The Design and Use of Detention Facilities for Stormwater Management Using DETPOND

Robert Pitt, Ph.D., P.E., DEE
Environmental Engineer

Detention ponds are probably the most common management practice for the control of stormwater. If properly designed, constructed, and maintained, they can be very effective in controlling a wide range of pollutants and peak runoff flow rates. There is probably more information concerning the design and performance of detention ponds in the literature than for any other stormwater control device. Wet detention ponds are also a very robust method for reducing stormwater pollutants. They typically show significant pollutant reductions as long as a few design-related attributes are met. Many details are available to enhance performance, and safety, that should be followed. Many processes are responsible for the pollutant removals observed in wet detention ponds. Physical sedimentation is the most significant removal mechanism. However, biological and chemical processes can also contribute important pollutant reductions. The extensive use of aquatic plants, in a controlled manner, can provide additional pollutant removals. Wet detention ponds also are suitable for enhancement with chemical and advanced physical processes.

This course will use the DETPOND stormwater detention pond model (model and complete documentation included) to evaluate and design stormwater detention ponds for a wide range of conditions. DETPOND is based on the same modeling approach used in SLAMM, but provides more detail to enable more effective evaluations. This course also includes extensive documentation of successful pond designs and approaches.

Abstract

This course discusses one of the most often used and most effective stormwater control practice: wet detention ponds. There are many stormwater control practices, but all are not suitable in every situation. It is important to understand which controls are suitable for the site conditions and can also achieve the required goals. This will assist in the realistic evaluation for each practice of: the technical feasibility, implementation costs, and long-term maintenance requirements and costs. It is also important to appreciate that the reliability and performance of many of these controls have not been well established, with some still in the development stage. This is not to say that emerging controls cannot be effective, however, they do not have a large amount of historical data on which to base designs or to be confident that performance criteria will be met under the local conditions. The most promising and best understood stormwater control practices are wet detention ponds. Less reliable in terms of predicting performance, but showing promise, are stormwater filters, wetlands, and percolation basins (Roesner, *et al.* 1989). Grass swales also have shown great promise during the EPA's Nationwide Urban Runoff Program (NURP) (EPA

1983) and other research projects. During the last 10 to 20 years, much additional experience has been gained with many stormwater practices, especially source controls and stream restoration efforts. An effective stormwater management program likely must contain elements of many control practices to be most cost-effective. The combinations of practices that are most efficient for a specific area must be selected based on many site specific conditions and local objectives. In almost all cases, however, the use of wet detention ponds is an important stormwater control that should be given serious consideration.

Wet detention ponds are also one of the most robust stormwater control practices available. Although a good maintenance program is necessary to ensure the best performance and minimize associated problems, many stormwater ponds have functioned well with minimal maintenance. In addition, as long as certain design guidelines are followed, many design details that are worthwhile to consider do not create critical problems if incorrectly implemented. Finally, it is possible to retro-fit stormwater ponds and correct many of these problems as experience dictates. These robust attributes are rare for most stormwater control practices. As an example, a study of 11 types of stormwater quality and quantity control practices used in Prince George's County, Maryland (Metropolitan Washington Council of Governments 1992) was conducted to examine their performance and longevity. This report concluded that several types of the stormwater control practices had either failed or were not performing as well as intended. Generally, wet ponds, artificial marshes, sand filters, and infiltration trenches achieved moderate to high levels of removal for both particulate and soluble pollutants. Only wet ponds and artificial marshes were found to function for a relatively long time without frequent maintenance. Control practices which were found to perform poorly included infiltration basins, porous pavements, grass filters, swales, smaller "pocket" wetlands, extended detention dry ponds, and oil/grit separators. Infiltration stormwater controls had high failure rates which could often be attributed to poor initial site selection and/or lack of proper maintenance. The poor performance of some of the controls was likely a function of poor design, improper installation, inadequate maintenance, and/or unsuitable placement of the control. Greater attention to these details would probably reduce the failure rate of these practices. The wet ponds and artificial marshes were much more robust and functioned adequately under a wider range of marginal conditions. The following are general conclusions pertaining to stormwater detention facilities.

Expected Detention Pond Performance

- Dry ponds have little documented direct water quality benefits due to scouring of bottom sediments. Decreased receiving water velocities will decrease receiving water bank erosion and will improve aquatic habitat, however.
- Wet ponds have been extensively monitored under a wide variety of conditions. If well designed and properly maintained, suspended solids removals of 70 to 90% can be obtained. BOD_5 and COD removals of about 70%, nutrient removals of about 60 to 70%, and heavy metal removals of about 60 to 95% can also be obtained. Limited bacteria control (maybe up to 50%) can be expected in the absence of disinfection. Wet ponds can also be designed to obtain significant flood control benefits.

Potential Detention Pond Problems

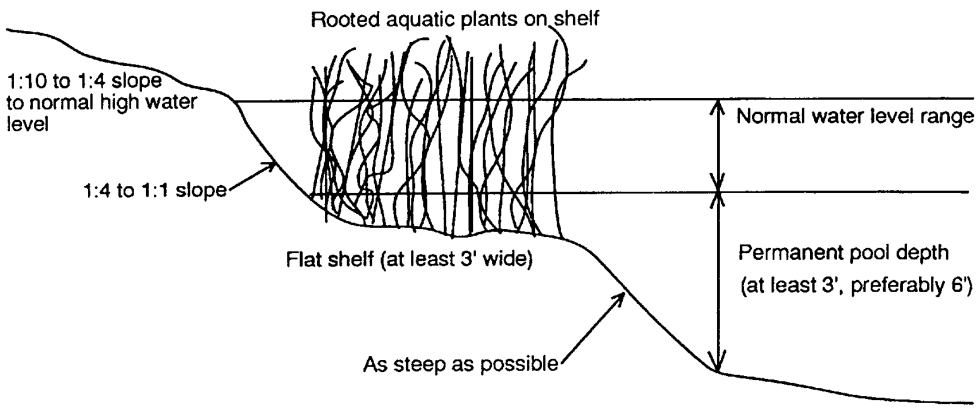
- Wet ponds can require about three to six years to obtain an ecological balance. During the initial unstable period, excessive algal growths, fish kills, and nuisance odors may occur.
- Wet ponds can have poor water quality and water contact recreation and consumptive fishing should be discouraged.
- Careful watershed-wide planning is needed to insure composite flood control benefits from many ponds in a watershed.

Wet Detention Pond Design Guidelines to Minimize Potential Problems

- Keep pond shape simple to encourage good water circulation. The length should be about three to five times the width for maximum detention efficiency and the inlets and outlets need to be widely spaced to minimize short-circuiting.
- Need at least three and preferably six feet of permanent standing water over most of the pond to protect sediments from scouring, to decrease light penetration (to minimize rooted aquatic plant growths), and to increase winter survival of fish.

• Increase flushing during dry weather, possibly with groundwater, to improve water quality. Reduce contaminated baseflows from entering the pond through source controls.

• Correct pond side slopes are very important to improve safety and aesthetics and to minimize mosquito problems and excessive rooted plant growths. An underwater shelf near the pond edge needs to be planted with rooted aquatic plants to prevent children's access to deep water, to improve pond aesthetics, to increase pollutant removals through biochemical processes, and to improve aquatic habitat. If waterfowl are desired users of the pond, then no more than one-half of the pond perimeter should be heavily planted. The following general dimensions for pond side slopes are suggested:



• Outlet structures should be designed for low outflows during low pond depths to maximize particulate retention. Place underwater dams or deeper sediment trapping forebays near pond inlets to decrease required dredging areas. Provide a drain to completely de-water the pond for easier maintenance.

• Protect the inlet and outlet areas from scour erosion and cover the inlets and outlets with appropriate safety gratings. Provide an adequate emergency spillway. Minimize water elevation changes to discourage mosquito problems.

Required Stormwater Detention Pond Maintenance

• If the pond does not require any maintenance, it is not producing very many water quality benefits. Ponds need to be periodically dredged to remove contaminated bottom sediments.

• Plan extra pond depth for sacrificial volume to lengthen dredging intervals (approximately one inch per year, much more in forebays). Also plan for heavy equipment access to pond edges.

• Remove excessive algae to prevent decomposition and nutrient cycling and associated nuisance conditions.

Basic Wet Detention Pond Design Guidelines

• Engineering design guidelines (covering such things as foundations, fill materials, embankments, gratings, anti-seep collars, and emergency spillway construction), such as published by the U.S. Natural Resources Conservation Service and the Corps of Engineers must be followed.

• Pond size is dictated mostly by desired particle control and water outflow rate. The following table is an estimate of pond surface requirements for different land uses and conditions. Five µm control will remove all particles greater than five µm from the runoff water and corresponds to about 90% suspended solids reductions in urban runoff. Twenty µm control will result in about 65% suspended solids reductions.

Percent of drainage area required as pond for:

Land Use	5 µm control	20 µm control
Totally paved areas	3.0 percent	1.1 percent
Freeways	2.8	1.0
Industrial areas	2.0	0.8
Commercial areas	1.7	0.6
Institutional areas	1.7	0.6
Residential areas	0.8	0.3
Open space areas	0.6	0.2
Construction sites	1.5	0.5

Wet Detention Pond Costs

• Initial wet detention pond construction costs are roughly estimated to be about $40,000 per acre of pond surface (excluding land costs).

• Maintenance costs are estimated to be about $1500 per pond surface acre per year.

Pond Size Calculation

• The following table shows the minimum pond surface area (acres) required for different freeboard elevations above the invert of 60 degree and 90 degree V-notch weirs, for both five and twenty µm particle control:

	60^{o} V-notch weir			90^{o} V-notch weir		
Head	Discharge	Min. surface acres for:		Discharge	Min. surface acres for:	
(feet)	(cfs)	5µm	20µm	(cfs)	5µm	20µm
0.5	0.25	0.044	0.004	0.45	0.08	0.006
1	1.4	0.25	0.02	2.4	0.42	0.03
1.5	3.9	0.69	0.06	6.7	1.2	0.1
2	8.0	1.4	0.11	14	2.5	0.2
3	22	3.9	0.32	40	7.1	0.6
4	45	7.9	0.65	81	14	1.2

A discussion of wet detention pond design procedures must include three very important publications that all stormwater managers should have. Tom Schueler's *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices* (1987) includes many alternative wet pond designs for various locations and conditions. *Watershed Protection Techniques* is a periodical published by Schueler at the Center for Watershed Protection (Ellicott City, Maryland) and includes many summaries of current stormwater management research, including new developing design procedures and performance data for detention ponds. In addition, Peter Stahre's and Ben Urbonas's book on *Stormwater Detention for Drainage, Water Quality and CSO Management* (1990) includes in-depth discussions on many detention pond design and operational issues.

Background

There is probably more information concerning the design and performance of detention ponds in the literature than for any other stormwater control device. Wet detention ponds are also a very robust method for reducing stormwater pollutants. They typically show significant pollutant reductions as long as a few basic design-related attributes are met (most important being size). Many details are available to enhance performance, and safety, that should be followed. Many processes are responsible for the pollutant removals observed in wet detention ponds. Physical sedimentation is the most significant removal mechanism. However, biological and chemical processes can also contribute important pollutant reductions. The extensive use of aquatic plants, in a controlled manner, can provide additional pollutant removals. Magmedov, *et al*. (1996), for example, report on the use of wetlands for treatment of stormwater runoff in the UK and in the Ukraine, including design guidelines. Wet detention ponds also are suitable for enhancement with chemical and advanced physical processes. Lamella separators, air floatation, filtration, and UV disinfection are examples of treatment enhancements being investigated in France (Bernard, *et al*. 1996; Delporte 1996).

Multiple Benefits of Detention Facilities

The most common multiple benefit of detention facilities built for water quality improvements is flood control. If appropriately designed, wet detention ponds can provide significant peak flow rate reductions. Ponds by themselves provide little runoff volume reductions, but can be designed in conjunction with infiltration devices to provide water quality in addition to peak flow rate and water volume reduction benefits. In order to provide flood control benefits, substantial freeboard storage above the normal wet pond elevation must be provided. This has been commonly done in open space land uses such as parks and golf courses where periodic short-term flooding does not detract from the other uses of the land.

Many people enjoy wetlands (including wet detention ponds) in urban settings. Adams, *et al*. (1982) reports a typical comment from a resident living near a wet detention pond in Columbia, Maryland: "...now that they've matured, we're reaping rewards from all the wildlife using the ponds." Numerous ducks, herons, egrets, songbirds, mammals, and amphibians have been observed and highly prized by residents living near these small artificial wetlands. Establishing natural aquatic vegetation (rooted macrophytes) on the shallow shelf edges of the ponds make them more attractive to wildlife and enhances their beauty.

Fishing is also popular in many wet detention facilities, especially by children, although fish consumption should usually be discouraged due to the possibility of accumulations of toxic substances. Recreational fishing in wet detention facilities using catch and release is currently enjoyed by many.

The integration of properly designed, constructed, and maintained wet detention ponds into parks and linear green (and blue) belts can provide substantial community benefits, even if the water quality in the ponds is less than "good" (Jones and Jones 1982). Flood control, non-contact recreation, non-consumptive fishing, education, and aesthetics benefits have all been achieved at many wet detention ponds.

Dry Ponds

Dry ponds have been extensively used throughout the U.S. and other countries (EPA 1983). These ponds have been constructed to reduce peak runoff rates (peak shaving), with typically little consideration given to runoff quality improvement. Their main purpose has therefore been in flood control by reducing flows and water elevations in the receiving waters. These flow reductions can also improve the aquatic habitat by reducing flushing of fish and other organisms from urban creeks (Pitt and Bissonnette 1984). Flow reductions also reduce downstream channel bank erosion and bottom scour. The use of many dry ponds in a watershed, without regard to their accumulative effect, can actually increase downstream flooding or channel scour problems (McCuen, *et al*. 1984). The delayed discharge of a mass of water from a dry pond may be superimposed on a more critical portion of the receiving water hydrograph.

Because these ponds are normally dry and only contain water for relatively short periods of time, they can be constructed as part of parking lots, athletic fields, tennis courts and other multi-use areas. Their outlets are designed to transmit all flows up to a specific design flow rate, after which excess flows are temporarily backed-up. In many cases, they only contain water during a few rains each year.

Several dry detention ponds were examined as part of the NURP program, with monitored pollutant removals ranging from insignificant to quite poor (EPA 1983). Sedimentation may occur in dry ponds, but only during the major storms when flows are retained in the pond. The deposited material must be removed after each treated rain, or it can easily be resuspended by later rains and washed into the receiving waters. Adler (1981) found that new sediment deposits have little cohesion and without removal as part of a maintenance program, or without several feet of overlaying water, bottom scour is probable. Because of the poor documented stormwater pollutant control effectiveness of dry detention ponds, they cannot, by themselves, be recommended as viable water quality control measures. However, they can be very effective when used in conjunction with other stormwater control practices (such as between a wet detention pond and an infiltration or grass filter area).

Wet Detention Ponds

Wet detention ponds maintain several feet of water in a permanent pool. The runoff water is detained for varying periods of time, depending on the pond detention volume and the storm runoff flow rate and duration. Detention times (residence) can vary from several minutes for small ponds receiving high flows to many days for large ponds receiving relatively small flows. Monitored performance of wet ponds during the NURP program ranged from poor to excellent, generally depending on the size of the detention pond relative to the watershed area served and storm characteristics (EPA 1983). Sedimentation is the main pollutant removal process, but biological processes can also substantially reduce concentrations of soluble nutrients by converting them into algae and by providing substrate for beneficial bacteria. If the algae is removed from the detention pond, nutrient discharges to the receiving waters can be reduced. If algae is not harvested from the ponds, dead algae can be decomposed back into soluble nutrient forms (and exert biochemical oxygen demand) either in the detention pond or in the receiving water. Wet ponds can be very effective in the control of stormwater runoff flows and pollutants, but must be carefully designed and maintained to prevent nuisance conditions from developing.

Extended Detention (Combination) Ponds

Extended detention, or combination wet/dry ponds, are normally dry, but have special outlets that cause the slow release of impounded water. They are therefore not as conveniently used for other uses, such as parking lots. Outlet modifications can be easily made to existing dry ponds to make them into extended detention ponds and significantly improve their stormwater pollutant control effectiveness (EPA 1983). Since they are normally dry and lack a protective water cover over the deposited sediment, they must be frequently maintained to remove accumulated sediment before a flushing rain occurs. Biological activity is restricted, reducing the potential of high nutrient removals, but they also have reduced potentials for nuisance algal growths and mosquito production. Depending on their design, extended detention ponds may behave as artificial wetlands, grass filters or percolation ponds, with much greater pollutant removal benefits, compared to dry ponds.

Use with Other Controls

Detention facilities can be easily used in conjunction with other stormwater control devices. Upland infiltration can be used to treat parking lot and roof runoff, substantially reducing the size of “downstream” detention facilities. Even with source area controls, detention faculties can be very important in industrial areas to help treat dry weather urban runoff. A series of control devices has been described by Hawley, *et al*. (1981) that uses a preliminary sedimentation trap, followed by a grass filter strip and a wet detention pond. This arrangement would substantially decrease sedimentation (and required maintenance) and substantially reduce nuisance conditions in the detention facility.

Examples of Detention Pond Performance

The use of detention ponds for both water quality and quantity benefits is relatively new. Wet pond stormwater quality benefits have been commonly reported in the literature since the 1970s, while the water quality benefits of dry detention ponds have only recently been adequately described (Hall 1990).

The Nationwide Urban Runoff Program included full-scale monitoring of nine wet detention ponds (EPA 1983). The Lansing project included two up-sized pipes, plus a larger detention pond. The NURP project located in Glen Ellyn (west of Chicago) monitored a small lake, the largest pond monitored during the NURP program. Ann Arbor, Michigan, monitoring included three detention ponds, Long Island, New York, studied one pond, while the Washington D.C. project included one pond. About 150 storms were completely monitored at these ponds, and the performances ranged from negative removals for the smallest up-sized pipe installation, to more than 90 percent removal of suspended solids at the largest wet ponds. The best wet detention ponds also reported BOD5 and COD removals of about 70 percent, nutrient removals of about 60 to 70 percent, and heavy metal removals of about 60 to 95 percent.

Two wet detention ponds near Toronto, Ontario, were monitored from 1977 through 1979 (Brydges and Robinson 1986). Lake Aquitaine is 1.9 ha in size and receives runoff from a 43 ha urban watershed. Observed pollutant reductions were about 70 to 90 percent for suspended solids, 25 to 60 percent for nitrogen, and about 80 percent for phosphorus. The much smaller Lake Wabukayne (0.8 ha) received runoff from a much larger urban area (186 ha). The smaller Lake Wabukayne experienced much smaller pollutant reductions: about 30 percent for suspended solids, less than 25 percent for nitrogen, and 10 to 30 percent for phosphorus.

Gietz (1983) studied a 1.3 ha wet detention pond serving a 60 ha urban watershed near Ottawa, Ontario. Batch operation of the pond resulted in substantial pollutant control improvements for particulate residue, bacteria, phosphorus, and nitrate nitrogen. Continuous operation gave slightly better performance for BOD5 and organic nitrogen. Suspended solids reductions were about 80 to 95 percent, BOD5 reductions were about 35 to 45 percent, bacteria was reduced by about 50 to 95 percent, phosphorus by about 70 to 85 percent, and organic nitrogen by about 45 to 50 percent.

Numerous additional detention pond performance studies have been conducted in the years since the Nationwide Urban Runoff Program. Yousef, *et al*. (1986) reported some long-term nutrient removal information for a detention pond in Florida having very long residence times and substantial algal and rooted aquatic plant growths. He found 80 to 90 percent removals of soluble nutrients due to plant uptake. Particulate nutrient removals, however, were quite poor (about ten percent). These particulate nutrient forms were mostly nitrogen and phosphorus that were tied up with the plant cells and not the particulate nutrient forms that were discharged to the pond with the runoff (Driscoll 1986). It is difficult to design a detention pond to obtain a desired net removal of nutrients (soluble plus particulate forms) because of the plant uptake and conversion of soluble forms to particulate cellular forms. If the plants are not removed from the detention pond, the particulate cellular nutrients will be released back into the water as more available (soluble) forms during periods of plant die-off. The role of aquatic plants in nutrient (and other pollutant) removals for cold climatic conditions is not well understood. Substantial releases of pollutants that had been "removed" by aquatic plants during the growing season when the plants die back in the fall is expected, resulting in substantially less removals than indicated by warm weather monitoring alone.

Hvitved-Jacobsen, *et al*. (1987) along with Martin and Miller (1987) described pollutant removal benefits of wet detention ponds. Niemczynowicz (1990) described stormwater detention pond practices in Sweden. Van Buren, *et al*. (1996) also reported on the performance of a on-stream pond located in Kingston, Ontario. They describe their monitoring activities and measures taken to enhance performance.

Hvitved-Jacobsen, *et al*. (1994) examined the most effective treatment systems for treating urban and highway runoff in Denmark. They concluded that wet detention ponds were the most efficient and suitable solution for the removal of most pollutants of concern from both highway and urban runoff. Denmark does not have any effluent standards and the acceptable pollutant discharges are therefore determined based on specific receiving water requirements. They concluded that CSO problems were causing acute receiving water effects (hydraulic problems, oxygen depletion, high bacterial pollution, etc.), requiring treatment designs based on design storm concepts. However, both urban and highway runoff were mostly causing accumulative (chronic) effects (associated with suspended solids, toxicants, and nutrient discharges) and treatment designs therefore need to be based on long-term pollutant mass discharge reductions. It was evident that relatively low concentrations of pollutants must be reduced, and that large volumes of water must be treated in a short time period. For these reasons, and for the specific pollutants of concern, they concluded that wet detention ponds were the most effective option, even though the first wet detention pond was only constructed in Denmark in 1989. Their recommended design was based on: detention pond volume (about 250 m^3 per effective hectare of drainage area), water depth, pond shape, use of plants (covering at least 30% of the water surface), and the use of a grit removal forebay. This pond design was evaluated using the computer program MOUSE/SAMBA for long-term simulations using Aalborg, Denmark, rains. The resulting mass removals using this design were excellent for suspended solids (80 to 90%) phosphorus (60 to 70%) and heavy metals (40 to 90%).

Mayer, *et al*. (1996) examined sediment and water quality conditions in four wet detention ponds in Toronto. They found that poor water circulation in the summer months between rains decreased the pond water quality, especially for dissolved oxygen and nutrients. Anaerobic conditions near the pond water-sediment interface in two of the ponds caused elevated ammonia concentrations. They felt that decomposition of nitrogenous organic matter (from terrestrial and aquatic plant debris) was the likely source of the ammonia. They also found prolific algal growths in the same two ponds in the summer, with chlorophyll a concentrations of about 30 µg/L. The chlorophyll a concentrations in the other two ponds were much lower, between about 3 and 10 µg/L.

Maxted and Shaver (1996) examined the biological and habitat characteristics downstream from several headwater wet detention ponds in Delaware to measure beneficial effects. They found that the ponds did not improve the habitat conditions or several benthic indices, compared to similar sites without ponds, when the watershed impervious cover exceeded about 20%. They stress that more research is needed examining other stream indicators, especially in less developed watersheds and in other parts of the country. They concluded that riparian zone protection, which is commonly overlooked in extensively developed watersheds, needs much more attention. The use of stormwater management practices apparently only is able to overcome part of the detrimental effects of development.

Stanley (1996) examined the pollution removal performance at a dry detention pond in Greenville, NC, during eight storms. The pond was 0.7 ha in size and the watershed was 81 ha of mostly medium density single family residential homes, with some multifamily units, and a short commercial strip. The observed reductions were low to moderate for suspended solids (42 to 83%), phosphate (-5 to 36%), nitrate nitrogen (-52 to 21%), ammonia nitrogen (-66 to 43%), copper (11 to 54%), lead (2 to 79%), and zinc (6 to 38%). In all cases, the removals of the stormwater pollutants is substantially less than would occur at well designed and operated wet detention ponds.

Problems With Wet Detention Ponds

Wet detention ponds may experience various operating and nuisance problems. The following discussion attempts to describe these negative aspects of wet ponds, as reported in the literature, and to describe how they have been overcome through specific designs.

Safety of Wet Detention Ponds

The most important wet detention pond design guidelines are to maintain public safety. The following discussion briefly summarizes common suggestions to maintain and improve safety at wet detention facilities. Death by drowning is the most common safety concern associated with wet detention ponds. Marcy and Flack (1981) state that drownings in general most often occur because of slips and falls into water, unexpected depths, cold water temperatures, and fast currents. Four methods to minimize these problems include: eliminate or minimize the hazard, keep people away, make the onset of the hazard gradual, and provide escape routes. Many of the design suggestions and specifications contained in this discussion are intended to accomplish these methods.

Jones and Jones (1982) consider safety and landscaping together because landscaping can be an effective safety element. They feel that appropriate slope grading and landscaping can provide a more desirable approach than wide-spread fencing around a wet detention pond. Fences are expensive to install and maintain and usually produce unsightly pond edges. They collect trash and litter, challenge some individuals who like to defy barriers, and impede emergency access if needed. Marcy and Flack (1981) state that limited fencing may be appropriate in special areas. When the pond side slopes cannot be made gradual (such as when against a railroad right-of-way or close to a roadway), steep sides having submerged retaining walls may be needed. A chain link fence located directly on the top of the retaining wall very close to the water's edge would be needed (to prevent human occupancy of the narrow ledge on the water side of the fence). Another area where fencing may be needed is at the inlet or outlet structures. However, fencing usually gives a false sense of security, as most can be easily crossed (Eccher 1991).

A following discussion on pond side slopes stresses gradual slopes near the water edge and a submerged ledge close to shore. Aquatic plants on the ledge would decrease the chance of continued movement to deeper water and thick vegetation on shore near the water edge would discourage access to the water edge and decrease the possibility of falling into the water accidentally. Pathways should not be located close to the water’s edge, or turn abruptly near the water.

Marcy and Flack (1981) also encourage the placement of escape routes in the water whenever possible. These could be floats on cables, ladders, hand-holds, safety nets, or ramps. They should not be placed to encourage entrance into the water.

The use of inlet and outlet trash racks and antivortex baffles is also needed to prevent access to locations having dangerous water velocities. Several types are recommended by the NRCS (SCS 1982), as shown on Figure 1. Racks need to have openings smaller than about 6 inches to prevent people from passing through them and need to be placed where water velocities are less than three feet per second to allow people to escape (Marcy and Flack 1981). Besides maintaining safe conditions, racks also help keep trash from interfering with the outlet structures operation.

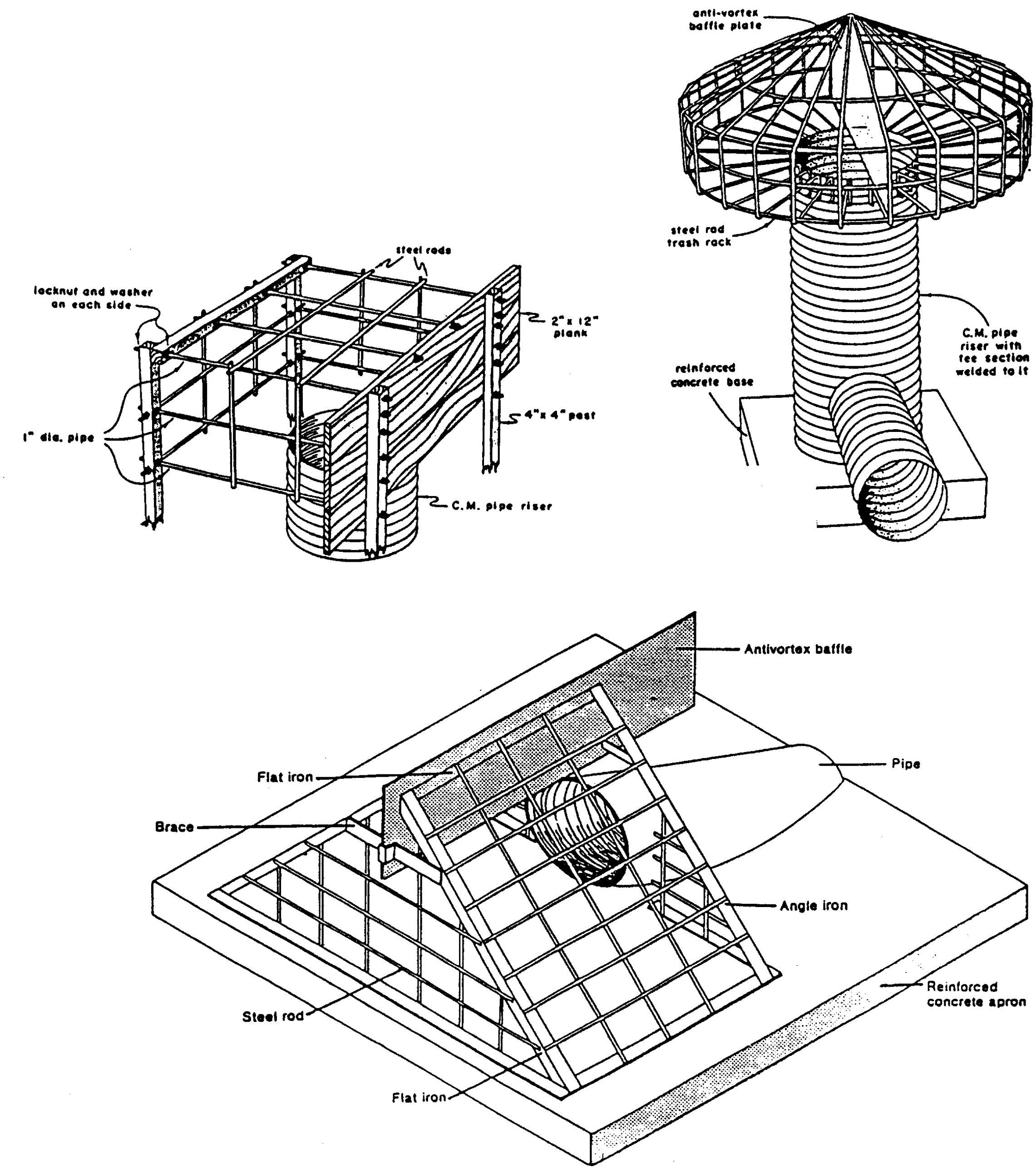


Figure 1. Various trash racks and baffles used by the NRCS (SCS 1982).

Eccher (1991) lists the following pond attributes to ensure maximum safety, while having good ecological control:

1) There should be no major abrupt changes in water depth in areas of uncontrolled access,
2) slopes should be controlled to insure good footing,

3) all slope areas should be designed and constructed to prevent or restrict weed and insect growth (generally requiring some form of hardened surface on the slopes), and
4) shoreline erosion needs to be controlled.

Attitudes of Nearby Residents and Property Values

Wet Detention ponds may create potential nuisance conditions if they are not properly designed or maintained. However, many people living near wet detention ponds do so because of the close presence of the wetlands, and their property values are typically greater than lots further from the ponds (Marsalek, *et al.* 1982). Emmerling-DiNovo (1995) reported on a survey of homeowners in the Champaign-Urbana area living in seven subdivisions having either dry or wet detention ponds. She reported that past studies have recognized that developers are well aware that proximity to water increases the appeal of a development. Detention ponds can create a sense of identity, distinguishing one development from another, and can be prominent design elements. Increased value is important because the added cost of the detention facility, including loss of developable land, must be recovered by increasing the housing costs. Others have also found that the higher costs of developments having stormwater detention facilities can also be offset by being able to sell the housing faster. In a prior survey in Columbia, MD, 73% of the respondents would be willing to pay more for property located in an area having a wet detention pond if designed to enhance fish and wildlife use. Although the residents were concerned about nuisances and hazards, they felt that these concerns were out-weighed by the benefits. In her survey, Emmerling-DiNovo (1995) received 143 completed surveys. Overall attractiveness of the neighborhood was the most important factor in purchasing their home. Resale value was the second most important factor, while proximity to water was slightly important. More than 74% of the respondents believed that wet detention ponds contributed positively to the image of the neighborhood and they were a positive factor in choosing that subdivision. In contrast, the respondents living in the subdivisions with the dry ponds felt that the dry ponds were not a positive factor in locating in their subdivision. Respondents living adjacent to the wet ponds felt that the presence of the pond was very positive in the selection of their specific lot. The lots adjacent to the wet ponds were reported to be worth about 22% more than lots that were not adjacent to the wet ponds. Lots adjacent to the dry ponds were actually worth less (by about 10%) than other lots. Dry detention ponds actually decreased the assessed values of adjacent lots in two of the three dry basin subdivisions studied. The respondents favored living adjacent to wet ponds even more than next to golf courses. Living adjacent to dry ponds were the least preferred location.

Maintenance Requirements of Wet Detention Ponds

In order for detention ponds to perform as anticipated, they must be regularly maintained. Poor operation and maintenance not only reduces the pollutant and flow rate reduction effectiveness of detention ponds, but can cause detention facilities to become eyesores, nuisances, and health hazards (Poertner 1974). If a pond does not “need” maintenance (such as sediment removal), then it is not providing significant water quality benefits. Ponds can be designed to minimize maintenance, however, a maintenance free detention facility (that is working properly) does not exist (SEMCOG 1981).

Institutional arrangements must be made to insure continued detention pond maintenance after construction. SEMCOG (1981) recommends that appropriate maintenance programs specifically identify the organization or person who will perform the maintenance and how the maintenance operations will be financed. They also found that major detention pond maintenance (dredging) is usually needed within about ten years after pond construction. More frequent (routine) maintenance may include: structural repairs (bank stabilization), removal of debris and litter from the water and surrounding land, grass cutting, fence repairing, algal control, mosquito control, and possible fish stocking. Wet detention ponds require a lot of attention.

Routine Maintenance Requirements

The following summary of routine maintenance requirements is based on a discussion by Schueler (1987).

Mowing. The most costly routine maintenance required of a detention facility is mowing the surrounding area. In residential areas, frequent mowing (up to 12 times a year) may be necessary to maintain a lawn surrounding the pond. Some native plants (such as in the small prairie surrounding the Monroe Street detention pond in Madison at the University of Wisconsin Arboretum) require much less maintenance. In all cases, the emergency spillway, side slopes, and pond embankments need to be mowed at least twice a year to control undesirable plants that may interfere with pond operation. Attractive landscaping and adequate landscaping maintenance are always needed. Careful plant selection (water and salt tolerant, disease and winter hardy, and slow growing) should be made in conjunction with a landscape architect or the Natural Resources Conservation Service.

Debris and Litter Removal. During the routine mowing operations and after each major storm, debris and litter should also be removed from the site, especially from the inlet and outlet grates and the water surface.

Inspections. Wet detention ponds need to be inspected at least once a year, and after each major storm. The inspection should include checking the pond embankments for subsidence, erosion, and tree growth. The conditions of the emergency spillway and inlets and outlets also need to be determined during the inspection. The adequacy of any channel erosion protection measures near the pond should also be investigated. Sediment accumulation in the pond (especially near, and in, the inlets and outlets) also needs to be examined.

Sediment Removal from Wet Detention Ponds

Large sediment accumulations in detention ponds can have significantly adverse affects on pond performance. Bedner and Fluke (1980) reported on the long term effects of detention ponds that received little maintenance. Lack of dredging actually caused the silted-in ponds to become a major sediment source to downstream areas. Poorly maintained ponds only delayed the eventual delivery of the sediment downstream, they did not prevent it.

Based on the NURP detention pond monitoring results (EPA 1983), a pond having a surface area of about 0.6 percent of the contributing area should remove about 90 percent of the settleable solids (particulate residue) from the runoff. The Milwaukee NURP project (Bannerman, *et al*. 1983) estimated an annual sediment delivery of about 500 pounds per acre for medium density residential land uses and about 2500 pounds per acre for commercial areas. Other land uses contribute sediment generally between these values. Assuming a density of about 120 pounds per cubic feet, about 3.6 and 18 cubic feet of sediment would be deposited in a well designed detention pond for each medium density residential or commercial acre per year. With a pond 0.6 percent of the contributing area in size, this would only result in the deposition of between 0.2 and 0.9 inches per year. McComas and Sefton (1985) report two measured sediment accumulation rates in Chicago area wet detention ponds (about two and three percent of the drainage pond in size) of 0.24 and 1.3 inches per year. Kamedulski and McCuen (1979) report a much greater sedimentation rate of about three inches per year in another pond. When uncontrolled construction site erosion is allowed to enter a detention pond, the pond can literally fill up over night.

Most of the sedimentation would occur near the inlet and the resulting sediment accumulation would be very uneven throughout the pond. Sediment removal in a wet pond may therefore is needed about every five to ten years, depending on the variation in sediment deposition over the pond and the sacrificial storage volume designed. It is therefore necessary to plan for required maintenance during the design and construction of detention ponds. Ease of access of heavy equipment and the possible paving of a sediment trap near the inlet would ease maintenance problems. Deposited sediment can be heavily polluted and may require special disposal practices. Sediment concentrations of up to 100,000 mg organic carbon, several thousand mg lead, several hundred mg zinc, and more than ten mg arsenic per kg dry sediment are not uncommon for lakes receiving urban runoff (Pitt and Bozeman 1979). Dredged sediment is usually placed directly onto trucks, or is placed on the pond banks for dewatering before hauling to the disposal location. One common practice is to keep an area adjacent to the detention pond available for on-site sediment disposal. Small mounds can be created of the dried sediment and covered with top soil and planted.

The estimated cost of removing sediment from a detention pond varies widely, depending on the amount to be removed and the disposal requirements. Costs as low as one dollar per cubic yard have been reported, but this low cost does not include any possible special disposal practices. Sediment removal costs are estimated to generally range from about $5 to $25 per cubic yard of sediment removed.

Problems with Contaminated Sediments in Wet Detention Ponds. Frequently, concern arises about the safety of disposing sediments from wet detention ponds. There have recently been several studies that have addressed this issue, as summarized in the following paragraphs.

Dewberry and Davis (1990) analyzed sediments from 21 ponds in northern Virginia. They found trace metals in many of the sediments, but the available forms of the metals were significantly less than applicable toxic thresholds. They concluded that the dredged materials could be safely disposed either on-site or at sanitary landfills without danger of health problems. However, they recommend that sediment samples from specific ponds be analyzed before dredging.

Jones (1995) and Jones, *et al*. (1996) discuss the implications that the Resource Conservation and Recovery Act (RCRA) may have on sediments that need to be removed from stormwater management facilities, as summarized in the following discussion. The “mixture” (40 CFR Section 261.3(a)(2)(iv)) and “derived from” (40 CFR Sections 261.3(c)(2)(1) and 261.3(d)(2)) rules can cause sediments having very low concentrations of pollutants to be classified as “hazardous.” These regulations are likely to be changed, with clearer definitions for non-hazardous operations and facilities. Sediments are evaluated as being hazardous when the wet detention pond is being dredged, not while they remain in-place. Many of the materials that are listed as hazardous under RCRA may enter stormwater, especially at vehicle service facilities, industrial facilities, and even golf courses and parks. These include solvents, degreasers, hydraulic fluids, herbicides, fungicides, and pesticides. For the sediments to be considered hazardous under the current RCRA mixture rule, the source of the specific material containing the listed hazardous material must contain more than 10% of the hazardous material. This is irrespective of how much of the material actually enters the stormwater. Therefore, site inventories become important tools in determining if a sediment would be classified as hazardous. If a listed material is used on the site, but it would not come in contact with rain (either through normal use or spills), the sediment would not likely be classified as hazardous. It is difficult to conduct detailed site surveys for a large drainage area having many separate owners, but it is feasible for small wet ponds serving single facilities. Jones (1995) and Jones, *et al*. (1996) also discuss other options to minimize the chance that wet pond sediment would be classified as hazardous under RCRA:

- Reduce the likelihood that listed substances would come in contact with precipitation or runoff.
- Inventory and track hazardous materials and encourage the use of less toxic replacement compounds.
- Install stormwater pre-treatment facilities to localize the problem.
- Reduce the accumulation rate, and increase the storage area for sediment in the pond.

Vegetation Removal from Wet Detention Ponds

In shallow detention ponds, excessive rooted aquatic plant (macrophyte) growths may occur over the entire pond surface. In deeper ponds, rooted aquatic plant growths are usually restricted close to the shoreline (Ontario 1984). Floating algae may create problems anywhere in a lake, irrespective of pond depth. As noted earlier, a narrow band of natural rooted aquatic plants along the narrow “safety” shelf is desirable as a barrier and to add habitat for pond wildlife.

Small weed harvestors can be delivered to a detention pond by trailer. The use of chemicals for algae control is popular, but must be carefully done to prevent contamination of the receiving water. Dead algae and rooted plants must also be removed to prevent odor and dissolved oxygen problems. Mechanical barriers can also be placed on the pond bottom to reduce rooted aquatic plant growth. AquaScreen is a fairly fine, dark mesh that is laid on the pond bottom that restricts sunlight from reaching the rooted aquatic plants. In tests conducted on Lake Washington, Perkins (1980) concluded that a two or three month use of the material resulted in about an 80 percent reduction of rooted aquatic plants where the material had been placed. Again, increased pond depth, possibly at less cost, can do the same thing.

Detention Pond Costs

Reported construction costs of detention facilities vary widely due to land value variations and special site or landscaping considerations. Even though the costs of detention facilities appear high, many benefits are available, besides just water quality, that offset these costs. Some of these other benefits directly affect the cost of the development and may include using the wet pond as part of a fire protection system (as described below), and the obvious cost savings associated with reducing the size of parts of the downstream drainage system . In many cases, wet detention ponds have also significantly increased the value of the property due to increased landscaping and recreation benefits.

In a cost analysis conducted by the Ontario Ministry of the Environment (1984), on-site drainage systems containing detention facilities were generally found to have about the same costs as conventional systems. However, in almost all cases no additional off-site stormwater management measures were needed, in marked contrast to the conventional systems. Off-site increased pipe sizes and channels increased the total construction costs of the conventional systems by about 150 to 300 percent as compared to the alternatives containing on-site detention. On-site detention also substantially decreased the flood plain along the main channels, increasing the total area available for development, even when considering the land needed for on-site detention.

The EPA (1983) analyzed costs associated with wet detention ponds construction for the NURP projects. A pond that covers 0.5 percent of a 150 acre watershed area would cost about $50 per watershed acre per year. This sized pond should remove between 80 and 90 percent of the annual suspended solids loading. These costs are for newly developed areas and are not applicable for estimating costs of retro-fitting a pond in an established area.

A detention pond and infiltration trench cost study in the Washington, D.C. area (Wiegand, *et al.* 1986) was based on a survey of engineering estimates and construction bids for 65 facilities constructed since 1982. They found that construction costs (excluding land purchase costs) varied mostly as a function of storage volume of the device (Vs). Their wet detention pond cost estimate equation was based on facilities having storage volumes (total storage in cubic feet, not just freeboard storage above the normal water level) greater than 100,000 cubic feet:

Cost = 34 Vs 0.64

This equation reflects a substantial cost savings with increasing size. As an example, a 0.5 acre pond (five feet deep) would cost about $50,000 (or $120,000 per pond acre), while a nine acre pond (also five feet deep) would cost about $400,000 (or about $40,000 per pond acre). In an interesting comparison, they did not find any significant differences in costs between large wet and dry detention ponds, probably because the wet ponds had greater economics of scale. However, smaller wet ponds were generally about 30 to 60 percent more expensive than small dry ponds (Schueler 1986). Schueler has recently reexamined these detention pond costs and has found that they have increased by about 15% since 1986 due to inflation (Schueler unpublished 1997).

Wiegand, *et al*. (1986) also examined the cost components of wet detention pond construction:

Cut and fill excavation	61%
Inlet and outlet works	18
Riprap	9
Land clearing	5
Sediment erosion control	5
Other	2

Maintenance is a necessary part of any stormwater management system, and the associated maintenance costs must be recognized along with the construction costs. Chambers and Tottle (1980) estimated that the annual maintenance costs for detention facilities to be about $35 (1978 dollars) per acre served per year, not considering sediment removal. About one-half of these annual costs are associated with maintaining the grassed embankments, about 25 percent is associated with weed and algae control, and the remaining 25 percent is associated with inspection and litter removal.

Sediment removal and disposal can be substantially greater than these other maintenance costs. Carr, *et al.* (1983) estimates that sediment removal and disposal for wet detention ponds in the Milwaukee area range from about $135 to $150 per acre of watershed served per year, depending on final disposal method (landfilling or land spreading). These costs ranged from about $5 to $25 per cubic yard (averaged $14). The differences in costs were associated with the sizes and accessibilities of the ponds. Small ponds (less than about 1/2 acre in size) had the lowest sediment removal costs of about $5 to $10 per cubic yard because front end loaders could be used after pond de-watering. Larger ponds required the use of much more expensive draglines or hydraulic dredges. If on-site disposal was not available, hauling and final disposal costs substantially added to these removal costs. Hauling costs added another

$5 to $10 per cubic yard, depending on the distance, and landfilling tipping fees could add another $15 to $25 per cubic yard to these costs. Therefore, in order to minimize sediment removal and disposal costs, Schueler (1986) stressed the need to provide adequate access to ponds, to provide small pre-sedimentation forebays near the inlets, to provide a drain in smaller ponds to allow complete de-watering, and to provide for on-site disposal of sediment near the pond (for at least two dredgings).

Guidelines To Enhance Pond Performance

The Natural Resources Conservation Service (NRCS, renamed from SCS, undated) has prepared a design manual that addresses specific requirements for such things as anti-seep collars around outlet pipes, embankment widths, type of fill required, foundations, emergency spillways, etc., for a variety of wet detention pond sizes and locations. That manual must be followed for detailed engineering requirements.

Insect Control and Fish Stocking

Mosquito problems at wet detention ponds are increased when large water level fluctuations occur, especially when vast amounts of aquatic plants are wetted and available for egg laying. If ponds drain to normal water levels within several hours after a rain has ended, if aquatic vegetation is kept to a minimum (such as only along a narrow ledge close to shore), and if the pond shape allows adequate water movement and wind disturbance, then mosquito problems should be minimal.

Schimmenti (1980) made several recommendations to reduce the possibility of mosquito problems in detention ponds. Wet ponds should have adequate water quality to support surface feeding fish, such as sunfish, and various minnows, that feed on mosquitoes. Carp or crayfish also make adequate biological controls for midges, reducing the need for chemical controls (Ontario 1984).

Some developers have tried to stock trout, yellow perch, and northern pike in detention ponds, but no reproduction and poor wintering soon eliminates these less tolerant fish. Detention ponds receiving urban runoff are likely to contaminate fish, making them unsuitable for consumption. Brydges and Robinson (1986) have conducted extensive heavy metal and pesticide analyses in fish in two wet detention ponds near Toronto, Ontario and have found little problem accumulations of these substances. However, many other studies have reported problem toxic pollutant concentrations in fish from waters receiving urban runoff, so allowing fish consumption in wet detention faculties should only be allowed after careful study. Therefore, game fish should not generally be used in ponds, and consumptive fishing should be discouraged. Fathead minnows, stocked for mosquito control, have survived in detention ponds in Ontario.

Aquatic Plants for Detention Ponds

Aquatic plants are used in many ways in detention ponds, including providing increased nutrient and other soluble pollutant removals, competition with nuisance plants, aquatic life habitat, physical barriers, and decorative landscaping elements. Obviously, care needs to be taken when selecting aquatic plants to ensure that the plants will support the desired objectives and be compatible with multiple objectives and the local growing conditions. It is best to consult professional aquatic plant specialists to determine the best species for each project.

Rooted aquatic plants should be planted along much of the shallow perimeter shelf to deter small children, for aesthetics and to provide wildlife habitat. The use of native aquatic plants is to be encouraged to lessen maintenance costs and to prevent nuisance plants from becoming established in a waterway (such as purple loosestrife). Plants that could be established in wet detention ponds include arrowhead and cattails. Cattails sometimes interfere with the operation of a surface outlet because of large floating pieces clogging the weir. Subsurface weirs and trash racks (both recommended) would reduce this problem. Many rooted aquatic plants may be used in wet detention ponds, but their selection and planting should be done in consultation with landscape architects and wildlife biologists. Fuhr (1996) warns against planting trees and brush on an impoundment because seepage problems may result by root action.

Table 1, from J.P. Ludwig (Ecological Research Services, The Academy Center, Bay City, MI 48708), is a cold region native wet site plant list for a seed mixture that was available in 1987. This seed mixture was suited for saturated, moist, or flooded sites, (especially for clay or loamy organic soils) including pond edges.

Table 1. Northern Native Seed Mixture for Wetlands

Agrimonia gryposepala	Agrimony
Amemone canadensis	Windflower
Apocynum cannibuim	Indian hemp
A. medium	Indian hemp
Asclepias incarnata	Swamp milkweed
Aster drummondii	Aster
A. novae-anglae	New England aster
A. pilosus	Aster
A. umbellatus	Aster
Bidens cernua	Begger tick
B. frondosa	Begger tick
Carex sparganioides	Sedge
C. Tenure	Sedge
Cephalanthus occidentalis	Buttonbush
Cirsium muticum	Swamp thistle
Convoloulus sepium	Bindweed
Cornus racemosa	Grey dogwood
C. stolonifera	Red-osier dogwood
Cyperus strigosus	Galingale
Epilobium angustifolium	Fireweed
E. hirsutum	Willow-herb
Eurpatorium maculatum	Joe-Pye weed
E. perfoliatum	Boneset
E. purpureum	Purple Joe-pyeweed
Gentiana andrewsii	Bottle gentian
G. crinita	Fringed gentian
G. procera	Gentian
Geum laniciatum	Avens
Glyceria canadensis	Mannagruss
Helianthus giganteus	Giant sunflower
H. grosseratus	Sawtooth sunflower
H. tuberosa	Jerusalem artichoke
Helinium antumnale	Sneezeweed
Iris versicolor	Iris
Jancus sp.	Rush
Leersia orizoides	Sawgrass
Liluim michiganese	Michigan lily
L. supurbum	Turk's-cap lily
Lobelia cardinalis	Cardinal flower
Lycopus americanus	Water horehound
Menaspermum canadensis	Moonseed
Onoclea sensibilis	Sensitive fern
Rosa palustrus	Swamp rose
Rudbeckia fulgida	Black-eyed Susan
R. hirta	Black-eyed Susan
R. subtomentosa	Black-eyed Susan
R. triloba	Black-eyed Susan
Saggitaria latifolia	Arrowhead
Scirpus americanus	Bulrush
Slphium terebinthinaceum	Prairie dock
Solidago graminifolia	Grass-leaved goldenrod
Sprirea tomentosa	Hardhack
Thelypteris palustris	Swamp fern
Verbena hastata	Vercain
Vernonia altissima	Tall ironweed

Source: Ecological Research Services, Bay City, MI

Locating Ponds

Ponds that require limiting access, because of uncontrollable nuisance conditions, can be more easily located in industrial or commercial sites (Chambers and Tottle 1980). Ponds offering non-contact recreation and non-consumptive fishing (such as small boat use, ice skating, and aesthetic enjoyment) must be better maintained because of their visibility and need to be located for easy access. As noted in the following paragraphs, basin-wide hydraulic analyses must be used in developing watersheds to identify the best locations for detention ponds to be used for peak flow rate control.

Stormwater wet detention ponds for water quality benefits should be carefully located, considering critical source areas and the use of other control practices. Placement of stormwater detention ponds on the mainstems of receiving waters is not recommended because of the large drainage area upstream that must be considered in the design and the difficulty of effectively using additional controls upstream. Retro-fitting detention ponds in existing areas requires a different approach than for new construction. In retro-fitting controls, detailed watershed analyses are needed to identify outfalls of drainages that contribute significant discharges and upland locations near critical sources (such as industrial and commercial areas), all in conjunction with other possible controls that can be applied simultaneously. They shouldn't be arbitrarily used at all outfalls.

For new construction, wet detention ponds are needed in areas that have large pollutant potentials and where infiltration controls can not be used because of possible groundwater contamination. Large parking or storage areas (paved or unpaved) greater than one acre in size need on-site wet detention ponds to serve as pre-treatment devices before infiltration. Smaller areas may be better served with large catchbasins and oil and grease traps, or sand filters, as infiltration pretreatment. Shopping centers are the most significant example of these areas. Additionally, industrial areas greater than about three acres need to be served with on-site wet detention ponds, with no infiltration. Large residential areas, especially if having high density single family or multi-family units, could also effectively use wet detention ponds as part of the landscaping plans to supplement the infiltration program.

It is usually easier to inspect (and maintain) a small number of relatively large facilities, and larger wet detention basins offer greater public use (such as noncontact recreation and nonconsumptive fishing, for example). Industrial areas or large shopping areas pose an important exception to large, regional detention basins. Public water contact in industrial area wet detention basins should be discouraged because they have very poor water quality. Industrial discharges should also be kept separated in their own detention basins to optimize any special controls that may be needed.

Industrial areas have been found to produce very large portions of the total urban runoff wasteload in cities, especially of heavy metals and toxic organics. Unfortunately, much of this material is discharged during dry weather, possibly as part of wash operations or minor spills. Wet detention basins at the outfalls of industrial developments are needed to control runoff from the industrial sites and to offer an opportunity to remove any dry weather industrial spills and discharges. Reported spills that enter the stormwater drainage system in industrial areas may also be contained for cleanup in outfall wet detention basins. Installation of detention basins during the early phases of a construction project (before the drainage system is installed) can significantly reduce sediment transport from a construction site to receiving waters.

Many stormwater control options can be used together very well. Infiltration trenches, for example, can treat runoff from rains having relatively low intensities but long durations (and therefore large rain volumes). Infiltration devices also remove most pollutants and flow volume from the runoff. However, they discharge these pollutants to the soil and groundwater systems, requiring careful consideration. In all cases, local groundwater contamination potential must be evaluated to reduce the probability of contaminating groundwater with stormwater infiltration. Detention basins, on the other hand, work well with high intensity, low volume rains, but do not reduce soluble forms of the pollutants or flow quantities. These two devices can be used together to treat many runoff pollutants for a wide range of rain conditions.

Rosmiller (1987) notes that the location and amount of detention pond storage in relation to the size of the watershed is important in determining the peak flow rate reduction potential of a pond. He found that large ponds on the mainstem of a stream and on its major tributaries result in greater reductions in peak flow rates than numerous smaller ponds spread throughout the watershed. Unfortunately, this can conflict with water quality and biological objectives in areas upstream of a mainstem detention pond. He concludes that the best peak flow rate reductions in downstream portions of a watershed are associated with detention ponds located in the middle portions of a watershed. Detention ponds located on tributaries in the downstream portions of watersheds can increase peak flows in the mainstem because of the superposition of peak flows from upper portions of the watershed and the peak flows from delayed hydrographs from the downstream detention ponds.

Figures 2 through 4, from Rosmiller (1987), illustrate how detention pond locations can greatly influence the resultant peak flow rates. Figure 2 shows a watershed with a downstream urbanizing tributary. Figure 3 shows the predevelopment (and pre-detention) tributary, mainstem, and combined hydrographs for this watershed. Figure 4 shows how a tributary detention pond located downstream of the urbanizing area maintains the predevelopment peak runoff rate for the tributary, but results in substantially greater combined flows downstream after combining with the mainstem hydrograph.

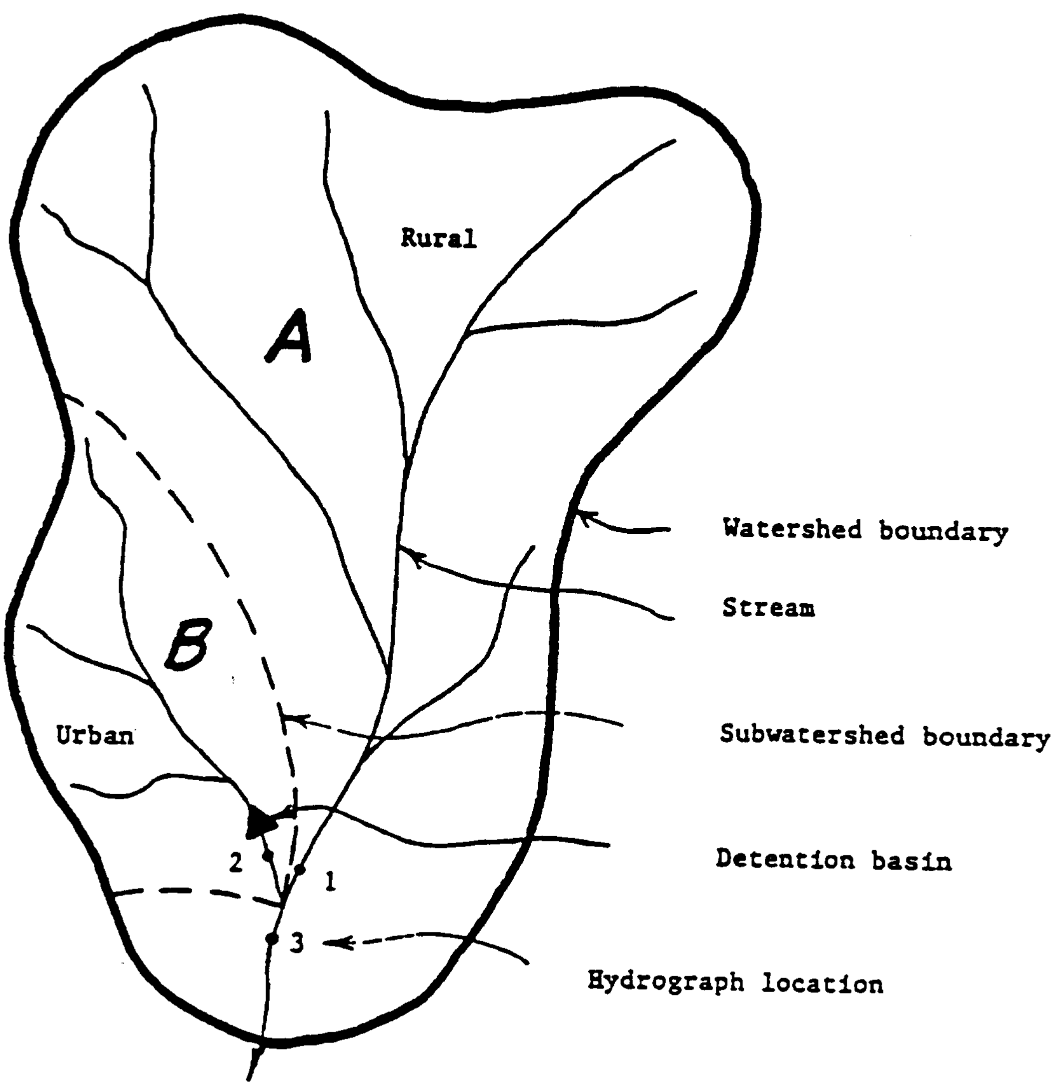


Figure 2. Detention pond located in downstream portion of watershed (Rosmiller 1987).

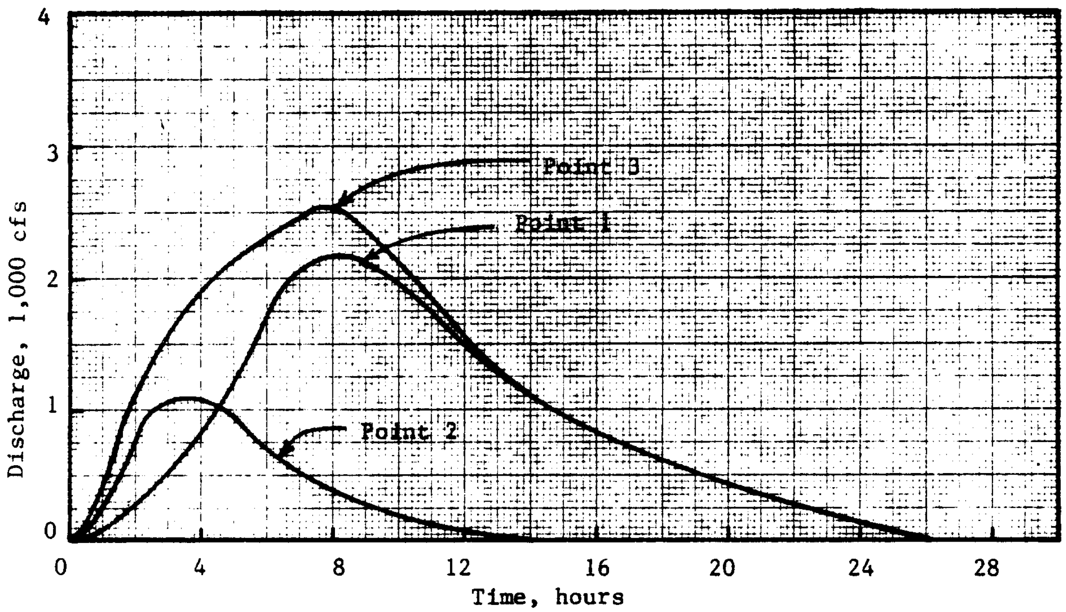


Figure 3. Hydrographs before urbanization without detention (Rosmiller 1987).

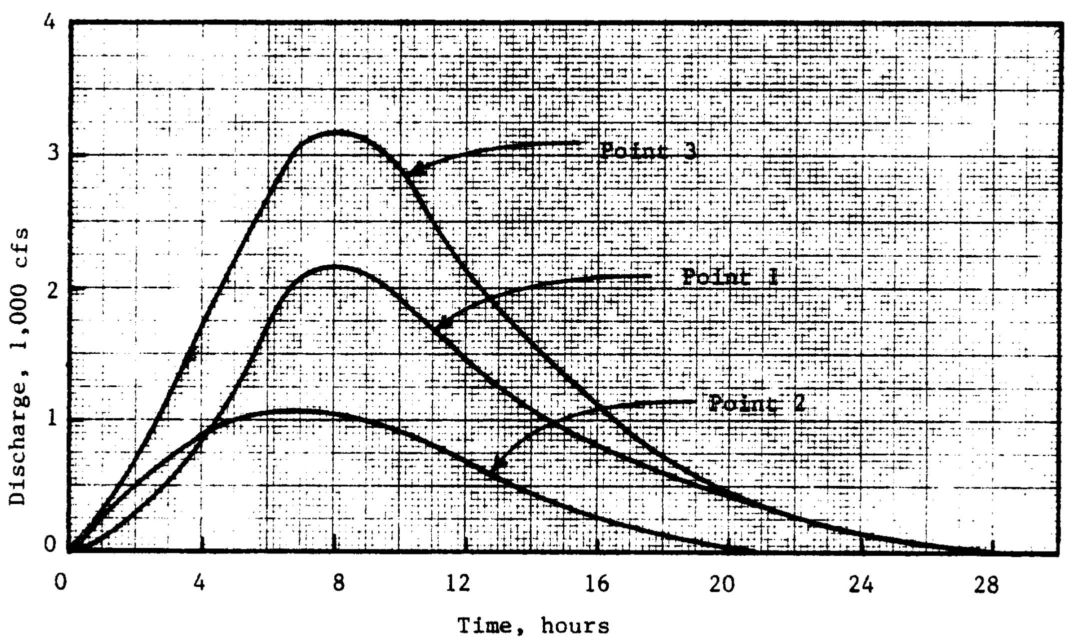


Figure 4. Hydrographs after urbanization with downstream detention (Rosmiller 1987).

A detention pond does not reduce the runoff volume, but can only delay the discharge of the runoff. Urbanization results in both increased peak runoff rates and runoff volume. Detention can radically alter the shape of a hydrograph (and therefore the peak runoff rate) but it cannot reduce the runoff volume. If the peak runoff rate is reduced, and no volume reduction occurs (such as from infiltration practices) then the hydrograph base must be expanded. This expanded base hydrograph, if from a downstream area, can interact with the naturally delayed portions of upstream hydrographs (assuming the rain duration was less than the total watershed time of concentration).

Rosmiller (1987) also states that similar problems may occur with detention facilities randomly located throughout a watershed. This can be caused by stormwater ordinances requiring detention facilities located at each development site that are to preserve pre-development peak runoff rates. He points out that detention ponds for peak flow rate objectives must be carefully located to minimize these interferences. He explains that effective stormwater management to obtain peak flow rate objectives must be met using a combination of regional ponds on the main stem and major tributaries for main stem protection and smaller on- and off-site ponds for local area protection. Rosmiller's (1987) three steps to minimize peak flow increases with interfering hydrographs from multiple ponds are as follows:

"1. Locate the regional ponds first and determine the volume of storage needed to obtain the attenuation needed to reduce future peak flows to pre-development peaks.

2. Address each watershed upstream of each regional basin in turn to determine where supplemental ponds are needed to give protection to the inhabitants and property in each watershed.

3. Design these localized on- and off-site ponds plus the regional pond for that watershed in concert with each other so that the overall effect is achieved."

Pond Surface Area and Shape

Surface area is one of the most important design considerations for particle removal. Surface area is also important if the pond is to be used for recreational purposes. A minimum pond size of about five acres is necessary for a pond to have much recreation value for anything but ice skating (Ontario 1984). Large pond volumes also reduce the chance of a rain displacing all of the pond volume and increases the residence times of the water for further water quality improvement (Hey and Schaefer 1983).

Hittman (1976) reports that pond length to width ratios of about five have produced maximum pond efficiencies (decreased short-circuiting) during dye tests. If a long and narrow pond cannot be constructed, Schueler (1986) suggests that baffles or gabions be placed within the pond to lengthen the flow path between the inlets and outlets. Bondurat, *et al*. (1975) has also suggested that the idealized pond shape would be triangular: narrow near the inlet and wider near the outlet. This triangular configuration would allow more efficient particle settling by having a continually decreasing forward velocity. Very irregular pond shapes may decrease circulation and cause localized nuisance problems. The pond shape should be irregular for aesthetic considerations, but with minimal opportunities for water stagnation.

Pond Water Depth

Chambers and Tottle (1980) state that pond water depth affects algae growth, aquifer contamination, water stratification, fish survival, sedimentation, and flood control. A storage volume above the permanent pool elevation of the pond affects the pond's ability to absorb excess flows for flood control. Harrington (1986) found that increasing the wet pool depth increases sedimentation efficiency (due to flocculation), but that surface area increases were much more effective in enhancing the water quality performance of wet ponds. A minimum wet pool depth is very critical in wet ponds to decrease scour losses of previously settled material. Without an adequate permanent pool depth, very little water quality benefits can be expected from wet ponds.

The NRCS (SCS 1982) recommends a pond depth of at least six or seven feet in agricultural areas to insure adequate water during dry periods. In urban areas, the runoff water yield per acre is substantially greater than in agricultural areas, and the depth could probably be less. However, in urban areas containing substantial infiltration devices (such as grass swale drainage ditches) this deeper depth may be needed.

To reduce widespread attached aquatic plant growth problems, a pond depth of at least four feet is recommended. This depth will generally prevent the growth of attached aquatic plants in clean ponds. Similarly, shallower pond depths are needed in areas where attached aquatic plants are wanted, such as along much of the recommended perimeter shelf of wet ponds. Schueler (1986) reports that many emergent plants require water depths of less than six inches, while submerged plants typically require water one to two feet deep. Deep ponds will therefore restrict plant growth. A water depth of about six feet over the major portion of the pond will also increase winter survival of fish.

Pond Side Slopes
Reported recommended side slopes of detention ponds have ranged from 1:4 (one vertical unit to four horizontal units) to 1:10. Steeper slopes will cause problems with grass cutting and may erode. Steep slopes are not as aesthetically pleasing and are more dangerous than gentle slopes (Chambers and Tottle 1980). Sclueler (1986) also recommends a minimum slope of 1:20 for land near the pond to provide for adequate drainage.

The slope near the waterline, and for about one foot below, should be relatively steep (1:4) to reduce mosquito problems (by reducing the amount of frequently wetted land surface), and to provide relatively fast pond drawdown after common storms. However, a flat underwater shelf several feet wide and about one foot below the normal pond surface is needed as a safety measure to make it easier for anyone who happens to fall into the pond to regain their footing and climb out. This shelf should also be planted with native rooted aquatic plants (macrophytes) to increase the aesthetics and habitat benefits of a pond and to create a barrier making unwanted access to deep water difficult.

Outlet Structures
Most of the effort given to alternative outlet structure designs has been for dry detention ponds. Wet ponds usually only have a surface weir, outlet pipe, or other simple overflow device to allow the passage of displaced pond water during rains. With the use of a more sophisticated outlet device, located at the normal wet pond surface elevation, more efficient particulate removals and flood control benefits may occur.

Controlled emptying of a detention pond at low outlet flow rates is desirable for effective sediment removal and flood control. A small diameter outlet pipe, or a small orifice on a plate, is usually used to achieve low outflows. The rate of discharge varies for these outlets because of varying overlying water levels. High flow rates occur with higher water levels and the outlet flows decrease with falling water levels. Selecting an appropriate outlet structure has significant effects on pond performance. To have a constant pond performance for all events (if desired), the shape of the outlet must allow a constant upflow velocity (pond outflow rate divided by pond surface area).

If water temperature increases are expected to be a problem, then subsurface outlets may be needed. Subsurface outlets also minimize trash fouling of the outlet. One method of achieving subsurface discharges is to use a submerged large diameter pipe (the pipe bottom must still be at least three feet off of the pond bottom to minimize sediment scour) discharging to a control box that contains the outlet weir (such as a v-notch weir) whose invert is above the top of the pipe.

Mason (1981) states that the benefits of regulating runoff from the frequent less intense storms are usually overlooked. Smaller storms produce less runoff per event, but may be heavily contaminated and occur frequently. Outlets having variable opening sizes with depth can be designed to provide some detention of small rains while allowing flood control benefits from the larger storms. V-notch weirs and multi-stage outlets can control both low and high flows and are recommended for general use. These devices need to be located with their lowest openings at the permanent pool water elevation in wet ponds to provide both desired water quality and flood control benefits.

Emergency Spillways
All detention ponds must also be equipped with emergency spillways. Mason (1982) states that the preferred location of an emergency spillway is on undisturbed ground rather than over a prepared embankment to reduce the erosion potential. Detention ponds treating runoff from small contributing areas can safely handle overflows as sheetflows through well designed swales.

The Natural Resources Conservation Service guidelines for designing runoff control measures must be followed when designing emergency spillways for wet detention ponds. In addition, if the detention pond is large, special regulations of the state and the Army Corps of Engineers must be followed.

Enhancing Pond Performance During Severe Winter Conditions

Oberts (1990 and 1994) monitored four urban wet detention ponds during both warm and cold weather in Minnesota. The ponds performed as expected during warm weather, providing typical removals of suspended solids (80%), lead (68%), and TP (52%). However, he found that the ponds did a much worse job of removing suspended solids (39%), organic matter (12% for COD), nutrients (4 % for TKN to 17% for TP) and lead (20%) in the winter. He found that thick ice, which can form as much as 1 m in thickness, effectively eliminated much of the detention volume for incoming snowmelt water. In addition, the first melting water was forced under the ice, causing scour of the previously sediments. Later snowmelt water flowed across the surface of the ice, with very little sedimentation opportunities. Any sediment that was accumulated on top of the underlying ice was later discharged when the ice melted. Similar research in Minnesota wetlands also showed similar dismal performance during winter conditions, for much the same reasons.

Oberts (1990 and 1994) proposed several improvements in stormwater management during winter conditions. His initial recommendation is to utilize infiltration and grass filtering in waterways before any detention facilities. He found that substantial infiltration can occur, even in clayey soils, underlying the snow. The ground under snowpacks is rarely frozen and infiltration can be significant until the soil becomes saturated. If the snowmelt is originating from areas having automobile activity (streets and parking areas) or sidewalks, care must be taken because the snowmelt likely would have high concentrations of salts which would adversely affect the local groundwater (Pitt, *et al*. 1996). The design of the detention pond should be modified for winter operations. A low flow channel leading to and through the pond will discourage the formation of ice. The pond can also be aerated to prevent ice formation, however, if it gets extremely cold, ice formation could then be very thick and rapid. The most important suggestion by Oberts is to use a special riser for the outlet of the pond that can be used to draw down the water elevation during the winter. Ice would then form near the bottom of the pond and seal off the sediments. As the snowmelt occurs, the bottom outlets on the riser should be closed, forming a deeper pond for better sedimentation. Figure 5 shows a schematic of this pond.

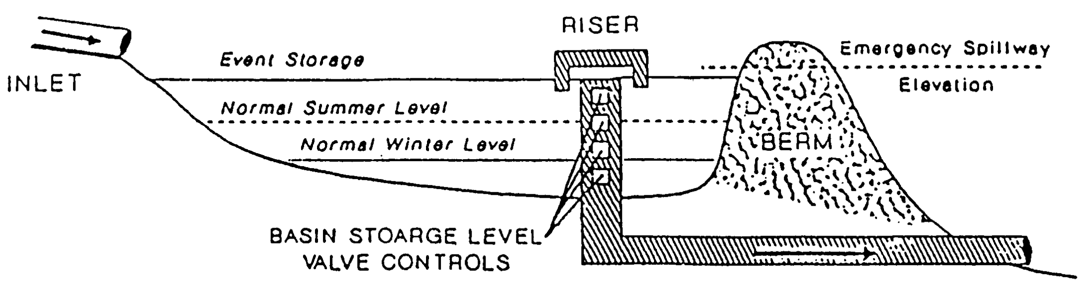


Figure 5. Wet detention pond outfall risers for winter conditions (Oberts 1994).

Droste and Johnston (1993) examined snowmelt quality from snow disposal areas in Ottawa and conducted treatability tests to examine the benefits of different settlement times in 1 L test columns. They found that 2 to 6 hour settling times in these columns produced suspended solids and metal removals approaching 90%. These tests were conducted in controlled laboratory conditions and were not subjected to the actual site problems identified by Oberts. These tests do indicate that sedimentation treatment of snowmelt is likely beneficial, especially if the unique problems of scour and ice formation can be overcome.

Mayer, *et al*. (1996) examined the performance of four wet detention ponds in Toronto during different seasons and during non-storm conditions. The thick ice cover on the ponds during the winter severely affected the pond water quality. In addition, snowmelt and runoff from rainfall occurring on an existing snowpack, were poorly treated by the ponds. Few of the biochemical processes that normally enhance pollutant removal in wet detention ponds during warm weather are available during the winter, plus the ice pack decreases the efficiency of the physical processes, as noted by Oberts. Water beneath the winter ice was typically devoid of oxygen, causing the release of ammonia from sediments and increasing the water column concentrations to about 0.5 mg/L. High grit concentrations in snowmelt, associated with winter sanding of streets, were effectively removed in the detention ponds. However, the high chloride concentrations, from salting of the streets, were not affected by the ponds, as expected.

Detention Pond Design Fundamentals

The basic design approaches for wet detention ponds consider either slug flow or completely mixed flow. Martin (1989) reviews these flow regimes and conducted five tracer studies in a wet detention pond/wetland in Orlando, FL, to determine the actual flow patterns under several storm conditions. Completely mixed flow conditions assumes that the influent is completely and instantaneously mixed with the contents of the pond. The concentrations are therefore uniform throughout the pond. Under plug flow conditions, the flow proceeds through the pond in an orderly manner, following streamlines and with equal velocity. The concentrations vary in the direction of flow and are uniform in cross section. The steady state resident time for both flow conditions is the same for both flow patterns, namely the pond volume divided by the discharge rate. Historically, wet detention ponds have been designed using the plug flow concept, probably because it had been used in conventional clarifier designs for water and wastewater treatment. In reality, detention ponds exhibit a combination flow pattern that Martin terms moderately mixed flow. He found that the type of mixing that actually occurs is dependent on the ratio of the storm volume to the pond storage volume. If the ratio is less than one, plug flow likely predominates. If the ratio is greater than one, the flow type is not as obvious. With faster flows in the pond, short-circuiting effectively reduces the available pond storage volume (and therefore the resident time), with less effective treatment.

Detention facilities can be designed to suppress the flows from small events and provide significant water quality benefits by using small primary outlets, such as stacked orifices or V-notch weirs. If adequate free-board storage is provided, significant flood control benefits from the same detention facilities are also possible. Alternately, wet detention ponds designed for water quality benefits can discharge to downstream dry detention facilities (through small primary outlets and emergency spillways) designed for flood control benefits alone.

Design considerations based on watershed scale is also important, especially for flood control purposes. Local flooding can be addressed by a relatively small detention facility that provides little, if any, downstream flood control benefit. From a water quality viewpoint, a detention facility can also be designed to protect a local sensitive water body that would produce very little downstream water quality benefits. These local objectives are legitimate, as long as downstream problems are not increased (as can occur with flood control facilities). Alternative local controls may also be available to alleviate both local problems and larger scale watershed problems.

Upflow Velocity

Linsley and Franzini (1964) stated that in order to get a fairly high percentage removal of particulates, it is necessary that a sedimentation pond be properly designed. In an ideal system, particles that do not settle below the bottom of the outlet will pass through the sedimentation pond, while particles that do settle below/before the outlet will be retained. The path of any particle is the vector sum of the water velocity (V) passing through the pond and the particle settling velocity (v). Therefore, if the water velocity is slow, slowly falling particles can be retained. If the water velocity is fast, then only the heaviest (fastest falling) particles are likely to be retained. The critical ratio of water velocity to particle settling velocity must therefore be equal to the ratio of the sedimentation pond length (L) to depth to the bottom of the outlet (D):

$$\frac{V}{v} = \frac{L}{D}$$

as shown on Figure 6.

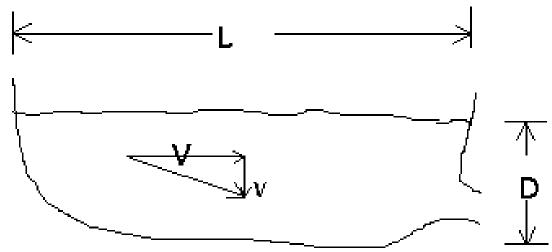


Figure 6. Critical Velocity and Pond Dimensions

The water velocity is equal to the water volume rate (Q, such as measured by cubic feet per second) divided by the pond cross-sectional area (a, or depth times width: DW):

$$V = \frac{Q}{a}$$

or

$$V = \frac{Q}{DW}$$

The pond outflow rate equals the pond inflow rate under steady state conditions. The critical time period for steady state conditions is the time of travel from the inlet to the outlet. During critical portions of a storm, the inflow rate (Q_{in}) will be greater than the outflow rate (Q_{out}) due to freeboard storage. Therefore, the outflow rate controls the water velocity through the pond. By substituting this definition of water velocity into the critical ratio:

$$\frac{Q_{out}}{WDv} = \frac{L}{D}$$

The water depth to the outlet bottom (D) cancels out, leaving:

$$\frac{Q_{out}}{Wv} = L$$

Or

$$\frac{Q_{out}}{v} = LW$$

However, pond length (L) times pond width (W) equals pond surface area (A). Substituting leaves:

$$\frac{Q_{out}}{v} = A$$

and the definition of upflow velocity:

$$v = \frac{Q_{out}}{A}$$

where Q_{out} = pond outflow rate (cubic feet per second),
A = pond surface area (square feet: pond length times pond width), and
v = upflow velocity, or critical particle settling velocity (feet per second).

Therefore, for an ideal sedimentation pond, particles having settling velocities less than this upflow velocity will be removed. Only increasing the surface area, or decreasing the pond outflow rate, will increase pond settling efficiency. Increasing the pond depth does lessen the possibility of bottom scour, decreases the amount of attached aquatic plants, and decreases the chance of winter kill of fish. Deeper ponds may also be needed to provide sacrificial storage volumes for sediment between dredging operations.

The EPA (1986) detention pond water quality analysis procedure includes a partial credit for the removal of particles having settling velocities less than the critical upflow velocity. This is based on the assumption of full depth and well-mixed inlet zones that are used in conventional water treatment clarifiers, but are not likely for stormwater detention ponds which mostly have surface (or near surface) inlets. For stormwater detention ponds, it should be assumed that inlet zones are restricted to the pond surface and that the outlet zones are full depth, providing a worst-case situation.

For continuous flow conditions (such as for water or wastewater treatment), the following relationships can be shown:

$$t = \frac{Volume}{Flow\ rate}$$

and

$$Flow\ rate\,(Q_{out}) = \frac{Volume}{t}$$

where t = detention (residence) time. With

$$v = \frac{Q_{out}}{A}$$

and substituting:

$$v = \frac{Volume}{(t)(A)}$$

but

$$Volume = (A)(depth)$$

therefore,

$$v = \frac{(A)(depth)}{(t)(A)}$$

leaving:

$$v = \frac{depth}{t}$$

It is seen that the overflow rate (Q/A) is equivalent to the ratio of depth to detention time. It is therefore not possible to predict pond performance by only specifying detention time. If pond depth was also specified (or kept within a typical and narrow range), then detention time could be used as a performance specification for a continuous or slug flow condition. However, it is not possible to hold all of the water in a detention pond for the specified detention time. Outlet devices typically release water at a high rate of flow when the pond stage is increased (resulting in minimal detention times during peak flow conditions) and lower flow rates at lower stages, after most of the detained water has already been released. The average detention time is therefore difficult to determine and is likely very short for most of the water during a moderate to large storm. It is much easier to design and predict pond performance using the upflow relationships for variable flow stormwater conditions.

The upflow ratio of outflow rate to pond surface area can be kept constant (or less than a critical value) for all pond stages. This results in a much more direct method in designing or evaluating pond performance. Pond performance curves can therefore be easily prepared relating upflow velocity (and therefore critical particle control) for all stages at a pond site.

Effects of Short-Circuiting on Particulate Removals in Wet Detention Ponds

Under dynamic conditions, particle trapping can be predicted using the basic Hazen theory presented by Fair and Geyer (1954) that considers short-circuiting effects:

$$\frac{y}{y_0} = 1 - \left[1 + \frac{v_o}{n(Q/A)}\right]^{-n}$$

where y_o = initial quantity of solids having settling velocity of v_o
y = quantity of these particles removed
y/y_o = proportion of particles removed having this settling velocity
Q = wet pond discharge
A = wet pond surface area
n = short-circuiting factor (number of hypothetical basins in series)

This equation is closely related to the basic upflow velocity equation developed previously and is also included in DEPTOND. The short-circuiting factor is typically given a value of 1 for very poor conditions, 3 for good conditions, and 8 for very good conditions. Short-circuiting allows some large particles to be discharged that theoretically would be completely trapped in the pond. However, field monitoring of particle size distributions of detention pond effluent shows that this has a very small detrimental effect on the suspended solids (and pollutant) removal rate of a pond.

The degradation of performance is much worse for particles having settling rates much larger than the critical rate. However, most wet detention ponds are greatly over-sized according to their ability to remove large particles, so this degraded performance has minimal effect on the overall suspended solids removal. The suggested detention pond design presented in this discussion only operates at the "design" stage (where the critical particle size is being removed) a few times a year. At all other times, the smallest particles being removed in stormwater wet detention ponds are much smaller than the critical size used in the pond design. Most larger particles are effectively trapped because they are much larger than the design particle size (the pond is over-sized for these large particles), even if they are not being removed at their highest possible rate. In most cases, a few relatively large particles (much larger than the critical design particle size) will be observed in the pond effluent, but they have little effect on the overall SS removal.

Figure 7 shows example particle settling distributions for a pond, comparing effluent conditions using the short-circuiting effects of Hazen's theory. The most common particle size (the mode) changes very little for the different effluent conditions. However, there are more larger-sized particles present in the effluent using Hazen's theory compared to the ideal theory, and the median size obviously increases as the value for n decreases.

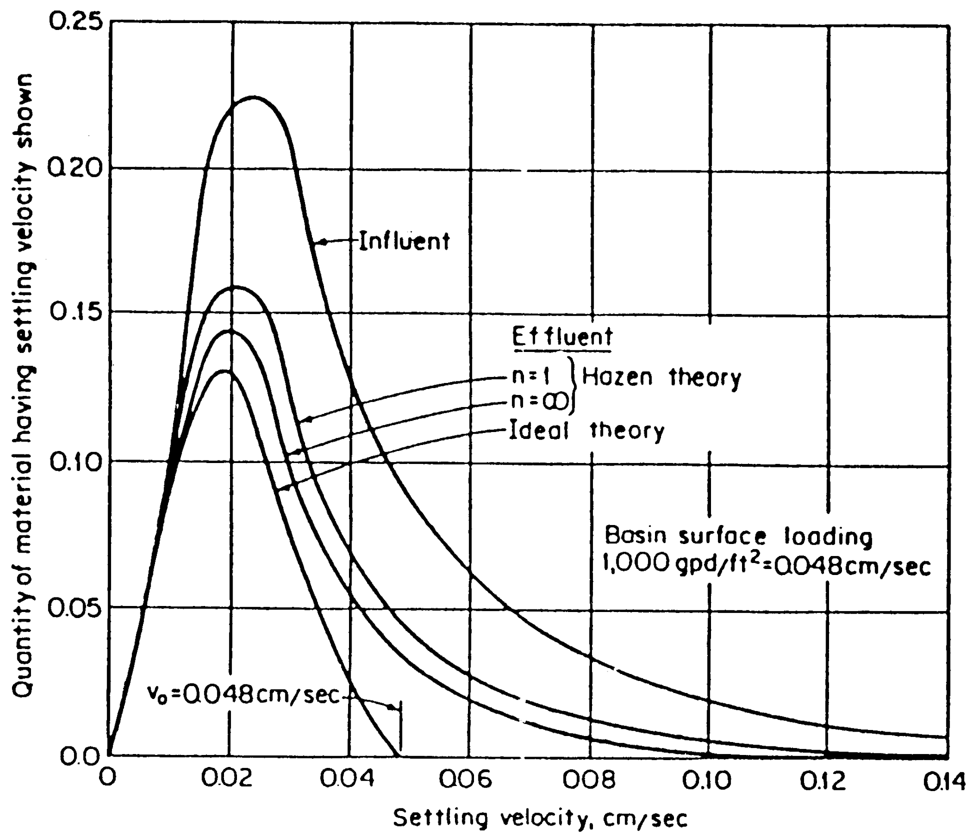


Figure 7. Influent and effluent particle settling rate distributions for settling basins of varying effectiveness (AWWA 1971).

Very little degraded performance was observed at a pond monitored during NURP (EPA 1983) in Lansing, MI, that was expected to have significant short-circuiting. A golf course pond located across the street from a commercial strip was converted into a stormwater pond, but the inlets and outlets were adjacent to each other in order to reduce construction costs. It was assumed that severe short circuiting would occur because of the close proximity of the inlet and outlet, but the pond produced suspended solids removals close to what was theoretically predicted, and similar to other ponds having much similar pond area to watershed area ratios. Actually, the close inlet and outlet may have resulted in less short-circuiting because the momentum of the inflowing waters may have forced the water to travel in a general circular pattern around the pond, instead of directly flowing across the pond (and "missing" some edge area) if the outlet was located at the opposite side of the pond.

In another example, the USGS and the Wisconsin Department of Natural Resources have been monitoring the Monroe St. wet detention pond in Madison for a number of years. Particle size distributions of influent (including bedload) and effluent have been monitored for about 50 storms. The actual particle size distributions and suspended solids removals have been compared to calculated pond performance, using the DETPOND computer program, for different short-circuiting factors. The calculated values of n (based on matching measured effluent particle size distributions with distributions calculated using different values of n) ranged from about 0.2 to 1, indicating "very poor performance", or worse. However, the pond is producing very good suspended solids removals (85 to 90% reductions) as designed, but the particle size distributions of the effluent indicate some short circuiting (some large particles are escaping from the pond). The short circuiting has not significantly reduced the effectiveness of the pond (measured as the percentage of suspended solids captured). Therefore, care should be taken in locating and shaping ponds to minimize short circuiting problems, but not at the expense of other more important factors (especially size, or constructing the pond at all). Poor pond shapes probably cause greater problems by producing stagnant areas where severe aesthetic and nuisance problems originate.

Residence Time and Extended Detention Ponds

During quiescent conditions, simple column sedimentation occurs, with very little flow through a wet pond. Lateral flow would be caused by a baseflow from the watershed, supplemental water pumped from wells, or groundwater intrusion. Urban area baseflows of about 0.001 cfs per acre of contributing watershed have been observed (Pitt and McLean 1986), but can vary widely. The corresponding lateral flow for most ponds would be very small during dry weather. A 200 acre watershed may only have a baseflow of about 0.2 cfs and a two acre wet pond adequate to serve this watershed may be about 200 feet wide and three feet deep. The dry weather lateral flow would therefore be about 3×10^{-4} ft/sec. It would therefore require very large baseflows and very small ponds to result in significant lateral flows during dry periods. Therefore, interevent settling mainly occurs as a quiescent process, similar to what would be observed during typical settling column experiments (water depth divided by the residence time equaling the critical particle settling rate).

Residence time is defined as the ratio of volume to average flow rate, resulting in a time dimension. It can be assumed to be the average length of time any parcel of water remains in the pond. As in any pond performance measure or design criteria, residence time values are very dependent on good pond configurations. Harrington (1986) stresses the need to subtract pond "dead zones" from pond volume when calculating residence times. Dead zones (and associated short-circuiting) can significantly reduce pond effectiveness.

Designing a wet pond for the treatment of stormwater runoff based on residence time is usually not recommended. Barfield (1986) states that residence (detention) time is not a good criteria for pond performance, but the ratio of peak discharge rate to pond surface area (the peak upflow velocity) is a good criteria of performance. The state of Maryland uses a residence time standard as part of their design criteria for "extended detention" ponds. These ponds are normally dry between events, or have a small and shallow wet pond area near the outlet, and greatly extend in surface area during storms. For these types of ponds, Harrington (1986) found, through computer modeling studies, that a residence time of about nine days is needed to achieve a 70 percent reduction of particulate residue. Nine days is longer than the inter-event period for most rains in the midwest and the southeast, which is about three to five days. These types of ponds are therefore not expected to be very useful for locations where the interevent periods of rains is short, or the drain-down time of the pond is rapid.

Extended detention ponds may be a suitable retro-fitting alternative for existing dry detention ponds to achieve some water quality benefits. It may not be cost-effective, or it may be excessively disruptive to convert a dry detention pond into a standard wet detention pond. Most dry detention ponds are designed for flow rate reduction benefits and need large amounts of storage volume, or are used as athletic fields during dry weather. Complete re-grading of the site could be very expensive. The use of a relatively small wet pond near the outlet area could achieve some water quality benefits in addition to the existing water flow benefits, be a cost-effective retro-fit control measure, and still allow multiple use of the site. For new ponds, much more cost-effective solutions meeting water quality, flood control, and recreation benefits could be achieved with the use of a conventional wet pond located above a dry pond which has an infiltration trench along the dry pond invert.

Unfortunately, dry ponds usually do not allow permanent retention of the settled particles. Subsequent storms usually scour the fine particles previously settled to the pond bottom. As stated previously, dry detention ponds have not been shown to be consistently effective water quality control devices. The use of a small permanently wet detention pond or wetland at the downstream end of a dry detention pond could help recapture some of these scoured particles. As noted above, a wet detention pond above a dry pond is usually a much better solution, as the wet pond would then act as a pre-treatment pond, keeping particles and debris out of the dry pond. This would reduce dry pond maintenance and increase its safety by eliminating the deposition of toxic pollutants associated with polluted dust and dirt particles. This is very important if the dry pond is to be used for recreation.

In some cases, shallow forebays (about one foot deep) have been recommended for wet detention ponds, based on this residence time relationship. It appears that shallow detention ponds would require less residence time to control particles. The particles would strike the pond bottom sooner for a shallow pond, but increased turbulence (because of the shallow flow) would not allow the particles to remain in place, washing them into the main body of the pond, or out the pond outlet.

The upflow velocity design procedure requires knowing the same stage-surface area and stage-discharge relationships that are also needed when designing ponds for flood control. These relationships also allow specific guidance in the selection of an outlet control device. The residence time design method should be used when designing extended detention ponds or for evaluating pond performance during dry intervals between rains when very little flow occurs.

Particle Size

Knowing the settling velocity characteristics associated with stormwater particulates is necessary when designing wet detention ponds. Particle size is directly related to settling velocity (using Stokes law, for example, and using appropriate shape factors, specific gravity and viscosity values) and is usually used in the design of detention facilities. Particle size can also be much more rapidly measured in the laboratory than settling velocities. Settling tests for stormwater particulates need to be conducted for about three days in order to quantify the smallest particles that are of interest in the design of wet detention ponds. If designing rapid treatment systems (such as grit chambers or vortex separators for CSO treatment), then much more rapid settling tests can be conducted. Probably the earliest description of conventional particle settling tests for stormwater samples was made by Whipple and Hunter (1981).

Figure 8 shows approximate stormwater particle size distributions derived from several upper Midwest and Ontario analyses, from all of the NURP data (Driscoll 1986), and for several eastern sites that reflect various residue concentrations (Grizzard and Randall 1986). Pitt and McLean (1986) microscopically measured the particles in selected stormwater samples collected during the Humber River Pilot Watershed Study in Toronto. The upper Midwest data sources were two NURP projects: Terstriep, *et al*. (1982), in Champaign/Urbana, IL, and Akeley (1980) in Washtenaw County, Michigan.

Relatively few samples have been analyzed for stormwater particle sizes and no significant trends have been identified relating the particle size distribution to land use or storm condition. However, the work by Grizzard and Randall (1986) does indicate significantly different particle size distributions for stormwaters from the same site having different suspended solids concentrations. The highest suspended solids concentrations were associated with waters having relatively few small particles, while the low suspended solids concentration waters had few large particles. The particle size distribution for the upper Midwest urban runoff samples falls between the medium and high particulate concentration particle size distributions.

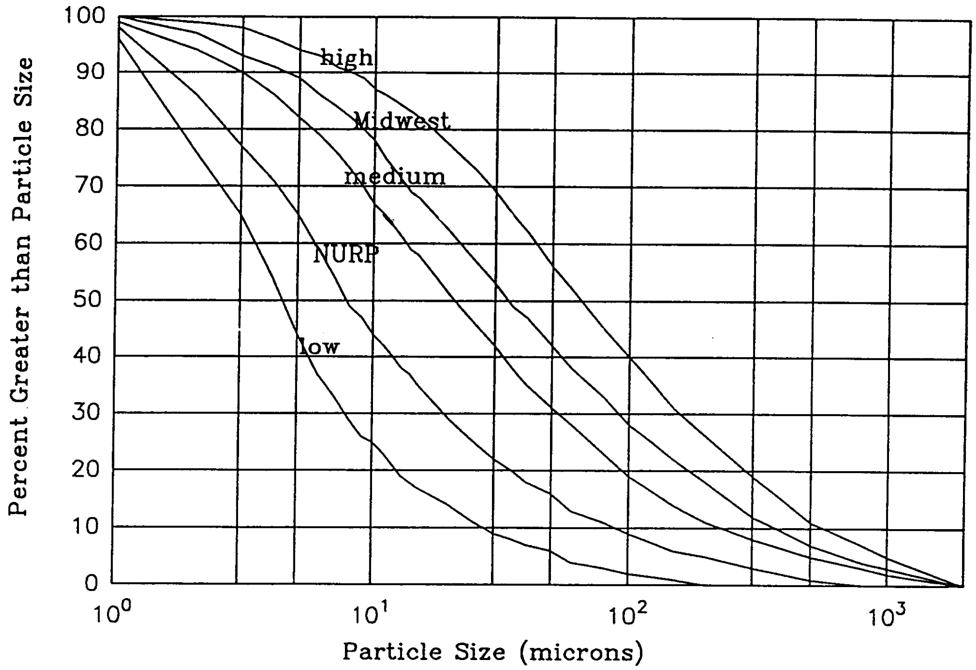


Figure 8. Particle size distributions for various stormwater sample groups.

For many urban runoff conditions, the median stormwater particle size is estimated to be about 30 µm, (which can be much smaller than the median particle size of some source area particulates). Very few particles larger than 1000 µm are found in stormwater, but particles smaller than ten µm are expected to make up more than 20 percent of the stormwater total residue weight. Similar observations of the predominance of very small particles have been made in other urban runoff detention pond studies (Ferrara 1982).

Tests have also been conducted to examine the routing of particles through the Monroe St. detention pond in Madison, Wisconsin (Roger Bannerman, Wisconsin Department of Natural Resources, personal communication). This detention pond serves an area that is mostly comprised of medium residential, with some strip commercial areas. This joint project of the Wisconsin Department of Natural Resources and the U.S. Geological Survey has obtained a number of inlet and outlet particle size distributions for a wide variety of storms. The observed median particle sizes ranged from about 2 to 26 µm, with an average of 9 µm. The following list shows the average particle sizes corresponding to various distribution percentages for the Monroe St. outfall:

Percent larger than size	Particle Size (µm)
10 %	450
25	97
50	9.1
75	2.3
90	0.8

These distributions included bedload material that was also sampled and analyzed during these tests. This distribution is generally comparable to the "all NURP" particle size distribution presented previously. The critical particle sizes corresponding to the 50 and 90 percent control values are as follows for the different data groups:

	90 %	50%
Monroe St.	0.8	9.1 µm
All NURP	1	8
Midwest	3.2	34
Low solids conc.	1.4	4.4
Medium solids conc.	3.1	21
High solids conc.	8	66

Particle Settling Velocities

The settling velocities of discrete particles are shown in Figure 9, based on Stoke's and Newton's settling relationships. Probably more than 90% of all stormwater particulates are in the 1 to 100 µm range, corresponding to laminar flow conditions, and appropriate for using Stoke's law. This figure also illustrates the effects of different specific gravities on the settling rates. In most cases, stormwater particulates have specific gravities in the range of 1.5 to 2.5. This corresponds to a relatively narrow range of settling rates for a specific particle size. Particle size is much easier to measure than settling rates and it is generally recommended to measure particle sizes using automated particle sizing equipment (such as a Coulter Counter Multi-Sizer IIe) and to conduct periodic settling column tests to determine the corresponding specific gravities. If the particle counting equipment is not available, then small scale settling column tests (using 50 cm diameter Teflon™ columns about 0.7 m long) can be easily used.

These settling velocities (or particle sizes) are used with the pond outflow rate to determine the required pond surface area. Particle settling observations in actual detention ponds have generally confirmed the ability of well designed and operated detention ponds to capture the "design" particles. Gietz (1983) found that particles smaller than 20 µm were predominate (comprised between 50 to 70 percent of the sediment) at the outlet end of a "long" monitored pond, while they only made up about ten to 15 percent of the sediment at the inlet end. Particles between 20 and 40 µm were generally uniformly distributed throughout the pond length, and particles greater than 40 µm were only found in the upper (inlet) areas of the pond. The smaller particles were also found to be resuspended during certain events.

Pisano and Brombach (1996) summarized numerous solids settling curves for stormwater and CSO samples. They are concerned that many of the samples analyzed for particle size are not representative of the true particle size distribution in the sample. As an example, it is well known that automatic samplers do not sample the largest particles that are found in the bedload portion of the flows. Particles having settling velocities in the 1 to 15 cm/sec range are found in grit chambers and catchbasins, but are not seen in stormwater samples obtained by automatic samplers, for example. It is recommended that bedload samplers be used to supplement automatic water samplers in order to obtain more accurate particle size distributions (Burton and Pitt 2000). Selected US and Canadian settling velocity data are shown in Table 2. The CSO particulates have much greater settling velocities than the other samples, while the stormwater has the smallest settling velocities. The corresponding "Stoke's" particle sizes for the geometric means are about 100 µm for the CSOs, about 50 µm for the sanitary sewage, and about 15 µm for the stormwater.

Table 2. Settling Velocities for Wastewater, Stormwater, and CSOs

Samples	Geometric Means of Settling Velocities Observed (cm/sec)	Range of Medians of Settling Velocities Observed (cm/sec)
CSOs	0.22	0.01 to 5.5
dry weather wastewater (sanitary sewage)	0.045	0.030 to 0.066
stormwater	0.011	0.0015 to 0.15

Source: Pisano and Bromback (1996)

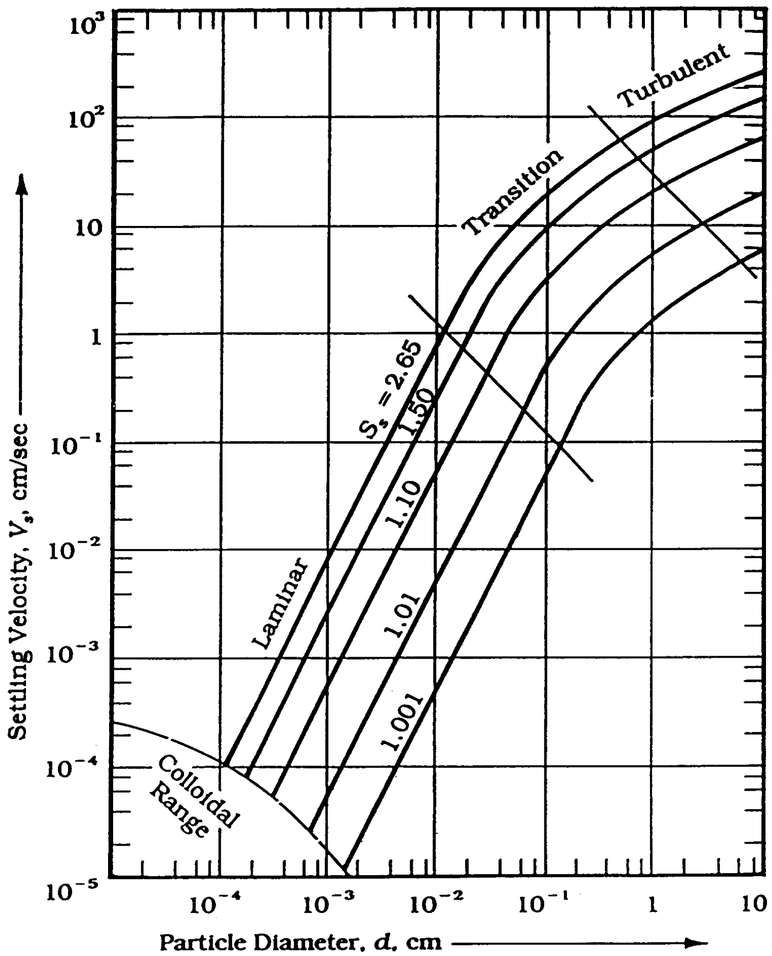


Figure 9. Type 1 (discrete) settling of spheres in water at 10° C (Reynolds 1982).

More than 13,000 CSO control tanks have been built in Germany using the ATV 128 rule (Pisano and Bromback 1996). This rule states that clarifier tanks (about 1/3 of these CSO tanks) are to retain all particles having settling velocities greater than 10 m/hr (0.7 cm/sec), with a goal of capturing 80% of the settleable solids. Their recent measurements of overflows from some of these tanks indicate that the 80% capture was average for these tanks and that the ATV 128 rule appears to be reasonable.

Control of Pollutants Other Than Suspended Solids

Wet detention ponds also are biological and chemical reactors. Changes in many pollutants can take place in the water column or in the sediments of ponds. Dally, *et al.* (1983) monitored heavy metal forms in runoff entering and leaving a wet detention pond serving a bus maintenance area. They found that metals entering the monitored pond were generally in particulate (nonfilterable) forms and underwent transformations into filterable (smaller than 0.2 µm in size) forms. The observed total metal remo vals by the pond were generally favorable, but the filterable metal outflows were much greater than the filterable metal inflows. This effect was most pronounced for cadmium and lead. Very little changes in zinc were found, probably because most of the zinc entering the pond was already in filterable forms. These metal transformations may be more pronounced in wet detention ponds that in natural waters because of potentially more favorable (for metal dissolution) pH and ORP conditions in wet pond sediments. Other studies have found similar transformations in the forms and availability of nutrients in wet detention ponds, usually depending on the extent of algal growth and algal removal operations.

Table 3 can be used to estimate the approximate controls for various pollutants. These ratios of pollutant removals to suspended solids removals are based on many field observations (mostly from the NURP studies, EPA 1983) of detention pond performance and can vary significantly. Three general groupings were identified: total lead and total copper were most efficiently removed, while organic nitrogen was the least efficiently removed. Many of the nutrients showed "negative" removals during monitoring, possibly because of biological cycling of the nutrients in the ponds. Wet detention ponds should not be expected to provide significant removals of any pollutants in "soluble" forms (associated with very small particles, colloids, or truly dissolved).

Table 3. Approximate Control of Stormwater Pollutants in Wet Detention Ponds

Constituent Group	Percentage Control as a Fraction of Suspended Solids Control
Lead and copper	0.75 to 1.00+
COD, BOD_5, soluble and total phosphorus, nitrates, and zinc	0.6
Organic nitrogen	0.4

Example: If 85% control of suspended solids, then:
Lead and copper: 0.75 to 1.0+ of 85% = 64 to 85+%
COD, etc.: 0.6 of 85% = 51%
Organic nitrogen: 0.4 of 85% = 34%

Vignoles and Herremans (1995) examined the heavy metal associations with different particles sizes in stormwater samples from Toulouse, France. They found that the vast majority of the heavy metal loadings in stormwater were associated with particles less than 10 µm in size, as shown on Table 4. They concluded that stormwater control practices must be able to capture the very small particles.

Table 4. Percentages of Suspended Solids and Distribution of Heavy Metal Loadings Associated with Various Stormwater Particulate Sizes (Toulouse, France) (Percentage associated with size class, concentration in mg/kg).

	>100 µm	50 to 100 µm	40 to 50 µm	32 to 40 µm	20 to 32 µm	10 to 20 µm	<10 µm
Suspended solids	15%	11%	6%	9%	10%	14%	35%
Cadmium	18 (13)	11 (11)	6 (11)	5 (6)	5 (5)	9 (6)	46 (14)
Cobalt	9 (18)	5 (16)	4 (25)	6 (20)	6 (18)	10 (22)	60 (53)
Chromium	5 (21)	4 (25)	2 (26)	6 (50)	3 (23)	9 (39)	71 (134)
Copper	7 (42)	8 (62)	3 (57)	4 (46)	4 (42)	11 (81)	63 (171)
Manganese	8 (86)	4 (59)	3 (70)	3 (53)	4 (54)	7 (85)	71 (320)
Nickel	8 (31)	5 (27)	4 (31)	5 (31)	5 (27)	10 (39)	63 (99)
Lead	4 (104)	4 (129)	2 (181)	4 (163)	5 (158)	8 (247)	73 (822)
Zinc	5 (272)	6 (419)	3 (469)	5 (398)	5 (331)	16 (801)	60 (1,232)

Source: Vignoles and Herremans (1995)

Design Based on NURP Detention Pond Monitoring Results

As summarized earlier, several NURP projects investigated the performance of different types of detention ponds. About 150 rain events were monitored at nine ponds located throughout the U.S. The EPA (1983) determined that long-term detention pond performance could be estimated based on geographical location and the ratio of the pond surface area to contributing source area.

Driscoll (1989; and EPA 1986) presented a basic methodology for the design and analysis of wet detention ponds. A pond operates under dynamic conditions when the storage of the pond is increasing with runoff entering the pond and with the stage rising, and when the storage is decreasing when the pond stage is lowering. Quiescent settling occurs during the dry period between storms when storage is constant and when the previous flows are trapped in the pond, before they will be partially or completely displaced by the next storm. The relative importance of the two settling periods depends on the size of the pond, the volume of each runoff event, and the inter-event time between the rains.

Driscoll (1989) produced a summary curve, shown as Figure 10, that relates wet pond performance to the ratio of the surface area of the pond to the drainage area, based on the numerous NURP wet detention pond observations. The NURP ponds were in predominately residential areas and were drained with conventional curb and gutters. This figure indicates that wet ponds from about 0.3 to 0.8 percent of the drainage area should produce about 90% reductions in suspended solids. Southeastern ponds need to be larger than ponds in the Rocky Mountain region because of the much greater amounts of rain and the increased size of the individual events in the southeast. Also, wet ponds intending to remove 90% of the suspended solids need to be about twice as large as ponds with only a 75% suspended solids removal objective.

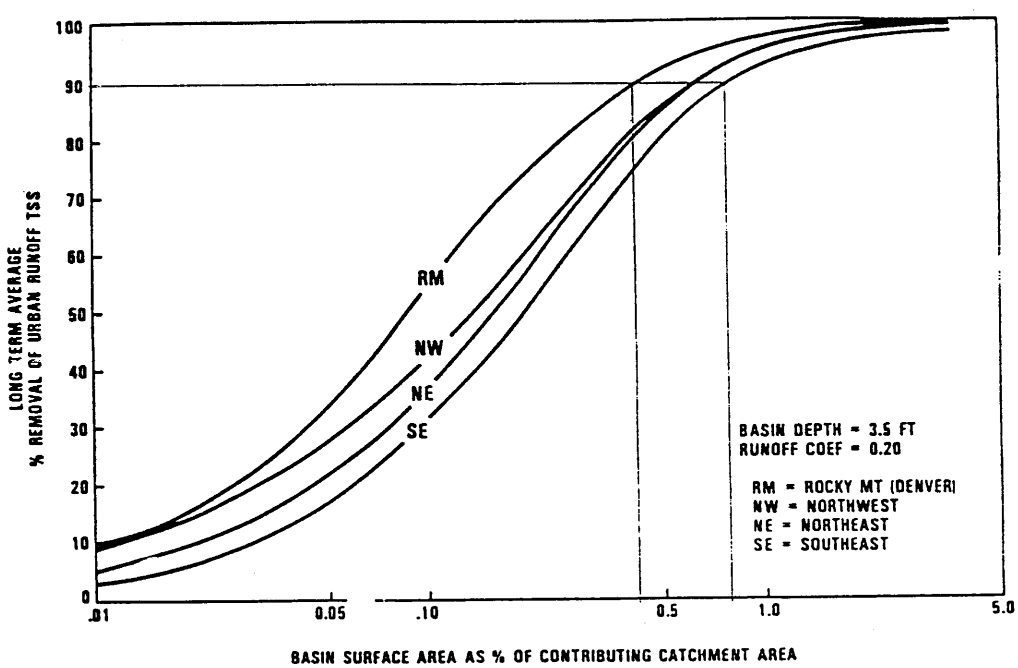


Figure 10. Regional differences in detention pond performance (EPA 1983).

The NURP detention pond monitoring results mostly included residential areas and therefore could did not effectively examine the effects of land use on pond performance. Hey and Schaefer (1983), during the West Chicago NURP project in Glen Ellyn, Illinois, prepared Table 5 showing how land uses with large fractions of impervious areas require about twice the pond surface area as suburban residential areas. These ratios are all substantially greater than shown on Figure 10 to provide an extra margin of safety for a broader range of expected rain conditions.

Table 5. Area Required for Wet Detention Ponds for Different Land Uses

Land Use	Percent Impervious	Storage Needed (inches)	Percent of Drainage Area Needed for Detention Storage[1]
Parking Lot	100%	1.0	2.8%
Suburban and Commercial	25	0.6	1.7
Suburban	10	0.5	1.3
Undeveloped	0	0.4	1.1

[1] Assuming an average depth of three feet.
Source: Hey and Schaefer (1983)

Selecting Outflow Control Devices To Meet Water Quality Objectives

A simple analysis procedure can be used to guide the selection of an outflow control device for a given stage-surface area relationship for a potential pond location and desired particle size control objective. The definition of upflow velocity (outflow rate divided by surface area) allows the simple evaluation of detention pond performance for any pond stage. Similarly, if the pond stage-surface area relationship is known for a potential pond location, an outfall device can be selected to obtain control of critical particle sizes.

Tables 6 through 9 provide a quick method of selecting appropriate outfall devices for a potential pond location. These tables indicate the minimum amount of pond surface area needed at each stage to provide a five µm critical control level for a variety of conventional outfall devices. Table 9 presents multipliers to adjust the minimum areas for other critical particle sizes. In order to improve the pond performance by selecting a two µm critical particle size instead of five µm, the pond surface area would have to be increased by about 6.7 times. If the critical particle size was increased to ten µm, then the required pond surface would be reduced by about 0.27 compared to the pond surface areas needed for five µm control.

Table 6. Surface Area Requirements for 5-µm Particle Size Control for Various V-notch Weirs.

Head (ft)	Flow (cfs)	22.5° Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	30° Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	45° Storage (ac-ft)	Reqd. area (acres)
0.5	0.1	<0.01	0.01	0.1	<0.01	0.02	0.2	<0.01	0.03
1	0.5	0.03	0.1	0.7	0.05	0.1	1.0	0.05	0.2
1.5	1.4	0.1	0.2	1.9	0.2	0.3	2.9	0.2	0.5
2	2.8	0.3	0.5	3.8	0.3	0.7	5.9	0.6	1.0
3	7.8	1.2	1.4	11	1.6	1.8	16	1.6	2.8
4	16	3.3	2.8	22	4.4	3.8	33	5.9	5.8
5	28	7.2	4.9	38	9.6	6.6	58	14	10
6	44	14	7.7	60	18	10	91	27	16
	Flow (cfs)	60° Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	90° Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	120° Storage (ac-ft)	Reqd. area (acres)
0.5	0.3	<0.01	0.05	0.4	0.02	0.08	0.8	0.04	0.1
1	1.4	0.07	0.3	2.5	0.2	0.4	4.4	0.3	0.8
1.5	4.0	0.3	0.7	6.9	0.6	1.2	12	1.7	2.1
2	8.2	0.8	1.4	14	1.5	2.5	25	3.3	4.4
3	28	3.5	3.9	39	6.2	6.8	69	12	12
4	46	9.5	8.1	80	17	14	140	30	25
5	81	21	14	140	36	25	250	69	43
6	130	39	22	220	67	39	390	120	68

Table 7. Surface Area Requirements for 5-μm Particle Size Control for Various Rectangular Weirs.

Head (ft)	Flow (cfs)	2 ft. Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	5 ft. Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	10 ft. Storage (ac-ft)	Reqd. area (acres)
0.5	2.1	0.10	0.4	5.7	0.3	1.0	12	0.5	2.0
1	6	0.5	1.1	16	1.2	2.8	33	2.4	5.7
1.5	10	1.2	1.8	29	3.2	5.0	59	6.3	10
2	15	2.3	2.6	43	6.4	7.6	90	13	16
3	24	5.7	4.2	80	17	14	160	35	29
4	32	11	5.6	110	34	20	250	71	43
5	37	17	6.5	150	47	26	340	120	59
6	39	23	6.9	190	77	33	430	190	75
	Flow (cfs)	15 ft. Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	20 ft. Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	30 ft. Storage (ac-ft)	Reqd. area (acres)
0.5	17	0.8	3.0	23	1.0	4.1	35	1.5	6.1
1	49	3.7	8.6	66	5.1	12	99	7.3	17
1.5	90	9.9	16	120	13	21	180	20	32
2	140	20	24	190	27	32	280	40	49
3	250	54	44	340	72	59	510	110	89
4	380	110	66	510	150	89	780	220	140
5	520	190	91	710	250	120	1100	390	190
6	680	290	120	920	390	160	1400	610	250

Table 8. Surface Area Requirements for 5-μm Particle Size Control for Various Drop-tube Structures.

Head (ft)	Flow (cfs)	8" Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	12" Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	18" Storage (ac-ft)	Reqd. area (acres)
0.5	0.5	0.02	0.09	0.9	0.04	0.2	1.6	0.07	0.3
1	0.7	0.07	0.1	2.2	0.2	0.4	4.4	0.3	0.8
1.5	0.7	0.1	0.1	2.2	0.4	0.4	6.5	0.8	1.1
2	0.7	0.2	0.1	2.2	0.6	0.4	6.5	1.4	1.1
3	0.7	0.3	0.1	2.2	0.9	0.4	6.5	2.5	1.1
4	0.7	0.4	0.1	2.2	1.3	0.4	6.5	3.6	1.1
5	0.7	0.6	0.1	2.2	1.7	0.4	6.5	4.7	1.1
6	0.7	0.7	0.1	2.2	2.1	0.4	6.5	5.8	1.1
	Flow (cfs)	24" Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	30" Storage (ac-ft)	Reqd. area (acres)	Flow (cfs)	36" Storage (ac-ft)	Reqd. area (acres)
0.5	1.6	0.07	0.3	1.9	0.08	0.3	2.0	0.09	0.4
1	5.6	0.4	1.0	6.3	0.4	1.1	7.2	0.5	1.3
1.5	11	1.1	1.8	13	1.3	2.3	16	1.5	2.8
2	14	2.1	2.4	21	2.8	3.7	27	3.4	4.7
3	14	4.5	2.4	25	6.9	4.4	42	9.4	7.3
4	14	6.9	2.4	25	11	4.4	42	17	7.3
5	14	9.3	2.4	25	16	4.4	42	24	7.3
6	14	12	2.4	25	20	4.4	42	31	7.3

Table 9. Corrections for Needed Surface Areas for Particle Size Controls other than 5 μm.

Particle size for control (μm)	Typical percentage of particles larger than indicated size	Particle settling rate (cm/sec)	Required area multiplier, compared to 5 μm
1	100	1.5×10^{-4}	27
2	94	6×10^{-4}	6.7
5	88	4×10^{-3}	1.0
10	78	1.5×10^{-2}	0.27
20	62	6×10^{-2}	0.067
40	47	2×10^{-1}	0.02
100	28	8×10^{-1}	0.005

If a site had a surface area of 3 acres at two feet above the lowest invert level, a number of outlet devices could be used to provide at least five μm critical control:

- all V-notch weirs from 22.5^{o} through 90^{o} (but not 120^{o})
- only a 2 foot long rectangular weir
- all pipes from 8” to 24”

Obviously, all stage levels have to be examined and the most critical device selected that provides the desired level of control. In a similar manner, it would be possible to specify the shape of a pond (area versus stage) to closely match the natural topography with minimal required grading by selecting an outfall structure that provides close to the required outfall rates.

Wet Pond Design Criteria for Water Quality

A wet detention pond performance specification for water quality control needs to result in a consistent level of protection for a variety of conditions, and to allow a developer a large range of options to best fit the needs of the site. It must also be easily evaluated by the reviewing agency and be capable of being integrated into the complete stormwater management program for the watershed. It should have minimal effects on the hydraulic routing of stormwater flows, unless a watershed-wide hydraulic analyses is available that specifies the specific hydraulic effects needed at the specific location.

The following suggested specifications should meet these objectives under most conditions. However, the specific pond sizes should be confirmed through continuous long-term simulations using many years of actual rainfall records for the area of interest (such as possible by using DETPOND). These guidelines should therefore be considered as a starting point and modified for specific local conditions. As an example, it may be desirable to provide less treatment than suggested by the following guidelines (Vignoles and Herremans 1996). The following guidelines were developed by Pitt (1993a and 1993b), based on literature information and on his personal experience.

1) The wet pond should have a minimum water surface area corresponding to land use, and desired pollutant control. The following values were extrapolated from extensive wet detention pond monitoring, mainly the EPA’s NURP (EPA 1983) studies:

Percent of Drainage Area Required as Pond for:

Land Use	5 µm control	20 µm control
Totally paved areas	3.0 percent	1.1 percent
Freeways	2.8	1.0
Industrial areas	2.0	0.8
Commercial areas	1.7	0.6
Institutional areas	1.7	0.6
Residential areas	0.8	0.3
Open space areas	0.6	0.2
Construction sites	1.5	0.5

Two levels of control are shown, corresponding to the control of particles greater than 5 µm and 20 µm. For most stormwater facilities, these would correspond to annual suspended solids controls of about 90 percent for the 5 µm particle size, and about 65 percent for the 20 µm particle size. These values are based upon early work done by Gene Driscoll for NURP (EPA 1983). During NURP, the use of stormwater detention ponds in residential areas was investigated. Ponds having surface areas between 0.5 and 1 percent of the drainage areas were found to provide about 90 percent control. As the runoff changes because of other land uses besides residential areas, the size of the wet pond must correspondingly change. These values are based on expected runoff volumes for typical development conditions and would therefore vary for different development practices (especially if drained using grass swales, or if have extensive infiltration practice).

2) The pond freeboard storage should be equal to the runoff associated with a 1.25 inch rain for the land use and development type. It should be noted that this storage volume is associated with the runoff volume from a specific type of rain and not for a set runoff volume. This has the benefit of providing the same level of control for all land uses. As an example, many ordinances require capture and treatment of the first 0.5 inch, or 1 inch, of runoff for an area. Unfortunately, this has the effect of providing very uneven levels of control because of different rainfall-runoff characteristics for different land uses. As an example, a residential area may require a rain of about 1.50 inches to produce 0.5 inches of runoff. However, a commercial area, such as a strip commercial development, would only require a rain of about 0.6 inches to produce 0.5 inches of runoff. It is obvious that the residential area is providing treatment for a much more severe rain, with a correspondingly greater level of annual control, compared to the commercial area. By requiring a set amount of control associated with a rain having the same re-occurrence interval, a more consistent effort and benefit is obtained throughout the community.

The following table summarizes the approximate runoff depths associated with 1.25 inches of rain for several curb and gutter drained land uses, based on Pitt's (1987) small storm hydrology procedures:

Land Use	Sandy Soil	Clayey Soil
Freeways	0.35	0.40
Totally paved area	1.1	1.1
Industrial	0.85	0.9
Commercial	0.75	0.85
Schools	0.2	0.4
Low density residential	0.1	0.3
Medium density residential	0.15	0.35
High density residential	0.2	0.4
Developed parks	0.5	0.6
Construction sites	0.5	0.6

Pitt (1987) found that currently used urban runoff volume prediction methods commonly result in inaccurate runoff volumes for the common small storms that are most responsible for annual pollutant discharges in urban areas. For sandy soil areas, this table shows that the runoff volume associated with 1.25 inches of rain can vary from a low of 0.1 inch for low density residential areas to a high of 1.1 inch for totally paved areas, such as a parking lot. The difference in runoff volumes for different land uses having sandy or clay soil conditions varies much more for land uses having larger amounts of pervious surfaces. For areas having less amounts of pervious surfaces, the runoff differences produced by similar land use areas for these different soil conditions varies less. If an area is drained with grass swales, has an unusual amount of disconnected roofs, or has extensive upland infiltration controls, then the runoff volume associated with a 1.25 inch rain would be much less than shown in the above table.

3) The selection of the outlet device for the wet detention pond. This outlet device must be selected based upon the desired pollutant control at every specific pond stage in the wet detention pond. This specification regulates the detention time periods and the "draining" period to produce consistent removals for all rains. The ratio of outlet flow rate to pond surface area for each stage value needs to be at the most 0.00013 $ft^3/sec/ft^2$ for 5 µm (about 90 percent annual) control and 0.002 ($ft^3/sec/ft^2$) for 20 µm (about 65 percent annual) control. In practice, the desired pond surface area to stage relationship (simply the "shape" of the hole) is compared to the minimum surface areas needed at each stage for various candidate outlet structures. As an example, the following list summarizes the minimum surface areas needed for 5 µm particle control for different stage values. Also shown are the freeboard storage values below each elevation:

	45° V-notch		90° V-notch		24" pipe	
stage feet	storage acre-ft	surface acres	storage acre-ft	surface acres	storage acre-ft	surface acres
0.5	<0. 01	0.032	0.02	0.08	0.07	0.28
1.0	0.05	0.18	0.15	0.44	0.39	0.98
1.5	0.22	0.5	0.56	1.2	1.1	1.8
2.0	0.60	1.0	1.5	2.5	2.1	2.4
3.0	1.6	2.8	6.2	6.8	4.5	2.4
4.0	5.9	5.8	17	14	6.9	2.4
5.0	14	10	36	25	9.3	2.4
6.0	27	16	67	39	12	2.4

The large stages above the normal wet pond depth may result in unsafe conditions for most wet detention ponds. A maximum depth of about 3 feet above the normal wet pond depth is recommended.

The selection of the outlet control device is based upon the concept of surface overflow rate. The surface overflow rate is equivalent to the settling velocity of a critical particle size. Particles that have greater settling velocities than the surface overflow rate will theoretically be retained in the detention pond. The surface overflow rate is defined as the ratio between the instantaneous discharge and the pond surface area. The advantage of using surface overflow rate as a design criteria for detention ponds arises from the fact that flows to a detention pond are very irregular. Surface overflow rate is equivalent to the ratio of detention time to pond depth. Unfortunately, the use of detention time alone, as commonly used in many ordinances and design guidelines, is not adequate to describe theoretical settling. In addition, detention time is very difficult to define for a stormwater detention pond because of the highly variable flow rates. However, the use of surface overflow rate works well because the ratio of discharge to surface area is known, or can be selected, for every pond stage. At any depth in a detention pond, the surface area is known, based upon the shape of the pond. The selection of a discharge device is therefore made simple because it must provide less than the critical discharge rate for each stage, and corresponding surface area.

Figure 11 is a schematic showing a cross section of the pond. The area below the invert of the major control device is the dead storage and is provided to minimize scour of the retained particulates. The water quality storage volume in the detention pond is the volume associated with the runoff associated with a 1.25 inch rain. The topmost layer in the detention pond is additional storage that is provided for drainage benefits. This storage would be provided (with the appropriate additional outlet structure) only if a basin-wide hydraulic analyses has been conducted to insure that inappropriate interferences of the different flood hydrographs would not occur. Also, it is important to note that an emergency spillway must also be provided above the water quality storage area. Therefore, the additional storage for drainage benefits as shown in this figure would at least be provided to cover the range of stage of the emergency spillway.

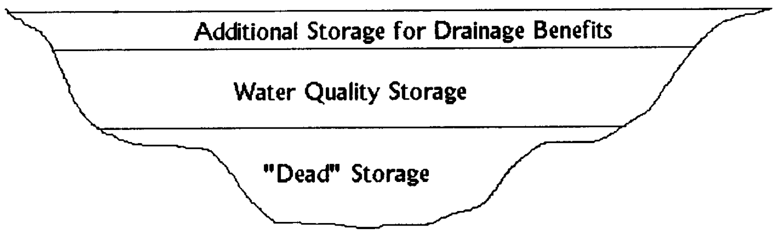


Figure 11. Cross-section of pond showing water quality storage portion.

4) The ponds must also be constructed according to specific design guidelines to insure the expected performance and adequate safety. The guidelines need to specify such things as pond depth, side slopes, vegetation, and shape.

These procedures will result in the largest storms that do not enter the emergency spillway to have treatment levels equal to the critical particle size specified. As an example, the above calculations focus on the 5 µm particle, at least, being controlled at all stage depths of the primary outfall structures in order to provide 90 percent control of suspended solids. The outfall device is selected to provide an outfall rate no greater than a critical value, that when divided by the pond surface area at that stage, will be no larger than the settling rate of the critical particle size. In almost all cases, the critical stage will be at the top of the primary outfall device, and all stages below that will more than meet the critical objective, and will therefore be controlling particles much smaller than the critical size specified in the objective. It may seem that the pond is therefore over-designed and that the pond is larger than needed. However, the 5 µm critical particle size is typically larger than the 90^{th} percentile particle size, and the added control provided at the lower stages in the pond is generally needed to provide this level of control on an annual basis. As indicated previously, the 90^{th} percentile particle size is more typically only 3 µm, or even smaller.

To check pond sizing criteria, a sensitivity analysis can be conducted using DETPOND, with varying pond sizes. DETPOND allows easy modifications of the pond surface areas by applying a multiplier to all surface area values. The model can then be re-run for each condition (after modifying the outlet structure to provide the critical flow rate at the pond stages). A typical plot (Figure 11a) would show the particle sizes controlled for different pond sizes. If the annual average control objective was 5 µm, then the pond can be substantially smaller than if the 5 µm particle size criterion was a worst-case situation. Correct interpretation of this sensitivity analysis generally requires particle size information for the test site. If a particle size distribution is used that is improperly biased with large particles, then the pond may be under-sized compared to the desired level of control. With local particle size information, this analysis can be used to develop appropriate local sizing objectives.

The Use of the DETPOND Program to Statistically Evaluate Wet Pond Performance

DETPOND was developed by Bob Pitt and John Voorhees to enable a continuous simulation of wet stormwater detention ponds. This continuous simulation is important to understand the storm to storm variation and long-term performance for typical rain conditions. The basic analysis procedures in DETPOND are similar to the detention pond analysis procedures provided in SLAMM, the Source Loading and Management Model, but offers some additional model output choices to enable more detailed evaluations of individual detention facilities. Appendix A is a user's guide for DETPOND which also includes a simple design example. Additional assistance is provided in the Help components of the model.

DETPOND uses conventional procedures to predict hydraulic conditions (pond storage-indication routing) and the behavior of particulates in stormwater as it passes through a detention pond (surface overflow rates described by the Hazen equation and quiescent settling using Stoke's and Newton's laws), as described in previous discussions. DETPOND was specifically designed for continuous long-term evaluations, using lengthy rain series. In its current Windows configuration, it is limited only by computer resources (and available time) in the number of rains that it

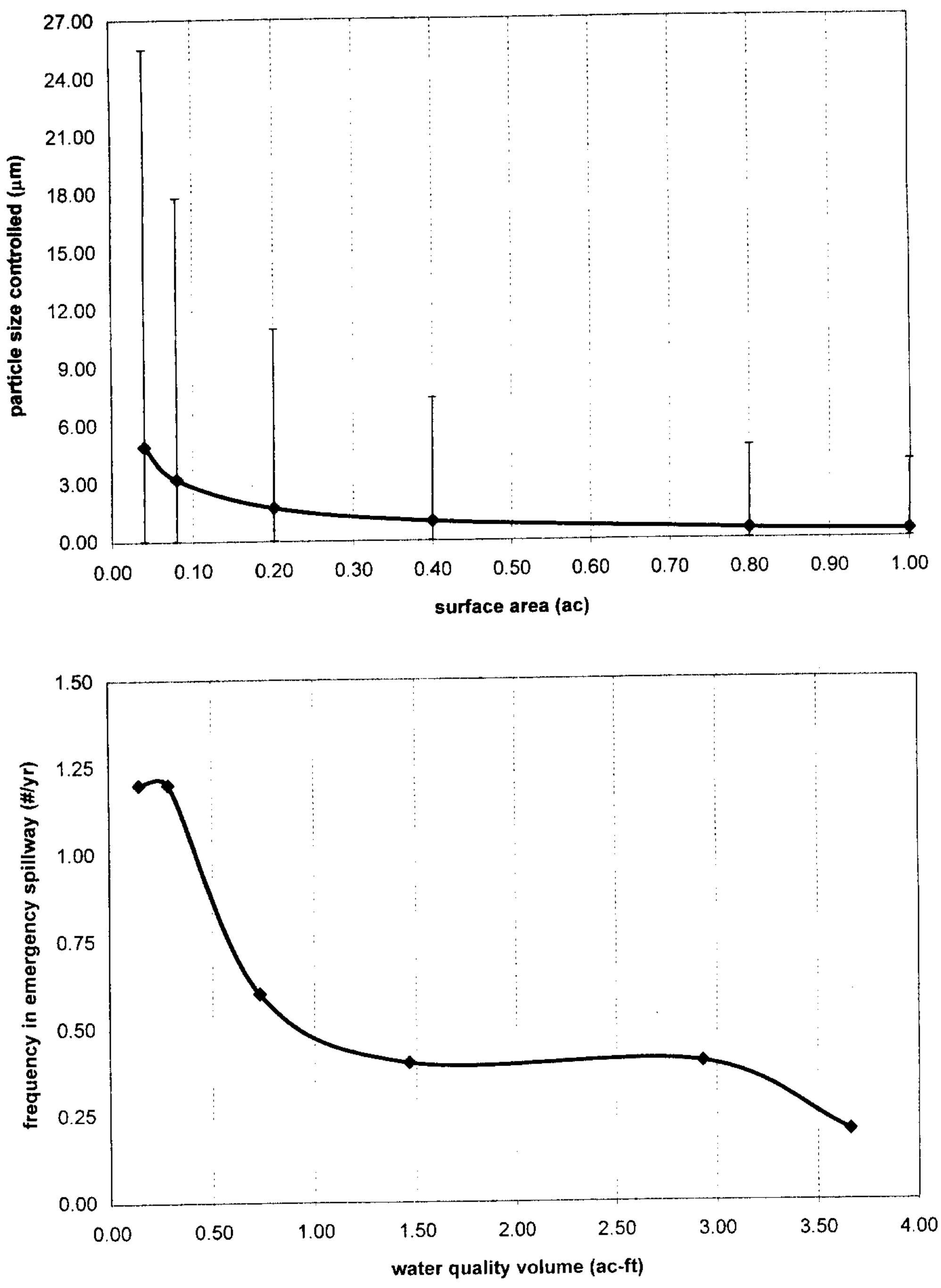


Figure 11a. Example sensitivity analyses of changing pond design on performance.

can evaluate. It is also currently quite fast, requiring only a few minutes on most computers to complete a single run using several decades of rainfall data. Whereas most computer-based pond models require time increment direction from the user and frequently crash due to unstable algorithms, DETPOND predicts reasonable calculation increments based on the duration of each rain and interevent period. If the calculation appears to approach unstable conditions, it automatically starts over with a reduced calculation increment. In addition, if the pond design is too small or if the outfall is inadequate, causing catastrophic overflow conditions, the program doesn't crash, but continues using the last known outfall or surface area value, and notes that the pond overflowed. The tabular output of the model can also be easily imported into spreadsheets and graphing programs to produce statistical summaries of the pond performance.

DETPOND can therefore be easily used to evaluate an existing design or pond under a wide variety of rain conditions. It can be used with a single event (most commonly used when observed influent hydrograph data is available) or with a lengthy rain series (when the program predicts runoff and hydrograph characteristics).

Example Pond Performance Using Suggested Design Specifications and DETPOND

An evaluation of the performance of a pond was conducted using the above specifications for a wide range of Birmingham, Alabama, rains. This example illustrates how the pond performed for these varying conditions. The following list shows the pond dimensions used:

- 100 acre medium density residential area watershed
- 0.8 acre (35,850) pond (0.8 percent of 100 acres to result in a 5 µm, or 95 percent control of suspended solids).
- 5 feet wet pond depth during dry weather (to minimize scour and to provide sacrificial storage for sediments between pond dredging). This results in a storage volume of about 175,000 cubic feet below the invert.
- 0.5 inch of runoff freeboard storage, corresponding to 1.25 inch of rain.
- pond surface area and stage relationship, above the normal pond elevation:

stage (ft)	surface area (ft^2)
0	35,850
0.8	50,600
1.6	65,340
2.4	81,680
3.2	98,010

- 90° V-notch weir from 0 to 3.2 feet of stage (above normal wet pond depth), and a 20 foot long emergency spillway from 1.6 to 3.2 feet of stage.

DETPOND was used to investigate the performance of this pond for many local rains. Analyses showed that the pond stage barely reached the emergency spillway and the hydraulic effects of the pond were not significant for a typical Birmingham design storm (4.1 inch rain). The peak runoff flow rate for this event was not changed, and the assumed triangular inlet hydrograph shape changed very little (Figure 12). However, the pond had significant suspended solids reductions (Figure 13), even for this moderately large rain. The flow-weighted average performance of the pond was better than 90 percent removal of suspended solids, and the worst performance, occurring at peak flow rates, was only reduced to about 85 percent. The pond could have been designed to also provide appreciable peak runoff flow rate reductions, but that was not desired due to the lack of a basin-wide hydraulic analysis. Peak flow rate reductions in detention ponds are only obtained through extending the period of flow. If not carefully done, this extended flow period can easily increase downstream peak flow rates to greater values than if no detention was used.

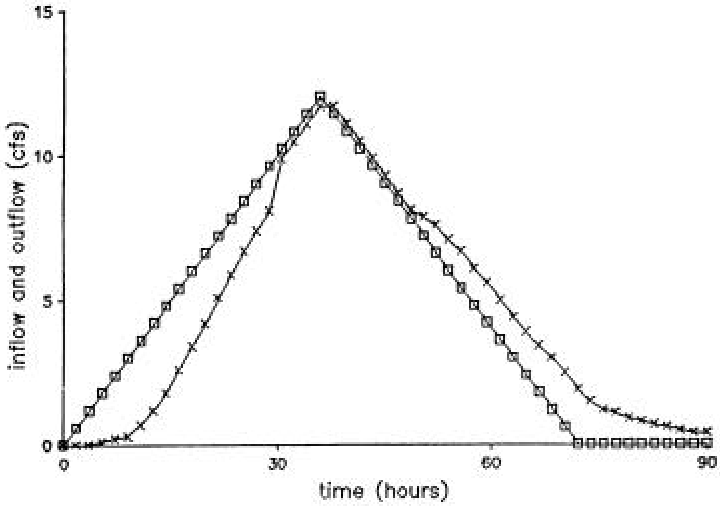


Figure 12. Modeled detention pond outflow hydrograph for 4.1 inch, 24-hour rain example.

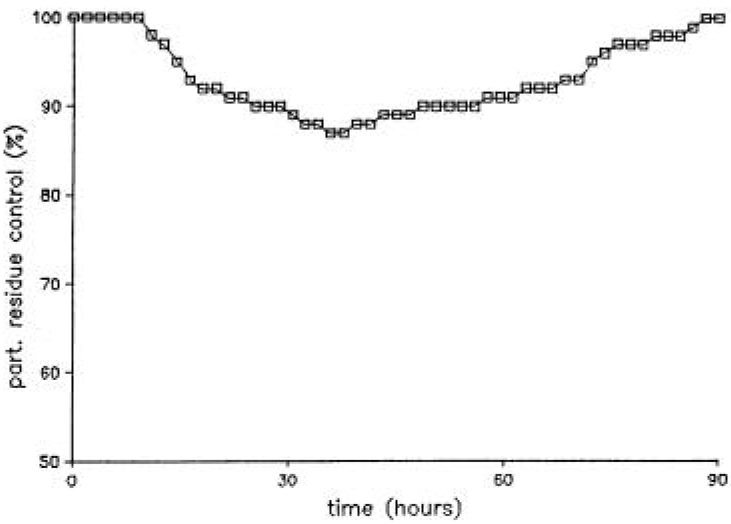


Figure 13. Modeled detention pond suspended solids removal performance for 4.1 inch, 24-hour rain example.

Pond performance was also modeled for many typical rain conditions (the 112 rains occurring during the 1975 Birmingham rain year) and for all major storms having 1 to l00-year frequencies and 1 to 24 hour durations. The pond achieved suspended solids reductions of greater than 86 percent for all typical events and achieved greater than 65 percent removals of suspended solids, even for the extremely intense 1 hour, 100-year event. Many of the drainage and flooding design storms had suspended solids removal rates of greater than 80 percent.

Figure 14 shows that the particle size control levels were closely related to rain intensity for the large storms, but were better related to rain depth for the typical rains. The typical rains all had similar rain intensities, narrowing the data scatter. Only two of the 112 storms in the 1975 rain year failed the 5 µm design criterion, and only by small amounts. The smaller rains all have much better removals than the 5 µm criterion. The median performance of the pond was greater than 95 percent control of suspended solids. Even for the extreme events, the detention pond should provide greater than a 65 percent control of suspended solids. Analyzing the extreme drainage and flooding rains is needed to check the adequacy of the emergency spillway. As noted, the initial designs for spillway capacity can be made using the procedures given in TR55 (SCS 1986).

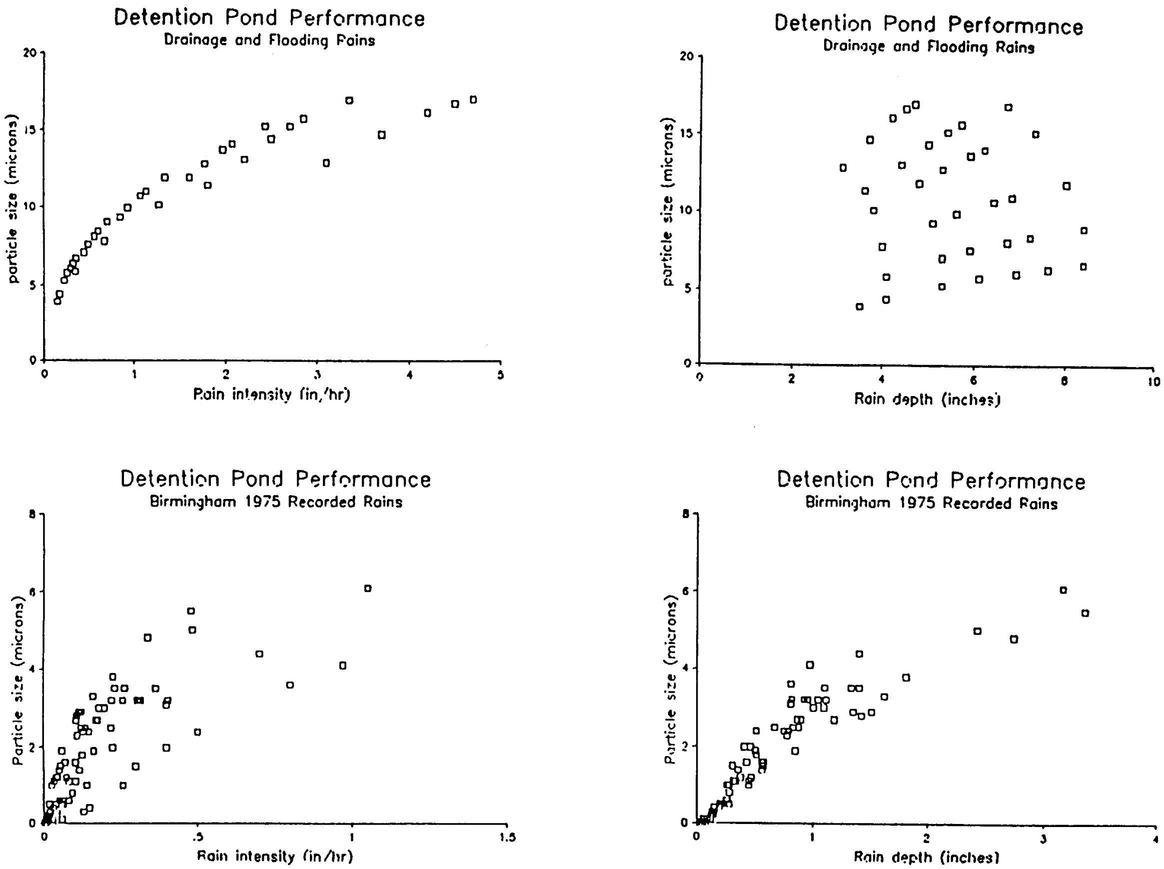


Figure 14. DETPOND modeled particle size removals by standard pond for various rain depths and intensities.

The flushing ratio is the ratio of the storm runoff volume to the pond storage volume below the lowest invert. A low flushing ratio indicates that much of the effluent from the pond is from the preceding dry period, while a high flushing ratio indicates that the pond may have been “blown out” during the event. Rain depth is the best indicator of flushing. Rains of about 1.5 inch in depth had runoff volumes about equal to the dry period storage volume. It is important to know the flushing ratio for a pond that is being monitored in order to understand the mixture of waters captured at the pond discharge. Consistently having low flushing ratios during most storms may indicate an over-sized pond, with unnecessary warming of the pond waters.

Peak reduction factor is a measure of the peak flow rate reduction, comparing the effluent to influent peak flow rates. A PRF value of 0.5 indicates a 50 percent flow rate reduction, while a PRF of 0.9 indicates a 90 percent reduction in flow rates. PRF values are usually of most concern during major storms. These values were quite low during these events. The most intense rains only achieved PRF values of about 0.3. Water quality ponds should have minimal effects on flow rate, unless actual flow rate reduction objectives are available, based on basin-wide hydraulic analyses.

DETPOND Verification using Data Collected at the Monroe St. Detention Pond, Madison, WI

The USGS and the Wisconsin Department of Natural Resources have been monitoring the Monroe St. wet detention pond in Madison for a number of years. Particle size distributions of influent (including bedload) and effluent have been monitored for about 50 storms. The actual particle size distributions and suspended solids removals have been compared to calculated pond performance, using DETPOND.

The original pond was creating severe downstream erosion in the channels between the pond and the receiving water, and the pond storage volume was not effectively being used for either flood control or water quality benefits. The outlets were modified and the pond has undergone extensive monitoring to confirm the water quality benefits of the retrofit.

The US Geological Survey (USGS), in cooperation with the Wisconsin Department of Natural Resources (WDNR) investigated the Monroe St. wet detention pond located in Madison, WI (House, *et al*. 1993). The University of Wisconsin Arboretum originally constructed the pond to protect the water quality and ecology of Lake Wingra and surrounding wetlands from stormwater. Figure 15 shows the location of the pond and the watershed. The pond is located on the downstream side of Monroe street at the outlet of a storm sewer that drains a 0.96-square km (237 acre) urbanized area. Land use in the watershed area consists mostly of single-family residences and commercial strip development, with some institutional uses (schools and churches). The average basin slope is 2.2 percent.

The Monroe Street pond has a surface area of 5,670 m^2 (1.42 Acre), a maximum depth of 2.3 m (7.5 ft) and an average depth of 1.1 m (3.6 ft) at normal pool elevation. The shape of the pond is basically round to oval with a small island. The inlet side is nearest to Monroe Street and the two outlets are on the far side away from Monroe Street. Figure 16 shown the bottom contours of the pond. The pond has a surcharge storage volume above the normal pool elevation that is capable of holding the 10-year, 24-hour storm-runoff volume without overtopping the containment berm around the pond. The pond has two outlets, each controlled by 90-degree V-notch weirs that drain to channels leading to Lake Wingra. The weirs are located in 8 ft. diameter concrete vaults, with 30 in. concrete pipes leading to the pond. The outlets in the pond are therefore submerged. Figure 17 is the pond composite outlet discharge curve. The bottom of the pond consists of a clay layer that inhibits infiltration of water from or into the pond.

The initial primary outlet configuration consisted of two 8 ft. long rectangular weirs located in the vaults, made with concrete block walls. The original flow capacity of these two weirs was enormous, being about 50 cfs at 1 ft. head and 250 cfs at 3 ft. head. As noted above, the discharges from the pond were little attenuated from the inflow velocities and severe channel erosion was occurring in the wetlands, negating the sediment trapping benefits of the pond. There was also no evidence that the emergency spillway was ever used since construction, even with several massive storms. In fact, the pond elevation barely fluctuated.

The outlets were therefore modified to reduce the downstream erosion problems by removing several courses of concrete blocks and installing 90-degree V-notch weirs made of plate steel in each vault. The pond normal water level was dropped about 6 inches with a lowered invert. The new primary outlets have total flow capacities of about 5 cfs at 1 ft. head and 80 cfs at 3 ft. head. The pond surface fluctuates more now, and the emergency spillway has been active every few years. Most significantly, the downstream channels are now stable.

The pond was designed for an expected 90% event mean concentration (EMC) removal for suspended solids (particulate residue). The ratio of pond to drainage area is 0.6 percent. This percentage is close to the value (0.4% to 0.8%) required for 5 µm control for the land uses in the watershed, which generally corresponds to a 90 percent reduction of suspended solids.

A total of 64 events were extensively monitored between February 1987 and April 1988. The monitored rains varied from 2 to more than 82 mm during this period. Periodic water quality and flow monitoring has also continued at this pond since 1988.

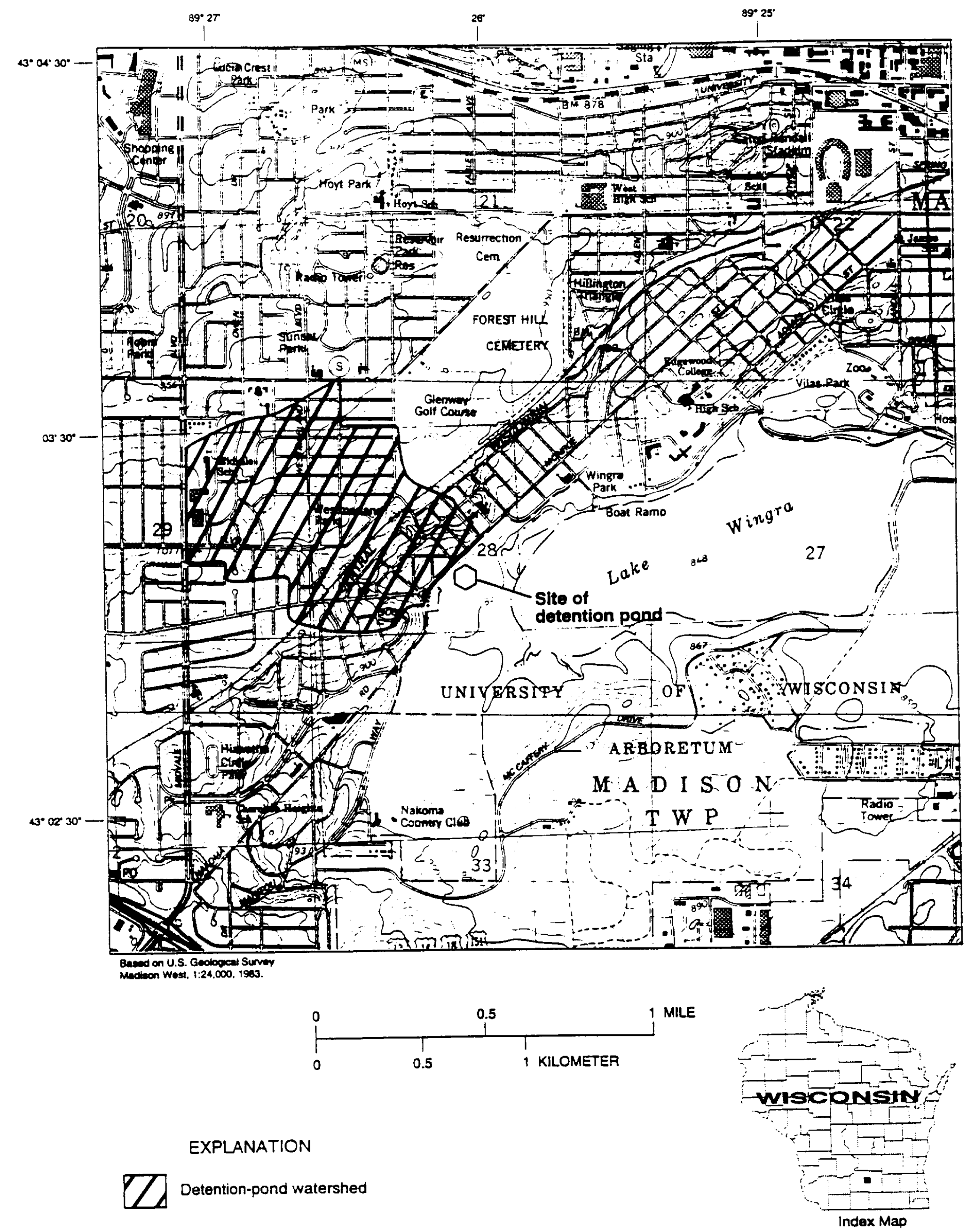


Figure 15. Monroe St. watershed area, Madison, WI.

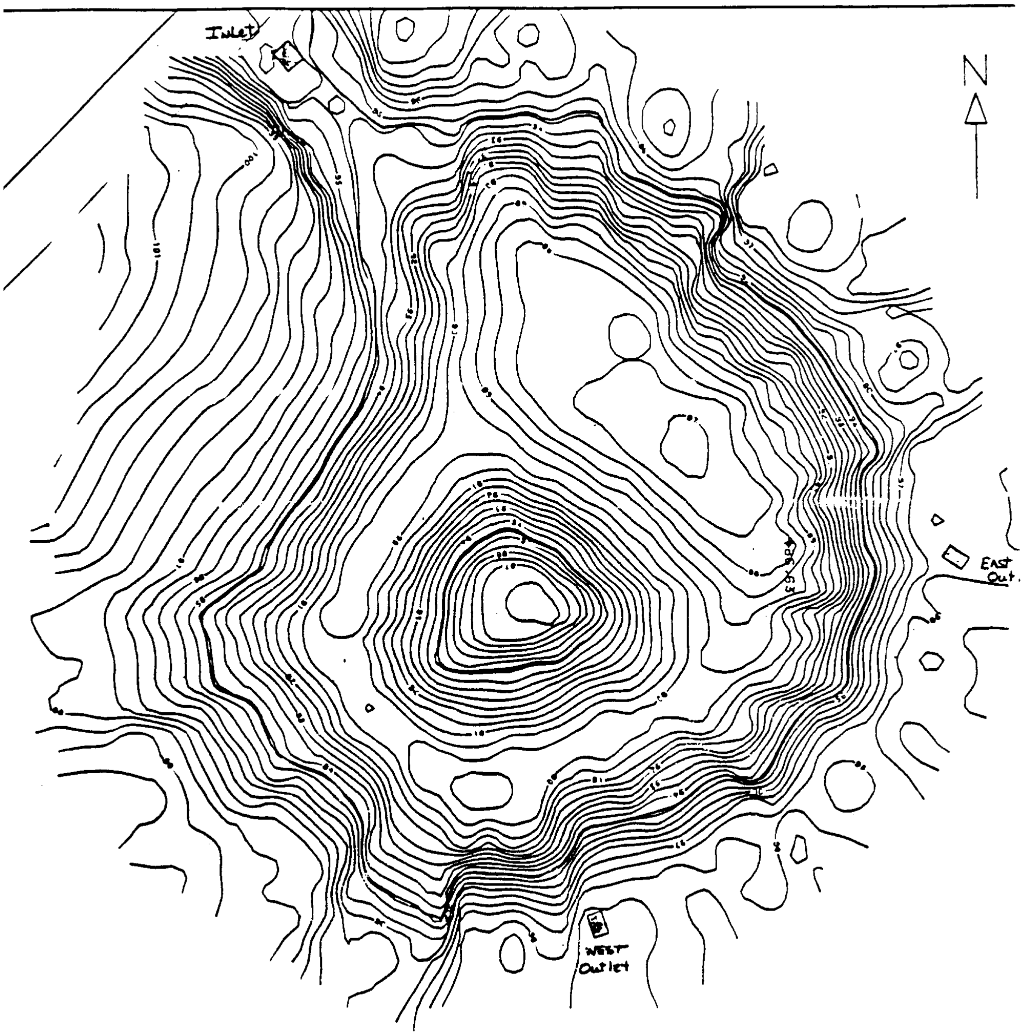


Figure 16. Monroe St. pond contour map.

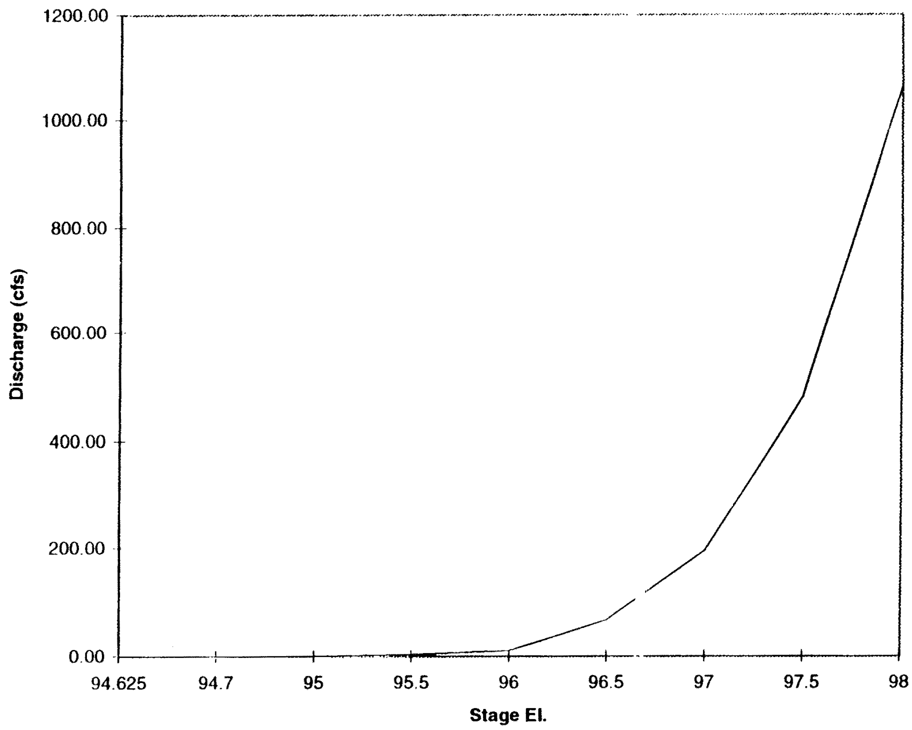


Figure 17. Stage-discharge curve for Monroe St. pond.

Method of Investigation

Water-quality data were collected by the U.S. Geological Survey (House, *et al.* 1993) using programmable automatic water samplers (refrigerated), installed at the inflow and outflow sites of the pond. The outflow data was collected at two locations, east and west. The samplers were programmed to obtain flow-proportional samples for each storm. These samples represent the flow-averaged constituent concentrations during a runoff event. These samples were removed from the samplers, preserved, and shipped to the Denver USGS laboratory for analysis within 24 hours of being collected. The samples were analyzed for suspended solids, volatile total solids, total and dissolved chemical oxygen demand (COD), total chloride, total and dissolved phosphorus, phosphate total and dissolved forms of total Kjeldahl nitrogen (TKN), nitrates, and total and dissolved forms of copper, zinc, and lead. Most of the copper and lead data were too low for the analytical method used and are not reported here.

Precipitation data were also recorded at 5-minute intervals during the storm events using a recording rain gage located at the pond site. Storm runoff (pond inflow) was monitored at the box culvert that was the terminus of the 0.96-km^2 drainage area. Discharge rates and flow volumes passing through the culvert were determined by use of a flow velocity sensor and water level indicator installed inside the culvert. The velocity and depth sensors were connected to a data logger that recorded the water level and velocity data and computed discharge rates based on the culvert geometry.

Data Analysis and Observations

The basic date are contained in the USGS report (House, *et al.* 1993).

Hydrograph/Flow Calibration. An important part of the Monroe St. project was validating the DETPOND wet detention pond water quality model that was used to design the retrofit of the outlet structures. The first step in the validation was to check flow volumes and peak flow rates, and the complete hydrographs.

Fifteen storm events were used to validate the flow portions of the DETPOND program. The program predicted outflow flow values from the inflow hydrographs using the storage-indication routing method. The outfall predictions (at 5 minute intervals) were compared to the observed outfall flow values. The predicted outflow hydrographs very closely matched the corresponding observed outflow hydrographs. In addition to comparing the general shape of the discharge hydrographs, the outflow total discharge volume, peak discharge flow rate, suspended solids removal, and outflow particle size distribution were also compared for validation. The predicted outflow volumes and peak discharges also very closely matched the observed outflow conditions. These comparisons are summarized on Figure 18 which compare the predicted and observed outflow volumes and the outflow peak flow rates. Figure 19 contains some of the actual outflow hydrographs, illustrating the close fits between the observed and modeled flows for highly different rain conditions.

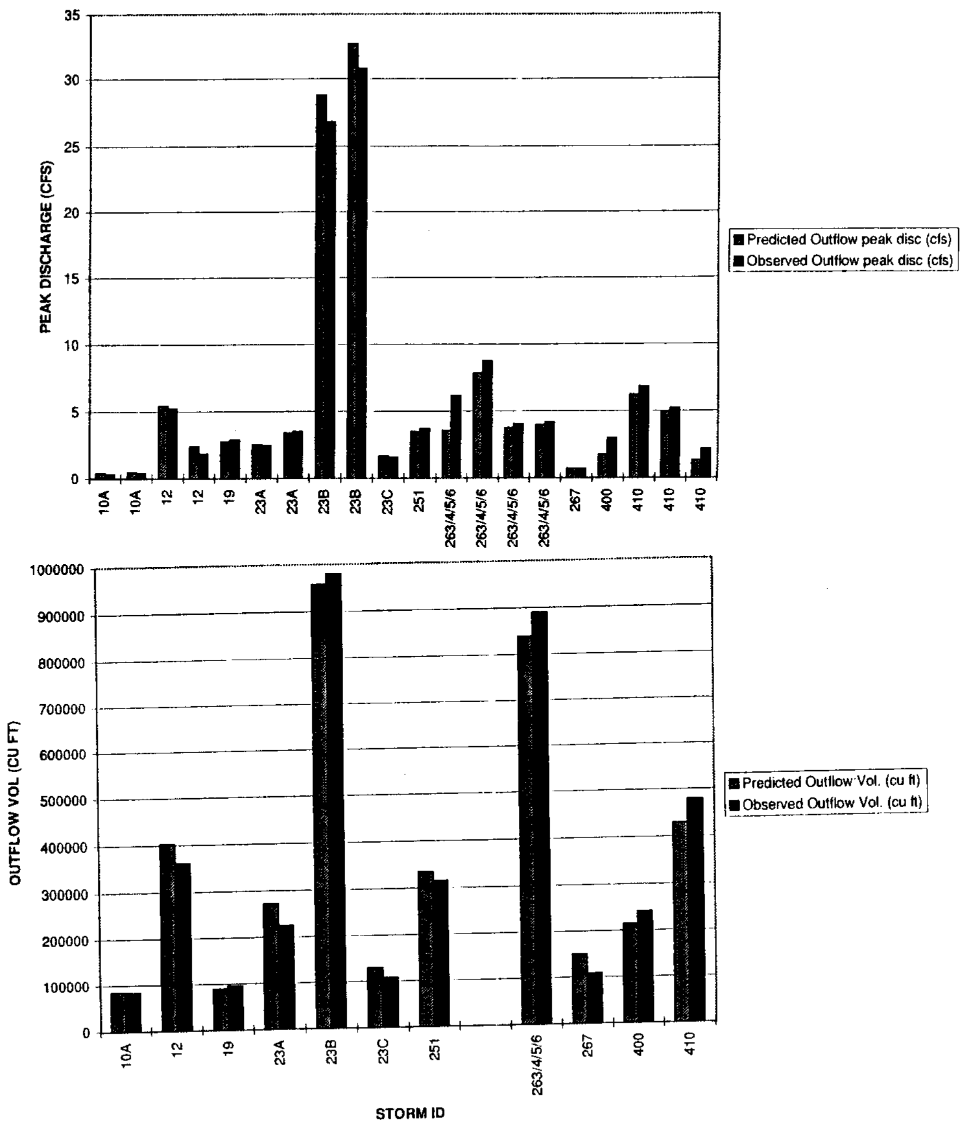


Figure 18. Predicted and observed flow volumes and peak flow rates.

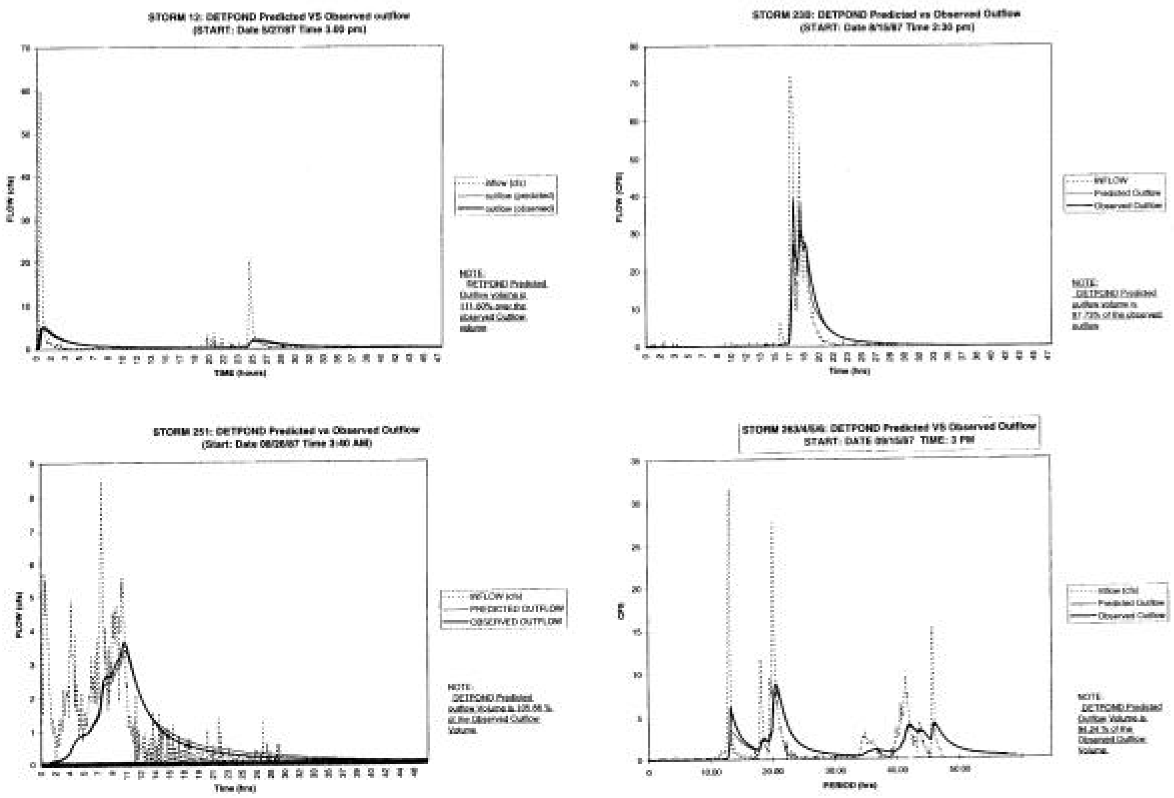


Figure 19. Predicted and observed hydrographs.

Observed Influent and Effluent Pollutant Concentrations. Table 10 lists the percentage removals observed at the pond, by probability of occurrence. Although the median removals were respectable and within the design range, there were relatively low removals for most constituents also.

Table 10. Summary of Observed Pollutant Removals at Monroe St. Pond

PROBABILITY IN % UNDER	10%	50%	90%
Suspended solids	35	87	97
Total Residue	<0	52	86
Volatile Residue	<0	41	76
Filtered Residue	<0	<0	56
Particulate COD	15	80	95
Total COD	29	60	84
FilteredCOD	<0	24	80
Particulate Phosphorus	-20	60	80
Total Phosphorus	<0	47	81
Filtered Phosphorus	<0	43	83
Particulate TKN	-40	40	80
Total TKN	<0	45	75
Filtered TKN	<0	12	68
Particulate Zinc	-117	70	95
Total Zinc	<0	31	69
Filtered Zinc	<0	<0	59

Particle Size Distributions and Short-Circuiting

Seven events were studied to find the short-circuiting "n" factors using observed and predicted particle size distributions in effluent water. Particle size distributions were measured using the Sedigraph method at the USGS Denver laboratory. This technique measures settling rates of different size suspended solid particulates down to 2 µm. The value of n is calculated using the concentrations of large particles that are found in the effluent. In ideal settling, no particles greater than the theoretical critical size (about 5 µm for Monroe St.) should appear in the effluent. However, there is always a small number of these larger particles. It is generally assumed that short-circuiting is responsible for these large particles.

The calculated values of n (based on matching measured effluent particle size distributions with distributions calculated using different values of n) ranged from about 0.2 to 1, indicating "very poor performance", or worse. The median value of n observed was about 0.35, indicating a degradation in annual average suspended solids capture efficiency of no more than about 10 percent. The effects of this short-circuiting, even with the extremely low values of n for Monroe St., only has a minimal effect on the suspended solids percentage removals. The Monroe St. pond provided an average suspended solids reduction of 87%, compared to the design goal of 90%. These values are quite close and the short-circuiting has a negligible effect on actual performance, as the pond surface is relatively large (0.6% of the drainage area) and the outlets were efficiently modified during the retrofitting activities.

Figure 20 shows the particle size distribution for the inflow events, including bedload. The median size is about 8 µm, but it ranges from about 2 to 30 µm. About 10% of the particles may be larger than 400 µm. The largest particle size observed was larger than 2 mm. The bedload added about 10% of the mass of these particulates and was associated with the largest sizes. The settling velocities of discrete particles can be predicted using Stoke's and Newton's settling equations. Probably more than 90% of all stormwater particulates (by volume and mass) are in the 1 to 100 µm range, corresponding to Laminar flow conditions. In most cases, stormwater particulates have specific gravities in the range of 1.5 to 2.5 (determined by conducting settling column, sieving, and microscopic evaluations of the samples, in addition to particle counting), corresponding to a relatively narrow range of settling rates for a specific particle size.

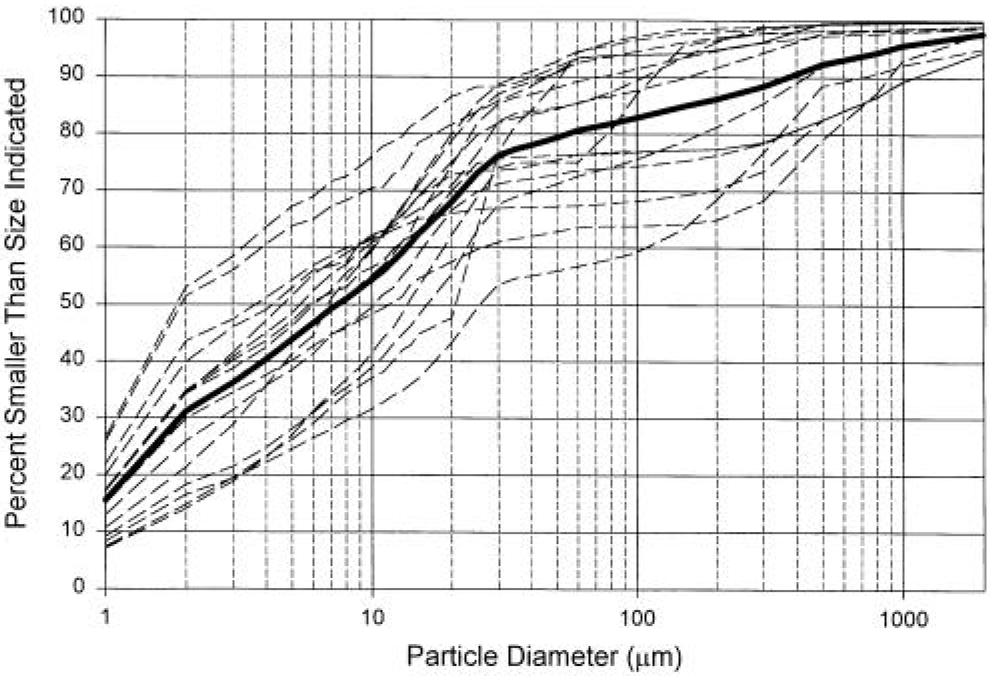


Figure 20. Inlet particle size distributions observed at the Monroe St. wet detention pond.

Monroe St. Pond Verification Conclusions

DETPOND successfully predicted the hydraulic, water quality, and particle size control at the Monroe St. detention pond in Madison, WI. In addition, DETPOND was successfully used to modify the outlet structure at the pond to enhance the pond's performance. The retro-fitting of the Monroe St. wet detention pond was very successful. Changing the outlet structures from large rectangular weirs to v-notch weirs significantly reduced effluent flows and reduced downstream channel erosion. The modification also improved the water quality benefits of the pond.

All constituents had outflow concentrations lower than associated inlet concentrations, except for chlorides, TDS, and filtered zinc. Suspended solids had a median removal of 87%, the median particulate COD removal was 60%, the median removal for total forms of the nutrients (TKN and phosphorus) were 40 to 45% and the median removal for total zinc was 30%. (The median particulate zinc removal was 70%). A well designed wet detention pond will remove 70 to 90% of suspended solids, 70% of COD, 60 to 70% of nutrients and 60 to 95% of the particulate forms of the heavy metals. The measured short-circuiting factor indicated a severe short-circuiting problem, but that could be a false indication due to minor scour near the effluent works in the pond. The Monroe Street pond is meeting all reasonable expectations in both downstream channel protection and in contaminant capture.

Issues Associated with Using a Continuous Record of Rains vs. a Single Event Storm

Single-event designs for hydraulic devices have been used for many decades with reasonably good success. They were developed to evaluate single parameter conditions (especially peak flow rate or maximum stage in drainage design). They are used with the assumption that if the hydraulic structure is designed to withstand this critical event, all events less critical would be safely handled. The critical single event for drainage design is selected from a local intensity-duration-frequency (IDF) curve for the drainage area time of concentration. The level of service is selected based on the return frequency of the design event (such as a "10-year" storm) and the intensity for the design storm is selected based on this level of service and an event duration equal to the watershed time of concentration. This is an effective approach for the design of relatively simple hydraulic structures and was developed due to the impracticality of evaluating a large series of events during a time of manual calculations.

The current availability of inexpensive computer facilities and software has largely negated the need to use a single-event for design (James and Robinson 1982). A much more suitable approach is to use continuous models for an extended period of time. This is especially critical when non-linear processes interact in unpredictable ways for different conditions and when more than simple single-parameter evaluations are needed. Wet weather flow water quality evaluations are much more complex than drainage design evaluations and require continuous simulations for the best results. Specifically, continuous evaluations enable calculations of probabilities of certain levels of performance being exceeded, such as the percentage of flow treated to a certain level.

This is not to say that single-event design storms should not be used for preliminary designs. Sizing of a wet detention pond (or other control practice) for water quality improvement can usually be made using relatively simple guidelines, based on historical performance data, local land use information, and rainfall statistics. However, it is possible and sometimes necessary to evaluate this design with a model under continuous and long-term conditions. This evaluation will produce much more useful information and will enable the "preliminary" design to be modified to more effectively meet the project objectives. In most cases, this long-term simulation only requires several minutes of time to conduct.

Stream Habitat Benefits Associated with Peak Flow Reduction Criteria

Some of the most serious effects of urban runoff are on the aquatic habitat of the receiving waters. A significant indirect benefit of flow controls for stormwater management is the reduction in associated stream power. Increased flows are probably the best know example of impacts associated with urbanization. Most of the recognition has of course focused on increased flooding and associated damages. This has led to numerous attempts to control peak flows from new urban areas through the use of regulations that limit post development peak flows to pre development levels for relatively large design storms. The typical response has been to use dry detention ponds. In addition to the serious issue of flooding, high flows also cause detrimental ecological problems in receiving waters. The following discussion presents several case studies where increased flows were found to have serious effects on stream habitat conditions, along with recommended approaches for their control.

The aquatic organism differences in urbanized and control streams found during the Bellevue Urban Runoff Program were probably mostly associated with the increased peak flows associated with urbanization. The increased flows in the urbanized Kelsey Creek resulted in increases in sediment carrying capacity and channel instability of the creek (Pederson 1981; Perkins 1982; Richey, *et al*. 1981; Richey 1982; Scott, *et al* . 1982). Kelsey Creek had much lower flows than the reference Bear Creek during periods between storms. About 30 percent less water was available in Kelsey Creek during the summers. These low flows may also have significantly affected the aquatic habitat and the ability of the urban creek to flush toxic spills or other dry weather pollutants from the creek system (Ebbert, *et al*. 1983; Prych and Ebbert undated). Kelsey Creek had extreme hydrologic responses to storms. Flooding substantially increased in Kelsey Creek during the period of urban development; the peak annual discharges almost doubled in the last 30 years, and the flooding frequency also increased due to urbanization (Ebbert, *et al*. 1983; Prych and Ebbert undated).

Snodgrass, *et al*. (1998) reported that in the Toronto, Ontario, area, flows causing bankfull conditions occur with a return frequency of about 1.5 years. Storms with this frequency are in general equilibrium with resisting forces that tend to stabilize the channel (such as vegetation and tree root mats), with increased flows overcoming these resisting forces causing channel enlargement. Infrequent flows can therefore be highly erosive. With urbanization, the flows that were bankfull flows during historical times now occur much more frequently (about every 0.4 years in Toronto). The channel cross-sectional areas therefore greatly increase to accommodate the increased stream discharges and power associated with the "new" 1.5 year flows that are trying to re-establish equilibrium.

Booth and Jackson (1997) found that the classical goal of detention ponds to maintain predevelopment flows was seriously inadequate because there is no control on the duration of the peak flows. They showed that a duration standard to maintain post development flow durations for all sediment-transporting discharges to predevelopment durations will avoid many receiving water habitat problems associated with stream instability. Without infiltration, the amount of runoff will obviously still increase with urbanization, but the increased water could be discharged from detention facilities at flow rates below the critical threshold causing sediment transport. The identification of the threshold discharge below which sediment transport does not occur, unfortunately, is difficult and very site specific. A presumed threshold discharge of about one-half of the pre-development 2-year flow was recommended for gravel bedded streams. Sand-bedded channels have sediment transport thresholds that are very small, with inevitable bed load transport likely to occur for most levels of urbanization.

MacRae (1997) presented a review of the development of the common zero runoff increase (ZRI) discharge criterion, referring to peak discharges before and after development. MacRae shows how this criterion has not effectively protected the receiving water habitat. He found that stream bed and bank erosion is controlled by the frequency and duration of the mid-depth flows (generally occurring more often than once a year), not the bank-full condition (approximated by the 2 yr event). During monitoring near Toronto, he found that the duration of the geomorphically significant pre-development mid-bankfull flows increased by a factor of 4.2 times, after 34% of the basin had been urbanized, compared to before development flow conditions. The channel had responded by increasing in cross-sectional area by as much as 3 times in some areas, and was still expanding. Table 11 shows the modeled durations of critical discharges for predevelopment conditions, compared to current and ultimate levels of development with "zero runoff increase" controls in place. At full development and even with full ZRI compliance in this watershed, the hours exceeding the critical mid-bankfull conditions will increase by a factor of 10, with resulting significant effects on channel stability and the physical habitat. MacRae (1997) concluded that an effective criterion to protect stream stability (a major component of habitat protection) must address mid-bankfull events, especially by requiring similar durations and frequencies of stream power (the product of shear stress and flow velocity, not just flow velocity alone) at these depths, compared to satisfactory reference conditions.

Table 11. Hours of Exceedence of Developed Conditions with Zero Runoff Increase Controls Compared to Predevelopment Conditions (MacRae (1997)

Recurrence Interval (yrs)	Existing Flowrate (m^3/s)	Exceedence for Predevelopment Conditions (hrs per 5 yrs)	Exceedence for Existing Development Conditions, with ZRI Controls (hrs per 5 yrs)	Exceedence for Ultimate Development Conditions, with ZRI Controls (hrs per 5 yrs)
1.01 (critical mid-bankfull conditions)	1.24	90	380	900
1.5 (bankfull conditions)	2.1	30	34	120

As seen, single-event criterion are not very effective for habitat protection unless relatively small events are used. Unfortunately, when only considering small events, serious drainage and flooding problems associated with large events may not be adequately mitigated. Therefore, flow criteria should consider at least several return frequency events (such as the recommended mid-bank flow condition, along with the less frequent drainage design storm). In addition, the duration of flows larger than critical sediment transport flows should also be controlled in order to provide protection of habitat. The use of continuous simulation including the more common events along with rarer storms causing flooding and drainage damage, should also be considered.

Benefits of Using Continuous, Long-Term Simulations

In order to predict receiving water problems caused by stormwater, accurate flow estimates and pollutant mass discharges must be known. Knowing where the potentially problem pollutants originate in the watershed is also valuable in order to select appropriate stormwater control candidates. Accurate knowledge of runoff volumes during different storms has been shown to be necessary when predicting pollutant discharges.

Most of the annual rain is associated with many small individual events, while most of the runoff volume and pollutant mass discharges are associated with a smaller set of intermediate events. The following discussion illustrates this, based on actual monitored rainfall and runoff distributions for Milwaukee, WI (data from the

Milwaukee NURP project, Bannerman, *et al*. 1983), and analyses of long-term rainfall histories and predicted runoff for Minneapolis.

Figure 21 includes cumulative probability density functions (CDFs) of measured rain and runoff distributions for Milwaukee during the 1981 NURP monitored rain year (data from Bannerman, *et al*. 1983). CDFs are used for plotting because they clearly show the ranges of rain depths responsible for most of the runoff. Rains between 0.05 and 5 in. were monitored during this period, with two very large events (greater than 3 inches) occurred during this monitoring period which greatly distort these curves, compared to typical rain years. Figure 22 shows CDFs of measured Milwaukee pollutant loads associated with different rain depths for a medium density residential area. Suspended solids, COD, lead, and phosphate loads are seen to closely follow the runoff volume CDF shown in Figure 21, as expected. Since load is the product of concentration and runoff volume, some of the high correlation shown between load and rain depth is obviously spurious. However, these overlays illustrate the range of rains associated with the greatest pollutant discharges.

Figure 21. Milwaukee rain and runoff cumulative probability density functions (CDFs).

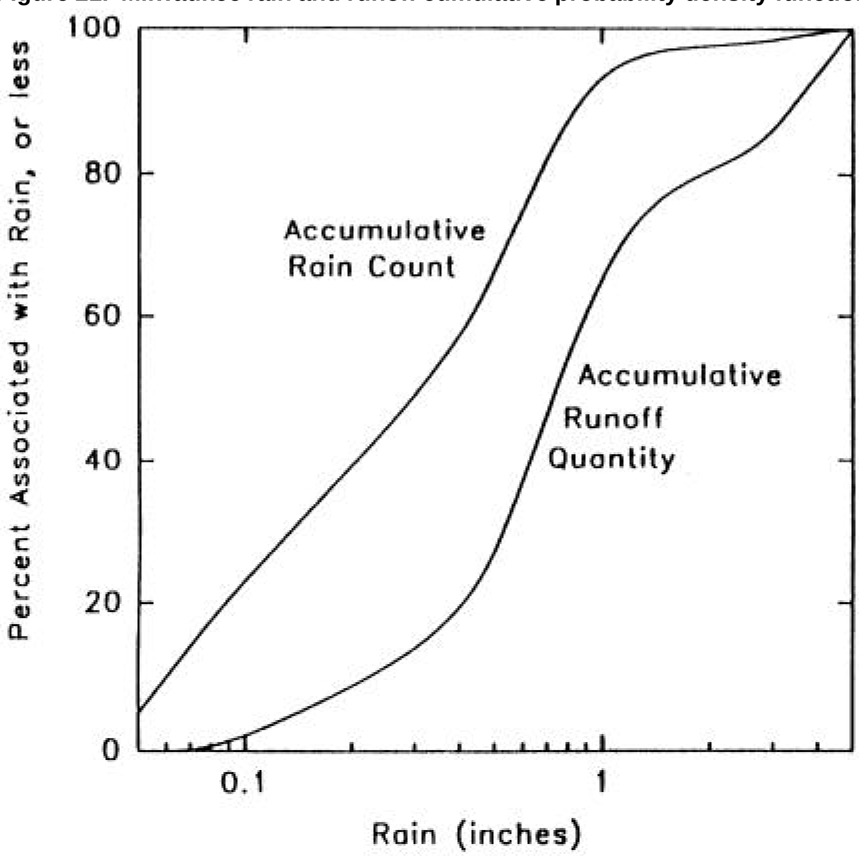
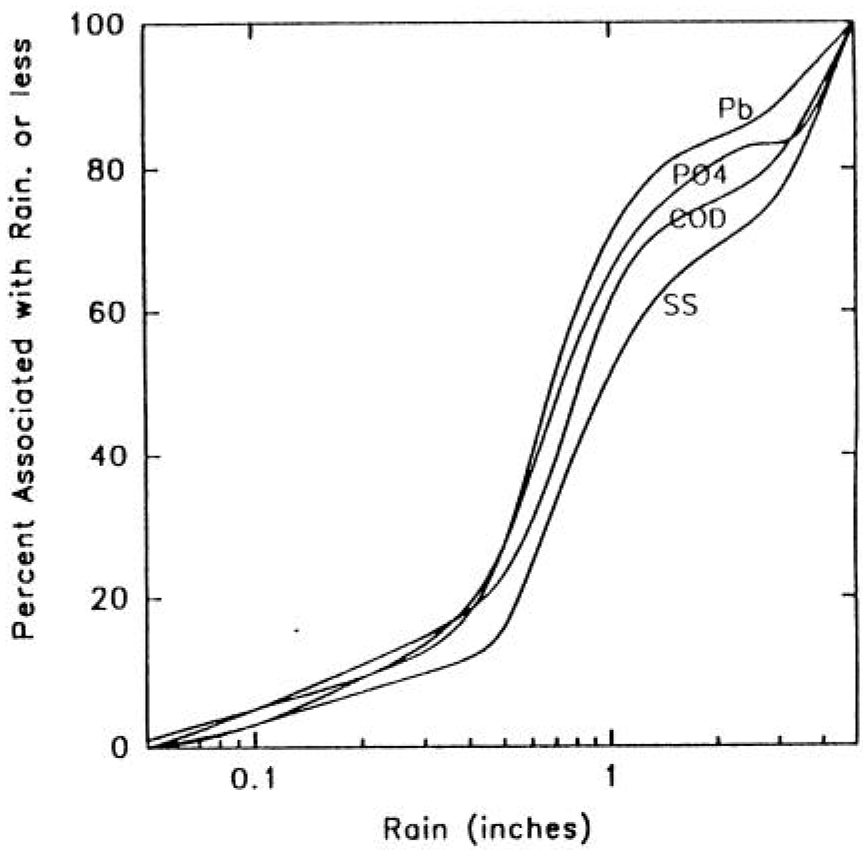


Figure 22. Milwaukee pollutant discharge cumulative probability density functions (CDFs).



The Milwaukee observations show that southeastern Wisconsin rainfall distributions can be divided into the following categories, with possible management approaches relevant for each category of rain:

- Common rains having relatively low pollutant discharges are associated with rains less than about 0.5 in. (12 mm) in depth. 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, especially bacteria and some total recoverable 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 generally did not produce noticeable runoff during the field monitoring in Milwaukee, but the lower "cutoff" rainfall would be mostly dependent on the amount of pavement in the drainage. These are key rains when runoff-associated water quality violations, such as for bacteria and total recoverable heavy metals, are of concern. 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. For most areas, the runoff from these rains can be relatively easily removed from the surface drainage system.

- Rains between 0.5 and 1.5 in. (12 and 38 mm) are responsible for about 75% of the runoff pollutant discharges and are key rains when addressing mass pollutant discharges. 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. 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 can 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 (such as in wet detention ponds) to prevent pollutant discharges from entering the receiving waters.

• Rains greater than 1.5 in. (38 mm) and less than 3 in (75 mm) are associated with drainage design and are only responsible for relatively small portions of the annual pollutant discharges. These rains produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year) to every few years. 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. Typical storm drainage design events fall in the upper portion of this category. Extensive pollution control 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 in the above categories would have some benefit in reducing pollutant discharges during these larger, rarer storms.

• In addition, extremely large rains >3 inches (>75 mm) also infrequently occur that can exceed the capacity of the drainage system and cause local flooding. This category is infrequently represented in field studies due to the rarity of these large events and the typically short duration of most field observations. The smallest rains in this category are included in design storms used for drainage systems in Milwaukee. These rains occur only rarely (once every several years to once every several decades, or less frequently) and produce extremely large flows. The 3-year monitoring period during the Milwaukee NURP program (1980 through 1983) was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<1% would be), and they produced about 15% of the annual runoff quantity and pollutant discharges. During a "normal" period, these rains would only produce a very small fraction of the annual average discharges. However, when they do occur, great 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 stormwater quality controls that would be necessary. The problem during these events is 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 and to possible infrequent/temporary detention areas (such as large playing fields or parking lots). Because these events are so rare, institutional memory often fails and development is allowed in areas that may not be indicated on conventional flood maps, but could suffer critical flood damage.

Example Use of DETPOND and Wet Detention Pond Analyses

Analysis of the Wet Stormwater Detention Pond for the Brook Highland Shopping Center

The following analysis was conducted by John Easton, a UAB graduate student, as part of a class assignment investigating current performance and possible retro-fit opportunities at existing wet detention ponds. The analyses included site surveys and peak flow evaluations using HydroCAD® and water quality analyses using DETPOND. This wet detention pond is located between Highway 280 and the Wal-Mart at the Brook Highland Plaza Shopping Center, in Shelby County, AL. The contributing area was estimated at 18 acres.

General Quality Criteria. A review of the plans and specifications, in addition to on-site field evaluations, indicates that the pond meets the depth criteria of 3 to 6 feet of permanent storage which is necessary to prevent scour, decrease light penetration (to minimize rooted aquatic plant growths), and to increase winter survival of fish.

This review indicates that the pond will maintain approximately 4 feet of dead water storage, but does not provide for much sediment storage. The pond might benefit from a deepened sump near the pond inlets where sediment would preferentially be captured. This would likely lower the maintenance costs for the pond by allowing easy access for removal of these larger particles.

The pond side slopes are 1:2 near the water edge, steeper than preferred. A 15 foot wide shelf slightly below the water surface is provided.

The pond significantly reduces the peak outflow rates from the contributing area. Theoretically, the 100-year storm's runoff rate is reduced from 141 cfs to about 38 cfs. The peak reduction factor (PRF = 1–Q_o/Q_I), for this event is 0.74, corresponding to a 74% reduction of the inflow hydrograph in the pond.. For the 50-year and 25-year storms, the PRFs are 0.73. Even in the case of the 100-yr storm, the pond still has half of a foot of freeboard storage below the invert of the emergency spillway.

For the typical rain events, DETPOND simulations demonstrate that the pond satisfies the maximum upflow velocity (or critical settling velocity) maximum of 0.00013 ft/sec which is necessary for 5µm particle control.

A pond's water quality storage should be equal to the runoff associated with 1-¼" rain based on the land use, and cover of the watershed served by the pond. HydroCAD, which uses SCS TR-20 methods for computing the composite curve number, calculated a CN of 95. This 95 CN is appropriate for a commercial area, and corresponds to approximately 0.85 inches of runoff for this rain size. Therefore, the minimum active pond storage (between the invert elevation of the lowest outlet and the secondary outlet discharge devices) required should be a least 1.3 acre-ft. The pond's water quality storage is approximately 1.6 acre-ft. There is an additional freeboard storage of 4.6 acre-ft for peak runoff rate reductions.

A pond's surface area should be sized as a percent of watershed's area based on land use and the particle size control desired. This site has commercial land use, with a recommended 1.7% of the watershed area needed for the pond surface area (or about 0.31 acres). The pond has a normal pool area of about 0.54 acres, exceeding this minimum recommendation.

In dry weather, the pond will be available to provide water for emergency fire protection. This pond should be a pleasing amenity for the retail mall area. The use of appropriate grasses adjacent to the pond may provide a grass filter for additional pollutant reduction.

Background Information Related to Site Evaluation. The peak inflow hydrograph values were determined by HydroCAD's SCS TR-20 methodology. For the site, a SCS Type III rainfall IDF curve was selected. Rainfall depths for the 100-year, 50-year, and 25-year storms were approximately 8.6", 7.8", and 7.1" respectively. The time of concentration (Tc = 5.1 minutes) for the watershed was also calculated using HydroCAD's built-in TR-20 methods. Given that the site is commercial, with an estimated 85% impervious area, a curve number of 95 was assigned.

Based on the information provided in the site's grading plans (given by Sain and Associates) and field observations, it was determined that the contributing watershed area that drains into the pond has an estimated area of approximately 18 acres. Slopes were determined to be very flat in the vicinity of the pond, approximately 1 foot per 100 feet, or 1%.

Analysis of Design Storms. The HydroCAD Stormwater Modeling System (version 4.53) was used to analyze the pond for flow attenuation during drainage design storms. This computer program calculates inflowing hydrographs, based upon design storm and watershed characteristics, and then routes these through a drainage system composed of subcatchments, reaches, and ponds.

The subcatchment component is used to model a given drainage area or watershed. In this case, there was only one subcatchment, with subcatchment 1 referring to the 18.0 acres of the Brook Highland commercial shopping center that drains into the pond next to Wal-Mart. The program uses built-in SCS TR-20 hydrology methods for determining the hydrograph characteristics. Next, the hydrograph is routed through a series of defined reaches and/or ponds. In this case, there is one hydrograph from the subcatchment, which is routed through a single pond.

The pond component of this model is described using a stage v. surface area curve. In addition, the model requires descriptions of the outlet structures. This data, as input to the model, is described in Figure 23 and Table 12.

Figure 23. Stage v. surface area curve.

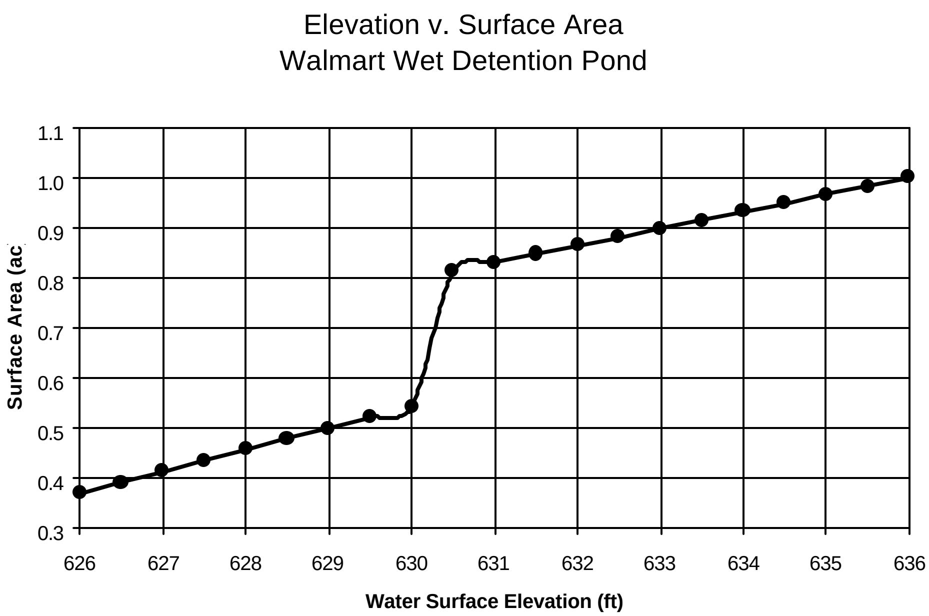


Table 12. Outlet Device Descriptions

#	Route	Invert	Outlet Devices
1	primary	630.0’	**36” culvert** n=0.013, length=38’, slope=0.13%, Ke=0.5, Cc=0.9
2	to #1	630.0’	**30” orifice**
2	to #2	630.0’	**22” orifice (two) (partially blocked by excessive cattail growths)**
3	to #2	632.5’	**sharp-crested rectangular weir** length=15.7’, height=3.5’ (square concrete box)
4	secondary	634.5’	**10’ broad-crested rectangular weir** emergency spillway

The HydroCAD simulations were run for three 24-hour, SCS type III design storm frequencies: 25-year (7.1”), 50-year (7.8”), and 100-year (8.6”). Table 13 summarizes these results. As previously mentioned, the peak reductions are about 73%, and the peak discharge lag is approximately 22 minutes. The peak elevation in the pond never reaches the maximum elevation (636 ft).

Table 13. Results of HydroCAD Simulations

Design Event	Rain Depth (in)*	Peak Elev. (ft)**	Peak Storage (AF)	Peak Qin (cfs)	Peak Qout (cfs)	Atten. (%)	Lag (min)
25-year	7.1	633.0	4.22	116.1	30.81	73	22.7
50-year	7.8	633.3	4.56	127.9	34.22	73	22.4
100-year	8.6	633.8	4.97	141.3	37.69	73	22.5

* Design storms are type III 24-hr for Shelby county (SCS methods).
** Flood elevation is at 636 feet.

DETPOND uses a simplified triangular hydrograph suitable for small rains. Therefore, the SCS hydrograph generated by HydroCAD was used in DETPOND to simulate water quality benefits during these large "design" storms. A comparison of the hydraulic results from HydroCAD (Table 14) shows that the hydraulic results are similar. Even under these extreme rain conditions, the pond is expected to remove approximately 75% of the TSS.

Table 14. DETPOND Summary for Design Storms

Storm Year	Max. Stage (ft.)	Max. Inflow (cfs)	Max. Outflow (cfs)	Max particle size discharged (µm)	Avg. Min Particle Size Controlled (µm)	% TSS Removed
25	633.01	115.0	31.3	32.5	7.9	76.1
50	633.40	126.7	34.4	32.5	8.3	75.1
100	633.83	140.0	37.9	32.5	9.0	73.5

Analyses Using Long-Term Rainfall Records. The advantage to using DETPOND is that the program allows analyses of actual rainfall events over an extended period of time. Rain files contain start and end dates and times, plus the rain depth. The model determines the rain duration, rain intensities, and interevent periods. DETPOND then routes a simple triangular hydrograph through the pond to evaluate the expected particulate removal. For this evaluation, DETPOND simulations were conducted using rain files created from the 1976 Birmingham monitoring year (a "normal" rain year containing 112 events, based on long-term records), and also on the complete 1952 through 1989 rain record. There were 2 events (out of a total of 4,107 in the Bham5289 rain file), in which the pond stage rises to the level of the second outlet. In addition, it never reaches the emergency spillway.

Short-term Simulation Series. The results of the simulations using the Bham76 file are presented in Table 15. On average, the pond will collect particle sizes 1.17 µm and greater in size, which represents 97% TSS control. The average rain depth is 0.5 inches, and the average duration is 12 hours. For the smallest storms, this pond is achieving close to 100% control, and for the largest storm in 1976 the pond is still removing about 86% of the TSS. These high removals, in addition to the large peak flow rate reductions, indicates that the pond is likely over-sized, possibly in anticipation of additional area being directed to the pond as the shopping center is further developed.

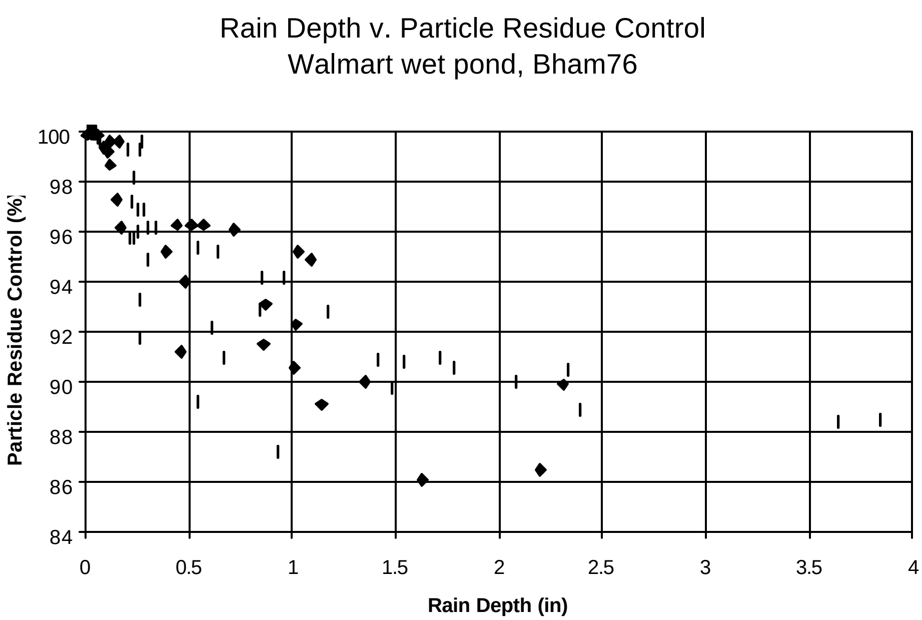
Table 15. Water Quality Output Summary for 1976 Rain Year (112 events)

Statistic	Rain Depth (in)	Rain Duration (hrs)	Intrevt Duration (days)	Rain Intensity (in/hr)	Max Pond Stage (ft)	Flow-weighted Particle Size	Approx. Part. Res. Control* (%)	Peak Reduction Factor	Event Flushing Ratio
Mean	0.50	12.01	1.81	0.04	630.16	1.17	97	0.29	0.39
Std. Dev.	0.75	10.77	2.36	0.06	0.23	1.23	4	0.21	0.64
COV**	1.51	0.90	1.30	1.48	0.05	1.05	0.04	0.73	1.63
Min.	0.01	1.00	0.25	0.01	630.00	0.00	86	0.04	0.00
Max.	3.84	45	11.68	0.31	631.04	4.00	100	0.74	3.31

* Approximate Particle Residue Control (TSS).
** Coefficient of Variation – standard deviation divided by the mean.

Figure 24 shows the water quality performance of the pond (% particulate control) versus the rain depth in inches. Generally, the percentage TSS control decreases as the rain depth increases, as expected. The scatter is due the fact that rainfall/runoff characteristics are quite variable and depth is only one parameter. The results are similar to a plot which shows the percentage TSS control versus rain intensity.

Figure 24. Rain depth v. particle residue control.



Long-term Simulation using Birmingham Rain, 1952-1989. Table 16 is a summary for the 4,107 rain events that occurred in Birmingham from 1952-1989. Notice that the minimum and maximum values are different than those from the 1976 simulations, but the mean values are quite similar, indicating that 1976 is likely a good indicator for a typical rain year. The mean particle control is about 95%, slightly less than the 97% value indicated for the 1976 rain year. This high removal rate over this extended period assumes that proper maintenance of the pond will occur.

Table 16. Water Quality Output Summary for 1952-1989 Rain File

Statistic	Rain Depth (in)	Rain Duration (hrs)	Intrevt Duration (days)	Rain Intensity (in/hr)	Max Pond Stage (ft)	Flow-weighted Particle Size	Approx. Part. Res. Control* (%)	Peak Reduction Factor	Event Flushing Ratio
Mean	0.50	6.31	2.57	0.09	630.26	1.64	95	0.42	0.38
Std. Dv.	0.75	6.88	3.54	0.11	0.33	1.37	5	0.22	0.62
COV**	1.50	1.09	1.38	1.31	0.00	0.83	0.05	0.52	1.62
Min.	0.01	1.00	0.00	0.00	630.00	0.00	74	0.01	0.00
Max.	13.58	93	44.31	1.45	632.41	7.70	100	0.77	8.06

* Approximate Particle Residue Control (TSS).
** Coefficient of Variation – standard deviation divided by the mean.

Design Storm Runs Using DETPOND. The pond inflow hydrograph from the HydroCAD analyses were used as a "user defined hydrograph" for input into DETPOND to evaluate the water quality control during these low frequency design storms.

Site Photographs:

Photo 1: Facing west, inlets on right, obscured by cattails (photo by John Easton).

Photo 2: Facing North, showing parking area that drain to pond (photo by John Easton).

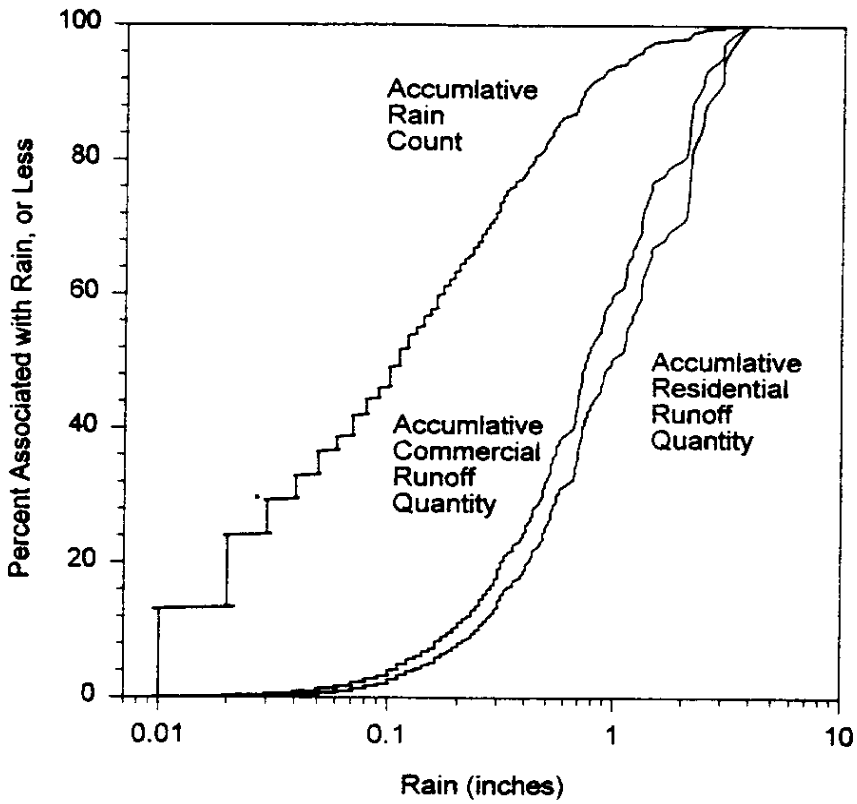
Photo 3: Outlet structure, showing cattails partially blocking the 22 in orifices through concrete wall (photo by John Easton).

The Use of DETPOND to Evaluate Wet Detention Pond for Minneapolis-St. Paul Airport

This discussion if summarized from a report originally prepared by Robert Pitt for Liesch Associates, Inc., in August 1999.

Long-Term Rain and Runoff Analyses for Minneapolis. The critical values defining the important rain categories affecting receiving water uses are highly dependent on local rain and development conditions. Computer modeling analyses for 7 years of rains for Minneapolis (1982 through 1989) were therefore conducted to examine the runoff distributions for typical residential and commercial areas. The plots from this modeling activity (shown in Figure 25) indicate the rainfall and runoff probability distributions. 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.

Figure 25. Recorded rain count and modeled runoff volume distributions for Minneapolis, MN (1983 through 1989).



These simulations were based on 7 years of rainfall records (1983 through 1989), from the NOAA station at the Minneapolis-St. Paul airport and were obtained from CD-ROMs distributed by EarthInfo of Boulder, CO. Hourly rainfall depths for the indicated periods were downloaded from the CD-ROMs into an Excel spreadsheet. The files were slightly modified (by eliminating the daily total rainfall column) and saved as a comma delineated file. This file was then read by an utility program included in the SLAMM package. This rainfall file utility combined adjacent hourly rainfall values into individual rains, based on user selections (at least 6 hrs of no rain was used to separate adjacent rain events and all rain depths were used, with the exception of the "trace" values). These rain files for each city were then used in SLAMM for typical medium density and strip commercial developments. The median rainfall was 0.11 inches, while rainfall depths of about 0.73 to 1.0 inch correspond to the median runoff depth, depending on the land use.

The CDF plot (Figure 25) shows two distinct "breakpoints" which separate the distributions into the following three general categories:

• less than lower breakpoint: small, but frequent rains. These generally account for 50 to 70 percent of all rain events (by number), but only produce about 10 to 20 percent of the runoff volume throughout the U.S. Figure 25 shows that the rain depth for this breakpoint was about 0.22 inches for Minneapolis during this 7 year period, and 68% of all rains were less than this value. Nine to 13% of the runoff volume was associated with these smaller rains, depending on the land use. These events are therefore most important because of their frequencies, not because of their mass discharges. These rains are therefore of great interest where water quality violations associated with urban stormwater occur. This would be most common for bacteria (especially fecal coliforms) and for total recoverable heavy metals which typically exceed receiving water numeric criteria during practically every rain event in heavily urbanized drainages having separate stormwater drainage systems.

• between the lower and upper breakpoint: moderate rains. These rains generally account for 30 to 50 percent of all rains events (by number), but produce 75 to 90 percent of all of the runoff volume throughout the U.S. Figure 25 shows that the rain depth of this upper breakpoint is about 2.8 inch for Minneapolis during this 7 year period, and about 84% of all runoff was between the two breakpoints, while only 32% of the rains were in this range. These intermediate rains also account for most of the pollutant mass discharges and much of the actual receiving water problems associated with stormwater discharges.

• above the upper breakpoint: large, but rare rains. These rains include the typical drainage design events and are therefore quite rare. During the period analyzed, less than 1 percent of the rains were greater than this breakpoint (only 11 events in 38 years, including a 10 inch rain that occurred on July 23, 1987, as shown in Table 17). These rare events accounted for about 5 percent of the runoff on an annual basis, as shown on Figure 25. Obviously, these events must be evaluated to ensure adequate drainage and for habitat protection.

Table 17. Very Large Rains Occurring from 1952 to 1990 at Minneapolis-St. Paul International Airport

Date	Rain Depth (inches)	Rain Duration (hours)
6/25/78	2.88	8
6/7/84	2.94	12
6/21/86	3	10
5/31/65	3.01	13
10/14/66	3.13	32
10/7/70	3.2	61
8/26/78	3.65	14
7/20/87	3.8	9
7/7/55	3.89	9
8/30/77	7.35	11
7/23/87	10	6

A continuous analysis of proposed water quality control practices is therefore needed in order to evaluate how the proposed practices affect the rains in each of these three major categories.

Estimated Performance of Minneapolis-St. Paul International Airport Pond Design. DETPOND was used to evaluate the proposed pond at the Minneapolis-St. Paul International Airport. Table 18 is a summary of the overall pond performance for the three major rain categories described above. Obviously, the smaller rains and flows experience a much greater level of treatment than the larger rains. The following summarizes the overall expected pond performance:

• the flow-weighted particle size control is about 5.1 µm, corresponding to an estimated flow-weighted suspended solids control of about 89% using the “midwest” particle size distribution.

• if using the “low” particle size distribution (made up predominately of smaller particles), then the estimated flow-weighted suspended solids control would be about 65%.

• if using the “high” particle size distribution (made up predominately of larger particles), then the estimated flow-weighted suspended solids control would be about 97%.

Table 18. Predicted Wet Detention Pond Performance at Minneapolis-St. Paul International Airport

Rain category	Occurrence of rains in this category (% of all rains)	Rain range (inches)	Predicted critical particle size control (μm) (flow-weighted)	Predicted suspended solids control (%) (flow-weighted)	Percentage of annual runoff volume in category
Frequent, small rains	68%	<0.22 inch	1.0 μm	99%	8.8%
Common, intermediate rains	32%	0.22 to 2.8 inches	4.8 μm	89%	84.1%
Rare, large rains	<1% (11 in 38 years)	>2.8 inches	15 μm	71%	7.1%

Table 19 is a statistical summary of the modeled pond performance for this proposed pond for the 38 year analysis period. This period contained almost 4,000 events, ranging from 0.01 to 10 inches, with interevent periods ranging up to 34 days. Only about 1% of the total pond outflow occurred as evaporation and only about 10% of the pond water was displaced during the median rain event. The pond displacement volume (the water volume in the pond at the beginning of the event) was about equal to a 0.5 inch rainfall. The intermediate rainfall category (0.22 to 2.8 inches) had event flushing ratios ranging from 0.25 to 6.8, with most of the events in this critical category displacing several times the pond volume during the event period. In other words, most of the treatment is likely occurring during the relatively short runoff period (5 to 24 hours) as dynamic settling and not during interevent periods as quiescent settling.

Table 19. Pond Performance Summary for 38 Year Rain Series for Proposed Airport Pond Design

	Rain depth (in)	Rain duration (hrs)	Interevent duration (days)	Rain intensity (in/hr)	Maximum pond stage (ft)	Minimum pond stage (ft)	Event inflow volume (ac-ft)	Event hydraulic outflow (ac-ft)	Event evaporation outflow (ac-ft)	Event total outflow (ac-ft)	Flow-weighted particle size controlled (μm)	Approximate suspended solids control (%)	Peak reduction fac tor	Event flushing ratio
number	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3680	3997
total	1033	24829	10647				40016	39535	444	39980				
% flow out								98.89	1.11					
num avg	0.26	6.21	2.66	0.05	6.25	5.24	10.01	9.89	0.11	10.00	1.45	97.31	0.68	0.61
fl wt avg											5.08	89.24		
median	0.10	4.00	1.46	0.02	5.81	5.20	1.67	2.24	0.05	2.36	0.60	99.90	0.76	0.10
min	0.01	1.00	0.00	0.00	4.89	4.77	0.01	0.00	0.00	0.01	0.00	59.30	0.02	0.00
max	10.00	79.00	34.31	1.67	25.34	6.48	807	807	1.25	807	23.30	100.00	1.00	49.04
st dev	0.43	6.8	3.4	0.08	1.24	0.17	23.7	23.4	0.14	23.4	1.94	4.40	0.26	1.44
COV	0.59	0.90	0.76	0.58	5.0	29	0.42	0.42	0.75	0.42	0.74	22	2.5	0.42

The first category, the most frequent, but smallest rains, account for about 68% of all rains (by count), but only 8.8% of the airport runoff quantity. These rains are most significant from a water quality standard violation standpoint, as almost all rains are likely to exceed water quality standards for bacteria and some of the total recoverable heavy metals. Much of these flows would be infiltrated through the grass-lined drainages at the airport. The directly-connected impervious areas draining directly to the drainage systems and the proposed detention pond will contribute most of the expected flows during these small rains. The proposed detention pond will remove almost all of the suspended solids in the runoff, and much of the associated other pollutants (especially the heavy metals) during these small rains, greatly reducing the frequency of water quality violations.

The intermediate category of rains are responsible for most of the annual runoff volume (84.1%). Runoff from this category of rains would most likely be responsible for most of the receiving water problems. Much of the runoff from the smallest rains in this category would likely be infiltrated at the upland grass waterways, but the larger rains would produce some runoff from these "disconnected" areas in addition to most of the runoff from the directly connected paved areas. The proposed pond is estimated to remove most of the particulate pollutants greater than about 5 µm in size (and about 89% of the suspended solids) from the runoff from these rains.

The third category of rains (>2.8 inches) account for only 7.1% of the annual airport runoff, and originate from only 0.3% of the rain events. Fifteen events over the 38 years would have been expected to cause an overflow of the emergency spillway of the pond, possible causing catastrophic pond failure (especially the maximum 10 inch rain, while the other excessive rains would have produced much less of an overflow). The proposed pond design therefore has a bypass structure that will divert large flows around the pond and discharge them directly into the Minneapolis River untreated. A later discussion presents an analysis to recommend the bypass flow rate. The water treated in the pond in this category would provide capture of all particulates greater than about 15 µm, corresponding to a suspended solids level of control of about 71%.

The estimated long-term averaged suspended solids control is therefore about 88%, mostly associated with the intermediate-sized events.

Sizing and Performance of Airport Wet Detention Pond Based on Simple Design Criteria. As a comparison to the preliminary pond design, an airport wet detention pond was sized based on simple guidance, ignoring actual site constraints. The performance of this pond was also evaluated using 38 years of airport rainfall data.

The first criteria in sizing a detention pond for water quality is to provide a surface area equal to about 3% of the paved drainage area in order to control particles larger than about 5 µm. For the airport site, 353 acres of pavement will drain to the pond, along with 622 acres of sandy soil pervious areas and 210 acres of pavement that is drained through surface swales across the sandy soil. Because of the high rate of infiltration of the sandy soil, the pond can be sized only for the directly connected paved area. Therefore, the optimal pond design would include a permanent pond surface area of about 10.6 acres.

The second criteria in sizing a pond is to provide a "live" storage volume equal to the runoff volume associated with a rain of about 1.25 inches in depth. A rainfall of 1.25 inches would produce about 55.6 acre-ft of runoff. Table 20 lists the resulting side slopes associated with different pond depths.

Table 20. Side Slope Calculations of Full-Size Airport Pond

Depth (above the normal water elevation)	Pond area at this depth	Resulting side slope of pond
2 ft.	46 acres	0.5%
3	27	1.3
4	17.0	3.9
5	11.7	25

In order to construct a pond having this volume, normal surface area, and a side slope of about 4%, the live storage pond depth above the normal water level would be about 4 feet. The surface area at 4 ft above the normal pond surface would therefore be about 17 acres.

The final criteria in sizing a wet detention pond is to select the outlet devices to provide at least 5 µm control at all pond stages. The critical settling velocity of a 5 µm particle is about 1.3 x 10^{-4} ft/sec. The maximum outlet discharge is equal to this velocity times the surface area (the surface overflow rate). Several choices are possible with this pond, including: a single 90^o v-notch weir, two 60^o v-notch weirs, a 5 ft. sharp-crested rectangular weir (a little too large), or two 36 inch vertical drop structures. Table 21 summarizes these outfall options.

Table 21. Alternative Discharge Devices for Full-Size Airport Pond

Stage above lowest invert	Pond area at this stage	Maximum allowable discharge at this stage for 5 ■m control	Discharge for a single 90^o v-notch weir	Total discharge for two 60^o v-notch weirs	Discharge for a single 5 ft. sharp-crested rectangular weir	Total discharge for two 36" drop structures
0 ft	10.6 acres	60 cfs	0	0	0	0
1	12.2	69	2.5	2.8	16	14
2	13.8	78	14	16	43	56
3	15.4	87	39	56	80	84
4	17.0	96	80	92	110	84

The 60^o v-notch weirs provide the best solution because they are the closest fit at the 4 ft stage, while providing substantially better performance at lower elevations than the rectangular weir or the drop structures.

In addition to these "water quality" discharges, another spillway needs to be provided for rarer events that may not be contained within these outlet devices. A rectangular weir 7.8 ft long and 2.5 ft high extending from the 4 ft stage (above the normal water surface) was included in the preliminary design and was therefore used for this design. In addition, a road crossing provides another emergency spillway for rare storms.

This pond design was evaluated using the rain history (3997 separate events) from the 38 year period from 1952 through 1989. Table 22 summarizes the performance of this hypothetical pond, for comparison to the proposed pond design. This larger pond provides a flow-weighted control for particles greater than 2.2 µm. For the "midwest" particle size distribution, this corresponds to an approximate flow-weighted suspended solids control of about 96%. Using the "low" particle size distribution, this would correspond to an approximate flow-weighted suspended solids control of about 85%, and using the "high" particle size distribution, this would correspond to an approximate flow-weighted suspended solids control of about 99%. Particles larger than 5 µm (at least) would be theoretically trapped in the pond whenever the surface water elevation was below the rectangular weir. If the pond water elevation was near the invert of the v-notch weirs, then the particle size control would be much better. Similarly, whenever the pond water level is within the rectangular weir, particles larger than 5 µm would be discharged. Of course, it is likely that some particles larger than 5 µm would be discharged at lower pond surface elevations due to potential short-circuiting. As shown previously, with large short-circuiting (not expected with the elongated design of the pond) the discharge of some large particles would occur, but the pond suspended solids control is only reduced by a small amount. This larger pond therefore has a relatively large marginal improvement over the proposed pond design (96% vs. 88%), but at about three times the area. However, this larger pond is not suitable for the site because of limited available space at the airport.

Table 22. Pond Performance Summary for 38 Year Rain Series for Large Pond Design

	Rain depth (in)	Rain duration (hrs)	Interevent duration (days)	Rain intensity (in/hr)	Maximum pond stage (ft)	Minimum pond stage (ft)	Event inflow volume (ac-ft)	Event hydraulic outflow (ac-ft)	Event evaporation outflow (ac-ft)	Event total outflow (ac-ft)	Flow-weighted particle size controlled (µm)	Approximate suspended solids control (%)	Peak reduction factor	Event flushing ratio
number	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3997	3492	3997
total	1033	24829	10648				40016	38854	1113	39967				
% flow out								97.22	2.78					
num avg	0.26	6.21	2.66	0.05	5.99	5.34	10.01	9.72	0.28	10.00	0.60	99.27	0.76	0.35
fl wt avg											2.24	95.82		
median	0.10	4.00	1.46	0.02	5.70	5.29	1.67	2.83	0.13	3.14	0.20	100.00	0.83	0.06
min	0.01	1.00	0.00	0.00	4.95	4.79	0.01	0.00	0.00	0.01	0.00	72.10	0.00	0.00
max	10.00	79.00	34.31	1.67	20.46	6.75	807.71	804.65	3.10	805.15	12.90	100.00	1.00	28.51
st dev	0.43	6.9	3.5	0.081	0.89	0.22	24	23	0.37	23	0.87	1.8	0.21	0.84
COV	0.59	0.90	0.76	0.58	6.7	24	0.42	0.43	0.76	0.44	0.69	56	3.5	0.42

Suggested Pond Modifications to Enhance Performance. The following discussion presents some suggestions to further enhance the performance of the proposed wet detention pond at the Minneapolis-St. Paul International Airport. The most important enhancements relate to special winter operations, where the pond water level should be drawn down during the winter to isolate the sediments by ice from snowmelt that may otherwise flow under the ice. This would also increase the effective storage volume for snowmelt and provide additional storage for winter runoff that may be contaminated by de-icing compounds. This would allow the winter runoff to be pumped to separate facilities for treatment of the de-icing compounds.

Another suggested enhancement would be to add a capability for surface aeration to the pond. This would increase mixing during interevent periods to reduce stratification, increase photo-degradation of toxicants, and provide an excess of dissolved oxygen (especially important considering the very high BOD_5 of common de-icing compounds that may enter the pond). Aeration could be used intermittently, depending on the pond conditions.

A subsurface outlet would enhance floatable control and would minimize icing problems. The outlet pipe should be located near the bottom of the pond, but on a sealed surface to minimize scour. The outlet pipe would then be connected to a large subsurface box where the outlet control weir is located. This box would also be outfitted with lower outlet controls for winter operation and for complete drainage of the pond for any required maintenance.

It is strongly suggested that a fore-bay be installed near the pond inlet to minimize the area where most of the sediment would accumulate. The area for the fore-bay should be between 10 and 20% of the total pond area and be separated from the main pond by a subsurface weir/dam (located below the low winter operational pond level). Special access provisions should be provided adjacent to this area to enable easy access to dredging equipment.

The inlet leading to the pond could also be provided with chemical feed facilities to allow chemical treatment under severe conditions. The use of alum has been shown to be problematic in northern areas where pH and buffering capacity of the water may be low, causing aluminum toxicity. However, alum is easy to apply and the floc can be discharged into the pond where it is relatively stable. Ferric chloride is generally a superior coagulant for stormwater, especially in northern areas, allowing the faster formation of a more stable floc that settles much more rapidly than an alum floc. Unfortunately, a ferric chloride floc becomes unstable under anaerobic conditions, which may occur near the sediment interface in a wet detention pond. Therefore, ferric chloride flocs are usually removed before discharge. It may be possible to capture most of the floc in the recommended fore-bay, and to ensure aerobic conditions there through the use of aeration in that area.

Finally, there are special recommendations for the use of wet detention ponds at airports that need to be addressed. These have to do with aircraft safety, especially by not providing an attraction to birds. Heavily vegetated perimeters of a pond generally decrease the pond's attractiveness to geese, but they also provide habitat to other wildlife and are not recommended by the FAA. The linear shape of the proposed pond meets the FAA's recommendations, but it is a wet pond, whereas they recommend dry ponds. Unfortunately, dry ponds do not provide adequate water quality treatment. They also recommend steep sides that are rip-rap lined, with minimal vegetation to discourage wildlife. The nearby location of the Valley National Wildlife Refuge and Meadow Lake may make this proposed wet detention pond much less attractive to wildlife than if it was the only body of water in the region.

Special Issues Associated with Wet Detention Ponds at Airports. The FAA published an Advisory Circular (No. 150/5200-33) on May 1, 1997 discussing hazardous wildlife attractants on or near airports. They list the wildlife that have been involved in damaging collisions with civilian aircraft in the U.S. in 1993 – 1995. Waterfowl were involved in 28% of the collisions and wading birds were involved in another 3%. Because of this, they are concerned about land use practices on and near airports that may attract waterfowl. The recommended distance between an aircraft's movement areas, loading ramps, or aircraft parking areas and any wildlife attractants is 10,000 ft for airports serving turbine-powered aircraft, and 5 miles if the wildlife attractant may cause hazardous wildlife movement across or into the approach or departure airspace.

They recommend that artificial marshes (wetland treatment systems for wastewater) not be located within these separation distances. They also recommend against the discharge of wastewater to unpaved airport areas, as the resultant soft or muddy conditions can severely restrict or prevent emergency vehicles from reaching accident sites in a timely manner. These incompatible land uses specifically deal with wastewater treatment facilities and not to stormwater. However, the issues may be similar. Obviously, many airports utilize grass swales to drain airport pavement areas. It is imperative that these swales are designed to minimize standing water and provide good infiltration conditions. Longitudinal infiltration trenches along the swale's lengths, or at least intermittent infiltration areas, could be provided to ensure adequate drainage in these areas. Wetland treatment of airport runoff may also be of concern.

The FAA also lists land uses that may be compatible with safe airport operations, specifically addressing stormwater dry and wet detention ponds. In general, the FAA does not consider these activities to be hazardous to aviation if there is no apparent attraction to hazardous wildlife, or wildlife hazard mitigation techniques are implemented to deal effectively with any wildlife hazard that may arise. They state that both dry and wet detention ponds control runoff (a necessary activity for safe aircraft operations), but also can attract hazardous wildlife. To best control hazardous wildlife, the FAA recommends using steep-sided, narrow, linearly-shaped, rip-rap lined dry detention ponds rather than wet detention ponds. Whenever possible, these ponds should be placed away from aircraft movement areas and that all vegetation in or around dry or wet detention ponds that provide food or cover for hazardous wildlife be eliminated. They also state that if soil conditions permit, the use of underground stormwater infiltration systems, such as French drains or buried rock field be used because they are less attractive to wildlife.

Conclusions

This course has shown that the use of relatively simple design criteria can be used to provide excellent water quality benefits over a wide range of storm conditions. DETPOND can be used to evaluate a wide variety of pond designs and can be used to develop appropriate design guidelines for different climatic conditions. Wet detention ponds for water quality control can also be used to provide drainage and flood control benefits by providing additional free board storage. However, a detailed hydrologic investigation of the complete watershed is necessary to make sure that these detention ponds do not actually increase drainage and flooding problems downstream.

Detention ponds are probably the most commonly used stormwater quality devices and have substantial literature documenting their performance and problems. Wet detention ponds have been shown to be very effective, if their surface area is large enough in comparison to the drainage area and expected runoff volume. Small wet ponds and all dry ponds have been shown to be much less effective. Detention ponds can be easily integrated into a comprehensive stormwater management program, but only if land is available and if installed at the time of development. They are very difficult and expensive to retro-fit into existing areas. Care must also be taken to minimize safety and environmental hazards associated with ponds in urban areas. In addition to safety concerns, contaminated sediment management and poor water quality are major issues.

Monitoring of stormwater detention ponds is needed to confirm the adequacy of any stormwater control design criteria, including the simple criteria as presented in this paper. If the performance is different than desired, then the criteria should be appropriately adjusted. Because of the relatively large volume of water contained in detention ponds, long-term continuous monitoring of influent and effluent quality is needed. Haphazard storm event monitoring can result in inaccurate evaluations of detention ponds. The effluent of the pond for relatively small storms may not be related to the current storm's influent, but can actually be mostly made of displaced water that had resided in the pond since previous events. Also, in order to effectively design wet detention ponds, along with many other sediment practices (including grass filters, catch basins, and other types of sumps) particle size and/or settling rate analyses are necessary. This information can be obtained using conventional settling column tests directly resulting in settling velocity information. Small sieves, ranging from 20 µm to up to several hundred µm, can also be used along with total solids gravimetric analyses to obtain particle size data. These tests would result in particle diameter measurements and specific densities would have to be assumed or measured using other procedures in order to calculate settling velocities. The use of laser or other types of particle counters may also be worthwhile in order to rapidly obtain the needed particle size data.

Wet detention ponds have been shown to be an extremely robust stormwater control practice. Even though their cost may be high, their level of pollutant reduction is also high, resulting in very cost-effective pollutant removals. Physical sedimentation is the main removal process occurring in wet ponds, resulting in much better removals of particulate bound pollutants than "filterable" forms of pollutants. Fortunately, for many of the stormwater pollutants of concern, particulate forms are much more abundant then filterable forms. Wet detention ponds can also be optimized to encourage biochemical processes that can further reduce many filterable pollutants. Even though wet detention ponds have been demonstrated to provide high levels of control, they may not be the best control for all conditions. Combinations of controls, determined using a comprehensive watershed evaluation tool, are likely to result in the best control program.

References and Bibliography

Adams, L.W., D.L. Leedy, and T.M. Franklin. "Wildlife enhancement in urban stormwater control." *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Adler, J. "Automatic device for emptying a detention pond at a constant low flow rate and velocity." *1981 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, July 1981.

Akeley, R.P. "Retention ponds for control of urban stormwater quality." In *Proceedings National Conference on Urban Erosion and Sediment Control: Institutions and Technology*, EPA-905/9-80-002, Chicago, January 1980.

APWA (American Public Works Assoc.). *Water Pollution Aspects of Urban Runoff*. Water Pollution Control Research Series WP-20-15, Federal Water Pollution Control Administration, January 1969.

Bannerman, R., K. Baun, M. Bohn. P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*. U.S. Environmental Protection Agency, PB 84-114164, Chicago, Ill., 1983.

Barfield, B. "Analysis of the effects of existing and alternate design criteria on the performance of sediment detention ponds." *1986 Sediment and Stormwater Conference*, sponsored by the Maryland Water Resources Administration, Sediment and Stormwater Division, Salisbury State College, Maryland, July-August 1986.

Bedner, R.E. and D.J. Fluke. *Demonstration of Debris Basin Effectiveness in Sediment Control*. Environmental Protection Agency, Industrial Environmental Research Laboratory - Cincinnati, EPA-600/7-80-154. Cincinnati, Ohio, 1980.

Bernard, C., P. Herviou, T. Poujol, and C. Zobrist. "Procedures for treatment of stormwater and quality objectives: two practical representative examples." Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Runoff*. Quebec City, Quebec. June 16 - 19, 1996. Water Environment Federation, Alexandria, VA. Pp. 15-59 - 15-68. 1996.

Bondurant, J.A., C.E. Brockway, and M.J. Brown. "Some aspects of sedimentation pond design." *Proceedings National Symposium on Urban Hydrology and Sediment Control*, University of Kentucky, Lexington, 1975.

Booth, D.B., C.R. Jackson. "Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation." *Journal of the American Water Resources Association*. Vol. 33, no. 5, pp. 1077 – 1090. October 1997.

Brydges, T. and G. Robinson. "Two examples of urban stormwater impoundment for aesthetics and for protection of receiving waters." *Restoration of Lakes and Inland Waters: International Symposium on Inland Waters and Lake Restoration*. Portland, Maine, September 1980. Proceedings published by the U.S. Environmental Protection Agency, Washington, D.C. 1986.

Burton, G.A. and R. Pitt. *Manual for Evaluating Stormwater Runoff Effects, A Tool Box of Procedures and Methods to Assist Watershed Managers.* CRC/Lewis Publishers, New York. Expected publication in 2000.

Carr, D.J., A. Geinopolos, and A.E. Zanoni. *Characteristics and Treatability of Urban Runoff Residuals*. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, EPA-600/S2-82-094, Cincinnati, Ohio, January 1983.

Chambers, G.M. and C.H. Tottle. *Evaluation of Stormwater Impoundments in Winnipeg*, Report SCAT-1, Environment Canada, Ottawa, April 1980.

Cheng, S. "Detention storage optimization in least-cost sewer system design." *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

Dally, L.K., D.P. Lettenmaier, S.J. Burges, and M.M. Benjamin. *Operation of Facilities for Urban Stream Quality Enhancement*. University of Washington, Department of Civil Engineering, Water Resources Series Technical Report No. 79, Seattle, Washington, July 1983.

Dalrymde, R.J., S.L. Hood, and D.C. Morin. *Physical and Settling Characteristics of Particulates in Storm and Sanitary Wastewaters*. EPA-670/2-79-050f, U.S. Environmental Protection Agency, Cincinnati, 1979.

Davis, R., X. Zhang, and J. Agarwala. "Particle Classification for Dilute Suspensions Using an Inclined Settler." *Industrial and Engineering Chemistry Research*. Vol. 28, pp. 785-93. 1989.

Debo, D N. and H. Ruby. "Detention basins -- An urban experience." *Public Works*. Vol. 113, No. 1, pg. 42, January, 1982.

Debo, T.N. "Detention ordinances -- Solving or causing problems?" *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Delporte, C. "Treating rainfall - enhancing discharges from urban areas using lamellar decantation." Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Runoff*. Quebec City, Quebec. June 16 - 19, 1996. Water Environment Federation, Alexandria, VA. Pp. 15-1 - 15-9. 1996.

Dewberry and Davis, Inc. *Investigation of Potential Sediment Toxicity from BMP Ponds*. Prepared for the Northern Virginia Planning District Commission, the Occoquan Policy Board, and the Virginia State Water Control Board. May 1990.

Driscoll, E. D. "Detention and retention controls for urban stormwater." *Engineering Foundation Conference: Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Driscoll, E. D. "Long term performance of water quality ponds." Engineering Foundation Conference: *Design of Urban Runoff Quality Controls*. Potosi, Missouri. July 10 - 15, 1988. Edited by L. A. Roesner, B. Urbonas and M.B. Sommen. Published by the American Society of Civil Engineers, New York, June 1989.

Droste, R.L. and J.C. Johnston. "Urban snow dump quality and pollutant reduction in snowmelt by sedimentation." *Canadian Journal of Civil Engineering*. Vol. 20, pp. 9-21. February 1993.

Duru, J. O. "On-site detention: A stormwater management or mismanagement technique." *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

Ebbert, J. C., J. E. Poole, and K. L. Payne. *Data Collected by the U.S. Geological Survey During a Study of Urban Runoff in Bellevue, Washington, 1979-82*. Preliminary U.S. Geological Survey Open-File Report, Tacoma, Washington. 1983.

Eccher. C.J. "Thoughtful design is prime factor in water safety." *Lake Line*. pp. 4-8. May 1991.

Ellis, J.B. "Wetland BMP design for urban runoff pollution control in Europe and Australia." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 957 - 962. 1993.

Ellis, J.B., R. Hamilton, and A.H. Roberts. "Composition of Suspended Solids in Urban Stormwater." *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

Emmerling-DiNovo, C. "Stormwater detention basins and residential locational decisions." *Water Resources Bulletin*. Vol. 31, no. 3, pp. 515-521. June 1995.

EPA (USA Environmental Protection Agency). *Final Report for the Nationwide Urban Runoff Program*. Water Planning Division, PB 84-185552, Washington, D.C., December 1983.

EPA. *Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality*. Water Planning Division, EPA 440/5-87-001, Washington, D.C., September 1986.

Fair, G.M. and J.C. Geyer. *Water Supply and Waste Water Disposal*. John Wiley and Sons. New York. 1954.

Ferarra, R. A. "Stormwater detention and nonpoint source pollution control." *1982 International Symposium on Urban Hydrology, Hydraulics and Sediment Control*, University of Kentucky, Lexington, Kentucky, July 1982.

Fuhr, M. "Will your pond hold water?" *Land and Water*, Vol. 40, no. 6, pg. 38. Nov./Dec. 1996.

Gietz, R. J. *Stormwater Runoff Treatment by Impoundment: Barrhaven Pilot Study*. Report SCAT-8, Environment Canada, Ottawa, 1981.

Gietz, R. J. *Urban Runoff Treatment in the Kennedy-Burnett Settling Pond*. For the Rideau River Stormwater Management Study, Pollution Control Division, Works Department, Regional Municipality of Ottawa-Carleton, Ottawa, Ontario, March 1983.

Grizzard, T. J., C. W. Randall, B. L. Weand, and K. L. Ellis. "Effectiveness of extended detention ponds." *Engineering Foundation Conference: Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Hall, M.J. "The design of flood storage ponds: catering for both quality and quantity of runoff." *Developments in Storm Drainage - A Symposium on Infiltration and Storage of Stormwater in New Developments*. Sheffield City. Jan. 1990. Pp. 21 - 33. 1990.

Harper, H.H. and J.L. Herr. "Alum treatment of stormwater - The first ten years: What have we learned and where do we go from here?" North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Harrington, B. W. *Feasibility and Design of Wet Ponds to Achieve Water Quality Control*. Sediment and Stormwater Division, Maryland Water Resources Administration, July 1986.

Hawley, M. E., T. R. Bondelid, and R. H. McCuen. "A planning method for evaluating downstream effects of detention basins." *Water Resources Bulletin*, Vol. 17. No. 5, pg. 806, October 1981.

Heimbuch, R.J. "Rock filled detention reservoirs." *1981 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, July 1981.

Herr, J.L. and H.H. Harper. "The evaluation and design of an alum stormwater treatment system to improve water quality in Lake Maggiore, St. Petersburg, Florida" North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Hey, D.L. and G.C. Schaefer. *An Evaluation of the Water Quality Effects of Detention Storage and Source Control*. U.S. Environmental Protection Agency and the Northeastern Illinois Planning Commission, Chicago, August 1983.

Hittman Assoc. *Methods to Control Fine-Grained Sediments Resulting from Construction Activity*. U.S. Environmental Protection Agency, Pb-279 092, Washington, D.C., December 1976.

House, L.B., R.J. Waschbusch, and P.E. Hughes. *Water Quality of an Urban Wet Detention Pond in Madison, Wisconsin, 1987-1988*. U. S. Geological Survey, in cooperation with the Wisconsin Department of Natural Resources. USGS Open File Report 93-172, 1993.

Hvitved-Jacobsen, T., K. Keiding, and Y.A. Yousef. "Urban runoff pollution removal in wet detention ponds." Proceedings of the 4th *International Conference on Urban Storm Drainage*. Lausanne, Switzerland. August 1987. Water Resources Publications. pp. 137 - 142. 1987.

Hvitved-Jacobsen, T., N.B. Johansen, and Y.A. Yousef. "Treatment systems for urban and highway runoff in Denmark." *The Science of the Total Environment*. No. 146/147, pp. 499-506. 1994.

James, W. and Robinson, M. A. (1982). "Continuous models essential for detention design." *Proceedings of the Conference on Stormwater Detention Facilities*, American Society of Civil Engineers, 163-175.

Jones, J. "Beware the sediment scare." *Civil Engineering*. pp. 56-57. July 1995.

Jones, J. E. and D. E. Jones, "Interfacing considerations in urban detention ponding." *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Jones, J., S. Anderson, J. Fognani. F.R. McGregor, and T. Axley. "Stormwater best management practices: When is sediment considered hazardous?" *Water Environment & Technology*. Vol. 8, no. 10, pp. 51-57. October 1996.

Kamedulski, G. E. and R. H. McCuen. "The effect of maintenance on storm water detention basin efficiency." *Water Resources Bulletin*, Vol. 15, No. 4, pg. 1146, August 1979.

Karouna, N. 1989, Cost Analysis of Urban Retrofits. Unpublished Report. Metropolitan Washington Council of Governments. Washington, DC.

Land and Water "Storm pond turned into selling feature" Vol. 40, no. 6, pg. 35. Nov./Dec. 1996.

Linsley, R. K., and J. B. Franzini. *Water Resources Engineering*. McGraw-Hill, New York, 1964.

Luzkow, S. M., D. A. Scherger, and J. A. Davis. "Effectiveness of two in-line urban storm water best management practices (BMP'S)." *1981 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, Kentucky, July 1981.

MacRae, C.R. "Experience from morphological research on Canadian streams: Is control fo the two-year frequency runoff event the best basis for stream channel protection?" Presented at the *Effects of Watershed Developments and Management on Aquatic Ecosystems* conference. Snowbird, UT, August 4 – 9, 1996. Edited by L.A. Roesner. ASCE, New York, 1997.

Marcy, S. J. and J. E. Flack. “Safety considerations in urban storm drainage design.” *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

Marsalek, J., D. Weatherbe, and G. Zukovs. “Institutional aspects of stormwater detention.” *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Martin, E. and R.A. Miller. “Efficiency of an urban stormwater detention system.” Proceedings of the 4th *International Conference on Urban Storm Drainage*. Lausanne, Switzerland. August 1987. Water Resources Publications. pp. 143 - 148. 1987.

Martin, E.H. “Mixing and residence times of stormwater runoff in a detention system.” Engineering Foundation Conference: *Design of Urban Runoff Quality Controls*. Potosi, Missouri. July 10 - 15, 1988. Edited by L. A. Roesner, B. Urbonas and M.B. Sommen. pp. 164 - 179. Published by the American Society of Civil Engineers, New York, June 1989.

Mason, J.M.,Jr. “Multistaged outlet control for small on-site detention.” *1981 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, July 1981.

Mason, J.M.,Jr. “On-site stormwater detention: An overview.” *Public Works*, February 1982.

Maxted, J. and E. Shaver. “The use of retention basins to mitigate stormwater impacts on aquatic life.” Engineering Foundation Conference: *Effects of Watershed Development & Management on Aquatic Ecosystems*. Snowbird, Utah. August 4-9, 1996. Engineering Foundation, New York, 1997.

Mayer, T., J. Marsalek, and E. Delos Reyes. “Nutrients and metal contaminants status of urban stormwater ponds.” *Journal of Lake and Reservoir Management*. Vol. 12, no. 3, pp. 348-363. 1996.

McComas, S. R. and D. F. Sefton. “Comparison of stormwater runoff impacts on sedimentation and sediment trace metals for two urban impoundments.” In: *Lake and Reservoir Management: Practical Applications*, proceedings of the Fourth Annual Conference and International Symposium, October, 1984, North American Lake Management Society, McAfee, New Jersey, 1985.

McCuen, R.H. “Water quality trap efficiency of storm water management basins.” *Water Resources Bulletin*, 16(1):15-21, February 1980.

McCuen, R.H., S.G. Walesh, and W.J. Rawis. *Control of Urban Stormwater Runoff by Detention and Retention*, Misc. Public. No. 1428, U.S. Dept. of Agric., 1984(?).

Metropolitan Washington Council of Governments. *Analysis of Urban BMP Performance and Longevity*. Prince George's County, Department of Environmental Resources. 1992.

Niemczynowicz, J. “Swedish stormwater detention practices.” Proceedings of the 5th *International Conference on Urban Storm Drainage*. Osaka, Japan. July 1990. pp. 197 - 202. 1990.

Nix, S.J. and S.R. Durrans. “Off-line stormwater detention systems.” *Water Resources Bulletin*. Vol. 32, no. 6, pp. 1329 - 1340. December 1996.

Novotny, V., and Olem, H. *Water Quality: Prevention, Identification , and Management of Diffuse Pollution*. Van Nostrand Reinhold, New York, 1994.

Oberts, G. “Design considerations for management of urban runoff in wintry conditions.” Proceedings: *International Conference on Urban Hydrology under Wintry Conditions*. March 19 - 21, 1990. Narvik, Norway. 1990.

Oberts, G. Performance of stormwater ponds and wetlands in winter.” Technical note 16. *Watershed Protection Techniques*. Vol. 1, no. 2, pp. 64-68. Summer 1994.

Oliver, L.J. and S.G. Grigoropoulis. “Control of storm-generated pollution using a small urban lake.” *Journal Water Pollution Control Federation*, Vol 53, No. 5, May 1981.

Ontario Ministry of the Environment. *Province of Ontario Urban Drainage Design Guidelines* (Draft). Urban Drainage Policy Implementation Committee, Ontario Ministry of the Environment, Toronto, Ontario, March 1984.

Oscanyan, P. C. “Design of sediment basins for construction sites.” *National Symposium on Urban Hydrology and Sediment Control*, University of Kentucky, Lexington, Kentucky, 1975.

Pedersen, E. R. *The Use of Benthic Invertebrate Data for Evaluating Impacts of Urban Stormwater Runoff*, Masters thesis submitted to the College of Engineering, University of Washington, Seattle. 1981.

Perkins, M. A. “Managing aquatic plants with fiberglas screens.” In: *Restoration of Lakes and Inland Waters, proceedings of the International Symposium on Inland Waters and Lake Restoration*, Portland, Maine, September 1980, published by the U.S. Environmental Protection Agency, Washington. D.C., December 1980.

Perkins, M. A. *An Evaluation of Instream Ecological Effects Associated with Urban Runoff to a Lowland Stream in Western Washington*. U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory, Corvallis, Oregon, July, 1982.
Pisano, W.C. and H. Brombach. “Solids settling curves: Wastewater solids data can aid design of urban runoff controls.” *Water Environment & Technology*. Vol. 8, no. 4, pp. 27-33. April 1996.
Pitt, R. and M. Bozeman. *Lake Merritt Management Plan*. City of Oakland Department of Public Works, Oakland, California, May 1979.
Pitt, R. and P. Bissonnette. *Bellevue Urban Runoff Program Summary Report*, U.S. Environmental Protection Agency, Water Planning Division. PB84 237213. Washington, D.C. 173 pgs. 1984.
Pitt, R., and J. McLean. *Toronto Area Watershed Management Strategy Study: Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Ontario, 1986.
Pitt, R. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges*. Ph.D. dissertation. Dept. of Civil and Environmental Engineering, the University of Wisconsin, Madison, Wisconsin. Listed in Dissertation Abstracts International, University Microfilms International, Vol. 49, No. 1, 1988. November 1987.
Pitt, R. “Detention pond design for water quality improvement.” *National ASCE Hydraulic Conference*. San Francisco, California. July 1993a.
Pitt, R. “The stormwater quality detention pond model (DETPOND).” *26th Annual Water Resources Conference*. University of Minnesota. October 1993b.
Pitt, R., S. Clark, K. Parmer, and R. Field. *Groundwater Contamination from Stormwater.* ISBN 1-57504-015-8. Ann Arbor Press, Inc. Chelsea, Michigan. 219 pages. 1996.
Pitt, R. “Unique Features of the Source Loading and Management Model (SLAMM).” In: *Advances in Modeling the Management of Stormwater Impacts, Volume 6*. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. pp. 13 – 37. 1997.
Poertner, H.G. *Practices in Detention of Urban Stormwater Runoff.* American Public Works Association, OWRR Contract No. 14-31-0001-3722, Chicago, 1974.
Prych, E. A. and J. C. Ebbert. *Quantity and Quality of Storm Runoff from Three Urban Catchments in Bellevue, Washington*, Preliminary U.S. Geological Survey Water Resources Investigations Report, Tacoma, Washington. Undated.
Randall, C. W. “Stormwater detention ponds for water quality control.” *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.
Randall, C. W., K. Ellis, T. J. Grizzard, and W. R. Knocke. “Urban runoff pollutant removal by sedimentation.” *Urban Runoff Pollutant Removal by Sedimentation", Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance,* Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.
Richey, J. S. *Effects of Urbanization on a Lowland Stream in Western Washington*, Doctor of Philosophy dissertation, University of Washington, Seattle. 1982.
Richey, J. S., M. A. Perkins, and K. W. Malueg. “The effects of urbanization and stormwater runoff on the food quality in two salmonid streams,” *Verh. Internat. Werein. Limnol.*, 21, 812-818, Stuttgart. 1981.
Rosmiller, R. *Detention Pond Workshop Notes*, University of Wisconsin-Madison, Wright Water Engineering, Denver, Colorado, 1987?.
Rospond, F. J. “Roof detention of rainfall to limit urban runoff.” *National Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, Kentucky, July, 1976.
Rutherford, J. B. “On-site multi-functional stormwater detention facilities; A case study.” *International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, Kentucky, July, 1977.
Schimmenti, F.G. “Stormwater detention basins must control more than runoff.” *American City and County*, December 1980.
Schueler, T. R. *New Guidebook Review Paper No. 2, Wet Pond BMP Design*. Metropolitan Washington Council of Governments, Washington, D.C., 1986.
Schueler. T. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices*. Metropolitan Washington Council of Governments. 280 pgs. 1987.
Schueler, T.R. and J. Galli. “The environmental impact of stormwater ponds.” Engineering Foundation Conference: *Urban Runoff and Receiving Systems: An Interdisciplinary Analysis of Impact, Monitoring, and Management*. Mt.

Crested Butte, Colorado. August 4-9, 1991. Published by the American Society of Civil Engineers, New York, June 1992.

Scott, J.B., C.R. Steward, and Q.J. Stober. *Impacts of Urban Runoff on Fish Populations in Kelsey Creek, Washington*. Contract No. R806387020, U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory, Corvallis, Oregon, May 1982.

SCS (now NRCS) (U.S. Soil Conservation Service). *Computer Program for Project Formulation, Hydrology*. Technical Release Number 20 (TR-20). U.S. Dept. of Agriculture, 1982a.

SCS (now NRCS) (U.S. Soil Conservation Service). *Ponds - Planning, Design, Construction*. Agriculture Handbook Number 590, U.S. Dept. of Agriculture, 1982b.

SCS (now NRCS) (U.S. Soil Conservation Service). *Urban Hydrology for Small Watersheds*. Tech. Release No. 55, U.S. Dept. of Agriculture, June 1986.

SEMCOG (Southeast Michigan Council of Governments). *Detention Basin Maintenance, Program Needs and Financing Options*. Technical Bulletin No. 3, Detroit, Michigan, May 1981.

Smith, W. G. "Water quality enhancement through stormwater detention." *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Snodgrass, W.J., B.W. Kilgour, L. Leon, N. Eyles, J. Parish, and D.R. Barton. "Applying ecological criteria for stream biota and an impact flow model for evaluation sustainable urban water resources in southern Ontario." In: *Sustaining Urban Water Resources in the 21st Century*. Proceedings of an Engineering Foundation Conference. Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. Malmo, Sweden. Sept. 7 – 12, 1997. To be published by ACSE, New York. 1998.

Stahre, P. "Assessment of BMP's being used in Scandinavia." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 939 - 944. 1993.

Stahre, P. and B. Urbonas. *Stormwater Detention for Drainage, Water Quality and CSO Management*. Prenticd Hall. Englewood Cliffs. 340 pgs. 1990.

Stanley, D.W. "Pollutant removal by a stormwater dry detention pond." *Water Environment Research*. Vol. 68, no. 6, pp. 1076 - 1083. Sept./Oct. 1996.

Stephenson, D. "Evaluation of effects of urbanization on storm runoff." *7th International Conference on Urban Storm Drainage*. Hannover, Germany. Sept. 9-13, 1996. Edited by F. Sieker and H-R. Verworn. IAHR/IAWQ. SuG-Verlagsgesellschaft. Hannover, Germany. pp. 31-36. 1996.

Striegl, R. G. *Effects of Stormwater Runoff on an Urban Lake, Lake Ellyn at Glen Ellyn, Illinois*, USGS Open File Report 84-603, U.S. Geological Survey, Lakewood, Colorado. 1985.

Terstriep, M.L., G.M. Bender, D.C. Noel. *Nationwide Urban Runoff Project, Champaign, Illinois: Evaluation of the Effectiveness of Municipal Street Sweeping in the Control of Urban Storm Runoff Pollution*. Contract No. 1-5-39600, U.S. Environmental Protection Agency, Illinois Environmental Protection Agency, and the State Water Survey Division, University of Illinois, December 1982.

Van Buren, M.A., W.E. Watt, and J. Marsalek. "Enhancing the removal of pollutants by an on-stream pond." *Water Science and Technology*. Vol. 33, no. 4 - 5, pp. 325-332. 1996.

Vignoles M., and L. Herremans. "Metal pollution of sediments contained in runoff water in the Toulouse city." (in French). *NOVATECH 95, 2nd International Conference on Innovative Technologies in Urban Storm Drainage*. May 30 - June 1, 1995. Lyon, France. pp. 611-614. Organized by Eurydice 92 and Graie. 1995.

Whipple, W. and J. V. Hunter. "Settleability of urban runoff pollution." *Journal WPCF*, Vol. 53, No. 12, pg. 1726, 1981.

Wiegand, C., T. Schueler, W. Chittenden, and D. Jellick. "Comparative costs and cost effectiveness of urban best management practices." Engineering Foundation Conference: *Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Wigington, P. J., C. W. Randall, and T. J. Grizzard. "Accumulation of selected trace metals in soils of urban runoff detention basins." *Water Resources Bulletin*, Vol. 19, No. 5, pg. 709, October 1983.

Williams, L. H. "Effectiveness of stormwater detention." *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

WWC (Woodward-Clyde Consultants). *Evaluation of Existing Stormwater Pump Stations in Santa Clara County for Pollution Control Potential*. Prepared for Santa Clara Valley Water District. July 1990.

Woodward-Clyde Consultants. *Sunnyvale Detention Basin Demonstration Project*. Prepared for Santa Clara Valley Nonpoint Source Pollution Control Program. November 1994.

Yousef, Y. A., M. P. Wanielista, and H. H. Harper. “Design and effectiveness of urban retention basins.” *Engineering Foundation Conference: Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Yousef, Y.A. and L.Y. Lin. “Toxicity of bottom sediments in detention ponds.” *Environmental Engineering: Proceedings of the 1990 Specialty Conference*. pp. 809 - 816. American Society of Civil Engineering, New York. 1990.

Zukovs, G. *Development of a Probabilistic Runoff Storage/Treatment Model*. Master of Engineering Thesis, University of Toronto, 1983.

Appendix A: User Guide for DETPOND

The following example shows the initial steps in designing a wet detention pond and the development of a DETPOND file for that pond in order to enable water quality evaluations. The pond sizing criteria can be examined in relation to site constraints and the pond design modified, if needed, based on these evaluations.

Example Design Calculations and Evaluation Using DETPOND

The following discussion presents a calculation example using the design criteria presented earlier:

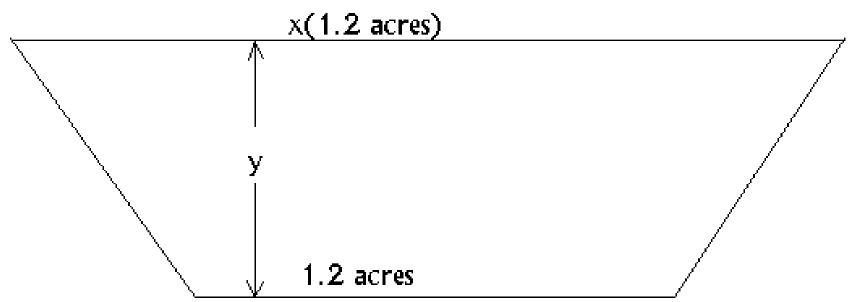
- Assume a medium density residential area of 150 acres with a goal of approximately 90% suspended solids control (corresponding to 5µm critical particle size).

- The wet pond surface would therefore be: 0.008(150 acres) = 1.2 acres

- The runoff volume for 1.25" rain => 0.5" runoff (based on typical development conditions and small storm hydrology; CN= 90 and Rv= 0.4).

- Therefore, wet storage volume: 0.5"(150 acres) => 6.3 acre-feet

- The depth associated with the wet storage volume can be estimated assuming a prismatic cross-section (simplified, compared to a conical section):



Approximately: [1.2 + x(1.2)]y/2 = 6.3 acre-ft.

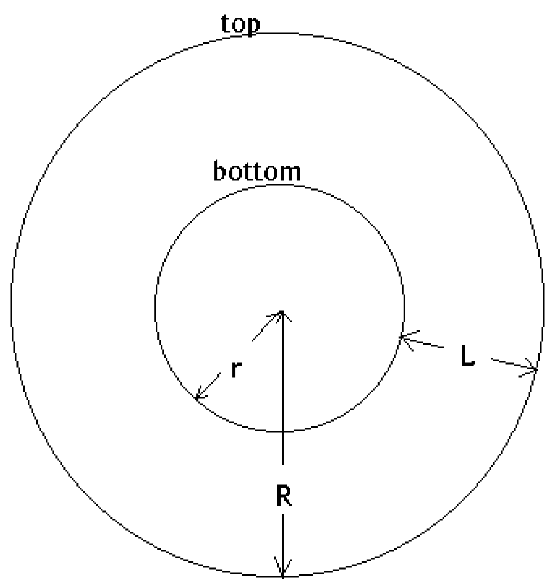
re-arranging gives: x =[(10.5)/y] - 1

The following table can be used to give simultaneous depths for different x multipliers and top of pond areas for the "live-storage" area of the pond (the section affected by the primary water quality outlet device and located on top of the permanent pool depth, and below the invert of the emergency spillway and additional storage needed for flood control):

y (depth, ft)	x (multiplier)	top area
2	4.3	4.3 (1.2 acres) = 5.2 acres
3	2.5	3.0 acres
4	1.6	1.9 acres
5	1.1	1.3 acres

Depths less than 2 feet are too shallow and could require very large pond top surface areas for this example. “Live depths” greater than 5 feet may be too deep for most locations and obviously result in very steep side slopes for this example.

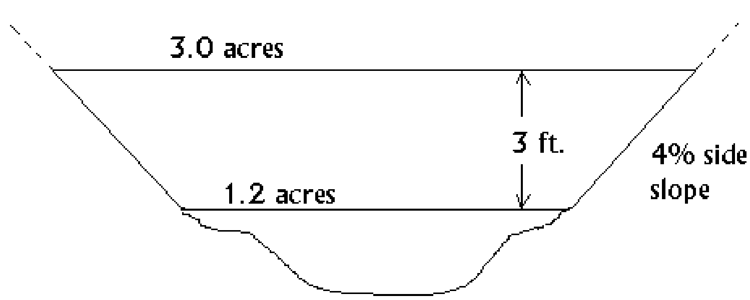
The following table summarizes the calculations for the side slopes of the pond (assuming a simple circular shaped pond, as shown below):



$r = (A/\pi)^{1/2} = [1.2\text{acres}(43{,}560\ \text{ft}^2 \text{ per acre})/\pi)]^{1/2} = 130$ ft

Depth (ft)	Top Area (acres)	Top Radius (ft)	Slope Length (ft)	Side Slope
2	5.2	270	270 - 130 = 140	2/140 = 1.4%
3	3.0	200	200 - 130 = 70	3/70 = 4.3%
4	1.9	160	160 - 130 = 30	4/30 = 13%
5	1.3	135	135 - 130 = 5	5/5 = 100%

• The preliminary pond cross-section is therefore:



• The outfall device is selected by comparing the maximum allowable discharge rate for the surface area of the pond at several pond depth increments. These maximum allowable discharges are compared with weir ratings (as tabulated in the text, for example) to select the permissible weirs that can be used:

$Q_{out} = vA$

$v = 1.3 \times 10^{-4}$ ft/sec for 5 µm particle

Stage (above normal water surface, ft)	Pond Area (acres)	Maximum Allowable Discharge (cfs)
0	1.2	6.8
0.5	1.5	8.5
1	1.8	10
1.5	2.1	12
2	2.4	14
3	3.0	17 (usually most critical)

Therefore, use a single 45^{o} V-notch weir, or two 22-1/2^{o} V-notch weirs.

• Select emergency spillway (mandatory) and additional flood control storage volume (if necessary) using NRCS TR-55 (SCS 1986) procedures.

• Figure A-1 is an example program check sheet for a DETPOND model evaluation, while the next section shows how this information is entered into a data file for analysis.

Figure A-1a. DETPOND model check sheet for example calculation.

150 acre MDR "90%" control

n=5 directly connected impervious 45 acres (30%)

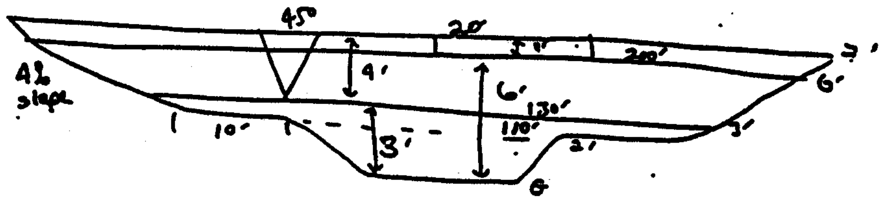
medium cpz pervious 75 acres (50%)

Brown 76 + Brown Fld impervious areas draining to pervious 30 acres (20%)

150 acres

Wet Detention Ponds W

Diagram Outlet Structures in space below



1. Initial stage elevation (ft) above datum: 3
2. Number of stage elevation increments required: (constant 0→7' by ½')
3. Total number of outlets (10 max): 2
4. Stage, pond area, seepage, and other outlet information:

Entry Number	Stage (ft)	Pond Area (Acres)	Natural Seepage (cfs)	Other Outflow (cfs)
0	0	* 0		
1	0.5	0.1		
2	1	0.13		
3	1.5	0.17		
4	2	0.2		
5	2.5	0.9		
6	3	1.2		
7	3.5	1.5		
8	4	1.8		
9	4.5	2.1		
10	5	2.4		
11	5.5	2.7		
12	6	3.0		
13	6.5	3.3		
14	7	3.6		
15				
16				
17				
18				
19				
20				
21				
22				

Figure A-1b. DETPOND model check sheet for example calculation.

Wet Detention Ponds (continued)

5. Other outlet characteristics
   1. Rectangular Weir
      1. Weir length (ft): 20'
      2. Height from bottom of weir opening (invert) to top of weir: 1'
      3. Height from datum to bottom of weir opening (invert) (ft): 6'
   2. V-Notch Weir Characteristics:
      A) Weir angle:
         1. 22.5 degrees
         2. 30 degrees
         3. 45 degrees
         4. 60 degrees
         5. 90 degrees
         6. 120 degrees

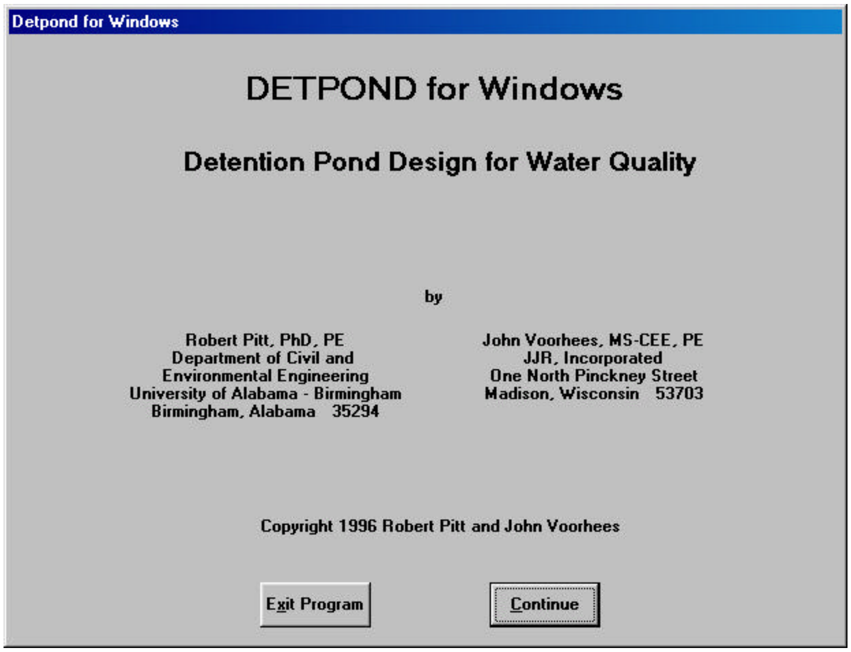
      B) Height from bottom of weir opening (invert) to top of weir: 4'

      C) Height from datum to bottom of weir opening (invert) (ft): 3'
   3. Orifice characteristics:
      1. Orifice diameter (ft): ______
      2. Invert elevation above datum (ft): ______
   4. Seepage Basin characteristics:
      1. Infiltration rate (inches/hr): ______
      2. Width of device (ft): ______
      3. Length of device (ft): ______
      4. Invert elevation of seepage basin inlet above datum (ft): ______
   5. Monthly Evaporation Rate

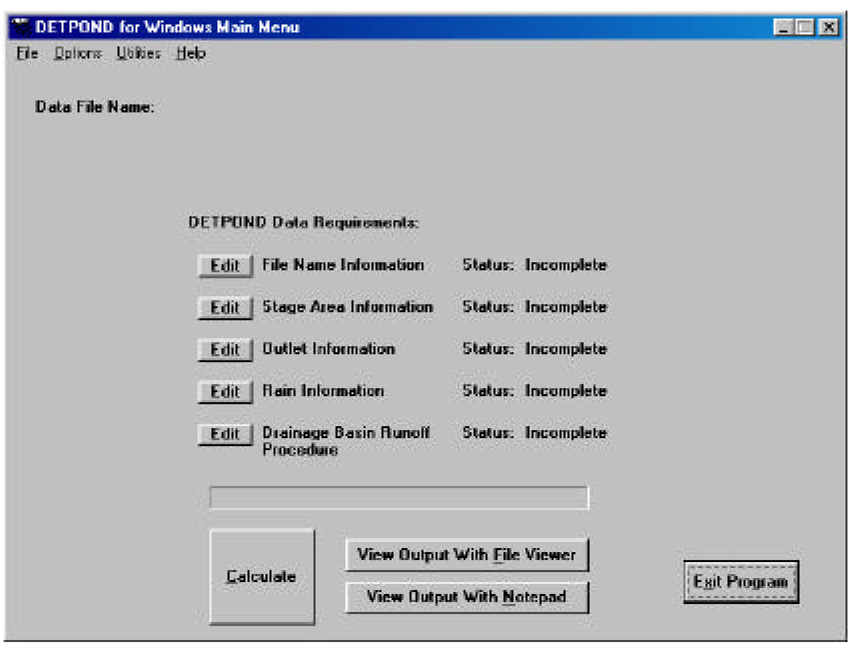
Month Number	Month	Evaporation (in/day)
1	January	
2	February	
3	March	
4	April	
5	May	
6	June	
7	July	
8	August	
9	September	
10	October	
11	November	
12	December	

Steps in Entering Data for Evaluation in DETPOND

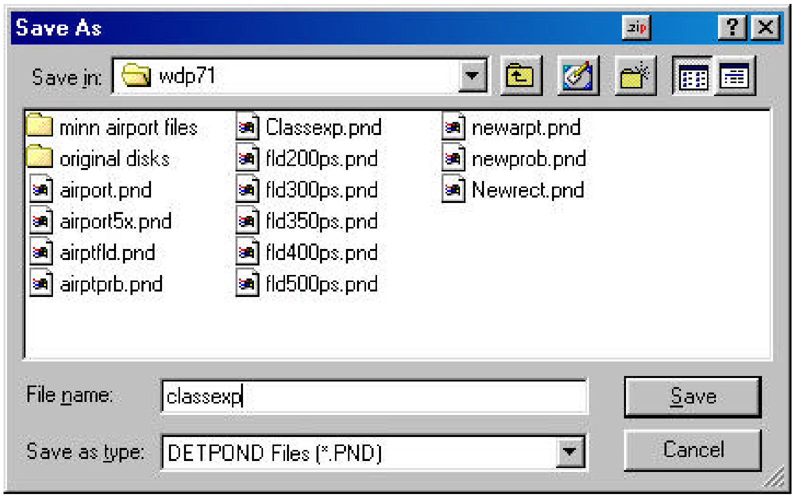
Enter the main DETPOND program by double-clicking on the WinDetpond.exe file located in the directory where the program was installed, or select the file from the "start, programs, WinDetpond" list. The following window will open:



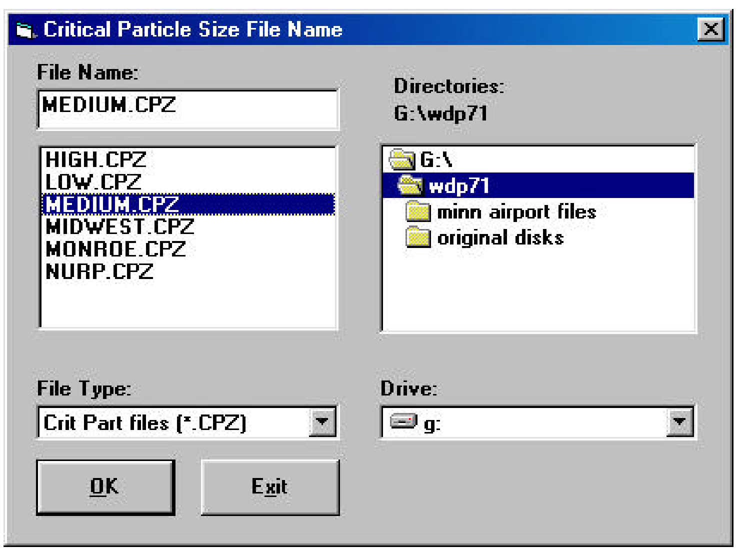
Select the "continue" button to open the following window:



Notice that the status for each of the four main categories are listed as "incomplete." The next steps in creating the file include entering this data. The first step for this window is to select the file name "edit" box and entering a file name, as shown below:

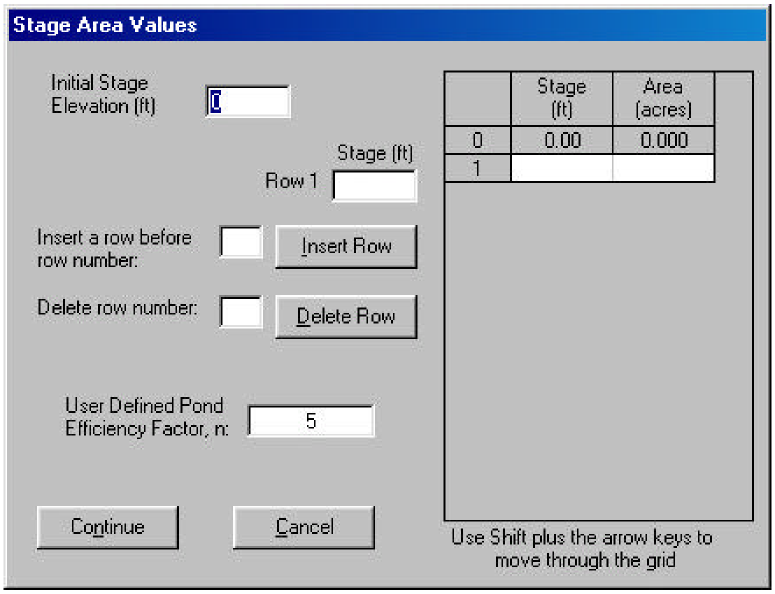


After the file name is typed in, click on the save button, after ensuring that the correct directory is listed. The next step under "file name information" is to enter a site description. Any short statement can be entered that will enable tracking the files or the site test conditions. The last part of this element is selecting the particle size file, as shown below:

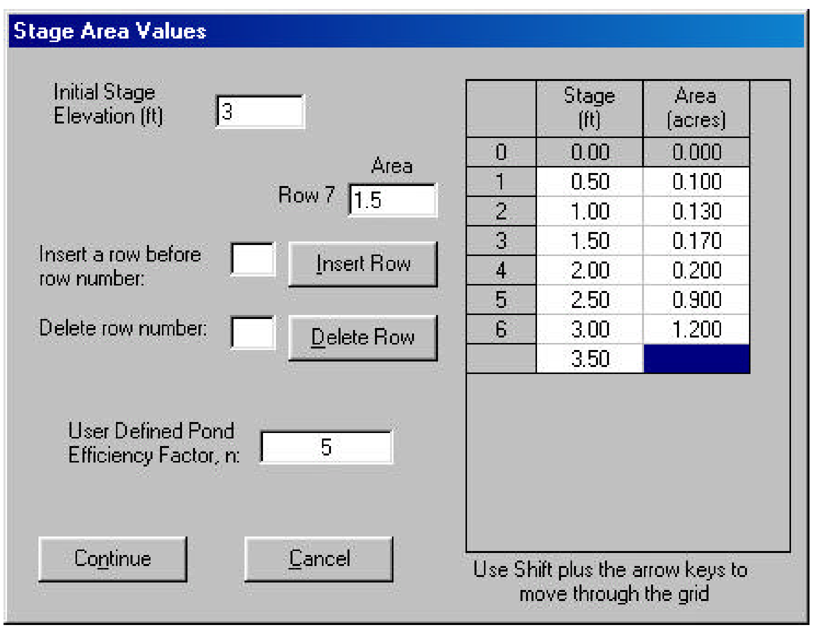


All available particle size files are listed. If the desired file is not listed, check the directory to ensure that the correct directory is shown. When the desired file is selected, click "OK."

The next major category of information is the stage-area values. When that "edit" box is selected, the following window is displayed:

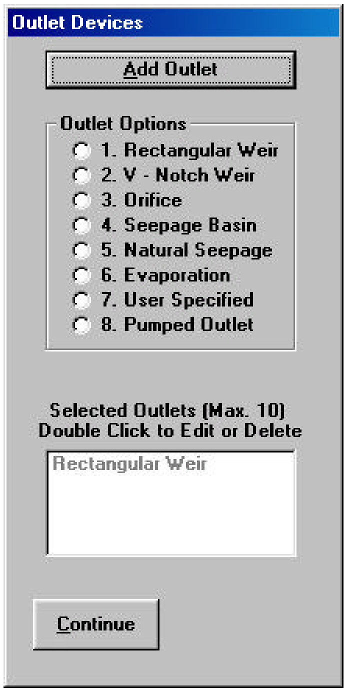


The first information to be entered is the initial stage elevation. This is the water depth in the pond at the beginning of the study period. It is generally the normal water elevation (above the pond bottom datum). However, it can be different reflecting actual conditions (such as being lower than the lowest invert because of evaporation that may have occurred during an extended dry period, or higher because the pond has not completely drained since the preceding rain). When that number is entered, the program automatically starts requesting stage and surface area data. The bottom-most stage (at depth zero) is already entered (required to have a surface area of zero acres). When all of the stage-area data is entered, select continue, or change the user defined pond efficiency factor first. The sequence is displayed in the following window:

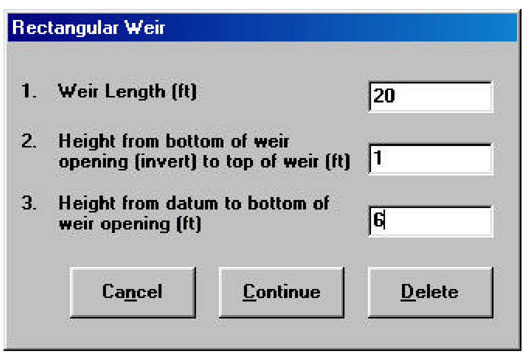


The "User Defined Pond Efficiency Factor, n" is given as 5, but can be changed by over-typing. This is the n factor used in the Hazen equation and is equivalent to the number of pond cells. Large numbers imply very little short-circuiting, while small numbers imply that substantial numbers of large particles may be leaving the pond.

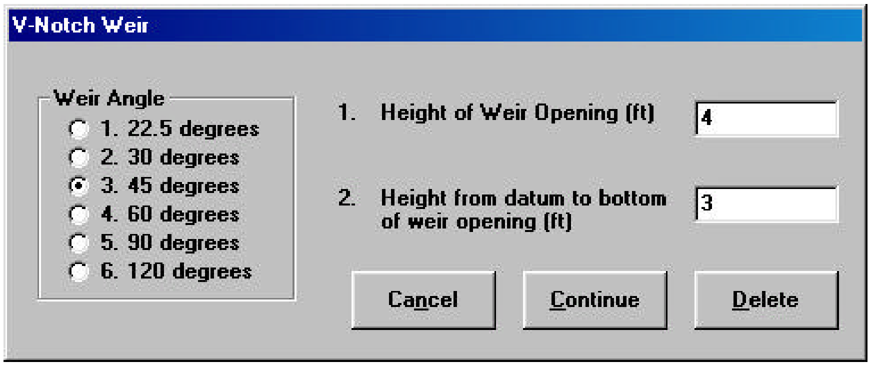
The next major data requirement group is the outlet information. Select "edit" to bring up the following window (this one has the rectangular weir already listed, normally, this would be empty and the user would select the desired outlet):



When the rectangular weir is selected, the following window is brought up to enable the user to describe the weir dimensions and location:

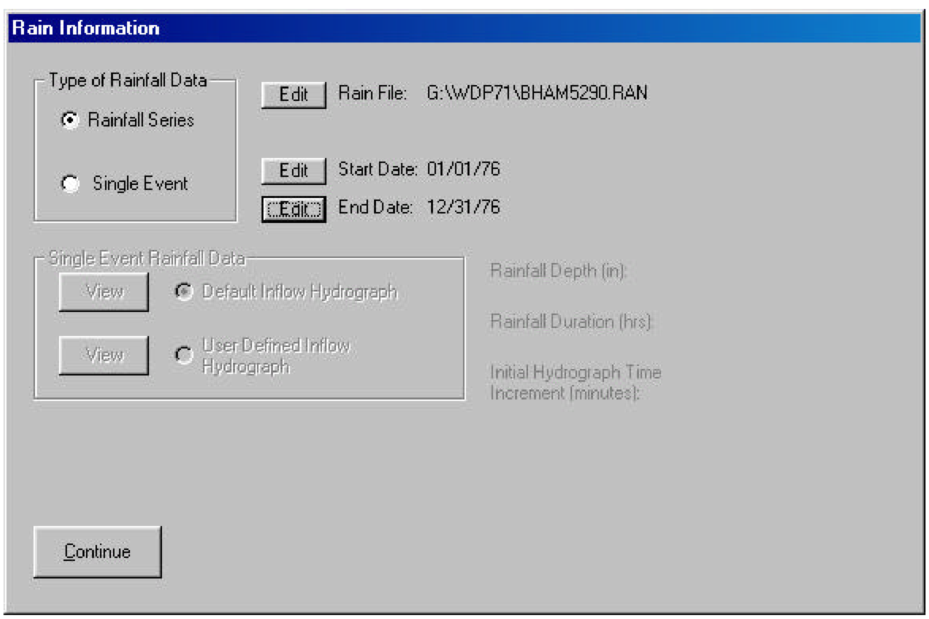


The user needs to refer to the diagram (on Figure A-1) to ensure that the weir heights are correct. The program also checks to make sure that the sum of the "height of bottom of weir opening to top of weir" plus the "height from datum to bottom of weir opening" adds up to equal the total depth of the pond entered previously. After entering the data and clicking on "continue", the user selects the V-notch weir for this example, bringing up the following window:



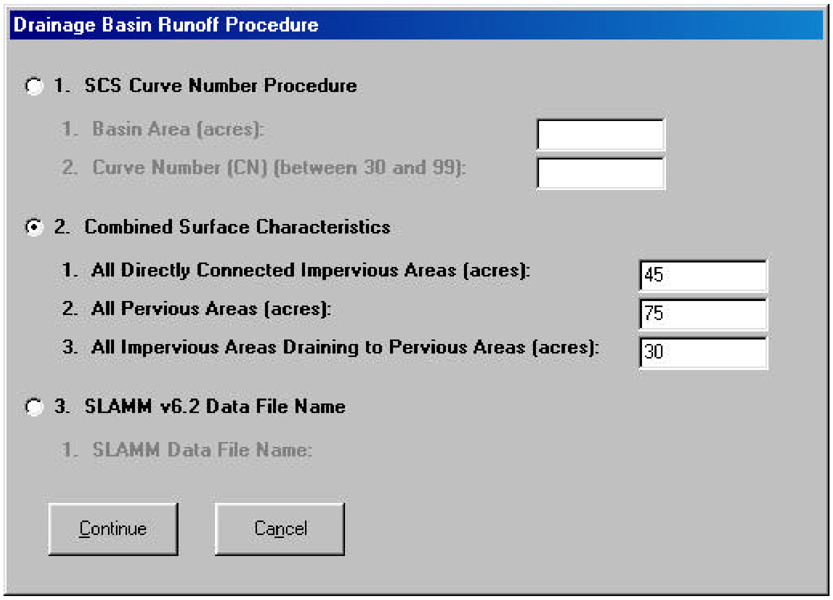
The user selects the v-notch weir angle and the height data, and then clicks “continue.”

The next data requirement set relates to the rain file. A rainfall series is selected from the available list, and the starting and ending dates contained in the file are automatically listed. If these dates are not correct, they can be edited by selecting the “edit” button near each date, as shown in the following window, and typing in the desired dates:

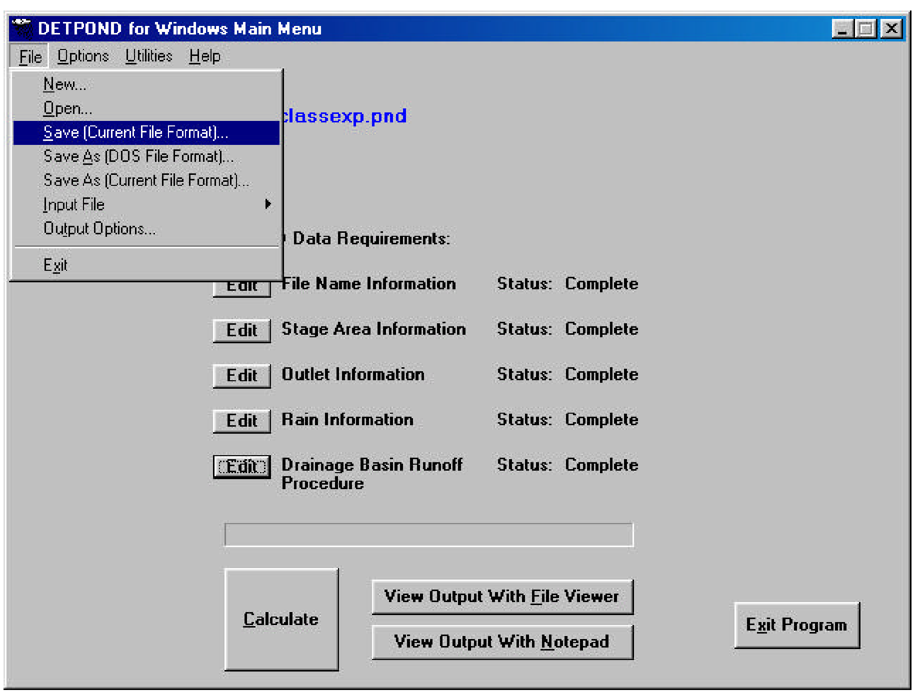


If a user-defined hydrograph is to be evaluated (such as for entering a single design storm calculated using TR-55, for example, or to enter actual observed inflow rates), then the “single event” type of rainfall data is selected and the program prompts for that information.

The last series of data requirements is the drainage basin information, as shown in the following window:

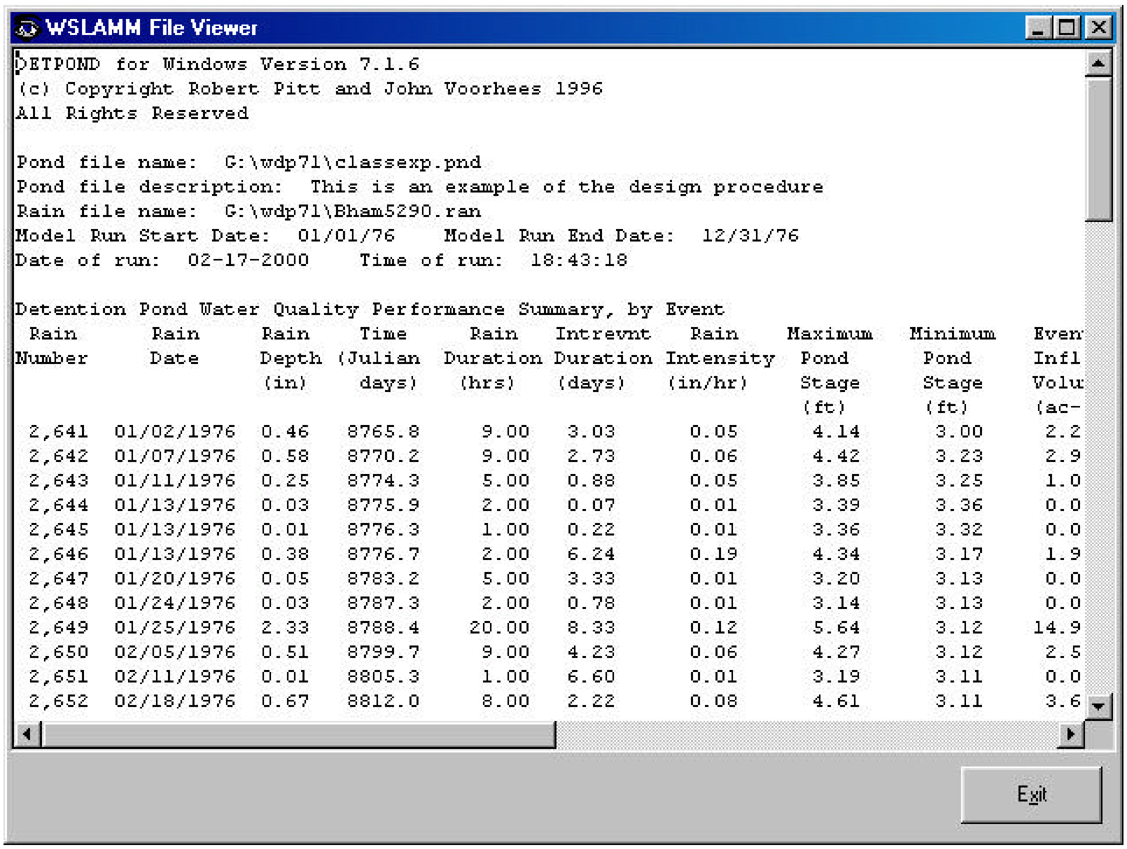


In our example, the "combined surface characteristics" is selected, which uses the correct runoff characteristics associated with small and intermediate-sized events. The area associated with each surface category is entered, and then the "continue" button is clicked. The "SCS Curve Number Procedure" simply uses a constant curve number for each event, but still uses the basic triangular hydrograph (and not the TR-55 tabular hydrograph, which is not accurate for these smaller rains). The SLAMM data file option allows more resolution in describing the surface areas, and is especially helpful if the same file is being used for a SLAMM analysis, but the greater detail in DETPOND is desired for an outfall wet detention pond. When these data are entered, the main screen shows that the status of each data requirement category is "complete." The file needs to be saved again, as shown in the following window:



The file name is verified by clicking on “OK” in the following dialog box:

Finally, the large “calculate” button is clicked and after a few seconds, the program is completed. The file viewer is then clicked and the output file is selected. The following window then appears:



DETPOND for Windows Version 7.1.6
(c) Copyright Robert Pitt and John Voorhees 1996
All Rights Reserved

Pond file name: G:\wdp71\classexp.pnd
Pond file description: This is an example of the design procedure
Rain file name: G:\wdp71\Bham5290.ran
Model Run Start Date: 01/01/76 Model Run End Date: 12/31/76
Date of run: 02-17-2000 Time of run: 18:43:18

Detention Pond Water Quality Performance Summary, by Event

Rain Number	Rain Date	Rain Depth (in)	Time (Julian days)	Rain Duration (hrs)	Intrevnt Duration (days)	Rain Intensity (in/hr)	Maximum Pond Stage (ft)	Minimum Pond Stage (ft)	Even Infl Volu (ac-
2,641	01/02/1976	0.46	8765.8	9.00	3.03	0.05	4.14	3.00	2.2
2,642	01/07/1976	0.58	8770.2	9.00	2.73	0.06	4.42	3.23	2.9
2,643	01/11/1976	0.25	8774.3	5.00	0.88	0.05	3.85	3.25	1.0
2,644	01/13/1976	0.03	8775.9	2.00	0.07	0.01	3.39	3.36	0.0
2,645	01/13/1976	0.01	8776.3	1.00	0.22	0.01	3.36	3.32	0.0
2,646	01/13/1976	0.38	8776.7	2.00	6.24	0.19	4.34	3.17	1.9
2,647	01/20/1976	0.05	8783.2	5.00	3.33	0.01	3.20	3.13	0.0
2,648	01/24/1976	0.03	8787.3	2.00	0.78	0.01	3.14	3.13	0.0
2,649	01/25/1976	2.33	8788.4	20.00	8.33	0.12	5.64	3.12	14.9
2,650	02/05/1976	0.51	8799.7	9.00	4.23	0.06	4.27	3.12	2.5
2,651	02/11/1976	0.01	8805.3	1.00	6.60	0.01	3.19	3.11	0.0
2,652	02/18/1976	0.67	8812.0	8.00	2.22	0.08	4.61	3.11	3.6

This example shows the default file output format, or one line per event. The “file, output” drop down menu offers several other options. The file is automatically saved as a comma separated value (CSV) file that can be directly opened with a spreadsheet program. In addition, the input file can also be saved to a file that can be opened in a spreadsheet for examination. The input file for this example is shown as Table A-1, while the output file (after adding some column statistics in Excel) is shown in Table A-2. It is also possible to plot these data from within the spreadsheet, or in any graphing program.

Table A-1. Input File Associated with Example Problem

```
Pond file name:  G:\WDP71\CLASSEXP.PND
Pond file description:  This is an example of the design procedure
Particle Size file name:  G:\WDP71\MEDIUM.CPZ
Output Format Option:  Water Quality Summary:  One Line per Event
Output device:  Print Output to File (extension .DPO)
Date:  02-17-2000


Drainage Basin Runoff Procedure:
         Combined Surface Characteristics
         1.  All directly connected impervious areas (acres):   45
         2.  All pervious areas (acres):   75
         3.  All impervious areas draining to pervious areas (acres):   30
Outlet Characteristics:
    Outlet number 1
      Outlet type:  V - Notch Weir
           1.  Weir angle (degrees):  45
           2.  Weir height from invert:   4
           3.  Invert elevation above datum (ft):   3
Outlet Characteristics:
    Outlet number 2
      Outlet type:  Rectangular Weir
           1.  Weir length (ft):   20
           2.  Weir height from invert:   1
           3.  Invert elevation above datum (ft):   6

Initial stage elevation (ft):   3
User defined pond efficiency factor (n):   5

Pond Stage, Surface Area, and Stage-related Outfall Devices (if applicable)
Entry    Stage     Pond Area     Natural Seepage    Other Outflow
Number    (ft)      (acres)          (in/hr)            (cfs)
   0      0.00       0.0000            0.00              0.00
   1      0.50       0.1000            0.00              0.00
   2      1.00       0.1300            0.00              0.00
   3      1.50       0.1700            0.00              0.00
   4      2.00       0.2000            0.00              0.00
   5      2.50       0.9000            0.00              0.00
   6      3.00       1.2000            0.00              0.00
   7      3.50       1.5000            0.00              0.00
   8      4.00       1.8000            0.00              0.00
   9      4.50       2.1000            0.00              0.00
  10      5.00       2.4000            0.00              0.00
  11      5.50       2.7000            0.00              0.00
  12      6.00       3.0000            0.00              0.00
  13      6.50       3.3000            0.00              0.00
  14      7.00       3.6000            0.00              0.00

Rain Information
Rain file name:  G:\wdp71\BHAM5290.RAN
         Rain starting date : 01/01/76
         Rain ending date : 12/31/76
```

Table A-2. Output Data for Example Analysis (one-line per event)

DETPOND for Windows Version 7.1.6

Pond file name: G:\wdp71\classexp.pnd

Pond file description: this is an example of the design procedure

Rain file name: G:\wdp71\bham5290.ran

Model Run Start Date: 01/01/76   Model Run End Date: 12/31/76

Date of run: 02-17-2000   Time of run: 18:43:18

Detention Pond Water Quality Performance Summary, by Event

Rain Number	Rain Date	Rain Depth (in)	Time (Julian days)	Rain Dur. (hrs)	Intrevnt Dur. (days)	Rain Intensity (in/hr)	Maximum Pond Stage (ft)	Minimum Pond Stage (ft)	Event Inflow Volume (ac-ft)	Event Hydr Outflow (ac-ft)	Event Infil Outflow (ac-ft)	Event Evap Outflow (ac-ft)	Event Total Outflow (ac-ft)	Flow-weighted Particle Size	Approx. Part Res Control (%)	Peak Reduction Factor	Event Flushing Ratio
2,641	1/2/76	0.46	8765.8	9	3.03	0.05	4.14	3.00	2.24	1.948	0	0	1.948	1.1	97.7	0.72	2.074
2,642	1/7/76	0.58	8770.2	9	2.73	0.06	4.42	3.23	2.931	2.906	0	0	2.906	1.5	96.2	0.63	2.714
2,643	1/11/76	0.25	8774.3	5	0.88	0.05	3.85	3.25	1.089	0.879	0	0	0.879	0.6	99.3	0.84	1.008
2,644	1/13/76	0.03	8775.9	2	0.07	0.01	3.39	3.36	0.017	0.068	0	0	0.068	0.2	99.8	0.39	0.015
2,645	1/13/76	0.01	8776.3	1	0.22	0.01	3.36	3.32	0.002	0.052	0	0	0.052	0.1	99.9	N/A	0.002
2,646	1/13/76	0.38	8776.7	2	6.24	0.19	4.34	3.17	1.939	2.122	0	0	2.122	1.7	95.3	0.89	1.795
2,647	1/20/76	0.05	8783.2	5	3.33	0.01	3.2	3.13	0.046	0.09	0	0	0.09	0	100	0.91	0.043
2,648	1/24/76	0.03	8787.3	2	0.78	0.01	3.14	3.13	0.017	0.016	0	0	0.016	0	100	0.95	0.015
2,649	1/25/76	2.33	8788.4	20	8.33	0.12	5.64	3.12	14.977	14.99	0	0	14.99	3.3	88.8	0.22	13.868
2,650	2/5/76	0.51	8799.7	9	4.23	0.06	4.27	3.12	2.523	2.427	0	0	2.427	1.3	96.9	0.68	2.336
2,651	2/11/76	0.01	8805.3	1	6.6	0.01	3.19	3.11	0.002	0.112	0	0	0.112	0	100	0.54	0.002
2,652	2/18/76	0.67	8812	8	2.22	0.08	4.61	3.11	3.678	3.444	0	0	3.444	1.7	95.3	0.63	3.405
2,653	2/21/76	0.61	8815.5	3	12.59	0.2	4.79	3.10	3.318	3.511	0	0	3.511	2.2	93.1	0.8	3.072
2,654	3/5/76	0.85	8828.5	23	0	0.04	4.47	3.10	4.801	4.465	0	0	4.465	1.7	95.2	0.36	4.445
2,655	3/8/76	1.11	8831.7	17	0.91	0.07	4.85	3.31	6.224	6.283	0	0	6.283	2.2	93.3	0.36	5.763
2,656	3/12/76	0.3	8835.1	5	0	0.06	4.01	3.31	1.366	0.642	0	0	0.642	1.2	97.6	0.81	1.265
2,657	3/12/76	1.18	8835.6	4	1.82	0.29	5.77	3.37	6.892	7.52	0	0	7.52	3.2	89.3	0.62	6.382
2,658	3/15/76	3.64	8838	27	1.24	0.13	6.02	3.24	25.13	25.319	0	0	25.319	3.8	86.7	0.12	23.268
2,659	3/20/76	0.04	8843.3	2	0.2	0.02	3.26	3.24	0.029	0.031	0	0	0.031	0.1	99.9	0.88	0.027
2,660	3/20/76	1.14	8843.8	6	2.93	0.19	5.4	3.24	6.616	6.576	0	0	6.576	2.8	90.8	0.58	6.126
2,661	3/24/76	0.04	8847.7	6	0.81	0.01	3.27	3.21	0.029	0.102	0	0	0.102	0.1	99.9	0.6	0.027
2,662	3/26/76	1.56	8849.4	17	0.62	0.09	5.22	3.21	9.111	8.928	0	0	8.928	2.7	91.1	0.31	8.436
2,663	3/29/76	2.2	8852.5	12	0	0.18	5.93	3.35	13.098	11.551	0	0	11.551	3.8	86.6	0.33	12.128
2,664	3/30/76	2.09	8853.4	22	8.99	0.09	5.44	3.11	12.864	14.718	0	0	14.718	3	89.8	0.2	11.911
2,665	4/11/76	0.21	8865.7	5	1.42	0.04	3.67	3.11	0.878	0.618	0	0	0.618	0.4	99.6	0.89	0.813
2,666	4/13/76	0.05	8867.9	7	9.74	0.01	3.32	3.1	0.046	0.32	0	0	0.32	0.1	99.9	0.56	0.043
2,667	4/24/76	0.84	8878.7	9	3.9	0.09	4.78	3.11	4.528	4.388	0	0	4.388	2	94.1	0.58	4.192
2,668	4/30/76	0.09	8883.9	8	0	0.01	3.31	3.21	0.165	0.055	0	0	0.055	0.1	99.9	0.87	0.153
2,669	4/30/76	0.94	8884.6	11	4.31	0.09	4.88	3.19	5.245	5.374	0	0	5.374	2.2	93.3	0.48	4.856

Table A-2. Output Data for Example Analysis (one-line per event) (cont.)

Rain Number	Rain Date	Rain Depth (in)	Time (Julian days)	Rain Dur. (hrs)	Intrevnt Dur. (days)	Rain Intensity (in/hr)	Maximum Pond Stage (ft)	Minimum Pond Stage (ft)	Event Inflow Volume (ac-ft)	Event Hydr Outflow (ac-ft)	Event Infil Outflow (ac-ft)	Event Evap Outflow (ac-ft)	Event Total Outflow (ac-ft)	Flow-weighted Particle Size	Approx. Part Res Control (%)	Peak Reduction Factor	Event Flushing Ratio
2,670	5/6/76	1.71	8890.5	15	0	0.11	5.44	3.19	10.482	8.863	0	0	8.863	3.3	88.8	0.32	9.705
2,671	5/7/76	0.03	8891.5	2	0.07	0.01	4.19	3.8	0.017	0.723	0	0	0.723	1.5	96.3	N/A	0.015
2,672	5/8/76	0.3	8891.9	8	1.34	0.04	4.17	3.34	1.386	2.109	0	0	2.109	1.1	97.6	0.56	1.283
2,673	5/10/76	0.06	8894.5	2	0.03	0.03	3.37	3.33	0.067	0.052	0	0	0.052	0.2	99.8	0.87	0.062
2,674	5/10/76	0.2	8894.8	6	1.68	0.03	3.78	3.29	0.832	0.905	0	0	0.905	0.5	99.5	0.8	0.77
2,675	5/13/76	3.83	8897.4	34	0	0.11	5.86	3.3	26.954	25.826	0	0	25.826	3.8	86.8	0.11	24.958
2,676	5/15/76	0.01	8899.4	1	0.68	0.01	4	3.54	0.002	0.784	0	0	0.784	1.2	97.8	N/A	0.002
2,677	5/16/76	0.07	8900.2	2	6.24	0.04	3.57	3.15	0.092	0.633	0	0	0.633	0.3	99.7	0.73	0.085
2,678	5/22/76	2.33	8906.8	25	0.21	0.09	5.47	3.15	15.033	14.822	0	0	14.822	3.1	89.5	0.19	13.919
2,679	5/26/76	0.02	8910.7	4	0.15	0	3.31	3.26	0.007	0.068	0	0	0.068	0.1	99.9	N/A	0.007
2,680	5/27/76	0.02	8911.5	1	0.43	0.02	3.27	3.24	0.007	0.039	0	0	0.039	0.1	99.9	0.74	0.007
2,681	5/28/76	0.23	8912	8	0	0.03	3.77	3.24	0.994	0.522	0	0	0.522	0.7	99.3	0.79	0.92
2,682	5/28/76	0.05	8912.9	3	3.05	0.02	3.56	3.22	0.046	0.548	0	0	0.548	0.3	99.7	0.2	0.043
2,683	6/1/76	0.48	8916.4	10	15.5	0.05	4.26	3.08	2.488	2.655	0	0	2.655	1.3	96.8	0.63	2.304
2,684	6/18/76	0.03	8933.4	1	0.6	0.03	3.1	3.08	0.017	0.005	0	0	0.005	0	100	0.99	0.016
2,685	6/19/76	1.78	8934.1	24	7.4	0.07	5.15	3.1	10.778	10.74	0	0	10.74	2.7	91.1	0.23	9.98
2,686	6/30/76	0.46	8945.1	3	3.63	0.15	4.4	3.13	2.414	2.256	0	0	2.256	1.6	95.5	0.85	2.235
2,687	7/4/76	1.17	8949.2	14	7.19	0.08	5	3.14	6.626	6.751	0	0	6.751	2.4	92.4	0.4	6.136
2,688	7/13/76	0.26	8958.5	1	2.89	0.26	3.88	3.14	1.163	0.99	0	0	0.99	0.9	98.9	0.97	1.077
2,689	7/16/76	0.03	8961.5	1	4.81	0.03	3.27	3.14	0.017	0.175	0	0	0.175	0.1	99.9	0.88	0.016
2,690	7/21/76	0.09	8966.5	1	1.89	0.09	3.26	3.14	0.164	0.1	0	0	0.1	0.1	99.9	0.99	0.152
2,691	7/23/76	0.26	8968.5	1	3.81	0.26	3.92	3.19	1.163	1.109	0	0	1.109	1	98.5	0.96	1.077
2,692	7/27/76	0.91	8972.5	2	0.07	0.46	5.43	3.23	5.207	3.302	0	0	3.302	3.2	89.1	0.82	4.821
2,693	7/27/76	0.1	8972.9	1	0.31	0.1	4.37	3.83	0.216	1.182	0	0	1.182	1.9	94.4	0.48	0.2
2,694	7/28/76	1.63	8973.3	6	0.35	0.27	6.06	3.69	9.856	10.094	0	0	10.094	3.6	87.5	0.46	9.126
2,695	7/29/76	0.17	8974.6	3	0.18	0.06	3.94	3.63	0.615	0.702	0	0	0.702	1	98.5	0.78	0.569
2,696	7/30/76	0.23	8975.2	3	0.76	0.08	4.06	3.49	0.947	1.173	0	0	1.173	1.1	97.8	0.81	0.877
2,697	7/31/76	0.07	8976.4	1	6.02	0.07	3.54	3.15	0.091	0.556	0	0	0.556	0.3	99.7	0.88	0.085
2,698	8/6/76	0.3	8982.6	2	0.57	0.15	3.99	3.16	1.392	0.826	0	0	0.826	1.1	98.1	0.93	1.289
2,699	8/7/76	0.54	8983.5	1	7.93	0.54	4.89	3.14	2.849	3.31	0	0	3.31	2.6	91.6	0.91	2.638
2,700	8/15/76	0.06	8991.5	3	0.47	0.02	3.19	3.14	0.066	0.027	0	0	0.027	0	100	0.96	0.061
2,701	8/16/76	0.93	8992.5	3	7.63	0.31	5.34	3.15	5.323	5.297	0	0	5.297	2.9	90.2	0.76	4.929
2,702	8/24/76	0.86	9000.5	11	1.23	0.08	4.76	3.15	4.763	4.502	0	0	4.502	1.9	94.3	0.52	4.41
2,703	8/27/76	0.34	9003.4	6	0	0.06	4.11	3.34	1.621	0.891	0	0	0.891	1.4	96.8	0.76	1.5
2,704	8/28/76	0.11	9004	4	0	0.03	3.84	3.69	0.28	0.471	0	0	0.471	0.9	99	0.52	0.259
2,705	8/28/76	0.17	9004.4	2	0.87	0.09	3.97	3.47	0.599	0.947	0	0	0.947	1	98.4	0.84	0.554
2,706	8/29/76	0.03	9005.6	1	2.47	0.03	3.47	3.24	0.017	0.351	0	0	0.351	0.2	99.8	0.53	0.016
2,707	9/1/76	1.41	9008.2	10	0.71	0.14	5.44	3.24	8.393	8.109	0	0	8.109	2.9	90.5	0.43	7.771
2,708	9/3/76	0.25	9010.4	7	0	0.04	3.92	3.44	1.097	0.763	0	0	0.763	1	98.6	0.73	1.016
2,709	9/4/76	0.05	9011.2	7	0	0.01	3.65	3.43	0.046	0.383	0	0	0.383	0.4	99.6	N/A	0.043
2,710	9/5/76	0.44	9012	14	0	0.03	4.16	3.43	2.195	2.054	0	0	2.054	1.3	97	0.53	2.032
2,711	9/6/76	0.04	9013.6	1	0.64	0.04	3.54	3.39	0.03	0.235	0	0	0.235	0.3	99.7	0.64	0.028
2,712	9/7/76	0.11	9014.4	2	2.2	0.05	3.55	3.26	0.278	0.463	0	0	0.463	0.3	99.7	0.92	0.257

Table A-2. Output Data for Example Analysis (one-line per event) (cont.)

Rain Number	Rain Date	Rain Depth (in)	Time (Julian days)	Rain Dur. (hrs)	Intrevnt Dur. (days)	Rain Intensity (in/hr)	Maximum Pond Stage (ft)	Minimum Pond Stage (ft)	Event Inflow Volume (ac-ft)	Event Hydr Outflow (ac-ft)	Event Infil Outflow (ac-ft)	Event Evap Outflow (ac-ft)	Event Total Outflow (ac-ft)	Flow-weighted Particle Size	Approx. Part Res Control (%)	Peak Reduction Factor	Event Flushing Ratio
2,713	9/10/76	0.01	9016.9	1	10.89	0.01	3.26	3.09	0.002	0.217	0	0	0.217	0.1	99.9	0.05	0.002
2,714	9/21/76	0.06	9028	2	5.16	0.03	3.15	3.09	0.067	0.06	0	0	0.06	0	100	0.99	0.062
2,715	9/26/76	0.12	9033.4	2	0.45	0.06	3.35	3.1	0.345	0.085	0	0	0.085	0.1	99.9	0.98	0.319
2,716	9/27/76	0.03	9034.2	1	1.43	0.03	3.3	3.22	0.017	0.115	0	0	0.115	0.1	99.9	0.84	0.016
2,717	9/28/76	2.39	9035.8	16	4.93	0.15	5.85	3.17	15.04	15.111	0	0	15.111	3.5	88	0.26	13.926
2,718	10/6/76	0.04	9043.1	2	0.16	0.02	3.19	3.17	0.029	0.014	0	0	0.014	0	100	0.95	0.027
2,719	10/6/76	0.01	9043.5	1	1.35	0.01	3.18	3.15	0.002	0.036	0	0	0.036	0	100	0.6	0.002
2,720	10/8/76	0.01	9045	1	0.39	0.01	3.15	3.15	0.002	0.01	0	0	0.01	0	100	0.73	0.002
2,721	10/8/76	0.15	9045.6	5	7.33	0.03	3.48	3.13	0.506	0.526	0	0	0.526	0.2	99.8	0.92	0.469
2,722	10/16/76	0.05	9053.7	6	2.47	0.01	3.16	3.12	0.046	0.054	0	0	0.054	0	100	0.93	0.043
2,723	10/20/76	0.15	9057	2	4.66	0.08	3.47	3.12	0.491	0.428	0	0	0.428	0.2	99.8	0.97	0.455
2,724	10/25/76	0.64	9062	14	2.86	0.05	4.39	3.17	3.35	3.286	0	0	3.286	1.5	96.1	0.52	3.102
2,725	10/30/76	0.54	9067	11	10.77	0.05	4.32	3.11	2.762	2.901	0	0	2.901	1.4	96.4	0.6	2.557
2,726	11/11/76	0.23	9079.4	13	0.8	0.02	3.66	3.11	0.996	0.751	0	0	0.751	0.4	99.6	0.76	0.922
2,727	11/14/76	0.91	9082.1	19	3.28	0.05	4.62	3.19	5.072	5.205	0	0	5.205	1.8	94.6	0.37	4.696
2,728	11/20/76	0.22	9088.3	7	4.95	0.03	3.73	3.17	0.938	0.965	0	0	0.965	0.5	99.5	0.83	0.868
2,729	11/26/76	0.12	9094.3	9	0	0.01	3.38	3.17	0.332	0.145	0	0	0.145	0.1	99.9	0.88	0.307
2,730	11/27/76	0.02	9095.4	2	0.24	0.01	3.31	3.28	0.007	0.052	0	0	0.052	0.1	99.9	0.27	0.007
2,731	11/28/76	0.73	9096	22	5.12	0.03	4.37	3.15	3.941	4.109	0	0	4.109	1.5	95.9	0.38	3.649
2,732	12/6/76	0.59	9104.4	19	1.86	0.03	4.23	3.15	3.089	2.979	0	0	2.979	1.3	96.9	0.47	2.86
2,733	12/11/76	1.09	9109.1	38	0	0.03	4.45	3.23	6.291	6.124	0	0	6.124	1.8	95	0.22	5.825
2,734	12/14/76	0.25	9112.8	5	4.33	0.05	3.91	3.19	1.089	1.304	0	0	1.304	0.8	99	0.81	1.008
2,735	12/20/76	0.87	9117.9	9	3.94	0.1	4.84	3.2	4.703	4.685	0	0	4.685	2.1	93.7	0.56	4.354
2,736	12/25/76	1.35	9123.2	13	3.3	0.1	5.22	3.21	7.948	7.934	0	0	7.934	2.7	91.3	0.39	7.359
2,737	12/30/76	0.01	9128.5	1	0.18	0.01	3.21	3.21	0.002	0.014	0	0	0.014	0	100	0.39	0.002
2,738	12/30/76	0.19	9128.8	7	1.99	0.03	3.65	3.21	0.765	0.696	0	0	0.696	0.3	99.7	0.84	0.708
		Rain Depth (in)		Rain Dur. (hrs)	Intrevnt Dur. (days)	Rain Intensity (in/hr)	Maximum Pond Stage (ft)	Minimum Pond Stage (ft)	Event Inflow Volume (ac-ft)	Event Hydr Outflow (ac-ft)	Event Infil Outflow (ac-ft)	Event Evap Outflow (ac-ft)	Event Total Outflow (ac-ft)	Flow-weighted Particle Size	Approx. Part Res Control (%)	Peak Reduction Factor	Event Flushing Ratio
	minimum:	3.83		38.00	15.50	0.54	6.06	3.83	26.95	25.83	0.00	0.00	25.83	3.80	100.00	0.99	24.96
	maximum:	0.01		1.00	0.00	0.00	3.10	3.00	0.00	0.01	0.00	0.00	0.01	0.00	86.60	0.05	0.00
	st dev:	0.76		7.71	3.22	0.09	0.83	0.15	5.03	4.95	0.00	0.00	4.95	1.15	4.04	0.25	4.66
	average:	0.56		7.57	2.70	0.08	4.13	3.23	3.21	3.20	0.00	0.00	3.20	1.22	96.55	0.64	2.97
	COV	1.35		1.02	1.19	1.18	0.20	0.05	1.57	1.55	na	na	1.55	0.94	0.04	0.40	1.57
	median:	0.24		5.00	1.39	0.05	3.96	3.19	1.04	0.90	0.00	0.00	0.90	1.00	98.45	0.68	0.97
	total:	55.15		742	265				314	314	0.00	0.00	314				291
	number:	98															

Example 1: Create a Rain File for Use in DETPOND

Create a rain file with the following four rainfall events:

01/14/87	11:00	01/15/87	03:00	0.21
01/16/87	14:00	01/16/87	16:00	0.05
01/17/87	18:00	01/19/87	02:00	3.79
01/21/87	21:00	01/22/87	07:00	0.46

Step Number	Command or Model Parameter	Enter Value:
1	Run the parameter module	DPPARA55
2	Select option 1: Rain data files	1
3	Select option 1: Create a rain file	1
4	Enter the number of rain events	4
5	Enter the last two digits of the year of the rain events	87
6	Enter the beginning date for the first event in the format MMDD	0114
7	Enter the beginning time for the first event in the format HHMM	1100
8	Enter the ending date for the first event in the format MMDD. If the ending date is the same as the beginning date, press enter	0115
9	Enter the ending time for the first event in the format HHMM	0300
10	Enter the rainfall depth multiplied by 100	21
11	Enter the second rainfall event	0116 1400 <ENTER> 1600 5
12	Enter the third rainfall event	0117 1800 0119 0200 379
13	Enter the fourth rainfall event	0121 2100 0122 0700 46
14	Enter the new rain file name	EX06
15	Exit the program	9 3

Example 2: Edit the Rain File Created in Example 1

Edit the rain file created in example 1 by:

1. Changing the beginning time of the second rainfall from 14:00 to 13:00
2. Insert this new rain event between events 3 and 4:
   01/20/87 03:00 01/20/87 12:00 0.34
3. Changing the rainfall depth of the fourth rainfall from 0.46 to 0.57

Step Number	Command or Model Parameter	Enter Value:
1	Run the parameter module	DPPARA55
2	Select option 1: Rain data files	1
3	Select option 2: Review or edit a rain file	2
4	Enter the name of the rain file you want to edit	EX06
5	Select the option to change a rain event	2
6	Enter the rain number you want to edit	2
7	Change the beginning time of the second rainfall from 14:00 to 13:00 using the format HHMM. Press enter to bypass those values you do not want to change	<ENTER 1300 <ENTER> <ENTER>
8	Before inserting a new rain event, enter the event year	4 87
9	Add a new rain event	1
10	Enter the rain number you want to insert the new rain after	3
11	Enter the beginning date for the new event in the format MMDD	0120
12	Enter the beginning time for the new event in the format HHMM	0300
13	Enter the ending date for the new event in the format MMDD. If the ending date is the same as the beginning date, press enter	<ENTER>
14	Enter the ending time for the new event in the format HHMM	1200
15	Enter the rainfall depth, multiplied by 100, for the new event	34
16	Select the option to change a rain event	2
17	Enter the rain number you want to edit	5
18	Change the rainfall depth of the fifth rainfall from 0.46 to 0.57. Press enter to bypass those values you do not want to change	<ENTER> <ENTER> <ENTER> <ENTER> 57
19	Enter the new rain file name	EX07
20	Exit the program	9 3

Example 3: Create a Rain File from CD ROM Data

Use the Parameter Module to create a DETPOND/SLAMM-formatted rain file directly from rainfall data. The program will create the rain file based upon the minimum number of hours between rains and the minimum rainfall event depth values entered by the user. The data must be in the following comma-separated value format, which begins with the date and is followed by 24 values of hourly rain totals:

```
02/05/1976,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.00 ,0.01 ,0.10 ,0.18 ,0.01 ,0.05 ,0.00 ,0.01 ,0.00 ,0.04 ,0.10 ,0.05 ,0.12 ,0.30
```

Step Number	Command or Model Parameter	Enter Value:
1	Run the parameter module	DPPARA55
2	Select option 1: Rain data files	1
3	Select option 8: Create a rain file from standard format data	8
4	Enter the name of the comma-separated-value file that you want to convert to a DETPOND/SLAMM rain file. Include the extension	EXHOUR.CSV
5	Enter the name of the file you want to save the rain file created from EXHOUR.CSV	EX08
6	Enter the minimum number of hours you want between rainfall events	4
7	Enter the minimum rainfall depth you want in the rain file	0.01
8	Exit the program	9 3

Example 4: Stochastically Generate a Rain File

Statistically evaluate an existing rain file to determine the rank correlation between rainfall depth and duration, the average depth, average duration, and average time between rains. Use this information to create a stochastically generated rainfall series.

Step Number	Command or Model Parameter	Enter Value:
1	Run the parameter module	DPPARA55
2	Select option 1: Rain data files	1
3	Save an existing rain file in a format with duration and interevent calculations appended to the data	4 BHAM77
4	Calculate the statistics for the rain file	7 2 BHAM77.RES
5	Record the results of the rainfall data analysis: Rank Correlation: 0.595 Rainfall Average: 0.62 Duration Average: 0.48 days or 12 hours Interevent Period Average: 3.29 days or 79 hours	
6	Exit the data analysis screen	<ENTER>
7	Select option 6: Create a generated rain file	6
8	Create a generator data file	3
9	Enter a generator file name	1 EX09
10	Enter the mean depth for the generated rain file	2 0.62
11	Enter the minimum recorded rain depth (in)	3 .01
12	Select the rainfall duration distribution (exponential in this example) and enter the mean rain duration, 12 hours, (for both exponential and gamma distributions) and duration variance (gamma distribution only)	4 1 12
13	Enter the mean time between rains (hours)	5 79
14	Enter the minimum time between rains (hours)	6 6
15	Generate 100 events	7 100
16	Select the seed. Enter an integer value or select zero to use the timer	8 42
17	Enter the depth-duration rank correlation coefficient	9 0.595
18	Enter the desired rainfall starting date in the format MMDDYY	10 01/01/88
19	Save the rain generator data file	14
20	Create a generated DETPOND/SLAMM format rain file using the data file you just created	1 EX09
21	Exit the program	9 3

Example 5: Create a Particle Size Distribution File

Create a particle distribution file from the MIDWEST data particle size distribution.

Step Number	Command or Model Parameter	Enter Value:
1	Run the parameter module	DPPARA55
2	Select option 2: Particle Size data files	2
3	Select option 1: Create a new particle size distribution file	1
4	Enter the name of the new particle size distribution file	EX10
5	Enter the description of the new particle size distribution file	Midwest
6	For each entry, enter the percent of the particles that are greater than the corresponding critical particle size	for 1 micron: 100 for 2 microns: 98 for 3 microns: 94 for 4 microns: 91 for 5 microns: 88 for 6 micron: 86 for 7 microns: 84 for 8 microns: 82 for 9 microns: 80 for 10 microns: 78 for 11 micron: 75 for 12 microns: 72 for 13 microns: 70 for 14 microns: 67 for 15 microns: 64 for 20 micron: 60 for 25 microns: 57 for 30 microns: 53 for 35 microns: 48 for 40 microns: 44 for 50 microns: 42 for 60 microns: 38 for 80 micron: 34 for 100 microns: 28 for 150 microns: 18 for 200 microns: 16 for 300 microns: 12 for 500 micron: 7 for 800 microns: 4 for 1000 microns: 3 for 2000 microns: 1
17	Exit the program	4 3