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Integrated Watershed Management

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Introduction

Before stormwater control programs can be selected and evaluated, it is necessary to understand the problems in local receiving waters. The lists below give typical receiving water problems, both those associated with the long-term accumulation of pollutants and those caused by short-term (event-related) problems.

Long-term problems associated with accumulations of pollutants in waterbodies include:

- Sedimentation in stormwater conveyance systems and in receiving waters.
- Nuisance algal growths from nutrient discharges.
- Inedible fish, undrinkable water, and shifts to less sensitive aquatic organisms caused by toxic heavy metals and organics (such as with contaminated sediment).

Short-term problems associated with high pollutant concentrations or frequent high flows (event related) include:

- Swimming beach closures from potentially pathogenic microorganisms.
- Water quality violations, especially for bacteria and heavy metals.
- Property damage from increased flooding and drainage system failures.
- Habitat destruction caused by frequent high flow rates, although actual stream bed enlargement may take place over several years (bed scour, bank erosion, flushing of organisms downstream, etc.).

Many of these problems have been commonly found in urban receiving waters in many areas of the U.S. (as summarized by Burton and Pitt 2002, for example). Because these problems are so diverse, a wide variety of individual stormwater controls usually must be used together to form a comprehensive wet weather management strategy, and in conjunction with suitable wastewater collection and treatment methods. The integration of water use considerations also can be an important tool in an integrated watershed management program. Unfortunately, combinations of controls are difficult to analyze either using most available stormwater models or directly from the results of monitoring activities. These difficulties will require new modeling techniques that will enable an effective evaluation of a wide variety of control practices and land uses that may affect the entire suite of receiving water problems, while at the same time the design and implementation of these practices must meet the over-riding storm drainage objective of flood control.

Wet Weather Flow Management: Lessons Learned from the Past and Elsewhere

One of the biggest impediments identified over the years to improved approaches to watershed management is rapid implementation of newly developed (and proven) technology. McPherson (1975; 1978) voiced concerns 30 years ago and offered suggestions to reduce the technology transfer (development to implementation) lag time. Many worthwhile tools that have been successfully demonstrated have not been adequately examined when working together. Some of the urban water issues that have been examined in the past and elsewhere that offer opportunities for future sustainable development include:

- Many areas undergo periodic droughts and implement strict water conservation measures. Unfortunately, few technical evaluations of the benefits of these conservation measures on wastewater production and treatment have been made.
- Similarly, there are many water reuse options that have been used in scattered areas, but many are reluctant to adopt these seemingly exotic approaches until conditions become critical.
- Many modern combined sewage systems are being designed and built in developed nations and that provide treatment for both dry and wet weather flows. This approach, which is not considered in the US, may be the most suitable method for some areas.
- Inflow and infiltration still plagues many conventional wastewater collection systems, while vacuum or pumped systems cannot tolerate leakage. Inappropriate discharges into storm drainage systems are important pollutant sources during dry weather, with sanitary and industrial wastewaters being important sources of these discharges. Improved wastewater collection systems would reduce these problems.
- On-site wastewater treatment, originally developed for use in rural areas, has become more common in suburban areas. Unfortunately, there are few options for correction when failure occurs. Higher densities of on-site systems are usually related to increased groundwater contamination and inappropriate discharge problems in storm drainage systems.
- Conservation design can result in minimal stormwater discharges from new developments. Combinations of infiltration and treatment practices are usually the most robust and cost-effective. Groundwater protection, appropriateness of the soils for infiltration and critical source area controls must also be considered, along with capture and reuse of less contaminated stormwater for non-potable uses (irrigation, toilet flushing, fire fighting, etc.).

There are a number of moderate- to large-scale applications of many of these practices. A few representative examples that come to mind include:

- German and Swiss regulations prohibiting stormwater discharges originating from roofs and grounds near buildings from entering combined sewers. This has lead to large-scale implementations of advanced combined sewer designs and controls, plus stormwater infiltration.
- The Experimental Sewer System in Tokyo is a large-scale implementation of infiltration and treatment in a heavily developed area. Captured stormwater for toilet flushing is also more commonly used in large buildings.
- “Low Impact Development” and “Better Site Design” are emerging and very popular stormwater design approaches in many areas of the US, especially in the Chesapeake Bay area and Pacific Northwest, stressing “softer” approaches to stormwater management that emphasize infiltration and reduce amounts of hard surfaces.
- About six percent of the treated wastewater at the Hyperion sewage treatment plant in Los Angeles, CA, is pumped to a water reclamation plant where it is further treated and then used to irrigate golf courses and parks and to provide industrial water to local businesses.
- Los Angeles Veterans Hospitals use stormwater ponds for fire fighting water supplies.
- Phoenix, AZ, use of treated sanitary wastewaters for golf course irrigation.
- Auckland, NZ, region: roof runoff capture with cisterns and rain barrels for toilet flushing and irrigation reuse. Many residents in rural areas also use roof runoff for all household water needs.
- Sydney Water states that approximately 61 per cent of the total wastewater produced by an average household (not including kitchen wastewaters) can be used as grey water. Companies sell household tanks and treatment units to reuse household grey water for toilet flushing and irrigation. Commercial systems are also available for rain water consumptive use inside the home.
- Austin, TX, residents in rural areas frequently rely on roof runoff and commercial tanks and household water treatment systems to supply all their water needs. It is common for outbuildings to be sized to provide the necessary roof runoff capture area and for the water storage tanks to be located within the structures.
- Stormwater as a landscaping element has been taken to great heights by Herbert Dreiseitl Waterscapes (Überlingen, Germany), making cities easier to live in by emphasizing the attractive nature of moving water.

These above examples illustrate the varied aspects of urban water that could be simultaneously considered in an integrated watershed management program. Unfortunately, quantitative assessments of an integrated design which considers the interaction of these components is currently very complex, requiring the simultaneous use of several models and other tools.

Selecting a design that is optimal in terms of pollutant control, receiving water impacts, and cost will eliminate many characteristics that may lead to unsustainable development. Optimization is a relatively recent addition to wet weather flow management, but variations have existed in the past. Essentially, the selection of a “best” method has always occurred, but it did not involve mathematical algorithms considering a range of possible alternatives. The implementation of mathematical optimization would have made decisions more objective and efficient.

Stormwater Drainage Design Objectives

An idealized wet weather flow management system would include several attributes affecting the conveyance of the stormwater. Basic to these is an understanding of the different objectives of stormwater 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. Figure 1 is an example of observed rainfall and runoff observed at Milwaukee, WI, (Bannerman, *et al.* 1983) as monitored during the Nationwide Urban Runoff Program (EPA 1983). This observed distribution is interesting because of the unusually large rains that occurred twice during the monitoring program. More than half of the runoff from this common medium density residential area was associated with rain events that were smaller than 0.75 inches. These two large storms (about 3 and 5 inches in depth), which are included in the figure, distort this figure because, on average, the Milwaukee area only expects one 3.5 inch storm every five years. If these large rains did not occur, such as for most years, then the significance of the smaller rains would be even greater. Figure 1 also shows the accumulative loadings of different pollutants (suspended solids, COD, phosphates, and lead) monitored during the Milwaukee NURP project. When these figures are compared, it is seen that the runoff and discharge distributions are very similar and that variations in the runoff volume are much more important than variations in pollutant concentrations for determining pollutant mass discharges. These rainfall and runoff distributions for Milwaukee can be divided into four regions:

- <0.5 inch. These rains account for most of the events, but little of the runoff volume, and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants (bacteria and some total recoverable heavy metals). They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week (accounting for about 60% of the total rainfall events and about 45% of the total runoff events that occurred), but they only account for about 20% of the annual runoff and pollutant discharges. Rains less than about 0.05 inches did not produce noticeable runoff. In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas. These rains should be removed from the surface drainage system.

- 0.5 to 1.5 inches. 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. They account for about 35% of the annual rain events, and about 20% of the annual runoff events, by number. These rains occur on the average about every two weeks during the spring to fall seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows. The small rains in this category should also be removed from the drainage system and the runoff re-used on site for beneficial uses or infiltrated to replenish the lost groundwater infiltration associated with urbanization. The runoff from the larger rains should be treated to prevent pollutant discharges from entering the receiving waters.

• 1.5 to 3 inches. These rains produce the most damaging flows from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. Only about 2 percent of the rains are in this category and they are responsible for about 10 percent of the annual runoff and pollutant discharges. Storm drainage design events can fall in the upper portion of this category, depending on the time of concentration and the rain intensity. Extensive pollution controls designed for these events would be very costly, especially considering the relatively small portion of the annual runoff associated with the events. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. The infiltration and other treatment controls used to handle the smaller storms would have some benefit in reducing pollutant discharges during these larger storms.

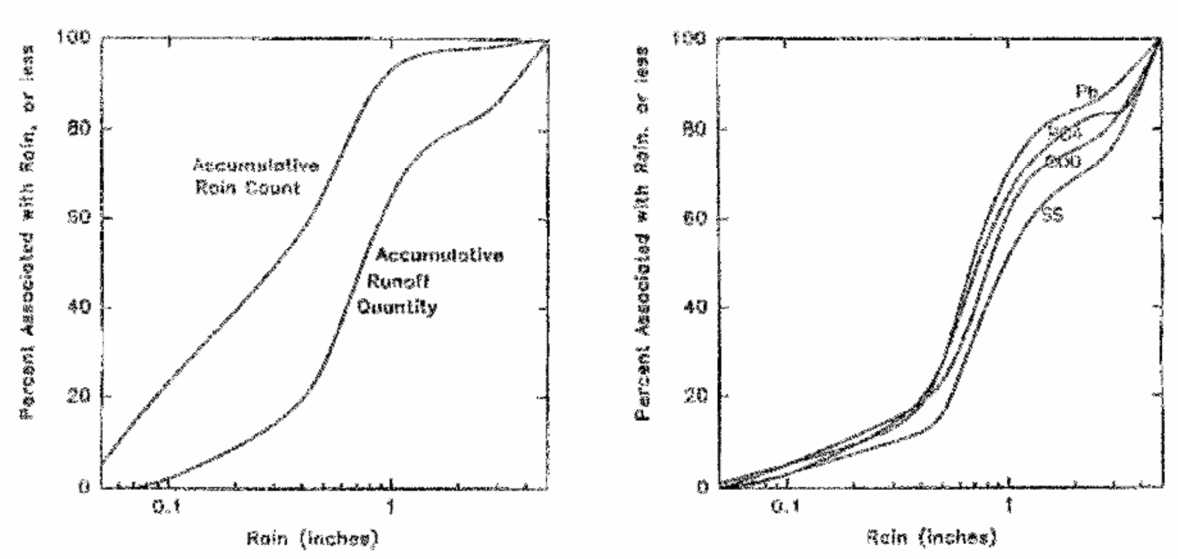

Figure 1. Milwaukee rainfall and runoff probability distributions, and pollutant probability distributions.

• >3 inches. The smallest rains in this category are included in design storms used 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. The monitoring period during the Milwaukee NURP program was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<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. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of 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. The problems occurring during these events are massive property damage and possible loss of life. These rains typically greatly exceed the capacities of the storm drainage systems, causing extensive flooding. It is critical that these excessive flows be conveyed in "secondary" drainage systems. These secondary systems would normally be graded large depressions between buildings that would 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 would suffer critical flood damage.

The above specific values are given for Milwaukee, WI. 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 regions 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 stormwater quality and drainage design objectives will require the use of long-term continuous simulations in conjunction with upland and end-of-pipe stormwater quality controls. The complexity of most receiving water quality problems prevents a simple analysis. The use of simple design storms, which was a major breakthrough in effective drainage design more than 100 years ago, is not adequate when receiving water quality issues must also be addressed.

Design Methodology Framework

The literature contains many design methodologies and planning strategies for wet weather flow management. However, few have gained wide practice, possibly because of the lack of enforcement, and the fact that most are not geared towards the practicing engineer. A well-accepted design methodology needs to:

- be focused on micro-development (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.

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. There are a wide variety of well-documented control methods with adequate performance data collected under wet weather conditions. Different technologies have different strengths and weaknesses that must be matched with their suitability for each watershed and the water quality objectives of the associated receiving water.

The analysis of the 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 rains. The problems associated with design rains are many and discussions can be found in a number of publications (McPherson 1978; Nix 1982; Adams and Howard 1985; Huber and Dickinson 1988; Nix 1994, amongst 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. The use of single design rains is also problematic when trying to evaluate water quality problems associated with stormwater. 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 environmental conditions. Continuous simulation can overcome these deficiencies by driving a model of the urban watershed (and any control technologies) with many decades of rainfall data and analyzing the frequency and severity of occurrence of various runoff quantity and quality characteristics.

Decision Analysis Evaluations of Alternative Control Programs. Decision analysis techniques may be used as an important tool to help select an urban runoff control program. Decision analysis is a systematic procedure that enables one to study the trade-offs among multiple and usually conflicting program objectives. A simple procedure is to separately determine the programs necessary to meet each objective and to use the least costly program that satisfies all the identified critical objectives. This is an acceptable procedure some of the time, but it 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 can produce a great deal of information concerning a control strategy. As an example, WinSLAMM, the Source Loading and Management Model (Pitt 1986; 1997; 1999; 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. The model is normally used to evaluate several decades of rainfall data for the study area. Recent modifications to the model's batch processor allow automated evaluations of numerous different scenarios for a site, and produce a formatted output that can be further evaluated using an appropriate decision analysis approach and integration into Geographic Information Systems. The model can be used to 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 stormwater reuse using rain barrels, cisterns and ponds.

The model can be integrated with detailed hydraulic drainage models (such as SWMM) and receiving water models (such as HSPF). The results from the calculations of the water reuse benefits of the stormwater for such uses as toilet flushing and irrigation and for fire fighting water storage, can be integrated with a water use and network model (such as EPANET) to quantify the water system savings. 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 stormwater 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 described by Kenney and Raiffa (1976), can be a great asset to 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 well-documenting the selection process. Pitt and Voorhees (2007) illustrate how this process can be used for comparing and ranking different wet weather flow management alternatives in conjunction with the batch processor option of WinSLAMM.

Conclusions

The following list indicates some likely effective wastewater collection scenarios for several different conditions for the future:

- low and very low density residential developments (<2 acre lot sizes). Sanitary wastewater should be treated on site using septic tanks and advanced on-site treatment options. Domestic water conservation to reduce sanitary wastewater flows should be an important component of these systems. Most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bioretention areas. Roof runoff also can be captured for irrigation reuse. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Roads should have grass swale drainages to accommodate moderate to large storms.

- medium density developments (¼ to 2 acre lot sizes). Separate sanitary wastewater and stormwater drainage systems should be used. Sanitary wastewater collection systems must be constructed and maintained to eliminate I/I, or they should use vacuum or pressurized conveyance systems. Again, most stormwater 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 should be used for walkways, driveways, overflow parking areas, etc. Disturbed soil areas should use compost-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. Commercial and industrial areas should also use grass swales, depending on groundwater contamination potential and available space. Wet detention ponds should be used for controlling runoff from commercial and industrial areas. Special controls should be used at critical source areas that have excessive pollution generating potential.

- high density developments. Combined sewer systems could be effectively used in these areas. On-site infiltration of the least contaminated stormwater (such as from roofs and landscaped areas) is needed to minimize wet weather flows. Extensive use of in-line and off-line storage, and the use of effective high-rate treatment systems would minimize the number and size 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.

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 trade-offs, representing different viewpoints. Monte Carlo options available in WinSLAMM can also be used to consider the uncertainties in the calculated attributes for each option. In summary, decision analysis has several important advantages. It is very explicit in specifying trade-offs, objectives, alternatives, and sensitivity of changes to the results.

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