The Effectiveness of Stormwater Detention

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ABSTRACT

The effectiveness of stormwater detention is discussed in terms of quantity, water quality, and institutional constraints; and research needs are identified. The results of a study by the Urban Drainage and Flood Control District in Denver, Colorado, are presented to assess the effectiveness of random on-site detention in controlling flow rates along major drainageways. The study consisted of modeling an actual 7.85-mile^2 watershed in the Denver area under the 2-, 10-, and 100-yr rainstorm scenarios. The study suggests for the Denver region that random on-site detention has the potential of being reasonably effective in controlling the 10- and 100-yr flows along major drainageways. It also suggests that random on-site detention may not be effective in controlling frequently occurring flows such as runoff from 2-yr or smaller storms. The authors also discuss the design accuracy of stormwater systems and that institutional structure is needed to ensure the design, construction, and the continued operation of detention facilities. They conclude that such a structure is a must if detention is to be an effective part of the total stormwater management program.

The approach to drainage until the early 1970s relied on swales, curb and gutter, inlets, storm sewers, and channels to carry away flow as quickly as possible. In recent years this approach has been modified by the introduction of detention storage to hold back runoff and to release it downstream at controlled rates. The concept apparently has considerable appeal because it has been widely embraced throughout the United States, Canada, and many other countries throughout the world.

Although the concept of detention storage has been widely accepted, the questions regarding its effectiveness in managing stormwater runoff persist. It is relatively easy to study the hydrologic effectiveness of individual detention sites. It is another matter to study and quantify the effectiveness of a system of detention ponds, particularly if they occur randomly as to time of construction and in their location.

The investigation of the effectiveness of detention in managing or controlling urban runoff cannot be limited to hydraulic or hydrologic functions alone. Detention ponds, once built, become a part of the overall stormwater management system. They can play a vital role in controlling downstream flooding and have to be accepted into the infrastructure of the metropolitan areas they serve. Thus, the institutional arrangements and systems that can ensure adequate design, proper construction, and perpetually continuing maintenance need also to be considered and evaluated when the effectiveness of any stormwater detention system is assessed.

Even more recently (i.e., within approximately the last 5 years), stormwater detention began assuming an ever increasing role in controlling the water quality of urban runoff. Although attempts to use detention for this purpose date back at least 10 years, data from field installations have become available only recently. These new data now provide a glimpse of the potential effectiveness of detention storage in enhancing urban runoff water quality.

In August 1982 the Engineering Foundation and the Urban Water Resources Research Council of the American Society of Civil Engineers (ASCE) cosponsored a week-long conference on stormwater detention facilities planning, design, operation, and maintenance. Hydrology, water quality, and institutional issues were thoroughly discussed in the context of effectiveness of stormwater detention. The authors, who co-chaired this conference, used some of the information presented there, as well as their own work, to assess the effectiveness of stormwater detention and to identify topics that require further research and development. The purpose of this paper is to discuss the effectiveness of stormwater detention in terms of quantity, quality, and institutional constraints.

RECENT INVESTIGATIONS--QUANTITY

In November 1974 McCuen published an article (1) reporting the results of his modeling effort using 17 subwatersheds and two systems of detention storage. In one system, he modeled 12 ponds and, in another, he modeled 17 ponds. He used 10 storm events at the Gray Haven Watershed (2) to calibrate a "linked-process hydrograph simulation model" before adding the detention ponds to the system. The modeled watershed consisted of 23.3 acres of which 52 percent was impervious. Although the design of individual detention facilities was not described in the article, McCuen reported that the 17 subwatershed scenario had a total of 22,000 ft^3 of storage. On the basis of his modeling results, he suggested:

> 1) that the "individual-size" approach to stormwater detention may actually create flooding problems rather than reduce the hydrologic impact of urbanization; and 2) that a regional approach to urban stormwater management may be more effective than the "individual-site" approach.

In June 1976 Hardt and Burges published a report (3) on their investigation of detention effects from a hypothetical 2,000-acre watershed. Their investigation, using a Soil Conservation Service (SCS) runoff model and a kinematic channel routing technique, was limited to three subwatersheds; nevertheless, it was one of the earlier attempts to examine the effects of detention systems. Their findings are summarized in the following quote from their report:

> Restricting the outflow from a retention facility to a level less than the undeveloped rate could achieve a composite peak flow rate that would equal the pre-urbanization flow but would run for a much greater duration at that rate. The increased flow duration would have potentially undesirable effects on the channel system.

Linsley and Crawford (4) suggested the use of continuous simulation models in urban hydrology. Although this suggestion has considerable merit, it suffers from the fact that continuous record of rainfall is often not available. When it is available, the cost of such modeling can be very expensive, and the majority of design practitioners are not prepared to use continuous long-term modeling in the design of stormwater detention facilities. Walesh (5,6) suggested a technique to reduce a continuous hyetograph record to a reasonable number of discrete hyetographs that represent desired recurrence frequency storms. These representative recorded hyetographs can then be used to design stormwater management facilities, including detention. The reason for suggesting continuous simulation or the use of representative recorded hyetographs stems from the questioning of the validity of using a design storm (7-9).

This design storm controversy has not been resolved; however, the authors believe that there are definite applications, particularly water quality-oriented, where continuous simulation or quasi-continuous simulation should be used whenever rainfall data are available. On the other hand, the authors believe that the design of basic storm sewer systems, channels, and detention ponds can be accomplished with reasonable accuracy by using properly developed design storms. Urbonas (10), based on hydrologic studies in Denver, Colorado, expressed the following opinion:

> It is possible to develop design storms that reasonably duplicate the peak flows from small urban basins at various recurrence intervals. However, this requires substantial rainfall-runoff data to permit calibration of computer models, long term simulation of runoff using recorded rainstorms, and statistical analysis of simulated peaks and volumes.

Such design storms need to be developed for each locale using representative rainfall-runoff data. When developed, they can be used with confidence that the designs for the region will be reasonably accurate and responsive to the stormwater management needs of the region.

RECENT INVESTIGATIONS--QUALITY

Although the use of stormwater detention to enhance urban runoff water quality has been discussed for the last 10 years, only during the last 3 years has reliable data on stormwater detention effectiveness begun to emerge. Initial investigations were limited to efficiencies of sediment entrapment, which were correlated to the fall velocity of sediment particles in still water (11-13). These studies, however, did not identify the differing efficiencies of various pollutant entrapments.

In 1981 Whipple and Hunter (14) reported settleability measurements using a stilling glass tube. Measurements were made for hydrocarbons, suspended solids, 5-day biodegradable oxygen demand (BOD_5), total phosphates, lead, copper, zinc, and nickel for five urban storm runoff samples in New Jersey. They reported that stormwater retention can be effective in removing significant portions of particulate pollutants from runoff if sufficient retention time is provided. They also reported that the settleability varied widely between specific pollutants and even between storms for the same pollutants. They concluded that considerable research is still needed.

Rinella and McKenzie (15) have developed a methodology relating suspended chemical concentrations in stormwater to suspended-sediment particle-size classes based on settling velocities in quiescent native water. These relationships may help to characterize the removal rates of pollutants by sedimentation. The procedure is quite involved and requires one person 6 to 14 hours to separate suspended sediments into particle size classes. Nevertheless, it has the potential of becoming a basis for design of settling treatment ponds for urban runoff pollutants.

Randall et al. (16) also reported on studies of pollutant settleability in runoff for three shopping centers in Virginia. They found that after 32 hours of settling time, an average of 90 percent of the total suspended solids, 46 percent of chemical oxygen demand (COD), 34 percent of total organic carbon (TOC), 56 percent of total phosphorus, 33 percent of total nitrogen, 44 percent of zinc, 86 percent of lead, and 64 percent of BOD_5 had been removed from the water column. However, the levels of many of these constituents in the water column still remained higher than would be acceptable for maintenance of many stream standards.

As a result of the Environmental Protection Agency's National Urban Runoff Program, studies such as reported by Rinella and McKenzie (15), Whipple and Hunter (14), and Randall et al. (16) are beginning to develop some of the information needed for design of detention ponds for water quality enhancement. However, much more field data are needed to verify design technology before it can be confidently stated how effective a design will be in removing pollutants from urban runoff. In another paper, Randall (17) reported on the effectiveness of three ponds based on field observations. The results varied considerably between the sites. As a rule, the two ponds that had a permanent water pool outperformed the dry pond. For the dry pond, the concentrations of nitrogen constituents were greater in the outflow than in the inflow. Results such as these reveal that all of the basic water quality processes that occur in detention ponds are still not understood. Additional research will be required to identify and to quantify them and to develop design techniques that can reliably predict the performance of detention ponds used for water quality enhancement.

HYDRAULIC EFFECTIVENESS OF RANDOM DETENTION

The Urban Drainage and Flood Control District has an interest in stormwater detention in the Denver metropolitan area because it may affect the peak flows along major drainageways. For the purposes of this paper, a major drainageway is defined as one having at least a one-fourth $mile^2$ area tributary to it. In 1969 the District contracted with the U.S. Geological Survey (USGS) to collect simultaneous rainfall and runoff data, which were used to develop regionalized rainfall and runoff estimating procedures. These procedures were then the basis for calibrating a storm water management model for a rapidly urbanizing watershed in the metropolitan area, which was used to study the effects of random detention on the peak flow rates along major drainageways.

A study conducted by the District used an actual Denver area watershed as a study basin. The study watershed had an area of 7.85 $mile^2$, a watershed length of 6.4 miles with an average watershed slope of 0.015. Its shape and drainage pattern is shown in Figure 1, and it was estimated that 1.9 percent of its area was impervious before land development began. After full development, the watershed area is projected at 38 percent impervious.

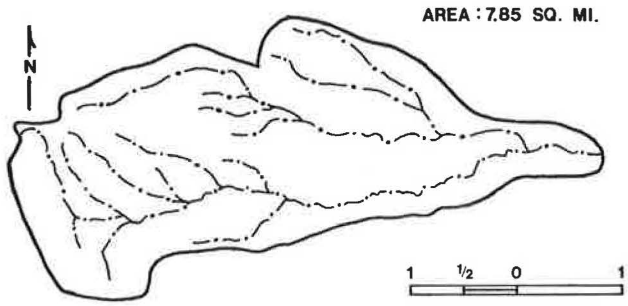

FIGURE 1 Study basin.

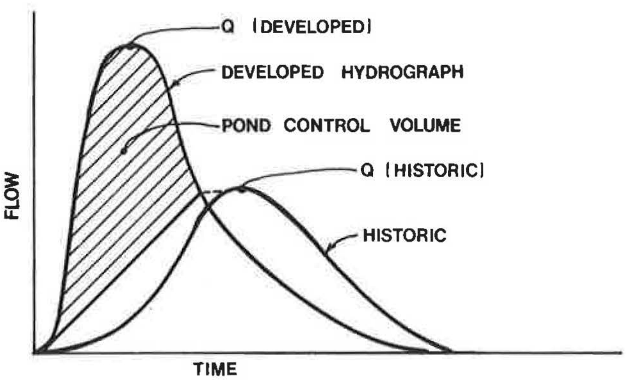

FIGURE 2 Determination of detention pond volume.

Runoff was modeled using 2-hr design storms for the 2-, 10-, and 100-yr recurrence frequencies. These design storms were developed for the Denver area by using the rainfall-runoff data collected by USGS. Modeling was done using stationary storms and mobile storms that traversed the watershed at 6 mph upstream and downstream. In addition, runoff was modeled by using three recorded rainstorms under the stationary and moving storm scenarios. Although the runoff results reported in this paper are for the stationary design storm scenarios, the effects of stormwater detention on each storm scenario are similar. Namely, if a reduction in peak flow is calculated with detention for the stationary storm scenario, then a similar reduction is also observed for the same moving storm scenario when compared with the undetained condition.

The results of the District's study have greatest validity for the Denver metropolitan area and other areas of United States having similar meteorological and hydrologic conditions. Because the modeling was for a 7.85-mile^2 watershed, conclusions of this study should not be extrapolated beyond 10 mile^2 watersheds. This appears to be a severe limitation; however, many of the observed rainstorms in the semi-arid climates have a rather limited footprint where the intense rainfall occurs. Thus, it is possible that for many intense rainstorms in semi-arid climates, controlling runoff from 10-mile^2 or lesser watersheds may be very beneficial for flood control purposes. The intent of the District's study was to gain an understanding of the generalized trends of stormwater detention effectiveness, and the results presented herein need to be viewed from that perspective.

The study watershed was subdivided into 56 subcatchments and 52 channel segments. After calibration, runoff was modeled using the various storm scenarios for the undeveloped and the urbanized land use conditions. The model was then modified to include 28 randomly located detention ponds. The ponds intercepted 91 percent of the total area with runoff from 9 percent of the area being undetained. Each pond was sized on the basis of the hydrographs from the before and after development conditions. The control volume was estimated using a process illustrated in Figure 2, where the control volume was assumed to be equal to the shaded portion of the runoff hydrograph.

The hydraulic characteristics of each pond's outlet was designed assuming that the outlet functioned as an orifice until the design control volume was filled, at which point the pond's overflow functioned as a weir. On the basis of observed trends in several individual designs, an outlet discharge versus storage volume relationship was developed in a nondimensional form. This facilitated the design and evaluation of a large number of detention control conditions. Figures 3 and 4 show the design characteristics used for the 28 ponds in the model. In Figure 3, Q_h is the peak flow from an undeveloped subbasin, Q_d is the peak flow from a developed subbasin, and V_T is the design control volume of the pond. In Figure 4, Q_h and Q_d represent

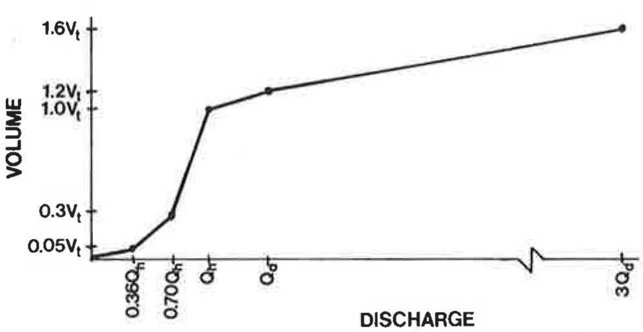

FIGURE 3 Volume versus discharge: 2-, 10-, or 100-year design.

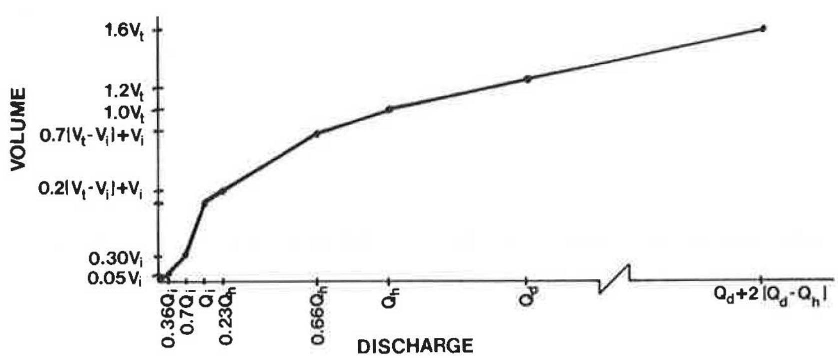

FIGURE 4 Volume versus discharge: 10- and 100-year combination design.

the undeveloped and developed 100-yr storm peak flows, V_T represents the 100-yr control volume, and Q_i and V_i represent the undeveloped peak flow and the required control volume to the 10-yr storm.

Many of the results of the District's random detention study can be found in Glidden (18). Following herein is a series of five figures (i.e., Figures 5-9) that summarize the generalized trends projected by the random detention modeling study. Each figure relates the size of the watershed to the nondimensional peak flow of that size of watershed. The nondimensionalized peak flow was obtained by dividing the actual peak flow by the peak flow from the undeveloped watershed. As an example, a value of one on the ordinate represents no change from the undeveloped condition and a value of two represents an increase in peak flows by a factor of two from the undeveloped condition.

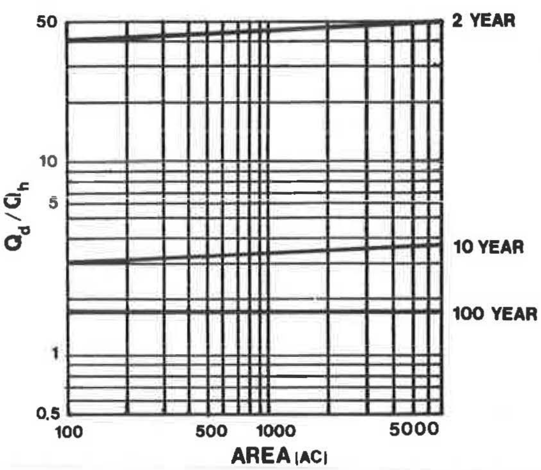

FIGURE 5 Urban runoff trends—developed without detention.

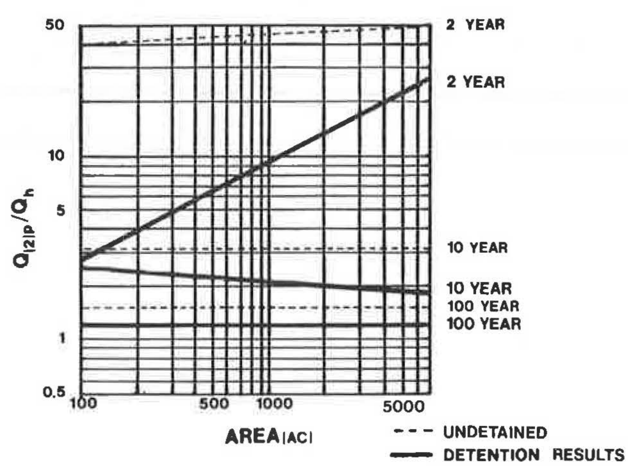

FIGURE 6 Two-year design effectiveness.

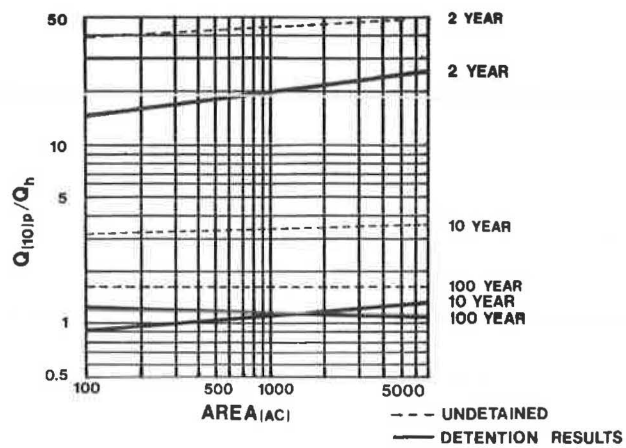

FIGURE 7 Ten-year design effectiveness.

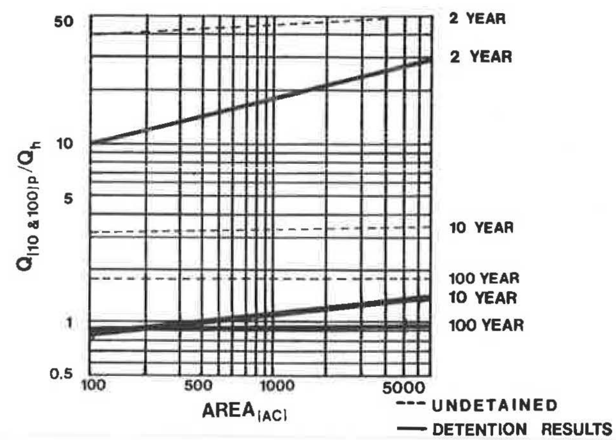

FIGURE 8 One hundred-year design effectiveness.

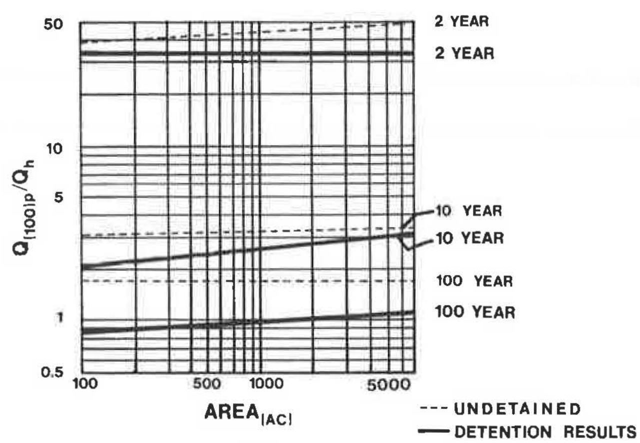

FIGURE 9 Ten- and 100-year combination effectiveness.

The subscript d in Figure 5 refers to the flow conditions when the basin is developed, and the subscripts 2p, 10p, 100p, and 10 and 100p refer to the flow conditions under different detention policy scenarios. Figure 5 shows the estimated trends in peak flows along the major drainageways without on-site detention, and Figures 6 through 9 show the trends when different on-site detention designs are used. It is important to recognize when studying these figures that the trends they suggest are applicable only to semi-arid meteorological zones similar to the Denver region.

A study of Figures 6 through 9 reveals the following trends:

1. The 2-yr random detention pond design was effective only on an individual pond site basis in controlling the 2-yr storm runoff. As the number of

ponds increased with the increasing tributary area, the 2-yr design rapidly diminished in effectiveness. This is because the 2-yr storm volume increased manyfold after development and, although the peaks were controlled at the detention individual sites, the resulting flat peaked outlet hydrographs added directly as the flow progressed downstream. In contrast, before development the individual tributary hydrographs had small volumes and were out of phase with each other. The 2-yr design reduced somewhat the 10-yr and the 100-yr storm runoff peaks when compared with the undetained condition.

2. The 10-yr random detention pond designs were relatively effective in limiting runoff peaks along the major drainageways from the 10-yr storms and was somewhat effective in controlling the 100-yr storm, but was virtually ineffective in controlling the 2-yr design storm.

3. The 100-yr design was effective in controlling the 100-yr storm but was virtually ineffective in controlling the 2- and 100-yr storms.

4. The combination 10- and 100-yr pond design was effective in controlling the 10- and 100-yr storm runoff, but was ineffective in controlling the 2-yr storm runoff. The two frequency designs appeared to be more effective in controlling their two design storms than the individual 10- and 100-yr frequency designs were in controlling their respective recurrence storm runoff.

The results of the District's study appear to verify some of the conclusions of other investigators (3). The one surprise, although predictable, was that the 2-yr design was not very effective in controlling peak flows along the major drainageways from the smaller storms. It may be that McCuen's (1) study, because it used recorded data, was limited to such smaller storms. It does not mean that the 2-yr design is ineffective for individual sites and may be more effective than the study results indicate if the spatial distributions of the smaller storms are considered. Additional work is needed to quantify realistic spatial storm patterns before the 2-yr detention design effectiveness in controlling peaks along major drainageways can be assessed.

DESIGN ACCURACY AND EFFECTIVENESS

The topic of design accuracy was indirectly mentioned in the earlier discussion of the design storm concept. The possible citations concerning urban design storms are numerous and have been tabulated by the Design Storm Task Committee of the Urban Water Resources Research Council into an Annotated Bibliography (19) that can be obtained on request from ASCE. The mere fact that design storms or their substitutes are used as input in the sizing of detention basins leaves a lot of room for argument concerning their design accuracy and their effectiveness. Although the questioning has merit and should not stop if technology is to move forward, it should not paralyze a designer into an endless analysis process. In the authors' opinion, it is important that the designers recognize the limitations in the accuracy of the rainfall input, yet move forward to design what are considered reasonably sized facilities in line with current state of the art.

Unlike many other fields of engineering, the statistics of hydrologic data have very wide bounds of design confidence. As an example, a 1980 USGS document (20) provides regression equations and techniques for estimating flood peaks, volumes, and hydrographs on small streams in South Dakota. The maximum estimated ranges in the standard error of estimate are +152 and -60 percent for the flood peaks and +136 and -58 percent for the runoff volumes. Such uncertainties, as an example, in structural analysis would be considered intolerable and would be dealt with through the use of very large safety factors. On the other hand, drainage and flood control engineers work with similar kinds of uncertainty all the time whether they know it or not. Thus, whenever accuracy or effectiveness is discussed, the randomness of the physical phenomenon involved should be kept in mind as well as the fact that the data base that was used in developing all of the surface runoff calculating techniques oftentimes had very broad bands of data scatter.

Institutional Constraints

In their discussion, Jones and Jones (21) point out that many communities mandated misuse of detention ponding with resultant waste of land and economic resources. They encourage communities to avoid arbitrary specification of single recurrence probability in their ordinances. Instead, communities need to reexamine their selected design basis and attempt to arrive at a design basis that is demonstrably cost-effective. Too often, either the extreme rare event or the small frequent event are the basis for local requirement, which, when applied uniformly and without regard to the effects downstream, can lead to either local drainage and erosion problems or to flooding problems. Jones and Jones stated further:

> It follows that design of detention pond outlet works often should have a multi-probability basis: (a) for frequent low flow conditions; (b) for the detention design discharge condition; and (c) for the extreme runoff (emergency spillway) condition.

The District's study revealed that even though the smaller storms may be the pond design criteria, the increased runoff volume resulting from urbanization virtually precludes design of on-site ponds that can effectively control peak flows along downstream drainageways. This mandates that downstream drainage facilities cannot arbitrarily be sized to accommodate flow from historic or undeveloped watershed only on the basis of on-site detention policy. It is incumbent on communities to also examine the detention requirements for each site, when detention is required, to ensure that pond releases will not create hazards or damages to downstream properties.

Requiring on-site detention is not an assurance that the drainage needs of the community and those of the new development are satisfied. Communities and developers need to recognize that detention, when used, is only one element of a total formalized (or natural) drainage system and that it cannot be treated haphazardly. Thus, institutional arrangements in communities are equally as important as sound design practices. In other words, communities need an institutional structure that not only ensures sound design, but also ensures that the required detention ponds fit the system and are not used merely to pacify local regulatory requirements.

Beyond this, an institutional structure is needed to ensure that detention ponds are properly constructed and maintained for as long as they are a part of the community's drainage system. Assessing the potential hydraulic effectiveness of a detention ordinance can be compared to weighing candy with only one-half of a balance scale. Even though the product looks attractive, it is impossible to know the quantity. If there is an emerging theme among the stormwater management professionals, it is that more often than not such institutional structures are not in place, are inadequate, or are underfunded. Thus, the true effectiveness of detention systems cannot be assessed without knowledge of how policy requirements translate into physical facilities and how these facilities will continue to function over the many years they are expected to operate.

RESEARCH NEEDS

During the 1982 Stormwater Detention Facilities Conference, workshops were held to identify research needs regarding the quantity, quality, and institutional aspects of stormwater detention. Summaries of these workshops are included in the conference proceedings (22), which contain probably the most comprehensive listing of research needs ever compiled on the topic of stormwater detention. It is not really possible to add to those lists; however, some of the research needs considered particularly relevant to the topic of effectiveness are highlighted here.

In the area of hydrology and hydraulic effectiveness, there still remains a need to improve runoff estimating techniques. Any additional research on this topic has to be field data-based. There are sufficient models of every sort at this time; what is still lacking is good quality long-term data for rainfall and simultaneous runoff. In addition, very little is understood at this time by hydrologists about meteorological processes and spatial patterns of rainfall. It is not enough to collect point rainfall data. Hydrologists need to learn more about weather movements and the causes of different types of storms. This will require the setting up of dense raingauge networks before sufficient data can be collected to quantify spatial patterns of rainfall. Such information, once developed, may permit the confidence limits in urban surface runoff hydrology to be narrowed.

Additional research work is also needed in the area of random on-site detention effectiveness. The District's work was very limited and site specific. Considerable additional work is needed before we can be confident of the effectiveness trends by various random systems at on-site detention. Also a corollary effort is needed to determine if there is merit to variable on-site detention requirements. That is, should all detention in the watershed be sized for the same requirement, or is it more cost-effective to require different volumes and release rates depending on the location and development patterns in the watershed? Lakatos and Kropp (23), on the basis of their modeling work, have suggested just such an approach in Pennsylvania.

In the area of water quality, considerable research, using field data, is needed to develop reliable water quality enhancement design procedures. In addition, there is an immense lack of understanding of the basic physical, chemical, biochemical, and biological processes taking place in ponds used for water quality enhancement of urban runoff. In the authors' opinion, these processes need to be identified and understood before real progress can be made in developing sound design procedures.

Finally, work is needed in the institutional-related areas. Institutional elements contributing to successful programs need to be clearly identified so that professionals in other communities have models to follow. As part of the institutional issues, the needs and cost of an on-site detention maintenance program need to be quantified. Such information is vital if communities are to make sound decisions concerning detention requirements. For example, what are the elements of a pond that facilitate easy, low cost maintenance and what are the elements that do just the opposite?

CONCLUSIONS

The effectiveness of on-site detention ponds was addressed from the quality, quantity, and institutional aspects. Recent investigations have begun to indicate that detention ponds can be effective in improving the water quality of urban runoff. Generally, one-half to one- and one-half days of retention time is required in the pond to show a significant improvement. Also, it appears that ponds with a permanent waterpool are more effective than dry ponds. However, much more data and experience are needed to draw firm conclusions over the long term.

The model study of random on-site detention in one Denver area watershed has indicated the following:

1. When ponds are designed to control the peak flow from a single recurrence event, the effectiveness of the system in controlling flow rates along major drainageways is limited only to events of the same design recurrence frequency.
2. Ponds designed to control peak flows of two separate recurrence frequencies appear to be effective in controlling flow rates along major drainageways for a range of flows and also appear to be more effective in controlling the two individual design storms.
3. Designs intended to control frequent events (e.g., 2 years) are effective immediately downstream of each pond. They appear to be less and less effective in controlling the flows along the major drainageway as more and more ponds contribute to the system. A much better understanding of spatial distribution of rainstorms will be needed to fully substantiate this conclusion.

Finally, any assessment of the effectiveness of random on-site detention needs to consider the institutional structure that ensures adequate design, proper construction, and long-term operation and maintenance. Otherwise, an assessment of the effectiveness of any individual community's detention system is an exercise in futility.

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