banks against erosion is also recommended (U.S. EPA, 1983).

Although the effectiveness of non-structural runoff control measures widely varies, they are widely practiced because of their low costs and their implementation by a legislation was proposed (Field, 1987).

2.1.2 Structural and Semi-Structural Controls. Structural and semi-structural control measures require some physical modifications in construction of urban areas and comprise such measures as infiltration facilities, overland flow modifications, on-site detention and retention, and solids separation.

As shown in Fig. 3, development of urban land leads to reduced infiltration of rainwater into the ground, reduced recharge of ground water aquifers, and increased surface runoff. Consequently, stormwater management attempts to reverse these processes by enhancing stormwater infiltration either in natural drainage elements or in specially designed infiltration facilities which include porous pavements, and infiltration inlets, trenches, wells, and ponds (Takahasi, 1988). The use of these practices leads to such additional benefits as ground water recharge, and prevention of saltwater intrusion or land subsidence (Geiger et al., 1987).

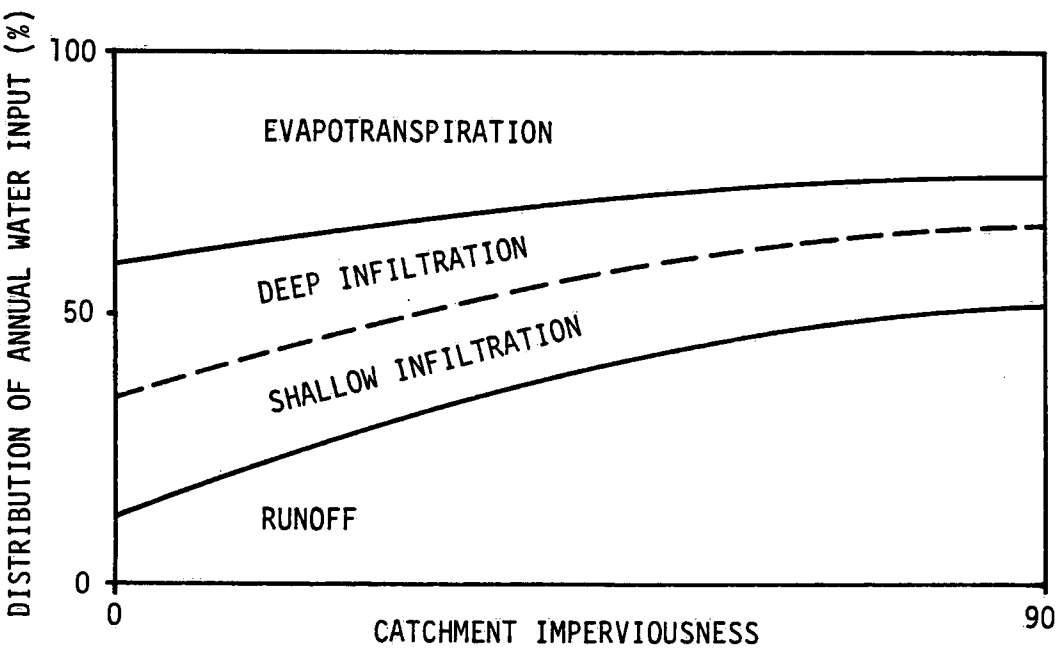

Fig. 3. Water Balance in Urban Catchments

The use of infiltration facilities for runoff control is not universally feasible, but should be based on considerations of local conditions. In particular, infiltration facilities are feasible only in soils with certain minimum infiltration rates, a minimum height of the proposed facility bottom above the ground water table, favourable topography, and minimum distances from building foundations and potable water supplies (Shaver, 1986). Prevention of contamination of ground water supplies is particularly important. In some locations, runoff infiltration does not impact on ground water quality

(Malmqvist and Hard, 1981); in others, ground water contamination by phthalates, polynuclear aromatic hydrocarbons, pesticides, and some inorganics was reported (German, 1987). Sustainable operation of infiltration facilities requires good maintenance and sediment control. Recommendations for dimensioning of infiltration facilities were presented by Jonasson (1984).

Porous pavements use porous asphalt courses (Field et al., 1977; Niemczynowicz and Hogland, 1987), permeable concrete blocks (Pratt et al., 1988; van Dam and van de Ven, 1984), and artificial turf (Ichikawa and Yamamoto, 1984) to allow rainwater percolation into the pavement structure and the underlain soils. Pratt et al. (1988) reported that a high percentage of storms over a permeable concrete-block pavement did not produce any runoff. Porous asphalt pavements may retain up to 50% of total solids, phosphorus and heavy metals in surface runoff. Further evaluations of porous pavement durability, susceptibility to clogging and cleaning are underway.

Infiltration facilities are designed in various geometrical and structural forms. Fujita (1987) and Izumi et al. (1988) reported on the use of infiltration inlets which allow stormwater draining off the streets to infiltrate into the soil through the permeable walls of inlet manholes. Other types of facilities include dry wells (German, 1987), and infiltration trenches and basins (Holmstrand, 1984; Shaver, 1986; Sieker, 1984). Infiltration or recharge basins are sometimes designed as centralized or even regional facilities with good operational control and maintenance (Geiger et al., 1987; Hartigan, 1986). Removal of sediment from stormwater entering infiltration facilities is an important task required to prevent the clogging and reduced effectiveness of these facilities.

On-site stormwater storage refers to detention or retention of runoff prior to its entry into a drainage system. This control measure is widely practiced and recognized as a highly cost effective measure with potential to control both runoff quantity and quality (Province of Ontario, 1983; U.S. EPA, 1983). The literature on stormwater detention is very extensive and includes several handbooks or conference proceedings dealing with this subject (APWA, 1974; DeGroot, 1982; Whipple et al., 1983).

Simple ponding techniques are employed in areas where stormwater may be accumulated without causing any damage or disrupting essential activities. Typical facilities for on-site storage include detention and retention basins/ponds, and dual purpose facilities, such as rooftops, parking lots, manholes, and urban open spaces.

Detention or retention stormwater basins/ponds belong to the most widely practiced runoff controls. The early facilities, which were typically designed as shallow or dry ponds for runoff peak shaving, did not produce any improvements in water quality (Dally and Lettenmaier, 1984; Hampson, 1987). The latest designs control both runoff quantity and quality and generally serve some additional functions as well (e.g., ground water recharge, water supply, and recreation). Extensive experience with stormwater basins/ponds led to the development of guidelines for their design (Grizzard et al., 1986; Hvitved-Jacobsen et al., 1987).

In runoff quality control practice, wet ponds are preferred to dry ponds and the facilities can be sized using the design charts similar to that developed for the U.S. conditions and shown in Fig. 4 (U.S. EPA, 1983). The pond geometry is important from the functional and pollutant removal points of view. Other recommended pond features include elongated shapes with the inlet

and outlet structures at the opposite ends, sediment controls at the pond entrance, outlet structures providing long settling times for frequent runoff events, and gently sloping banks with vigorous vegetation encouraging pollutant uptake by plants (Grizzard et al., 1986; Urbonas and Ruzzo, 1986). Some detention facilities also employ additional control measures, such as stormwater infiltration or effluent treatment. Wanielista et al. (1981) reported the use of a filtration system at the detention facility for effluent polishing.

Flat rooftops, designed for snow load, can be used effectively for detaining up to 0.1 m of rainwater by controlling roof drains (APWA, 1974; Province of Ontario, 1983). However, specially built facilities for detaining stormwater on rooftops may not be cost-effective (Weijland et al., 1988). Similar depths of water can be detained in specially designed parking lots with suitable grading and restricted sewer inlets (APWA, 1974; Province of Ontario, 1983). Stormwater runoff from individual lots can also be detained in oversized manholes with controlled outflow (Phillips, 1987).

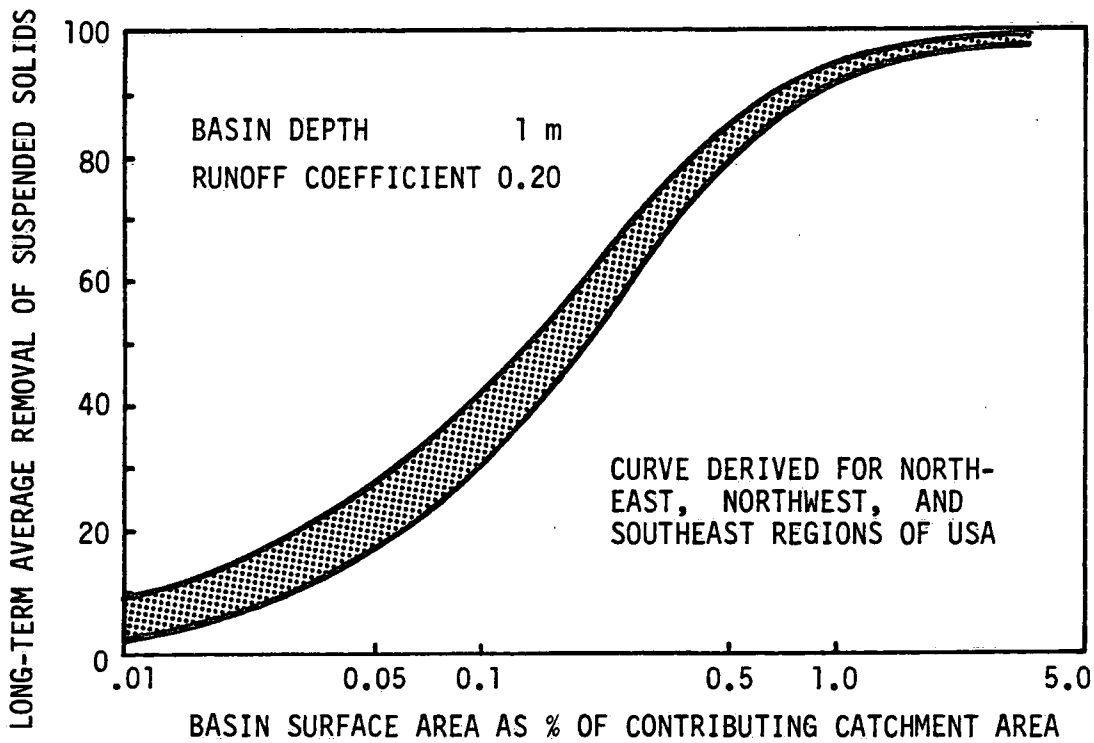

Fig. 4. Sizing of Runoff Quality Control Basins (after U.S. EPA, 1983)

Dual purpose detention facilities are economically attractive. Among these, detention of residential stormwater in parks was found to be the most cost-effective method (Wisner et al., 1981). For specific conditions, such facilities occupied about 2% of the total area serviced and allowed water ponding to a depth of 1 metre. The park would be flooded about once in five years and the water would drain in several hours (Province of Ontario, 1983).

On-site storage is often designed to provide dual or multiple benefits of aesthetics, recreation, ground water recharge, irrigation, sediment control, And others. Examples include ground water recharge on Long Island (U.S. EPA, 1983), stormwater storage in parkettes (Province of Ontario, 1983), or even stormwater storage for water supply (Tay and Chan, 1984). It is acknowledged that these measures generally lead to significant reductions in drainage costs and are therefore readily accepted by land developers (Field et al., 1977).

Overland flow modifications include the use of grassed swales and diversion structures for deceleration of runoff and enhancement of stormwater infiltration. Design should consider maintenance problems; e.g., swales should be designed with a wide bottom to facilitate mowing (Province of Ontario, 1983). Some of these measures were discussed earlier under non-structural measures.

Separation of solids from stormwater is an important consideration in design of practically all structural controls. Excessive influx of sediment into control structures can prevent their proper functioning by clogging soil pores, blocking of outlets, siltation of storage spaces, spoiling of aesthetics, and generation of odor. Prevention of such problems starts with erosion and sedimentation controls discussed earlier and solids separation from stormwater. The removal methods reported include sedimentation basins/traps installed at the inlet to control facilities (Goyen et al., 1987), filters, screens, and swirl or vortex separators (Brombach, 1987; Field, 1986).

Construction costs of runoff source control facilities correlate well with the storage volume created and such correlations can be used in planning-level cost estimates. Multi-purpose water quality control facilities serving larger areas are particularly attractive. Besides economic factors, pollutant removal, aesthetics and recreational values are becoming important factors in the selection of source control options (Wiegand et al., 1986).

2.2 Collection System Controls

Runoff generated on urban surfaces enters drainage collection systems which present opportunities for stormwater controls. Sewer systems are either separate or combined, and each of these types lends itself to certain control measures. Typical control measures discussed in this section include sewer separation; inlet controls; improved design and maintenance of catch basins, sewers, regulators and tide gates; and, real-time flow control.

2.2.1 Sewer Separation. Sewer separation, which is a conventional method of abatement of combined sewer overflows, is no longer considered to be an universal method of pollution abatement, because of high costs, disruption of economic life, and questionable benefits in terms of pollution control. There are, however, cases where the need to improve hydraulic capacity of the existing sewers favours the implementation of complete or partial sewer separation.

2.2.2 Inlet Controls. The rate of runoff inflow into sewers is controlled by sewer inlets and, consequently, sewer inlets can be utilized for effective control of inflows into sewers. In this connection, two types of inlets can be distinguished; street sewer inlets and inlets (connections) of small drains to street sewers. Both types of inlets can employ inlet controls.

Street sewer inlets divide runoff into surface and subsurface drainage components, depending on inlet spacings and hydraulic capacities. The subsurface component, conveyed by sewers, can be reduced by increasing inlet spacing

and/or restricting their capacities. The latter solution is often preferred because it allows corrections, if the surface water ponding is excessive and there is a spare sewer capacity. Inlet restrictions are achieved by installing orifices or other inserts at the inlets (APWA, 1974; Province of Ontario, 1983; Townsend et al., 1981).

Catch basins are installed at the inlets into sewers with the main objective of intercepting large sediment at the entrance to the sewer system and trapping sewer gases. Catch basin designs are not standardized and many of the existing designs are rather ineffective in sediment trapping (Aronson et al., 1983) and may even contribute to stormwater pollution by decomposition of retained materials during dry weather (Fletcher and Pratt, 1981). Consequently, a number of research studies addressed the operation of catch basins (Pratt and Adams, 1981; Aronson et al., 1983; Wada and Miura, 1987) and improvements in their design by incorporation of inlet strainers (Aronson et al., 1983; Fujita, 1987), filters (Broeker, 1984), flow restrictors and siphon drainage (Grottker and Hurlebush, 1987). To maintain catch basins effectiveness in pollutant retention, they have to be cleaned regularly (Pitt, 1986). These problems should be mitigated by new designs with flow limitation and siphon drainage which ensure complete emptying of the catch basin contents and reduce the needs of cleaning (Grottker and Harlebush, 1987).

Connections of property drains to sewers offer another opportunity for inlet controls. In this particular case, the inflow can be restricted by using hydraulic devices which allow a constant design discharge under a varying head (Brombach, 1988). As the runoff discharge increases, stormwater is backed up upstream of these controllers and additional inflows are either temporarily stored in storage manholes and on the catchment surface, or diverted into small underground storage tanks (Walesh, 1986). One of such designs is shown in Fig. 5 (Phillips, 1987).

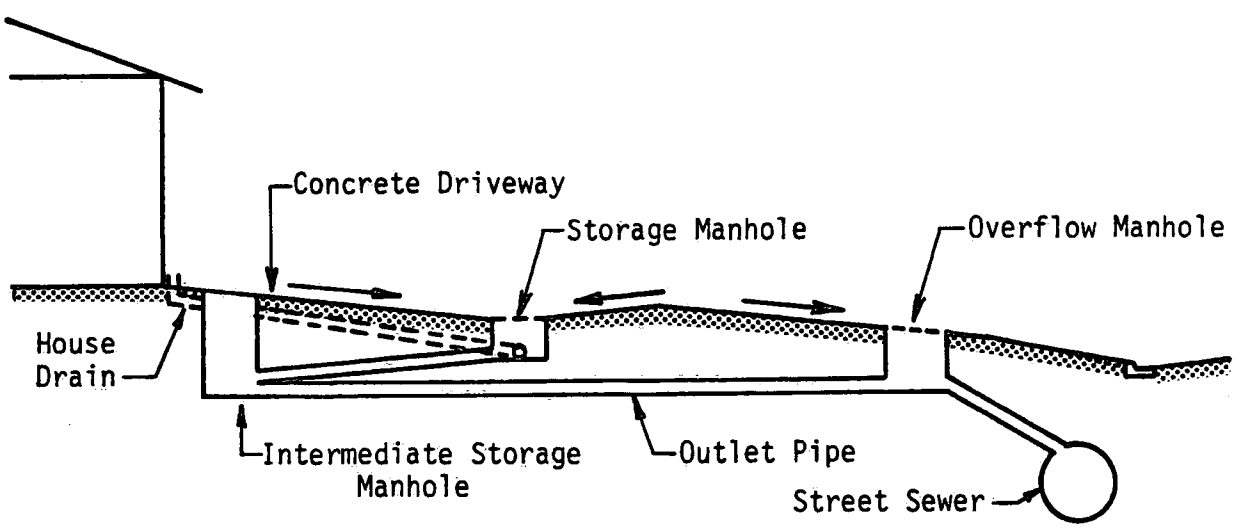

Fig. 5. Inlet Controls: On-Site Storage (after Phillips, 1987)

2.2.3 Sewer Pipe Controls. Sewer pipe controls comprise a number of measures aimed at reducing the inflows by reducing infiltration and inflow of extraneous flows into sewers, reducing the flows conveyed by exfiltration, increasing the pipe capacity by reduction of head loses, increasing the in-system storage, and reducing sludge depositions in sewers by proper hydraulic design or maintenance.

Sewer systems may be receiving more flow than provided for in their design because of illicit connections and infiltration of extraneous flow into sewers. In worst cases, these additional flows may reach 30% of the total flow (U.S. EPA, 1971). Such vast volumes of extraneous water are particularly harmful by using up the pipe capacity, and, in the case of combined sewers, contributing to increased operational and capital costs of wastewater treatment plants. Practical instructions for detection, monitoring, and correction of excessive infiltration and inflow have been developed (U.S. EPA, 1971).

Discharges carried by sewers can be reduced by using perforated sewer pipes allowing exfiltration of stormwater (Pitt, 1986). Under favourable hydrogeologic conditions, permeable drainage pipes were found effective in reducing the upstream inflow by exfiltration (Wada et al., 1987). The same restrictions as in the case of infiltration facilities apply.

Sewer pipe capacities can be increased and frequencies of overflows reduced by reducing head losses in the existing sewer systems. Such reductions can be achieved by reducing skin friction in pipes and/or form losses at pipe junctions and appurtenances. Soluble polymers reduce turbulent skin friction in pipes and increase sewer capacities. Frequencies of combined sewer overflows can be reduced by polymer injections resulting in polymer concentrations of 70 ppm, which should increase the pipe capacity by about 30% and be economic in favourable cases (Oles and Bewersdorff, 1987). Form losses at pipe junctions are reduced by installing hydraulically efficient benchings (Marsalek, 1988a).

Detention of runoff in sewers and reduction in the controlled outflow at the downstream end can be achieved by using over-sized pipes which are also referred to as the superpipes. The outfall requires an appropriate throttling control to force flow storage in the superpipe. These structures are relatively expensive and may require an overflow to limit surcharge levels for infrequent storms (Province of Ontario, 1983).

Sewer deposits represent a source of various pollutants mobilized during wet weather with concomitant high sewage flows. To prevent pollutant scouring, sedimentation in combined sewers has to be reduced. In new drainage systems, control of solids deposition starts with hydraulic design based on maintenance of self-cleansing velocities (Field et al., 1977). In the existing installations, such control measures as sewer flushing (Field et al., 1977), passage of flushing balls to impede formation of depositions, and the dragging of a scouring board to remove the existing depositions were successfully tested (Broeker, 1984).

2.2.4 Sewer Flow Controls by Overflow Regulators. Overflow regulators protect collection lines, interceptors and sewage pumping and treatment plants against overloading by diverting excessive sewage flows and, in some cases, provide some pretreatment of such diverted flows. Reductions in discharged pollutant loads can be achieved by using new regulator designs, which provide effective flow control and either release the less polluted parts of sewage flows, or provide their pretreatment at the overflow structure. Thus, some control of stormwater overflows can be achieved by replacing the old-type regulators by new designs.

Recent improvements in the regulator technology include the development of air-regulated siphons and swirl or vortex devices which are used as regulators and/or solids separators. Air-regulated siphons are ideally suited for the use as overflow regulators, because of their simplicity, good flow regulation, and low maintenance requirements (Markland and Brombach, 1987).

The swirl flow device has been developed and extensively tested by the U.S. EPA (Field et al., 1977; Pisano, 1988). It has been used in various single or dual purpose applications, serving as a flow regulator/solids-liquid separator, degritter, and primary clarifier (Field et al., 1977). Recent experiences with swirl and helical devices were reported by Pisano (1988).

Vortex liquid-solid separators designed for reduction of solids loadings in combined sewer overflows were described by Brombach (1987), Balmforth et al. (1984), and Balmforth (1987). Such devices show a great promise in removing from 20 to 75% of solids from the overflows escaping from the sewers, but further field testing is desirable.

2.2.5 Real-Time Control of Sewer Flow and Pollutant Routing. Real-time control is the most advanced and sophisticated method of operation of sewer systems aimed at minimizing the volume, frequency, pollutional load, and receiving water impact of combined sewer overflows. The implementation of comprehensive real-time control systems requires peripheral monitoring and telemetering stations; computer facilities processing the incoming data, predicting sewer flows and their composition in various parts of the system, and identifying the preferred control strategy; and, a control system for remotely operating the sewer system to allow overflows of less polluted batches of combined sewage at points where the environmental impact is the least.

Many theoretical concepts for real-time control of flows in combined sewers were developed already in the seventies (Labadie et al., 1975) and over the years, some elements of real-time control were implemented in numerous cities. Schilling (1986) listed 18 cities in Canada and the U.S.A. which use some elements of real-time control in their combined sewer systems. Typical components of such systems include rainfall, water level, and overflow operation monitors; telemetering systems; central computer facilities for data storage and processing, and flow forecasting; and, remotely controlled regulators and pumping stations. Similar examples were reported in Japan (Sueishi and Kido, 1987) and several European countries (Delattre et al., 1986; Fuchs and Neumann, 1987; Nelen et al., 1987; Schilling, 1988; Weyand and Dohmann, 1987). Recent advances in to the development of real-time control systems include the use of weather radars (Denoux et al., 1987), the use of optical sensors in overflow quality sensing (Marchandise et al., 1987), development of real-time flow simulators (Mazadou et al., 1987) and control techniques (Beron et al., 1984), and the use of artificial intelligence in development of overflow control strategies (Fuchs and Neumann, 1987).

2.3 Storage and Treatment

Storage and treatment are applied jointly in stormwater management recognizing that storage by itself provides some treatment by sedimentation and that treatment requires flow balancing by storage.

2.3.1 Storage. Storage is perhaps the best documented abatement measure for control of combined sewer overflows and management of urban stormwater. Storage can be built into the drainage systems at various locations in the form of on-line or off-line facilities. On-line storage refers to oversized or multi-barrel sewer sections which were discussed earlier. Off-line storage refers to the storage facilities which are built outside of the sewer system and connected to it, usually in the downstream sections of drainage systems. The use of storage facilities in downstream sections of separate storm sewer systems is not common because of relatively high costs. On the other hand, off-line storage facilities for control of combined sewer overflows are very common. In this case, the stored volume of combined sewage is continuously drained in the form of underflow into the wastewater treatment plant. After the inflow subsides, the stored volume is returned to the wastewater treatment plant for treatment. An example of an off-line storage tank is shown in Fig. 6 (Onderdelinden and Timmer, 1988).

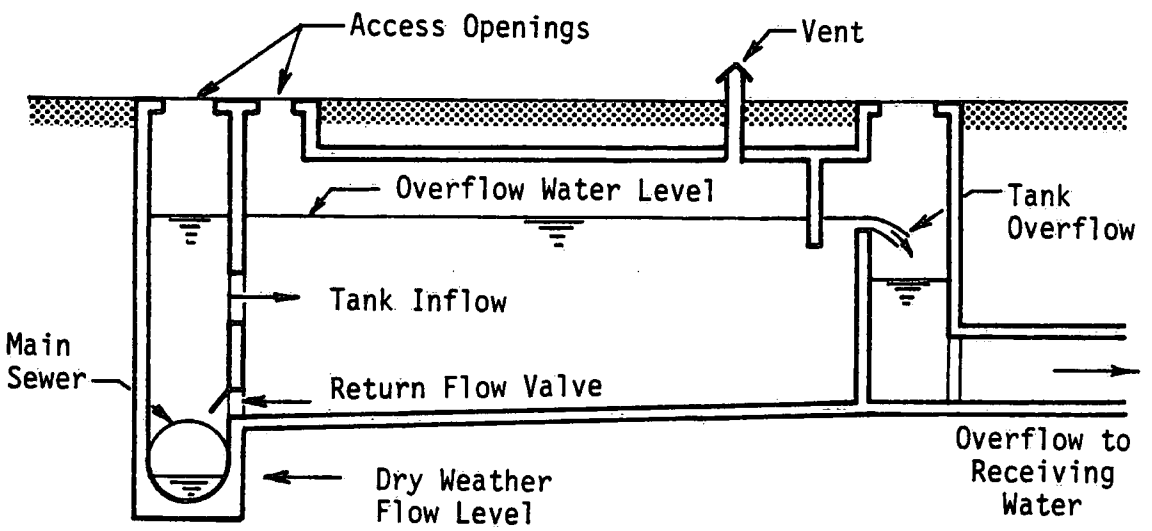

Fig. 6. Stormwater Sedimentation Tank (after Onderdelinden and Timmer, 1988)

Various types of facilities for storage of combined sewage have been proposed including storage tanks, deep tunnels, underwater facilities (Field, 1986), and in-receiving water flow balancing facilities (Soderlund, 1984).

Two types of pollution control by storage are recognized, indirect control by flow pattern modification and reduction of overflows, and direct control by treatment of the stored volume, primarily by sedimentation. In direct-control facilities, the most important design considerations include the geometrical configuration, and the pollution load and its settling characteristics (Stahre, 1986). Features favourable for efficient sedimentation include elongated shapes of facilities in the plan (length/width greater than 2), locations of inlets and outlets at the opposite ends, the use of baffles or flow retarding devices at the inlet, and the use of sand and grit traps at the inlet (Stahre, 1986). The design should further consider settling characteristics of the sewage sediment for the location studied. Many pollutants of concern, such as

phosphorus, heavy metals, and petroleum-derived organics, have high affinity for suspended solids and are removed with solids. The best removal efficiencies of suspended solids, as high as 70-80%, are obtained in large storage ponds with long detention times (Stahre, 1986).

Many storage facilities also serve additional auxiliary functions, such as flood protection and hazardous spill containment during dry weather. Disadvantages of storage controls include large sizes of storage structures and dependency on other treatment facilities for dewatering and solids disposal (Field et al., 1977).

2.3.2 Treatment. Stormwater effluent quality can be improved by treatment. Highly variable stormwater flows and shock pollutant loadings prevent the adaptation of traditional municipal sewage treatment methods to stormwater. Treatment plants for runoff quality control must allow a high-capacity automatic intermittent operation with rapid start-up and shut-down, and deal effectively with shock loadings (Field et al., 1977). In general, such requirements are better met by plants employing physical/chemical rather than biological treatment processes.

Applicabilities of many treatment processes to stormwater treatment have been demonstrated. Typical processes recommended for stormwater treatment include physical treatment processes/systems with or without chemicals, such as fine mesh screening, swirl degritting, fine-mesh screening/high rate filtration, sedimentation, fine-mesh screening/dissolved air flotation (Field, 1986), high-rate filtration and coagulation (Nakamura et al., 1987), and solids separation by vortex separators (Brombach, 1987). Among biological processes, the applicability of contact stabilization, high-rate trickling filtration, rotating biological contactors, and lagoons has been demonstrated in stormwater treatment (Field et al., 1977). In stormwater disinfection, high demands on disinfectant quantities and contact times were noted. Recent investigations focused on high-rate applications using static and mechanical mixing, high disinfectant concentrations, and the use of rapid oxidants (Field, 1986). Typical performances data for various treatment processes are summarized in the table below (Field, 1986).

Table 1. Efficiencies of Stormwater Treatment Processes

Device	Control Alternatives	Removal Efficiency (%)	
		BOD_5	Suspended Solids
Primary	Swirl concentrator	25 - 60	50
	Microstrainer	40 - 60	70
	High-rate filtration	60 - 80	90
	Dissolved air flotation	50 - 60	80
	Sedimentation	25 - 40	55
	Representative performance	40	60
Secondary	Contact stabilization	75 - 88	90
	Physical/chemical	85 - 95	95
	Representative performance	85	95

2.4 Integrated Stormwater Management Systems

Integrated systems represent the most promising approach to urban stormwater management. Comprehensive stormwater management systems employ wide varieties of source controls, collection system controls, and storage and treatment options. Examples described by Field (1986) included storage/treatment combinations, dual use of wet-weather flow/dry-weather flow facilities, and control/treatment/reuse schemes. Schilling et al. (1988) studied an integrated controls system comprising on-site detention, infiltration and stormwater reuse. Comparisons of performance and costs of several stormwater controls and their combinations were given by Pitt (1986), Weijland et al. (1988) and Wiegand et al. (1986).

3. Conclusions

During the last 20 years, the management of stormwater has evolved from rapid removal of runoff to comprehensive and cost-effective stormwater management approaches which provide flood protection and drainage convenience, and, at the same time, strive to minimize runoff impacts on the receiving waters. This progress has been achieved through an improved understanding of runoff processes and by the development of runoff controls. Even though the theoretical concepts of many control measures have been known for a long time, their applicability in stormwater management had to be tested in the field. In most cases, such extended-time testing has been successfully completed and a wide variety of field-proven runoff controls is now available for practical applications. In comparison to new drainage systems, retrofitting or rehabilitation of the existing drainage systems is more difficult and challenging, because the existing system constraints tend to restrict the applicability of some runoff controls. The most successful and cost-effective stormwater management schemes integrate all feasible and economic stormwater controls at the source, in the collection system, and off-line storage and treatment. The implementation of such measures limits the growth of drainage infrastructures and provides a better protection of the environment.

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