Integrated Storm-Water Management for Watershed Sustainability

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Abstract: One aspect of integrated watershed management evaluates the impact of development on the local hydrologic cycle and, in particular, drinking water, wastewater, and storm-water infrastructure. Sustainable storm-water management focuses on selecting storm-water controls based on an understanding of the problems in local receiving waters that result from runoff discharges. For example, long-term problems associated with accumulations of pollutants in water bodies include sedimentation in conveyance systems and receiving waters, nuisance algal growths, inedible fish, undrinkable water, and shifts to less sensitive aquatic organisms. Short-term problems associated with high pollutant concentrations or frequent high flows (event-related) include swimming beach closures, water quality violations, property damage from increased flooding, and habitat destruction. A wide variety of individual storm-water controls usually must be combined to form a comprehensive wet weather management strategy. Unfortunately, combinations of controls are difficult to analyze. This will require new modeling techniques that can effectively evaluate a wide variety of control practices and land uses, while at the same time ensure that the flood-control objectives also are met. The results of these new models and novel techniques used for storm-water control then can be incorporated into an evaluation of the urban water cycle for a specific service area to determine whether storm-water controls can provide additional benefits such as reduction of potable water use and reduction of sanitary sewer overflow events.

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Wet Weather Flow Management: Lessons Learned from Past and Elsewhere

One of the biggest impediments identified over the years to improved approaches to watershed management is the lag in the rapid implementation of newly developed (and proven) technology. Over 30 years ago, McPherson (1975, 1978) offered suggestions to reduce the technology transfer (development to implementation) lag time. Many worthwhile tools/techniques have been demonstrated successfully singly, but have not been adequately examined when implemented in combination throughout the watershed. Urban water issues that offer opportunities for future sustainable development and that need to be considered in an integrated watershed management approach include the following:

1. Periodic droughts and resultant implementation of strict water conservation measures. Unfortunately, few technical evaluations of the benefits on wastewater production and treatment of these conservation measures exist.
2. Water reuse. Water reuse has been implemented in scattered areas, but many jurisdictions are reluctant to adopt these "exotic" approaches until conditions become critical.
3. Combined sewerage systems. Developing nations often are installing combined systems to collect dry and wet weather flows. This approach may be optimal for areas such as ultra-urban districts of large cities if adequate storage and treatment can be provided.
4. Leak control on separate sewer systems. Improved wastewater collection systems, such as vacuum or pumped systems, reduce or remove the inflow and infiltration that plague many older systems, which reduces inappropriate discharges into the system.
5. On-site wastewater treatment concerns. On-site treatment has flourished in areas where land space and soil meet the existing guidance. Unfortunately, few options exist to correct failing systems. Higher densities of on-site systems usually are related to both increased groundwater contamination and inappropriate discharges of partially treated sanitary sewage to storm drainage systems.
6. Conservation design. Conservation design aims to minimize storm water discharges from new developments through combinations of better site design, infiltration, and treatment practices. The practice considers groundwater protection, appropriateness of soils for infiltration and critical source area controls, as well as capture/reuse of less contaminated storm water for nonpotable uses (irrigation, toilet flushing, firefighting, etc.).

The list below describes several moderate- to large-scale applications of many of these practices.

1. Germany and Switzerland: Regulations prohibit roof and pervious area runoff from entering combined sewers, which has

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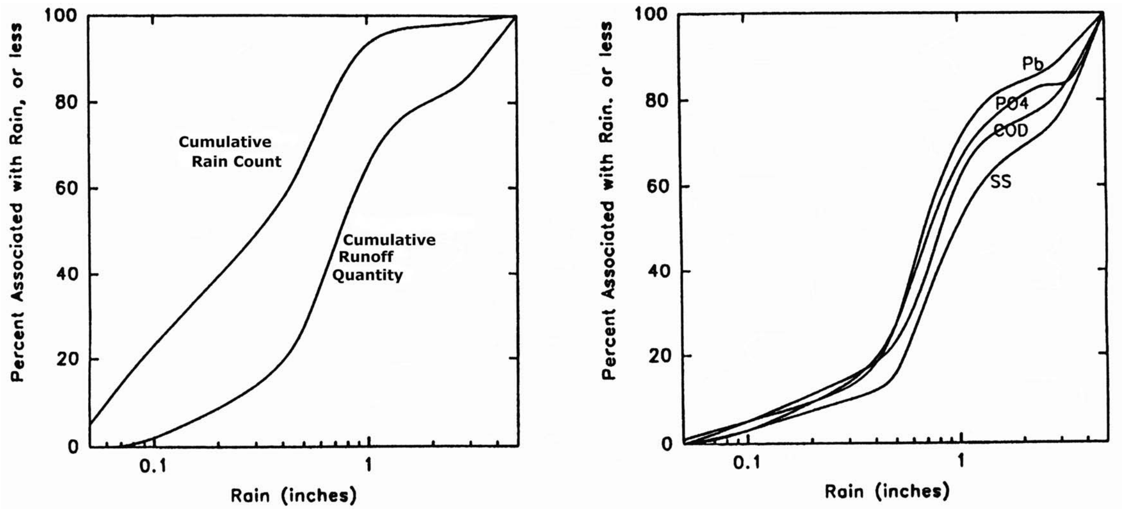

Fig. 1. Milwaukee rainfall and runoff probability distributions, and pollutant probability distributions (1 mm=0.039 in.) (Pitt et al. 1999)

led to wide implementation of advanced combined sewer designs and controls, plus storm-water infiltration in upland areas.

2. Japan (Tokyo): The experimental sewer system implemented large-scale infiltration and treatment in heavily developed areas. Captured storm water for toilet flushing is commonly used in large buildings.
3. United States (increasingly implemented in the mid-Atlantic/Chesapeake Bay and in the Pacific Northwest): "Low impact development" and "better site design" stress "softer" approaches to storm-water management, with emphasis on infiltration and reduction of impervious surfaces.
4. California (Los Angeles): The Hyperion sewage treatment plant pumps about 6% of its treated wastewater to a water reclamation plant prior to its use for golf course and park irrigation, as well as for industrial water. Veterans' hospitals use storm-water ponds for firefighting water supplies.
5. Arizona (Phoenix) and Tampa Bay (Florida): Treated sanitary wastewater used for golf course irrigation.
6. New Zealand (Auckland region): Roof runoff is captured with cisterns and rain barrels for toilet flushing and irrigation reuse. In rural areas, roof runoff serves all household water needs.
7. Australia (Sydney): Sydney Water found that approximately 61% of household wastewater (not including kitchen wastewater) is greywater that can be captured for reuse for toilet flushing and irrigation. Companies sell household water tanks and treatment units for household greywater reuse and for rainwater consumptive use inside the home and for irrigation.
8. Texas (Austin): Rural residents frequently rely on roof runoff (with commercial tanks and household water treatment systems) to supply all their water needs. Outbuildings are commonly sized to provide the necessary runoff capture area.
9. Storm water as a landscaping element has been emphasized by Herbert Dreiseitl Waterscapes (Überlingen, Germany). Cities are presumed to be more attractive to residents because of the nature of moving water.

These illustrate a few examples of the varied aspects of urban water that could be considered simultaneously in an integrated urban water management program. Unfortunately, quantitative assessments of integrated designs which consider the interaction of these components are very complex, requiring the simultaneous use of several models and other tools.

Optimization is a relatively recent addition to wet weather flow management practice, although simplified algorithms and techniques have been used in the past. The purpose of using an optimization procedure is to select a design that maximizes pollutant control, while minimizing receiving water impacts, and costs, while also possibly considering many other objectives. Using optimization will eliminate many designs that are unsustainable. The implementation of mathematical optimization will make decisions more objective and efficient, but there is still much "art" remaining in successful storm-water management.

Storm-Water Drainage Design Objectives

An idealized wet weather flow management system should include those attributes that directly affect storm-water conveyance. Basic to these is an understanding of the different objectives of storm-water drainage systems, and the associated rainfall and runoff conditions. There are at least four major aspects of the drainage system, each reflecting distinct portions of the long-term rainfall record. Fig. 1 is an example of observed rainfall and runoff observed at a medium-density residential area in Milwaukee, during the 1981 and 1982 rain years (Bannerman et al. 1983), as monitored during the Nationwide Urban Runoff Program (EPA 1983). Of note in this distribution are the two unusually large rains that occurred during this monitoring program. More than half of the runoff during this period was associated with rain events that were smaller than 19 mm (0.75 in). The two largest storms [about 75 and 125 mm (3 and 5 in.) in depth] distort this figure because, on average, the Milwaukee area only expects one 90 mm (3.5 in.) storm every 5 years. Without the influence of these large rains, e.g., more typical years, the significance of the smaller rains would be even greater. Fig. 1 also shows the cumulative loadings of different pollutants [suspended solids, chemical oxygen demand (COD), phosphate, and lead, as examples]. A comparison of the pollutant and rainfall-runoff distribution figures shows that the runoff volume and pollutant discharge distributions are similar, and that variations in the runoff volume are much more important than variations in pollutant concentrations for determining pollutant mass discharges.

As noted above, the rainfall and runoff distributions for Milwaukee can be divided into four regions, which then can be used to guide design practices:

1. <12.5 mm (<0.5 in). These rains account for most of the events (60% of the rainfall events and 45% of the runoff events; these occur 1–2 times/week), but little of the runoff volume (about 20% of the runoff and pollutant discharge). Rains less than about 1.3 mm (0.05 in.) did not produce noticeable runoff. This rain category produces much less pollutant mass discharges and probably has less receiving water effects than larger rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants for each of the numerous events (e.g., bacteria). They can also cause large numbers of overflow events in uncontrolled combined sewers. In most areas, this runoff should be totally captured and either reused for on-site beneficial uses or infiltrated in upland areas. Runoff from these rains should not enter the storm sewer system.
2. 12.5–40 mm (0.5–1.5 in). These rains account for the majority of the runoff volume (about 50% of the annual volume for this Milwaukee example) and produce moderate to high flows. By number, they account for about 35% of the annual rain events, and about 20% of the annual runoff events. These rains occur on average about every 2 weeks during the wet seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows. Small rains in this category should be captured on site for reuse or infiltrated to replenish the lost groundwater recharge associated with urbanization. Runoff from the larger rains and from critical source areas should be treated to prevent pollutant damage to receiving waters.
3. 40–75 mm (1.5–3 in.). These infrequent rains (occurring every several months; or about once to twice a year) produce the most damaging flows when considering habitat destruction. These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. They account for only about 2% of the rains, but they are responsible for about 10% of the annual runoff and pollutant discharges for this example. Storm drainage design events may fall in the upper portion of this category, depending on the time of concentration and the rain intensity. Extensive storm-water pollution controls for these events would be very costly, especially considering their relatively small portion of the annual runoff. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. Infiltration and other treatment controls used for the smaller storms would somewhat reduce pollutant discharges during these storms.
4. >75 mm (>3 in.). The smallest rains in this category include the design storms for drainage systems in Milwaukee, depending on the times of concentration and rain intensities. These rains occur only rarely (once every several years to once every several decades or less frequently) and produce extremely large flows. Even in this unusual year, less than 2% of the rains were in this category (typically $\ll$1% would be in this category), and they produced about 15% of the annual runoff quantity and pollutant discharges. However, when they do occur, substantial property and receiving water damage results, and loss of life is a concern. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of aquatic organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years. These storms, while very destructive, are sufficiently rare that the resulting environmental problems do not justify the massive controls that would be necessary to decrease their environmental effects. They typically greatly exceed the capacities of the storm drainage systems and it is critical that flows greater than the drainage system capacity be conveyed in planned "secondary" drainage systems, such as graded large depressions between buildings that direct the water away from the buildings and critical transportation routes. Because these events are so rare, institutional memory often fails, and development is allowed in areas that are not indicated on conventional flood maps, but still sustain periodic flood damage.

The above specific values are given for Milwaukee. Milwaukee was selected as an example because of the occurrence of two very rare rains during an actual monitoring period. Obviously, the critical values defining the different storm types would be highly dependent on local rain and development conditions. These plots indicate how rainfall and runoff probability distributions can be used for more effective storm drainage designs in the future. In all cases, better integration of storm-water quality and drainage design objectives requires the use of long-term continuous simulations as part of selecting and evaluating which upland and end-of-pipe storm-water quality controls to use on a particular site. The complexity of most receiving water quality problems prevents a simple analysis, such as the use of single-event design storms.

In order to examine the rainfall and runoff patterns in other locations, long-term continuous simulations were made using WinSLAMM, the source loading and management model (Pitt 1986, 1997, 1999; Pitt and Voorhees 2002) for 22 representative locations throughout the United States. These locations represent most of the major United States river basins and much of the rainfall variation throughout the country. These analyses were only intended to show the importance of these smaller and intermediate-sized rains for many different regions and conditions, and were not intended to be used for design purposes. The recommended approach for design is to continuously model with long rain records and using site-specific conditions.

These simulations were based on 5 to 10 years of hourly rainfall records, usually containing about 500 individual rains. The rainfall records were from certified NOAA weather stations and were obtained from CD-ROMs distributed by EarthInfo of Boulder, Colo. These data sets then were read by a utility program included in the WinSLAMM package. This rainfall file utility combined adjacent hourly rainfall values into individual rains, based on user selections (for this exercise, a 6 h minimum inter-event period (no rain) was selected; all rain depths were used, with the exception of the "trace" values). These rain files for each city were then used in WinSLAMM to predict runoff patterns for typical medium density and strip commercial developments. The outputs of these computer simulations were then plotted as shown in Fig. 2 for Atlanta, Austin, Tex., Billings, Mont., and Birmingham, Ala. The figures for the other cities can be found in Pitt et al. (1999).

Table 1 summarizes these rainfall and runoff distributions for different United States locations. Lower and upper runoff distribution breakpoints were identified on all of the individual distributions. The breakpoints separate the distributions into the following three general categories:

1. Small, but frequent rains (less than lower breakpoint). These

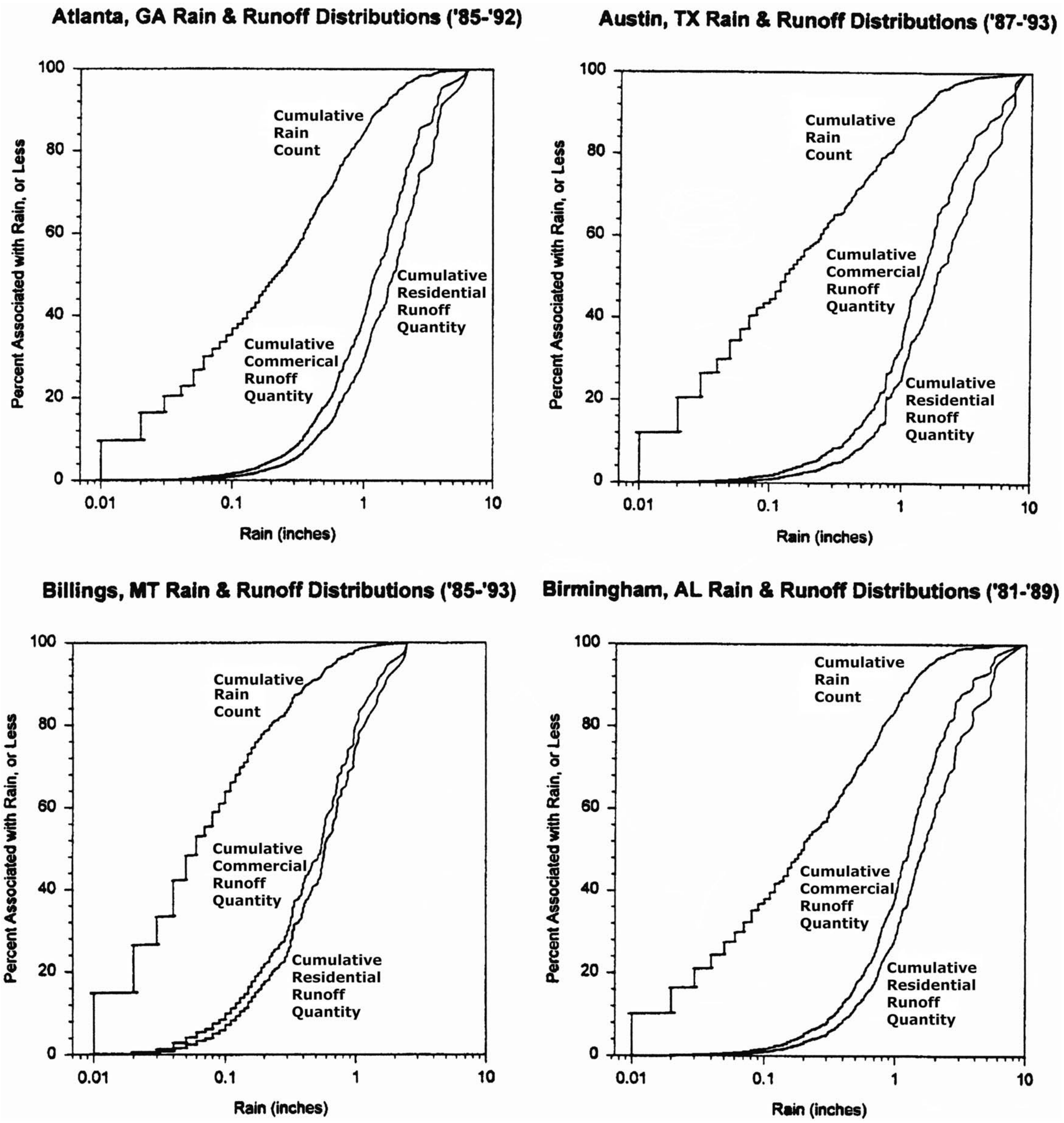

Fig. 2. Modeled rain, runoff, and pollutant distributions (1 mm=0.039 in.) (Pitt et al. 1999)

generally account for 50–70% of all rain events (by number), but only produce about 10–20% of the runoff volume and pollutant discharge. The rain depth for this breakpoint ranges from about 2.5 mm (0.10 in.) in the Southwest arid regions of the country, to about 12 mm (0.5 in.) in the wet Southeast. These frequent rains are likely sources of water quality violations associated with urban storm-water discharge, such as violations for bacteria (especially fecal coliforms) and total recoverable heavy metals.

2. Moderate rains (between the lower and upper breakpoints). These rains generally account for 30–50% of all rain events (by number), but produce 75–90% of all of the runoff volume and pollutant mass discharge. The rain depths associated with the upper breakpoint range from about 25 to 50 mm (1–2 in.) in the arid parts of the United States up to 75–90 mm (5–6 in.) in wetter areas. These intermediate rains account for much of the actual receiving water problems associated with storm-water mass discharges.
3. Large, but rare, rains (above the upper breakpoint). These rains include the typical drainage design events. During the period analyzed, many of the sites only had one or two, if any, events above this breakpoint. These rare events do account for about 5–10% of the runoff on an annual basis in most areas. These events must be evaluated to ensure that the primary and secondary drainage systems are adequate (and in the case of the secondary drainage system, its location is known).

Because of the importance of small and moderate rains on urban receiving waters, which are not the drainage design events, it is important to review the common urban hydrology methods used to predict runoff from urban areas. It is also critical to understand the limitations of these conventional design tools when applied to sustainable storm-water management.

Design Methodology Framework

The literature contains many design methodologies and planning strategies for wet weather flow management. However, few have

Table 1. Rainfall and Runoff Distribution Characteristics for Different Locations throughout the United States

	Median rain depth, by count (mm)	Corresponding percentage of runoff for rains less than the median rain depth (%)	Rain depth associated with median runoff depth (mm)	Lower breakpoint rain depth (mm)	Percentage of rain events less than lower breakpoint (%)	Percentage of runoff volume less than lower breakpoint (%)	Upper breakpoint rain depth (mm)	Percentage of rain events less than upper breakpoint (%)	Percentage of runoff volume less than upper breakpoint (%)	Percentage of runoff volume between breakpoints (%)	Percentage of rain events between breakpoints (%)
Columbia North Pacific											
Boise, Id.	1.8	3–5	7.6–8.9	2.5	52	9–11	23	99	89–93	80–82	47
Seattle	3.0	4–6	16–20	4.6	60	8–11	86	99	92–96	84–85	39
California											
Los Angeles	4.6	3–5	30–38	7.4	64	7–10	89	99	92–98	85–88	35
Great Basin											
Reno, Nev.	1.8	3–5	8.9–10	2.5	61	8–10	43	99	93–95	85	38
Lower Colorado											
Phoenix	2.5	4–6	14–17	4.8	64	9–12	58	99	94–98	85–87	35
Missouri											
Billings, Mont.	1.5	2–4	14–15	3.0	64	8–10	41	99	89–93	81–83	35
Denver	2.0	2–4	12–15	4.8	71	13–17	46	99	91–95	78	28
Rapid City, S.D.	1.5	2–4	12–14	3.8	69	10–13	48	99	92–96	82–83	30
Arkansas-White-Red											
Wichita, Kan.	3.3	2–5	28–36	7.9	65	10–13	76	99	88–93	78–80	34
Texas Gulf											
Austin, Tex.	3.6	2–3	36–46	12.7	72	8–12	150	99	88–94	80–82	27
Upper Mississippi											
Minneapolis	2.8	3–5	19–25	5.6	65	9–13	71	99	94–96	83–85	34
Madison, Wis.	3.0	3–5	20–25	5.8	65	9–13	89	99	97–99	86–88	34
Milwaukee	3.0	2–4	23–28	6.4	65	9–12	64	99	89–95	80–83	34
St. Louis	3.6	4–6	25–30	7.9	65	10–13	71	99	90–95	80–82	34
Great Lakes											
Detroit	5.1	7–11	18–21	5.1	50	7–11	61	99	92–95	85–84	49
Buffalo, N.Y.	2.8	2–4	15–18	3.0	64	8–12	53	99	88–93	80–81	35
Ohio											
Columbus, Ohio	3.0	3–5	20–25	5.6	63	8–12	56	99	85–91	77–79	36
North Atlantic											
Portland, Me.	3.8	2–4	28–38	7.6	64	8–12	4.5	99	90–96	82–84	35
Newark, N.J.	7.1	6–12	30–38	8.4	54	8–12	3.3	99	89–94	81–82	45
Lower Mississippi											
New Orleans	6.4	3–5	43–56	11.4	62	7–11	4.0	99	88–93	81–82	37
South Atlantic Gulf											
Atlanta	5.6	3–5	30–43	8.1	58	5–9	4.0	99	91–95	86	41
Birmingham, Ala.	5.1	3–5	30–38	10.2	64	8–13	5.0	99	90–96	82–83	35
Raleigh, N.C.	4.6	4–6	25–30	6.6	60	7–11	2.5	99	87–93	80–82	39
Miami	3.3	3–5	30–41	7.6	67	9–13	4.0	99	87–93	78–80	32

gained wide practice, possibly because of the lack of enforcement and because most are not geared towards the practicing engineer. A well-accepted design methodology needs to (Pitt et al. 1999):

- Focus on microdevelopment (the tens of acres level);
- Be robust and flexible;
- Be cognizant of the expense of data collection and management;
- Be reproducible and consistent;
- Use widely accepted models to simulate wet weather flow systems;
- Use the levels of spatial and temporal discretization appropriate to the task;
- Account for uncertainty in the real and modeled systems;
- Have a common-sense feel;
- Have a rationale that is easily conveyed to lay persons,
- Be relatively inexpensive to implement; and
- Produce results that are economically, politically, and socially acceptable in typical urban settings.

For sound and sustainable storm-water and watershed management, the selection of control technologies must be strongly influenced by actual performance data and the applicability of each control technology to given watershed conditions and receiving water problems. Different technologies have different strengths and weaknesses that must be matched with the desired performance requirements. Sustainable designs that address receiving water concerns must select technology based on actual performance of the control under wet-weather flow conditions and on the problems requiring control.

Overall Control Strategies Must Be Based on Long-Term Simulations

For many decades, the approach to wet weather management has been through the use of a single design storm for sizing both treatment practices and conveyance systems. The problems associated with design rains are many and discussions can be found in a number of early publications (McPherson 1978; Nix 1982, 1994; Adams and Howard 1985; Huber and Dickinson 1988; among others). One problem is that the frequency characteristics of a given rainfall event rarely, if ever, coincide with the frequency characteristics of the corresponding runoff event. Single design storms also are not appropriate for evaluating water quality problems associated with storm water. Receiving water problems are typically caused by a variety of different causative factors and no clear "design" condition can be used to guarantee acceptable receiving water conditions (Burton and Pitt 2002). Continuous simulation can overcome these deficiencies by driving a model of the urban watershed (and any associated control technologies) with many decades of rainfall data and then analyzing the frequency and severity of occurrence of various runoff quantity and quality characteristics.

Decision Analysis Evaluations of Alternative Control Programs

Decision analysis is a systematic procedure that enables one to study the trade-offs among multiple and usually conflicting program objectives. The simplest approach, often used in the past, is to separately determine the programs/techniques necessary to meet each objective and to use the least costly combination that satisfies all the identified critical objectives. This is acceptable some of the time, but may not result in the most cost-effective program, especially when multiple objectives need to be considered. Decision analysis considers the partial fulfillment of all the objectives. It translates these into their relative worth to the decision-maker or other interested parties.

Current wet weather flow models, used singly or in combination, can produce great quantitites of information concerning control strategies and predicted effectiveness. As an example, WinSLAMM, the source loading and management model (Pitt 1986; Pitt and Voorhees 2002) can calculate numerous attributes, including runoff volume (ft^3, Rv, source contributions), pollutants (mass discharges, concentrations, and source contributions), control program costs (capital, maintenance, and annualized total costs), flow-duration probability distributions, and expected biological conditions in the receiving waters. Several decades of rainfall data normally are used for simulation of the study area. The model's batch processor allows automated evaluations of numerous scenarios for a site, which then can be integrated into an appropriate decision analysis approach and, if desired, into geographic information systems. The advantage of this continuous simulation model is that the model can evaluate a wide range of source, drainage system, and outfall controls, including development characteristics, disconnections of drainage from roofs and pavements, bioretention devices, soil amendments, porous pavement, street cleaning, catchbasin cleaning, upflow filters, hydrodynamic devices, grass swales, wet detention ponds, percolation ponds, and storm-water reuse using rain barrels, cisterns and ponds.

In addition to integration with decision analysis models, the WinSLAMM results can be integrated with detailed hydraulic drainage models [such as the storm-water management model (SWMM)] and receiving water models [such as the hydrological simulation program-Fortran (HSPF)]. Rainwater capture volumes and timing then can be evaluated as a benefit (landscape irrigation, toilet flushing and fire-fighting uses, for example) in a water use and network model (such as EPANET) to quantify the water system savings in terms of the potable water system. Similarly, the reduced domestic water delivery needs for an area can be used to examine sanitary sewerage sizes and wastewater treatment needs. In an area having combined sewerage, the reduced storm-water discharges coupled with the reduced domestic sanitary wastewater flows can be used to calculate these benefits on the frequency and magnitude of overflows.

The techniques of decision analysis, such as that described by Kenney and Raiffa (1976), can aid in the selection process of alternatives. This decision analysis method uses utility curves and trade-offs between the different attributes. The utility curves should be based on data and not reflect personal attitudes or objectives, while the trade-offs between the attributes reflect different viewpoints. This decision analysis method is a powerful tool that can be used to compare the rankings of alternative integrated watershed management programs for different viewpoints and for extensively documenting the selection process.

A complete case study of WinSLAMM modeling integrated with decision analysis can be found in Pitt and Voorhees (2007). This summary is provided to briefly illustrate how this process can be used for comparing and ranking different wet weather flow management alternatives for a new, 40-ha industrial park in northern Alabama. The soils were sandy-loam, but compacted during construction (modeled as silty-loam). Total impervious areas equaled 9.7 ha (roofs, parking, streets), while pervious areas and sinkhole areas constituted the rest of the site. Base conditions, for comparison with storm-water management alternatives, were traditional curb and gutter with underground storm-water conveyance pipes. Storm-water management alternatives included on-site biofilter swales to collect runoff from roofs and paved parking, amended soils, pollution prevention through the use of noncontaminating roofing material, a large drainage swale that collects runoff from the smaller bioswales, and wet detention ponds that drain the developed area of the site.

The method used for determining the optimal management scenario considered several attributes [first, provided a minimum total suspended solids (TSS) removal efficiency of 80% is met and, second, provided several water quality criteria were met]. Once the water quality goals were met, then attributes of the site (RV, land area required, annual cost, amount of solids, and phosphorus removed) were evaluated using utility curves and tradeoffs between various objectives. The optimal management scenario that met the goals and maximized the utility function based on the tradeoff and utility curves was a small pond, a regional swale, and site biofilter swales, as opposed to other scenarios that included combinations of different sized ponds, various uses of site biofiltration, and different types of drainage systems. In most cases, basic combinations of unit processes using sedimentation and biofiltration, used with better site design, are the most effective.

Development Scenarios Optimized Based on Continuous Simulation

Integrated watershed storm-water management requires an evaluation of different development/management alternatives using several criteria, including water supply, sanitary sewage management, storm-water runoff management, and receiving water issues. The following list indicates some likely water delivery and wastewater collection scenarios for several different development patterns:

1. Low and very low density residential developments [>0.8 ha (>2 acre) lot sizes]. Sanitary wastewater should be treated on site using septic tanks and advanced on-site treatment. Domestic water conservation to reduce sanitary wastewater flows should be an important component. Most storm water should be infiltrated on site by directing runoff from paved and roof areas to small bioretention areas, which should be constructed on soils having minimal to no compaction. Roof runoff also can be captured for irrigation reuse. Disturbed soil areas should use amended soils to improve drainage and pollutant removal. Roads should have grass swale drainages to accommodate moderate to large storms.
2. Medium density developments [0.1–0.8 ha (1/4–2 acre) lot sizes]. Separate sanitary wastewater and storm-water drainage systems should be used. Sanitary wastewater collection systems must substantially reduce inflow and infiltration, or they should use vacuum or pressurized conveyance systems. Again, most storm water should be infiltrated on site by directing runoff from paved and roof areas to small bioretention areas, or captured for beneficial reuse. Paved areas should be minimized and the use of paver blocks or porous pavement should be used for walkways, driveways, overflow parking areas, etc. Disturbed soil areas should use amended soils and should otherwise be constructed to minimize soil compaction. Grass swale drainages should be encouraged to accommodate moderate to large storms for the excess runoff in residential areas, depending on slope, soil types, and other features affecting swale stability. Grass swales may also be used in commercial and industrial areas, but only after potential groundwater contamination problems are addressed and available space exists. Wet detention ponds are viable for controlling runoff from commercial and industrial areas. Special controls will be required at critical source areas that have excessive pollution-generating potential.
3. High density developments. Combined sewer systems could be used effectively in these areas. On-site infiltration of the least contaminated storm water (such as from roofs and landscaped areas) is needed to minimize wet weather flows. Extensive use of on-line and off-line storage, and the use of effective high-rate treatment systems would minimize the number and volumes of overflows. The treatment of the wet weather flows at the wastewater treatment facility would likely result in less pollutant discharges than if conventional separate wastewater collection systems were used.

Conclusions

Sustainable storm-water management, especially to mitigate receiving water degradation, requires a combination of control practices to be used at a development site. These controls should be selected based on site characteristics, including soils, and on the rainfall and runoff conditions. Water-quality problems due to storm-water runoff typically are associated with the smaller storms and not the design storms used by engineers for drainage. Because these storms are frequent and because the effects may not have time to dissipate before the next storm, it is critical that continuous simulations be used to evaluate the efficacy of selected control practices. The goal of sustainable storm-water management is to select and implement an optimal array of control practices that meet the water quality goals while minimizing detrimental considerations, including cost. The decision analysis approach mentioned in this paper has the flexibility of allowing for variable levels of analytical depth, depending on the problem requirements. The preliminary level of defining the problem explicitly in terms of attributes often serves to make the most preferred alternatives clear. Spreadsheet calculations with such a model are easily performed, making it possible to conduct several decision analysis evaluations using different tradeoffs that represent different viewpoints.

The ability of continuous simulation model results, such as those from WinSLAMM, to be integrated into hydraulic and fate-and-transport models allow for the user to consider the impacts not only of the development approach used on the site, but also to consider the benefits of optimal management on the watershed as a whole. These benefits may include increased groundwater recharge (reduction of groundwater depletion due to urbanization), decreased sewer flows and reduced numbers of overflows, and decreased potable water use through rainwater reuse in applications such as toilet flushing. It is imperative that development sites be seen not as isolated areas but instead, in the context of the watershed that contains them.

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