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TWO DECADES OF STORMWATER MANAGEMENT EVOLUTION

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INTRODUCTION

In late 1960 through early 1970 the use of on-site stormwater detention in the United States began to appear. It was a revolutionary concept at that time. Instead of building ever-larger conveyance systems, the concept called for the control of the peak rate of runoff from each development site to its pre-development rate. Immediately, all kinds of arguments arose among the practitioners and within the academic community. We were struggling with the idea at that time of shifting from the use of *Rational Formula* for drainage design to hydrographs. And now we were being asked to incorporate flood routing reservoirs on all new commercial, industrial and residential development. Clearly, if you were a consultant you did not relish the thought of having to tell your client that he will have to set aside some of his profit-making land for a detention basin. "We never had to do this before, why in hell do we have to do it now?" was often heard. Similarly, if you were an engineer, the last thing you wanted to do was to explain to your city manager or council why the city should require detention.

We had no field data to substantiate the value of this new concept. Our methods of analyzing whole systems were still very crude by today's standards. Although single event models were evolving, continuous simulation, although available, was virtually unheard of. We believed our calculations for flood routing of an individual event through a single basin (i.e., reservoir), but had no tools to describe of what happens system-wide, under continuous, randomly occurring, spatially varied rainfall patterns. We did learn quickly, however, that none of the new "physically-based" rainfall-runoff models predicted runoff accurately unless there was sufficient data to calibrate them. Thus, our first challenge was to look for ways to develop more reliable models or, at the minimum, have sufficient data locally to calibrate the ones we were using.

In 1976, I was fortunate to have joined the Urban Drainage and Flood Control District (UDFCD), a regional organization serving the Denver metropolitan area in Colorado. At that time the UDFCD has been cooperating with the U.S. Geological Survey (USGS) to collect simultaneous rainfall and runoff data from 30 of urban catchments. Shortly after joining UDFCD I began to analyze this data in order to develop more reliable urban runoff simulation techniques for the region. As a part of this effort we investigated the "design storm" concept in modeling, developed a regionally calibrated unit hydrograph-based rainfall-runoff model and investigated the effectiveness of a relatively large number of randomly located on-site detention basins in controlling peak flow rates along receiving streams. By 1984, these efforts solidified and supported the concept of detention for flood peak control and resulted in guidance on simplified sizing and design methods for on-site detention in the Denver metropolitan area. The latter were needed to provide local jurisdictions and land developers an equitable and defensible basis for the use of on-site detention throughout the region. The evolution of a "calibrated" design storm concept will be described in this paper followed by its use to study random detention effectiveness. Finally, the most recent ideas concerning water quality management and the management of runoff quantity to mitigate the effects of urbanization on receiving streams and their aquatic habitat will be addressed.

THE DESIGN STORM CONCEPT

Background

The use of *design storms* is very popular among drainage and flood control engineers and, except for continuous simulation and its proponents, had achieved almost universal acceptance. Its use assumes that a design storm of a given recurrence frequency will simulate a runoff peak and volume having the same frequency. Several techniques to develop the *design storm* from rainfall records have evolved or have been proposed in United States and Europe in the 20 years prior to late 1970's, including Keifer, et. al. (1957), Terstriep and Stall (1974), UDFCD (1969) and Federal Highway Administration (1976). All of these techniques were not verified against the statistics of recorded runoff at gauged sites.

The validity of the design storm concept has been questioned by McPherson (1975), since only rainfall data were analyzed, independent of the total rainfall-runoff process,. He pointed out the fallacy of assigning identical frequencies of occurrence to rainfall and runoff when in reality both processes can exhibit statistical non-homogeneity. Marsalek (1978) and Wenzel and Voorhees (1978) concluded that the method used for rainfall distribution is very important in generating realistic runoff peak flows. All had concerns with the validity of extrapolating to less frequent, large storm events, and believed that the accuracy of calculated runoff peaks for floods significantly larger than supported by calibration data were suspect.

Rainfall Analysis in Denver

By mid-1970s All cities and counties in the Denver metropolitan area have adopted the use of the UDFCD's (1969) Urban Storm Drainage Criteria Manual for the planning and design of drainage and flood control facilities. This manual contained rainfall isopluvial maps for 2- trough the 100-year storms in the Denver area. The manual also contained a procedure for converting the isopluvial information into *design storms*. Another set of isopluvial maps were published by the National Oceanic and Atmospheric Administration, NOAA (1973). The two sets of maps did not agree. As a result, disagreements occurred based merely on simple arguments (i.e., "my *design storms* are better than yours") and which were not backed by runoff statistics.

To examine the two design storm sets, 73 largest 30-minute rainfall depths recorded at the Denver gage from 1898 through 1971 were reduced to a lognormal probability plot shown in Figure 1. It also showed two lines representing the same information obtained from the UDFCD and NOAA isopluvial maps. Neither line fits the recorded rainfall data well. Thus, besides often being statistically non-homogeneous with runoff statistics, the *design storms* themselves may originate from information that may not be totally consistent with the rainfall data collected locally. Also shown on Figure 1 are the 7-day antecedent precipitation data corresponding to each of the rainstorm data points. This reveals that the antecedent precipitation in the Denver area is random and does not correlate with larger depths or rare storms. To determine the effects of antecedent precipitation, runoff for a 73-year period were simulated while accounting and not accounting for antecedent moisture conditions.

Runoff Analysis in Denver

Runoff simulation for 73 years of rainfall record were performed using the District's computer model calibrated for each gauged catchment. Detailed (i.e., 5-minute rainfall depths) were used for the largest three rainstorms of each year. For other storms, one-hour rainfall depths were used to save processing time. Keep in mind we did not have PCs in those days.

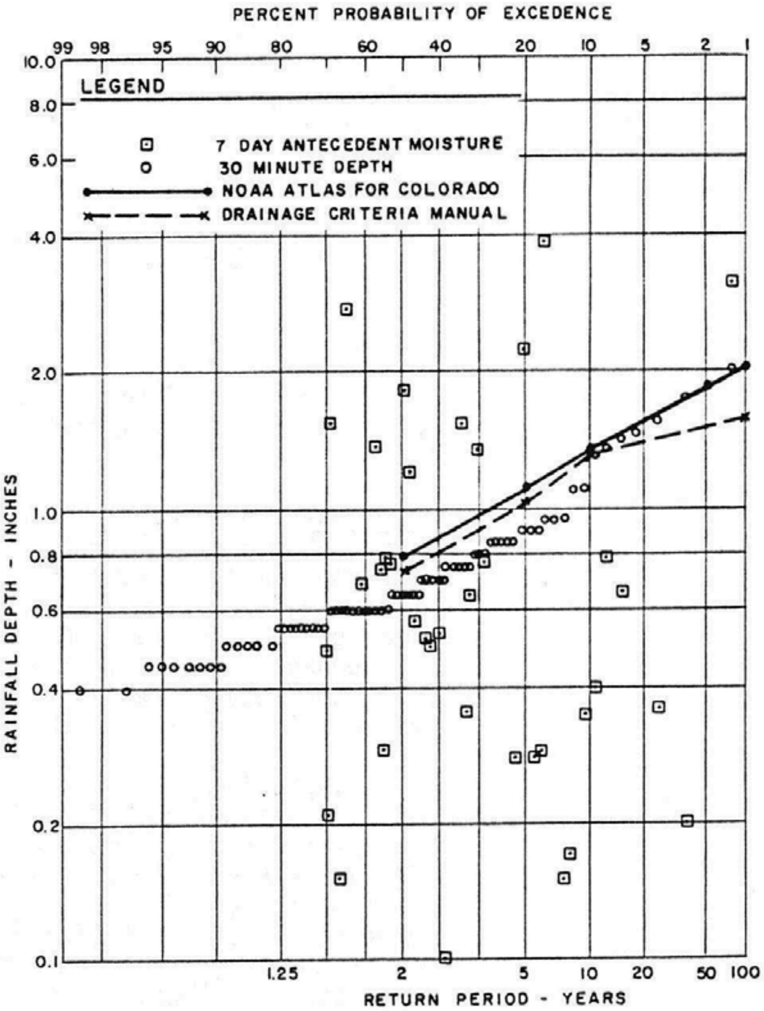

Figure 1. Probability distribution of 30-minute rainfall depths at Denver Raingauge, 1898 - 1971.

As a sideline, these investigations revealed that the urban runoff process, especially for 2-year and smaller storms, is virtually driven by impervious surfaces. We found runoff from impervious surfaces to be very quick and being the primarily cause of peak flow rates in urban catchments. Runoff from pervious areas occurs later in the storm and contributes little to the peak flow. As a result, in urban areas high antecedent moisture can increased runoff volumes from a storm, but appears to have very little impact on peak rates of runoff.

Figure 2 illustrate an example of the relative accuracy of runoff estimates using the two types of *design storms*. One was based on the, DRCOG (i.e., UDFCD Manual's) isopluvials and the other on NOAA Alas isopluvials. What became evident is that *design storms* developed solely from rainfall data can produce significant errors in the peak flows when compared to the statistical distribution of long-term record simulated peak runoff rates. The predominant trend for these *design storms* was to overestimate the peak flow rates. This is not surprising. The statistical analysis of rainfall maximizes all rainfall storm depths for all durations when publishing intensity-duration-frequency curves.

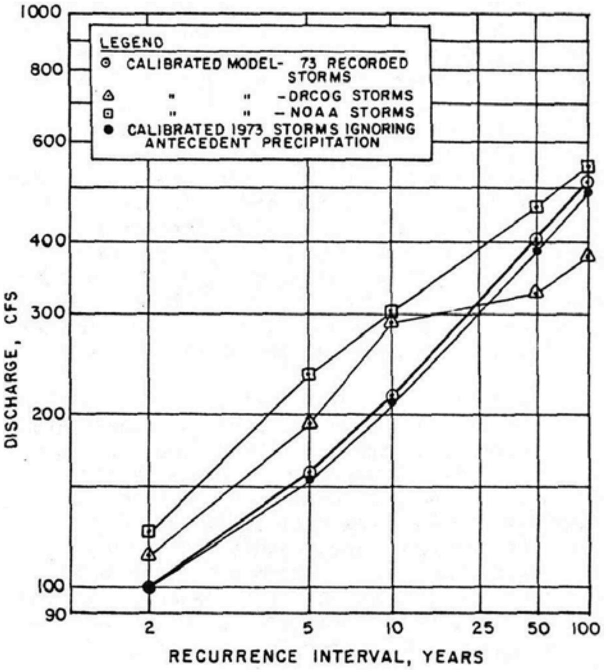

Figure 2. An Example of peak flow probability distribution for the Englewood site

A conclusion that was drawn in early 1980s from all of this is that the random nature of the temporal distribution of rainfall intensities during any storm cannot be represented by a simple *design storm* of a specified recurrence interval. *Design storms* do not represent typical rainstorms found in gauging records, they are a conglomeration of many storms that have occurred in the past. At the same time, the author felt at that time that properly conceived *design storms* can still achieve accurate runoff estimates needed for planning and design projects of urban storm drainage and flood control systems.

Design of a *Design Storm*

To achieve consistency in design my a variety of engineers, the UDFCD recognized the need for a simple, easy to use hydrologic approach that also included *design storms*. Because the NOAA Rainfall Atlas (1973) was more broadly used than the District's Manual, it was chosen as the basis of information for the development of more reliable *design storms*. The one-hour rainfall depths for the various recurrence intervals were taken from the NOAA Atlas and then a temporal rainfall distribution was developed for 2- through 100-year return periods that produced runoff estimates consistent with runoff statistics. Figure 3 illustrates an example of this match for one of the gauging catchments. Similar results were obtained with the same set of design storms at other gauged catchment locations. These tests provided confidence that the hydrology tools used in the Denver region can now produce reasonably accurate storm runoff rates and volumes needed for design and planning purposes. However, no simple universally applicable rule for the design of design storms evolved. It is necessary for each hydrologic region to examine its simultaneously collected rainfall-runoff data, calibrate continuous simulation models, produce long-term simulations of runoff and then design a set of design storms to match the runoff statistics. Only an approach similar to this can yield reliable design storms for using in planning and design of urban storm drainage systems. Also, with the availability of personal computers today and of long-term rainfall records, it is now possible to perform continuous simulations to extrapolate planning and design information provided calibration data are available. This bypasses the need for a design storm.

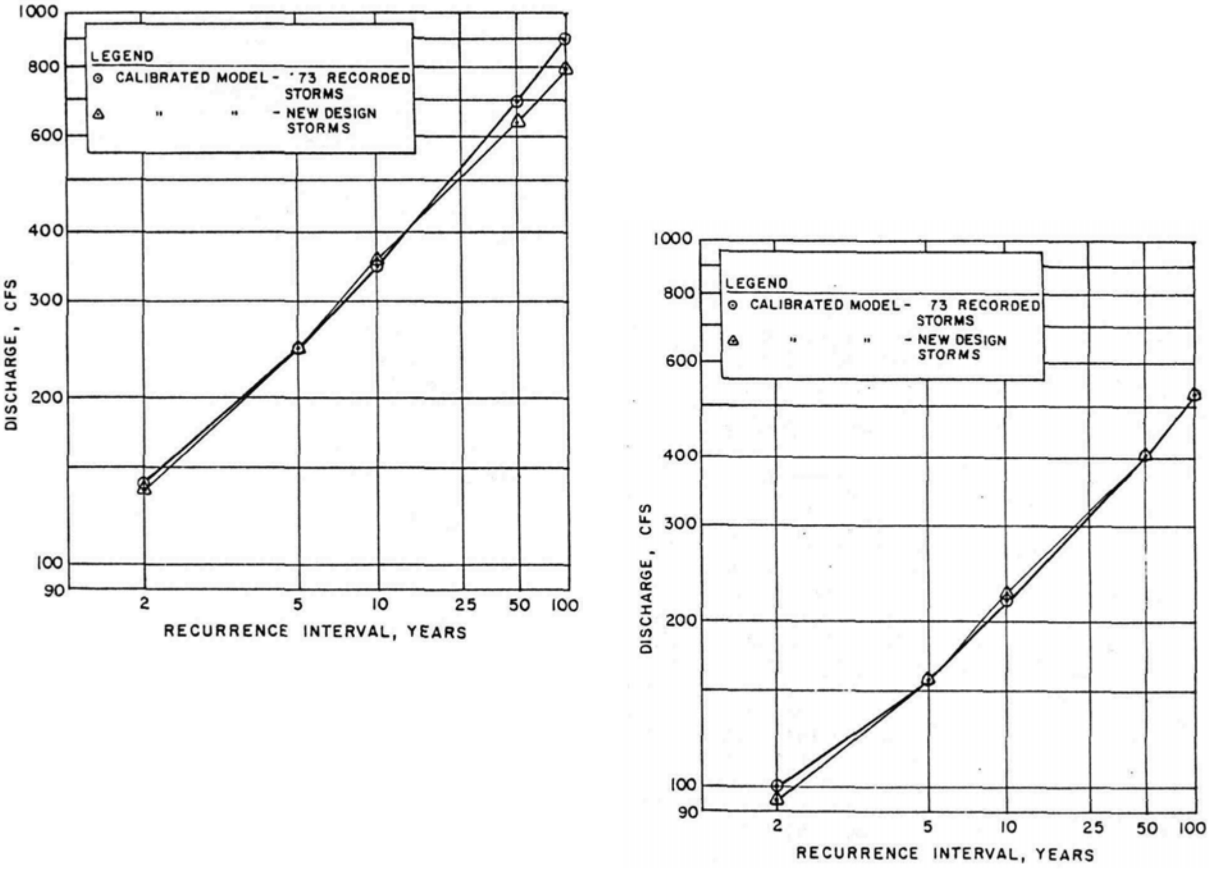

Figure 3. Examples of peak flow distribution at two gauged test sites using new *Design Storms* developed by UDFCD in 1979.

Alternatives to a *Design Storm*

One obvious alternative to the use of *design storms* in the planning and design of stormwater infrastructure is the use of long-term continuous simulation. As was expressed by Marsalek (1978), Wenzel and Voorhees (1978), McPherson (1975) and observed by the author, this requires the use of computer models calibrated over a wide range of storm runoff events to be considered credible, especially when estimating runoff from large storms. Some of the computer models that are currently available make continuous simulation relatively easy to do. However, despite the ease of use of the new tools, continuous simulation requires substantial expertise, time and budget.

Another area of concern with continuous simulation is the use of recorded rainfall data at a point on the ground without a history of each storms spatial distribution. We observed rainfall patterns covering from less that a one to hundreds of square kilometers in area. This diversity is especially pronounced in intense thunderstorms. The emerging high resolution Doppler radar hold promise in addressing this concern, but will require a number of years to collect sufficient data in any region of concern before we have sufficient population to make statistical extrapolations for large events credible. Regardless of how the historic rainfall records areas used, it is also important to recognize that it is a historic record and is not an absolute predictor of the future. In the meantime, engineers need to plan and design stormwater facilities and we, as engineers, need to use our best judgement in what is the most accurate and representative hydrologic tools for each project we face. There still is no magic bullet when it comes to hydrologic modeling!

EFFECTIVENESS OF DETENTION POLICIES

Background

In the 1970s the policy of stormwater detention in urban areas began to be embraced throughout the United States, Canada, Australia and many other countries throughout the world. By 1980 this practice had gained wide appeal. One approach was to require land developers to provide detention as a part of the development process. Although the concept of detention storage has been widely accepted, the questions regarding its effectiveness in managing stormwater runoff persisted. It is easy to study the hydrologic effectiveness of individual detention sites. It is also relatively easy to assess the effectiveness of large, publicly owned regional detention facilities. It is another matter to quantify the effectiveness of a system of randomly occurring on-site facilities. In the 1970s and early 1980s, the most commonly used policy was to limit the 100-year peak flows, with few cities requiring control of either 2-year and 100-year, 5-year and 100-year or 10-year and 100-year peak flows.

McCuen (1974) suggested that the sizing of each on-site detention individually can sometimes increase peak flows downstream instead of reducing the hydrologic impact of urbanization and that a “regional approach” to urban stormwater management is more effective than the on-site approach. Hardt and Burges (1976) suggested that restricting outflow form on-site detention to levels less than the pre-development condition can control downstream peak flow rate to the pre-urbanization rates, but these flows would run for a much greater duration. The increased flow duration may have potentially undesirable effects on the ecology and the geomorphology of natural stream system.

Studies in Denver Area

The UDFCD developed its concerns about the effectiveness of on-site detention in the early 1970s. Although it supported the concept, it could not quantify its effects on the larger receiving waters and creeks. Thus, beginning in late 1970s it conducted a series of studies to assess the "potential effectiveness" of on-site detention along major drainageways.

Experience and rainfall-runoff data in the Denver area show that very little, if any, runoff occurs from 2-year and smaller storms when the land is not urbanized. After the land develops runoff occurs from even rainstorms smaller than the 2-year storm.

The study catchment had an area of 20 square kilometers (7.85 mi^2), length of 4.0 kilometers (6.4 miles) and an average watershed slope of 0.015m/m. Its shape and drainage patterns are shown on Figure 4. Only 1.9% of the area was impervious before land development began. After full development, the watershed area was projected to be 38 percent impervious. Runoff was modeled for the 2-, 10-, and 100-year recurrence intervals under the stationary and moving storm scenarios. Although the reported results here are for the stationary design storm scenarios, the effect of stormwater detention with moving storms was found to be similar. It is important to stress that conclusions resulting from this study should not be extrapolated to catchment sizes much larger than the one studied. The catchment was subdivided into 56 sub-catchments and 52 channel segments. The computer model was run without and then with 28 randomly located detention basins that intercepted 91 percent of the total catchment’s area. Each basin was sized on the basis of the hydrographs for the pre-and post-developed conditions. Glidden (1981) reported the detailed findings in his Masters of Science thesis.

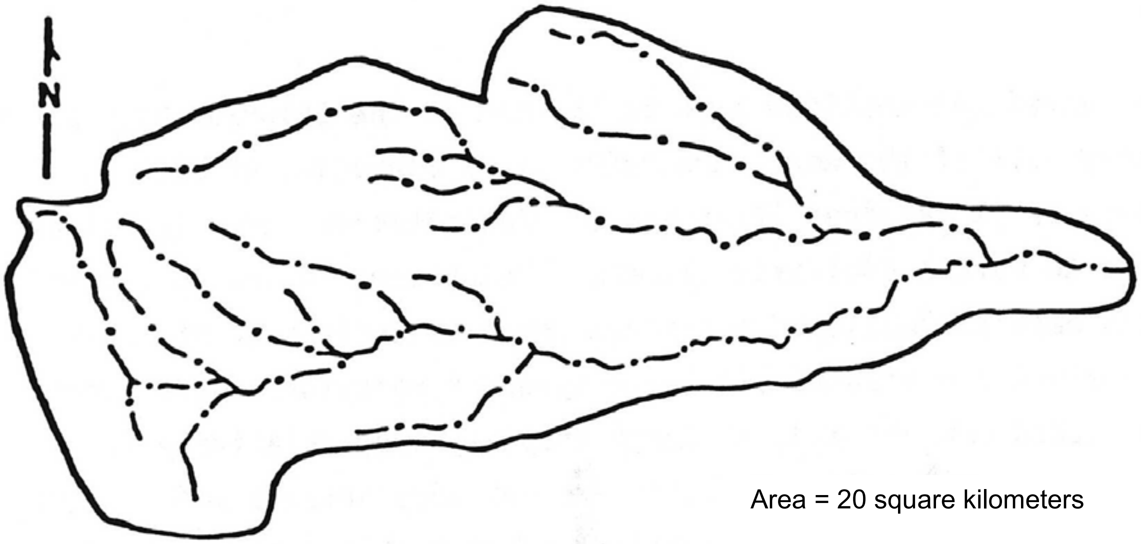

Figure 4. On-site detention effectiveness study catchment in the Denver area.

Figures 4, 5 and 6 show the trend of theses findings. Note that the size of the watershed is related to the non-dimensional change in peak flow. A value of "one" on the ordinate represents no change from the pre-developed condition and a value of "two" represent doubling of peak flows rate. Examination of these figures reveals the following trends:

1. The 2-year random detention basin design was effective in controlling the 2-year peak flows at individual basin sites only. As the number of basins increased with increasing tributary area, the 2-year design rapidly diminished in effectiveness in controlling the 2-year peak. The 2-year design somewhat reduced the 10-year and the 100-year storm runoff peaks.

2. The 10-year random detention pond designs were relatively effective in limiting runoff peaks

3. The 100-year design was effective in controlling the 100-year peaks but was virtually ineffective in controlling the 2- and 10-year storms.

4. The combination 10- and 100-year control design was effective in controlling the 10- and 100-year peaks, but was ineffective in controlling the 2-year storm peaks. The dual frequency design appears to be more effective in controlling a wider range of flood peaks than a single peak control policy. Extrapolating this, a multi-frequency control policy should be even more effective, but probably there are practical limits to the number of control stages that can be used. The author suggest considering three outlet control level, one for small events, one for moderate and one for large ones such as the 100-year flood.

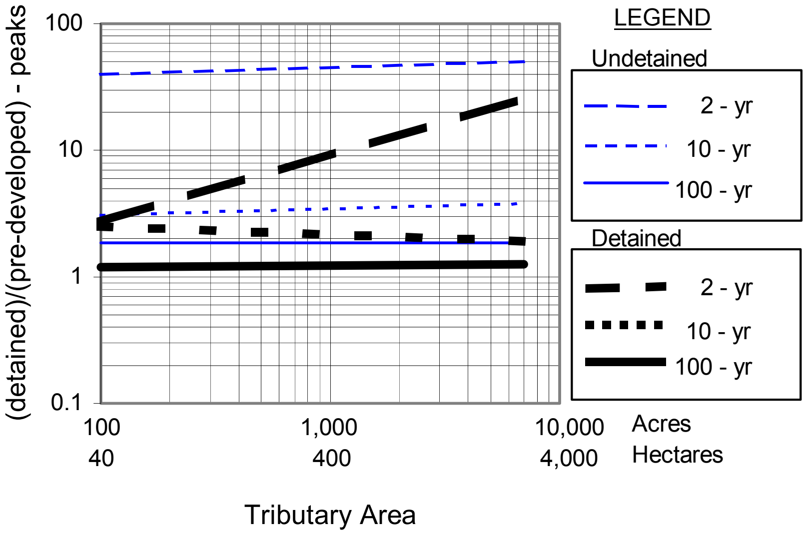

Figure 4. Effects of 2-year detention policy on peak flows along major drainageway

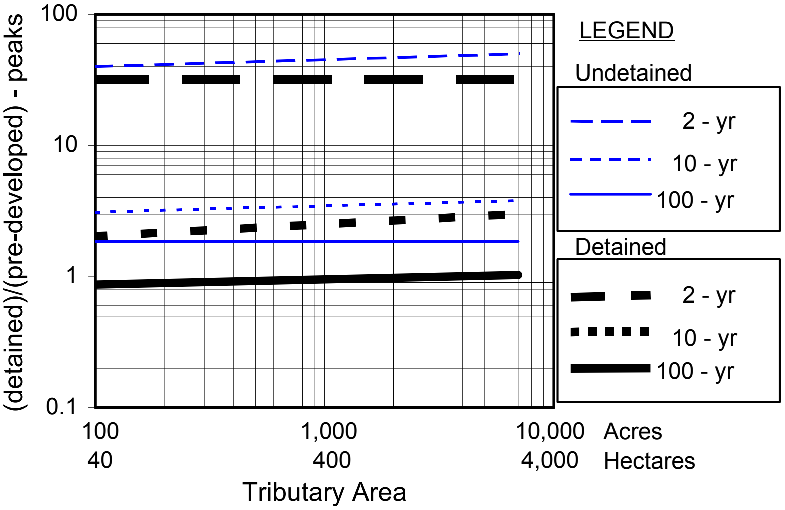

Figure 5. Effects of 100-year detention policy on peak flows along major drainageway

Developing Simplified Regional Criteria

The UDFCD also investigated developing simplified detention design criteria for the Denver region that does not require each moderately-sized land development site (i.e., less than 2 km^2) to perform extensive hydrologic calculations to size its detention basins. One valid concern was that the simplified local detention requirements take away the "creativity" from the designer. Although simplified detention requirements may not permit "optimization" for each on-site detention facility, they offer the advantages of simplicity, uniformity, and consistency. From the land developer's perspective, they offer equal treatment where all developments know early in their planning process what detention volumes and areas will have to be incorporated into a site.

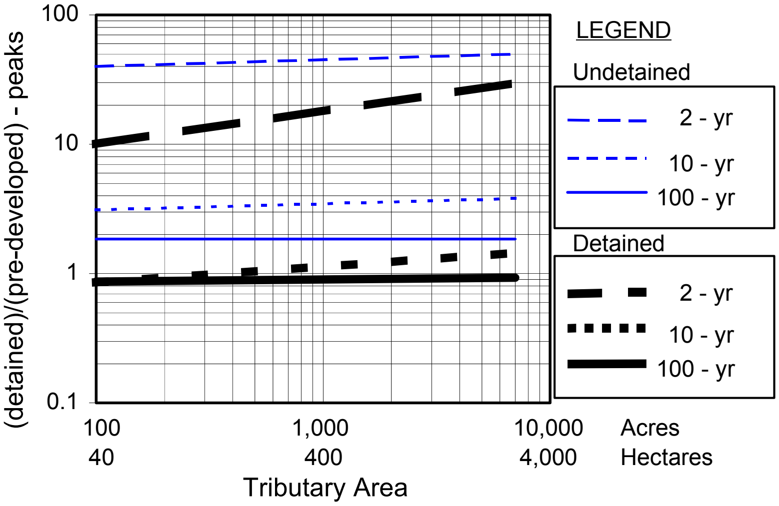

Figure 6. Effects of 10 & 100-year detention policy on peak flows along major drainageway

Simple equations were developed for the Denver area for detention sizing. Extensive testing confirmed that they, on the average, produced peak flow trends along major drainageways similar to the ones obtained using the rigorous analysis of each detention site. To illutrate their simplicity, as an example the 10-year control Volume (V_{10}) and allowable maximum release rate (Q_{10}) are given by the following equation. Similar relationships were developed for the 5- and 100-year volumes and allowable release rates as well.

$$V_{10} = (0.95 \cdot I - 1.9) \cdot A \div 1000 \tag{1}$$

$$Q_{10} = 0.24 \cdot A \tag{2}$$

in which, I = tributary catchment imperviousness in percent, and
A = tributary catchment area

Analysis of the 10-year and 100-year designs based on the simplified equations revealed the following trends in their use within the Denver area:

1. The 10- and 100-year designs using simplified regional sizing equations controlled peak flows along major drainageways almost as well as the rigorous individual designs.

2. The 10-year design based on simplified equations was less effective in controlling the 100-year peak storm flows than the rigorous 10-year design scenario.

3. The 100-year design based on simplified equations was more effective in controlling the 10-year peak storm flows than the rigorous 100-year design scenario.

4. The combined 10-year and 100-year design based on simplified equations was equivalent in controlling the 10-year and 100-year as was obtained using designs based on rigorous analysis.

Although the peak flow trends along the major drainageways were duplicated very well by the simplified design equations, there were detention basins in the system that had spillway. This was not considered a major concern since infrequent overflows were well within the accuracy of hydrologic projections. Nevertheless, the author cautions that it is up to the designer to provide safe overflow paths downstream of the basins.

STORMWATER QUALITY MANAGEMENT HYDROLOGY

Background

When we begin to examine the hydrology for the management of stormwater quality and for judging the impacts of urbanization on the receiving water system from ecological perspective, our hydrologic thinking has to shift dramatically. Hydrologists have traditionally addressed hydrologic extremes (i.e., infrequent events such as 2-, 5-. 10-year, etc. flows). This was done for the design of drainage and flood protection systems to provide for public safety. These are not the runoff events that have the greatest influence on geomorphic stability of streams or on their aquatic life and habitat.

After studying the precipitation records and runoff capture needs in the Denver area for water quality purposes, Urbonas et al. (1990), reported a point of "optimized" runoff capture volume (see figure 7). They also found that doubling this volume increased annual removal efficiencies of total suspended solids from urban runoff only by three percent, namely, increasing the capture volume beyond this point has little water quality benefit. Later Urbonas and Stahre (1993) redefined this point as the "maximized" volume, because it is the point where rapidly diminishing returns in the number of runoff events captured begins to occur with increasing capture volume.

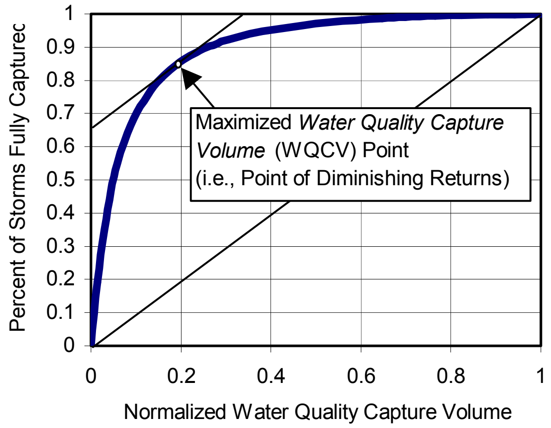

Figure 7. Point of water quality capture volume optimization. Ref.: Urbonas et at. (1990)

This "optimized" point is also evident on the six curves in Figure 8. Long-term simulations of runoff were examined by Roesner et al. (1991) for six cities in USA, namely, Butte, MT, Chattanooga, TN, Cincinnati, OH, Detroit, MI, San Francisco, CA, and Tucson, AZ using STORM (i.e., Storage, Treatment, Overflow, Runoff Model). In this study they used 24-hour drain time to empty the detention basins. Hourly precipitation records of 40 to 60 years were processed for a variety of detention basin sizes for the six cities. What they concluded is that 25 watershed millimeters (1.0 inch), namely, 254 cubic meters per hectare (0.08 ac-ft per acre) of storage captured over 90 percent of all runoff volume at all sites. Clearly, the largest numbers of runoff events in urban areas occur from small storms and it is these smaller events that have most impact on the receiving water ecology

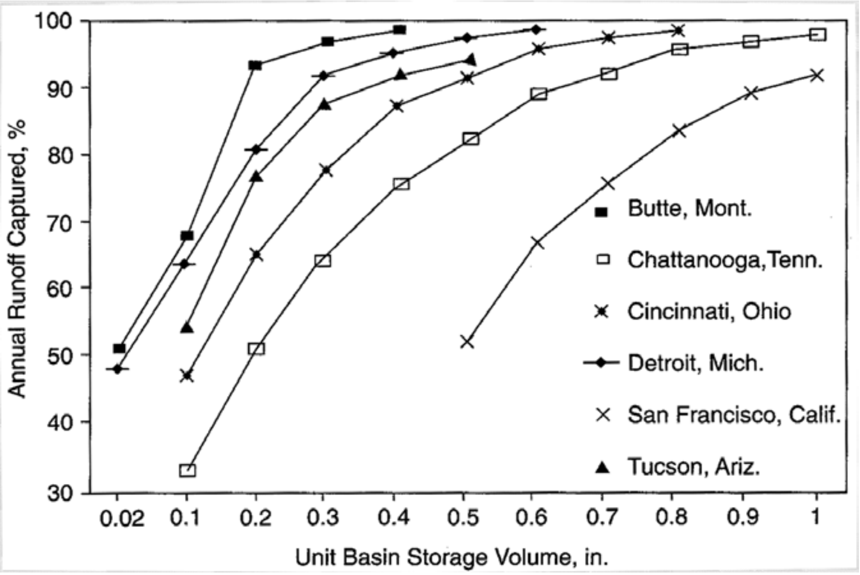

Figure 8. Runoff capture rates vs. unit storage volume at six cities. Ref.: Roesner et al. (1991)

Estimating a Maximized Water Quality Capture Volume

Whenever local resources permit, the stormwater quality capture volume is best found using continuous hydrologic simulation and local long-term hourly, or lesser time increment, precipitation records. However, Guo and Urbonas (1995), after analyzing a number of long-term precipitation records throughout the United States, found that it is possible to obtain very good first-order estimate of the needed capture volume using a very simple procedure. The simple regression, namely Equation 3 relates the *mean precipitation depth* at any location in USA (See figure 9) to *maximized* runoff capture volume. The coefficients of determination, r^2, range from 0.80 to 0.97, depending on the basins emptying time, for this simple equation. This implies a strong level of reliability. These mean depths shown in Figure 9 are based on a 6-hour inter-event time to define a new storm and a minimum depth of 2.5 millimeters (0.1 inches) of precipitation for a storm to produce incipient runoff.

$$P_o = (a \cdot C) \cdot P_6 \qquad (3)$$

in which, P_o = *maximized* detention volume in watershed millimeters (inches)
P_6 = *mean storm volume* taken from Figure 8 in watershed millimeters (inches)
C = watershed runoff coefficient, and
a = a regression constant taken form Table 1.

Table 1. Coefficient *a* for the *Maximized* water quality capture volume in Equation 3. Ref.: Guo and Urbonas (1996)

12- hour Brim-full emptying time	24- hour Brim-full emptying time	48- hour Brim-full emptying time
1.109	1.299	1.545

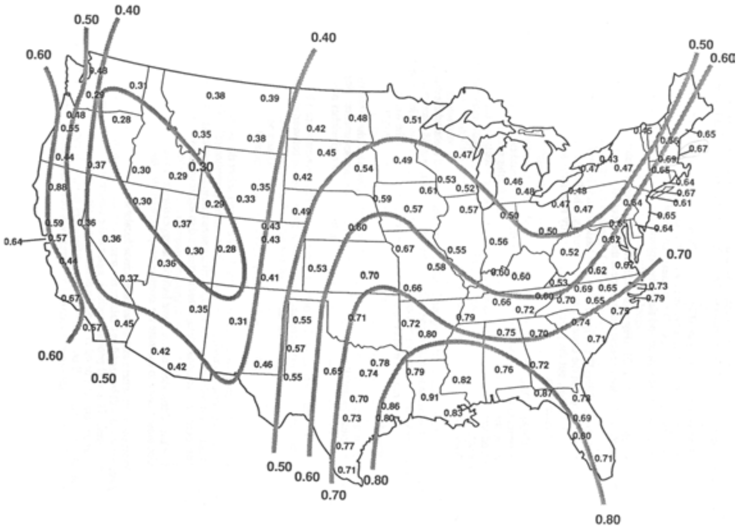

Figure 9. Mean storm precipitation depths, P_6, in United States in inches. Ref.: Driscoll et al., 1989.

The analytical procedure to derive this relationship required the transformation of each recorded storm's precipitation to a runoff volume using a coefficient of runoff, which was found to be well represented by a third order regression Equation 4. Urbonas, Guo and Tucker (1990) using EPA (1983) data collected at more than 60 urban watersheds in United States derived this. This equation should have broad applicability for estimating runoff from smaller storm events (i.e., 2-year and less) and fits well with the water quality design goals.

$$C = 0.858\, i^3 - 0.78\, i^2 + 0.774\, i + 0.04 \qquad (r^2 = 0.72) \qquad (4)$$

in which, C = runoff coefficient, and
i = watershed imperviousness ratio (i.e., % imperviousness÷100).

For these relatively small water quality detention facilities, runoff volumes that exceed the design volume either bypass the facility or receive less efficient treatment. If the design volume is much larger and it emptying time as does the smaller basin, the smallest runoff events will be detained only for a brief interval by the larger outlet. As a result, oversizing water quality detention basins can cause the less annual treatment than provided by the *maximized* volume basins.

SOME EXAMPLES OF DETETENTION FACILITIES

The following five figures are presented here to give the reader a taste of the flavor of urban stormwater detention facilities. These encompass a variety of urban setting in the Denver area. Although there are examples of detention basins that are not well integrated into the urban fabric and can be considered to be not an asset to the community, the figures show examples of detention facilities that provide an aesthetic fit and a public function, such as parks, within the developments they serve. Figure 10 illustrates a detention basin within the central business district of Denver and also serves a plaza–park for this very dense commercial district. It is almost ½ kilometer in length and about 10 meter in width and is located between several streets. Its function is to detain flows for up to the 100-year storm and release the water at a rate compatible with the capacity of the downstream storm sewers. During dry weather periods it provides a pleasant environment for the shoppers, business people and workers to rest, walk, eat lunch, socialize, etc.

Figure 10. Denver Skyline Park detention basin.

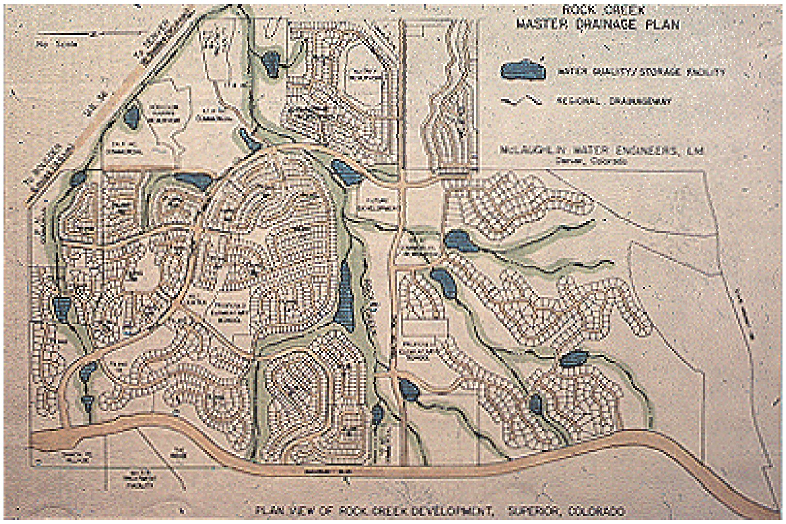

Figure 11. Master Plan for Rock Creek developments in Superior, Colorado (note detention basins).

Figure 12. Photograph of a portion the Rock Creek development in 1996 in Superior, Colorado.

Figure 13. A detention basin with a pond at an apartment complex in Aurora, Colorado.

Figure 14. A dry detention basin next to a MacDonalds Hamburger facility in Littleton, Colorado

Figure 15 is a photograph of a detention facility with a small lake in Lakewood, Colorado. The flood routing volume is above the permanent water surface of the lake. The lake and the adjacent gardens, playing fields and picnic grounds are the main feature the public sees, not that this is a detention basin.

Figure 15. A detention facility with a small lake in a public park in Lakewood, Colorado.

CLOSING THOUGHTS AND OBSERVATIONS

The field of urban stormwater runoff management has advance dramatically since the late 1960s. Since then we have seen the development of computer models that can simulate the hydrology of an entire urban stormwater drainage system. Some of these models offer continuous simulation capabilities that promise the demise in the use of the "design storm" in system planning and design. However, despite these promises, the need for regionally calibrated stormwater runoff models continues to be needed. That is because many of the high-powered models available today require significant amount of simultaneous rainfall-runoff data to calibrate. When they are calibrated, the question persists if the extrapolations beyond the calibration range are valid. The other drawback of some of these models is that they require more geometric date than can be collected and input into the model during most planning efforts to provide the accuracy being claimed. Although these models function with lumped geometric data, their accuracy becomes more suspect as bigger and bigger sub-catchments of an urban watershed are used to simulate the systems and the availability of calibrating data becomes much more important.

Development of Regionally Calibrated Hydrologic Tools

What evolved in the Denver region was a calibrated, simple unit hydrograph model that provided consistently accurate results. This runoff model was combined with a system flood routing model that permits analysis of very complex systems and their response. In addition, it was found that a set of *design storms* could be developed that produce runoff peaks and volumes approximating those obtained using long-term runoff record and long-term runoff simulations using a calibrated model. Their development, however, needs to be based on long-term runoff statistical targets that aim to have, fro example, the 10-year *design storm* actually produce a 10-year runoff peak flow. The combination of these regionally calibrated hydrologic tools permits reliable and efficient planning of systems for the future, mitigation of existing problems and the design of drainage and flood control projects.

Use of Stormwater Detention in Urban Systems

The use of stormwater detention in urban systems has gained wide acceptance throughout the United States, Europe, Australia and New Zealand and in many other parts of the world. It is a concept that is based on the principle that as land urbanize, their effects on stormwater runoff and stream ecology need to be mitigated by the parties responsible for the change in the land use. Building of ever increasing conveyance systems has shown to have its limits and counterproductive from the ecological perspective. At that the conveyance approach alone does is transfer flooding problems to downstream property owners. Detention facilities can be large-regional ones or small on-site facilities. In addition, source controls of runoff that reduce its volume, such as infiltration basins, porous pavement, swales, etc. can further mitigate the effects of urbanization on downstream receiving systems.

The effectiveness of on-site detention on the receiving water from larger catchments was studied in Denver. The findings showed that on-site detention could be designed to be very effective for limiting the effects on the receiving water of larger runoff events, somewhat effective in limiting the runoff from smaller storms such as the 5- to 10-year storm and of questionable effectiveness for very small storms. It is for this reason that source controls to reduce runoff rates and, possibly, volumes from small events are necessary to provide meaningful mitigation of effects on receiving system ecology.

Stormwater Quality Hydrology

What has emerged in recent years is that source controls to significantly reduce runoff rates and volumes from small events in urban areas are necessary to mitigate the effects on receiving system ecology. The study of rainstorm depth patterns throughout the United States revealed that the predominant numbers of runoff producing storm are relatively small to what drainage engineers use to design storm runoff management systems. It was also discovered that a point of diminishing returns was evident at all rain gauge sites and that increasing volumes of capture for water quality mitigation purposes was not very effective after this point was passed.

As engineers we need to recognize that it is the small, frequently occurring events that the stream, rive, lake, estuary, etc. see and are impacted by most often. The effect of uncontrolled urbanization of the receiving water systems is accelerated stream erosion, accelerated deposition of sediment in lakes and estuaries, the silting in of spawning beds and of micro invertebrate habitats, and the increased delivery of pollutants. A simple method was proposed and now has been adopted by the American Society of Civil Engineers and the Water Environment Federation in their joint Manual of Practice on stormwater quality management.

The challenges for the future are great and varied. We will continue to be challenged to solve drainage and flooding problems in our urban centers. No one single tool will accomplish this and will require a combination of practices such as conveyance systems in combination with detention and source controls. In addition, the ever-increasing demand for the protection of the environment will demand that we address the effects of urban stormwater runoff on the receiving systems ecology. This will be a moving target as new laws; policies, rules and regulations emerge with the intent of ecosystem protection and with little regard to technical and physical limitations. We see this trend in United States and some other countries, especially in Europe, New Zealand and Australia. It is only a matter of time before it is widespread throughout the world. Planning for and anticipating these emerging trends is recommended so that future systems can accommodate them. This will require thinking of urban systems as a part of the whole watershed system and how it interrelates with the ecological protection needs.

References

EPA (1983). *Results of the Nationwide Urban Runoff Program, Final Report*, U.S. Environmental Protection Agency, NTIS No. PB84-185545, Washington, DC.

Federal Highway Administration (1976). *Urban Storm Runoff Inlet Hydrograph Study*, *Vol. 4 - Synthetic Storms for Design of Urban Highway Drainage Facilities*, Report No. FHWA-RD76-119, Washington, D.C.

Glidden, M. W. (1981). *The Effects of Stormwater Detention Policies on Peak Flows in Major Drainageways*, Master of Science Thesis, Department of Civil Engineering, University of Colorado at Denver, Denver Colorado.

Guo, J.C.Y. and Urbonas, B. (1996). “Maximized Detention Volume Determined by Runoff Capture Ratio,” *J. Water Resources Planning and Management*, January/February.

Hardt, R. A. and Burges, S. J. (1976). "Some Consequences of Area Wide Runoff Control Strategies In Urban Watersheds", *Technical Release No. 48, Charles W. Harris Hydraulics Laboratory*, University of Washington, Seattle, WA, June, NTIS PB-261258.

Keifer, Clint J. and Henry Hsien Chu (1957). "Synthetic Storm Pattern For Drainage Design," *J. Hyd. Div.*, *ASCE Proc.*, Vol. 83, American Society of Civil Engineers, Reston, VA, August.

Marsalek, J. (1978). "Research on the Design Storm Concept", *ASCE Urban Water Resources Research Program*, TIM No. 33, September.

McCuen, R. H. (1974). "A Regional Approach To Urban Stormwater Detention", *Geophysical Research Letters*, 74-128, p. 321 - 322, November.

McPherson, M.B. (1975). "Special Characteristics of Urban Hydrology," *Prediction in Catchment Hydrology*, pp. 239-255, Australian Academy of Science, Canberra, ACT,.

McPherson, M.B. (1976). "Urban Hydrology: New Concepts in Hydrology for Urban Areas," *Notes for Presentation at Northwest Bridge Engineering Seminar*, Olympia, Washington.

NOAA (1973). *Precipitation-Frequency Atlas of the Western United States*, *Volume III - Colorado*, National Oceanic and Atmospheric Administration, Silver Springs, Maryland.

Terstriep, M.L., and J.B. Stall (1974). *The Illinois Urban Drainage Area Simulator*, ILLUDAS, Bulletin 58, Illinois State Water Survey, Urbana.

UDFCD (1969). *Urban Storm Drainage Criteria Manual*, Volume 1, Rainfall Section, Urban Drainage and Flood Control District, Denver, Colorado.

Urbonas, B. and Stahre, P. (1993). *STORMWATER - Best Management Practices and Detention*, Prentice Hall, Englewood Cliffs, NJ.

Urbonas, B., Roesner, L.A., and Guo, C.Y. (1996). “Hydrology for Optimal Sizing of Urban Runoff Treatment Control Systems,” *Water Quality International*, International Association for Water Quality, London, England.

Urbonas, B.R., Guo, C.Y. and Tucker, L.S. (1990). “Optimization of Stormwater Quality Capture Volume,” *Urban Stormwater Quality Enhancement*, Am. Soc. of Civil Engr., New York, NY.

Wenzel, Jr. H.G. and Voorhees, M.L., (1978). "Evaluation of the Design Storm Concept", Presented at the AGU Fall Meeting, San Francisco, California, December,.