Peak Flow Control for Full Spectrum of Design Storms

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Introduction

Background

Roofs, streets, parking lots, sidewalks, and other impervious surfaces that are part of the urban fabric increase the amount of stormwater surface runoff when compared to pre-development conditions. One of the primary goals of providing stormwater detention for years has been to address these increases in runoff by controlling peak stormwater runoff flow rates in downstream reaches. Although the knowledge of how to accomplish that goal for individual sites is understood, the effects of multiple detention basins in urban areas were not.

This topic was studied in the past by various investigators (e.g., McCuen, 1974; Hardt and Burges, 1976) for climates other than Colorado. Glidden (1981) and Urbonas and Glidden (1983) presented their findings of a modeling study that looked at the conditions in the Denver area. Their findings resulted in simplified equations for the sizing of on-site detention basins that were incorporated into Volume 2 of the Urban Storm Drainage Criteria Manual (USDCM) (UDFCD, 2001). However, these equations and other, so-called "simplified" methods in the USDCM, are limited in that they address the sizing of one return period at a time. They are of not much help in estimating the total detention storage volume requirements when multiple design storm events need to be controlled by the same facility.

The findings in the early 1980s by Urbonas and Glidden (1983) also revealed that it was possible to achieve pre-development peak flows in the downstream receiving waters for the larger design storms using randomly distributed on-site detention basins. It was also possible to design basins to control the 2-year storm releases to pre-developed levels just downstream of each basin, but as the watershed increased in size and the numbers of on-site basins also increased, the peak flows in the receiving waters were not being controlled to pre-development levels. It was concluded that this was the result of increases in post-urbanization runoff volumes.

When hydrographs are individually released from detention basins at low flow rates over extended periods of time, their flows add to each other as they travel downstream, resulting in increasing peak flows along the receiving waters as the urbanized watershed sizes served by on-site detention basins get bigger. Urbonas and Glidden (1993) concluded that merely controlling the peak runoff rates for the 2-year and smaller storm events did not control the peak flow rates along the receiving waters in the Denver area to pre-development levels. Something more had to be done.

Recent Technical Developments in Denver Area

The Urban Drainage and Flood Control District (UDFCD) in 1992 published Volume 3 of the USDCM, which was completely updated in 1999 (UDFCD, 1992 & 1999). This manual officially recognized, for the first time in the Denver area, the need to reduce to the maximum extent practicable the stormwater surface runoff volumes and flow rates that occur during large number of small storms from urban land uses as opposed to just controlling the peak flow rates from the larger events such as the 5- through 100-year storms. Smaller runoff events were not being controlled by the detention practices being recommended up to that time. Volume 3 of the USDCM attempted to fill this shortcoming by recommending Best Management Practices (BMPs) that include a Water Quality Capture Volume (*WQCV*) and a requirement that this volume be released volume over an extended period of time.

Some, but not all of the BMPs recommended in Volume 3 of the USDCM will not reduce runoff volumes, but they do reduce the energy and forces in the receiving waters that can cause geomorphic changes when lands urbanize. Thus, although the technical criteria in Volume 3 of the USDCM have improved the attenuation of the wet-weather peak flows resulting from small, frequently occurring events, some of the shortcomings discussed above still remain, namely, increases in runoff volumes, numbers of runoff events, flow rates and flow durations seen in the receiving waters.

Need for Improved Detention Sizing Practices

The profound geomorphic changes observed in local ephemeral, intermittent and perennial receiving gulches and streams clearly indicated the need to better control the frequently occurring smaller runoff events. Figure 1 illustrates a very common symptom of urbanization seen along ephemeral waterways, namely rapid degradation and bank erosion. It is expected that degradation will occur at reduced rates and, possibly, to lesser levels if runoff volume and peak rate are kept closer to predevelopment conditions.

Figure 1. Typical stream degradation in Denver area after a watershed urbanizes.

To have a chance at reducing stream degradation, better design guidance for stormwater detention basins is needed. The goal of such guidance would be to achieve peak flows close to pre-development conditions for the full spectrum of runoff events with greater confidence. While more robust and reliable detention designs can reduce the rates and extent of damages seen along receiving waters, it is not expected that implementing such designs can totally eliminate stream erosion and degradation, namely geomorphic changes in the receiving waters. In-stream measures will still be needed to keep the receiving waterways from excessive degradation and loss aquatic habitat or ecological function.

Full Spectrum Detention

In response to this need, different approaches toward designing stormwater detention were modeled. Although the testing was done using the design storm concepts employed by the UDFCD for the Denver area of Colorado, the underlying principles are sound and can prove to be the basis for developing similar design protocols in other hydrologic regimes. The stormwater detention design concept that best achieved the intent of controlling flow rates to pre-developed conditions for the full spectrum of design storms is presented next. It appears to provide designs that show promise in controlling stormwater peak flow rates along receiving waters for the full spectrum of runoff events from the smallest, such as one generated by the *mean storm*, up to the 100-year event.

This new design approach is termed *full-spectrum detention* and is based on the following:

1. The urban stormwater hydrology methods and detention sizing protocols as recommended by the USDCM are the basis for the findings and conclusions expressed in this paper. Other findings may be the case if other analysis methods are use. However, these findings are considered representative when looking for relative comparisons of detention effectiveness in the Denver area using the sizing and release requirements recommended in the USDCM.

2. The difference between urban runoff volume and predevelopment volume, called *excess urban runoff volume,* appears to be relatively consistent for a wide range of design storm sizes at any given level of imperviousness. When this *excess urban runoff volume* is captured and held back for an extended period, the remaining runoff from a site approximates the runoff volume for predevelopment conditions.

3. The first stage of a two-stage *full-spectrum detention* basin will capture the *excess urban runoff volume*. The release rate for this first stage is very slow to reduce the energy of flow in receiving streams. A 70-hour drain time was selected for this volume because it is an extrapolation of the 40-hour drain time used for the WQCV for a perforated plate outlet. For C/D soils the *excess urban runoff volume* is about twice the 40-hour drain time *WQCV* recommended in the USDCM.

4. The upper stage of a *full-spectrum detention* basin is sized to control the pre-development 100-year peak flow rate from the tributary sub-watershed. When using the design guidance for the Denver area, the total *full-spectrum detention* volume approximates the volume required currently to control the 100-year plus the *WQCV* with the recommended 20-percent of WQCV sediment storage. *Full-spectrum detention* sizing appears to require less total volume than the current sizing methods require for sites with imperviousness exceeding 50-percent.

5. The suggested *full-spectrum detention* sizing protocols were analyzed using site characteristics with various NRCS Hydrologic Soil Types while recognizing the variations in pre-development runoff rates and *excess urban runoff volumes* for different soil types.

In addition to meeting the goal of matching pre-development peak flow rates of runoff; UDFCD recommends reducing the runoff volumes from urban areas to the maximum extent practicable. This can be done through the use of practices that minimize directly connected impervious area (MDCIA) and other practices recommended in Volume 3 of the USDCM (e.g., porous landscape detention, porous pavement, etc.). The use of such practices can reduce *excess urban runoff volume* for a site and, as a result, the required size of detention facilities.

A recent analysis by Strecker et. al., (2004) of the data in the International BMP Database revealed losses in average annual surface runoff volumes for extended detention basins. Thus, additional reductions in *excess urban runoff volume* are possible from the use of *full-spectrum detention* since it brings its first stage into contact with vegetation and soil for extended periods, thus encouraging infiltration.

Analysis Methodology

Condition Modeled

To test the efficacy of *full-spectrum detention* sizing protocols, an example 5,000-acre watershed was created using 50 identical 100-acre sub-watersheds (Figure 2).

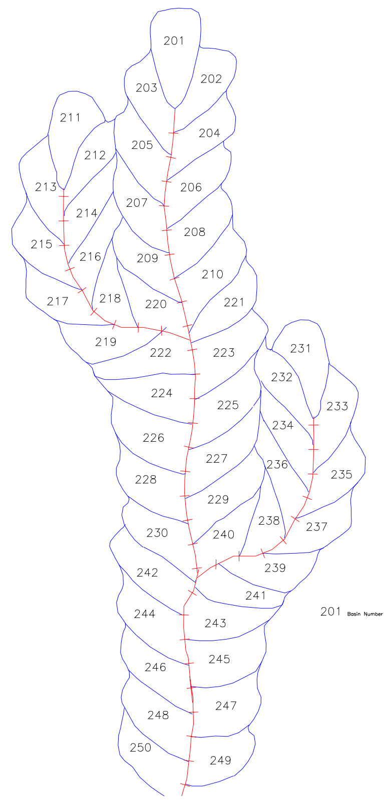


Figure 2. Example 5,000-acre watershed.

Imperviousness of 2% was used to represent the typical pre-development conditions found in the Denver region. The Colorado Urban Hydrograph Procedure (CUHP) was used to simulate the runoff using infiltration rates, decay coefficients, shape and slope parameters to yield 100-year peak discharges of 0.5, 0.85, and 1.00 cfs/acre for NRCS Hydrologic Soil Group A, B, and C/D, respectively (i.e., the recommended unit flow release rates in the USDCM). Appendix A shows representative subwatershed and channel routing parameters.

The CUHP model was then run using two small design storms that had total rainfall depths of 0.50- and 0.60-inches and six standard design storms with return periods of 2-, 5-, 10-, 25-, 50- and 100-years, ten different impervious values (i.e., 2%, 5%, 15%, 25%, 30%, 35%, 40%, 50%, 75% and 100%), and three different NRCS Hydrologic Soil Groups (A, B, C/D). The resultant runoff volumes for Soil Group C/D are summarized in Figure 3. Similar charts were prepared for Soil Groups A and B.

Excess Urban Runoff Volume

The *excess urban runoff volume* was estimated by subtracting pre-development runoff volume from the runoff volume estimated using the imperviousness values listed above. These findings for Soil Group C/D are shown in Figure 4. Best-fit lines were used to find equations to describe the *excess urban runoff volume* curves as functions of imperviousness. To obtain a representative estimate of *excess urban runoff volume* for the simulated range of storm events, an average *excess urban runoff volume* found for the 2-, 5-, 10-, and 100-year design storms was used. It was assumed that the WQCV is a part of this *excess urban runoff volume*. The UDSWM program was used to combine and flow-route the runoff from all of the sub-watersheds.

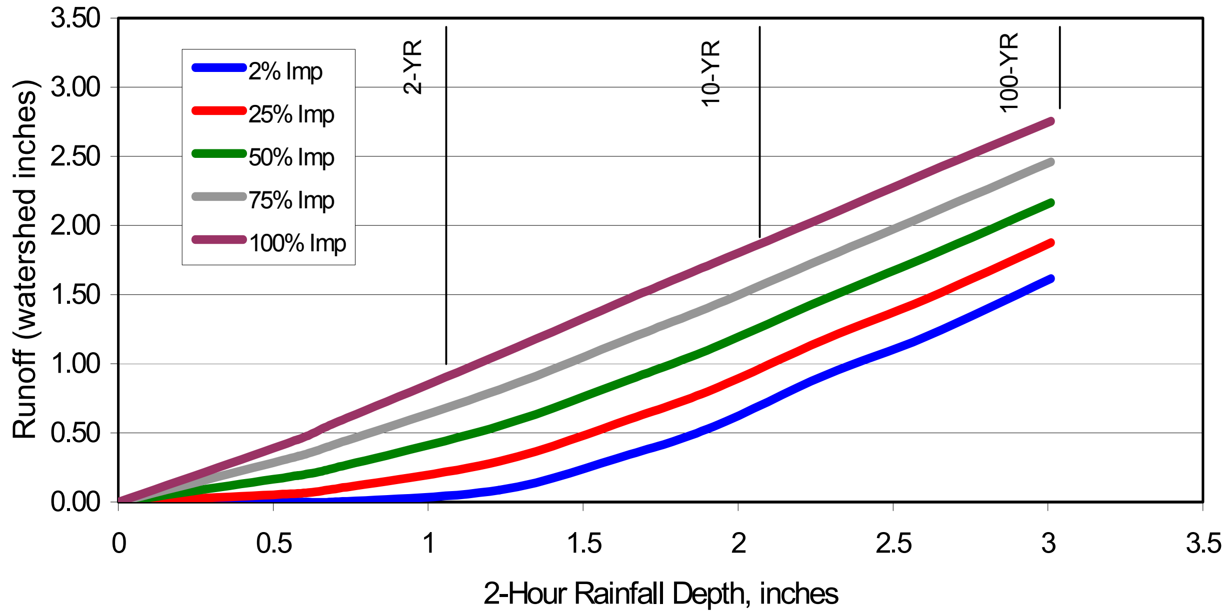


Figure 3. Runoff volume vs. 2-hour Rainfall Depth for Hydrologic Soil Group C/D.

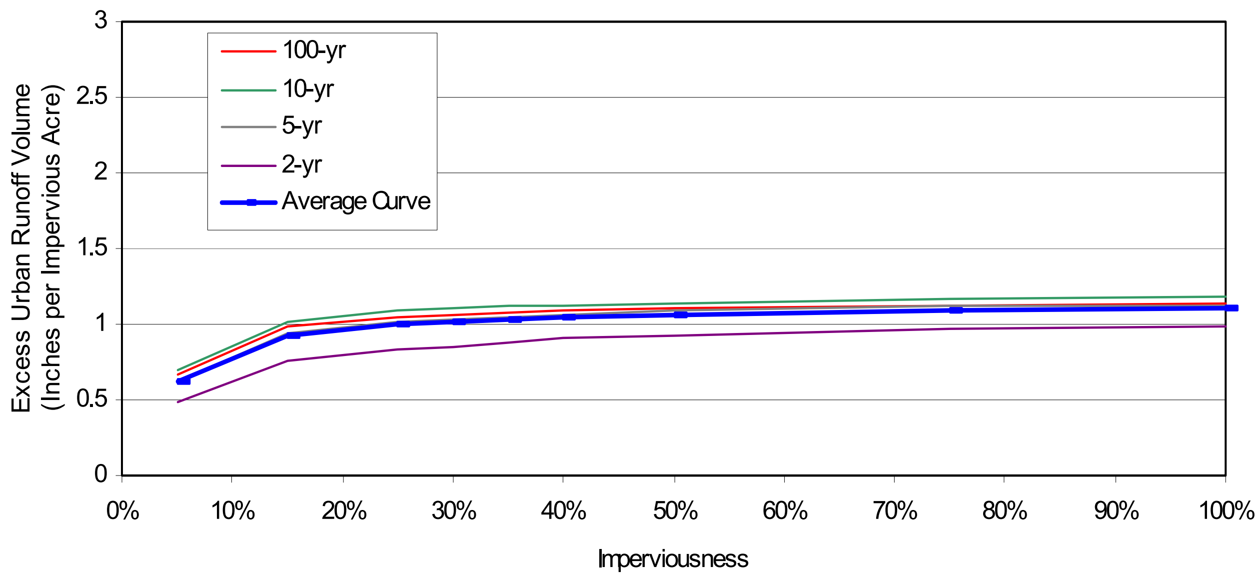
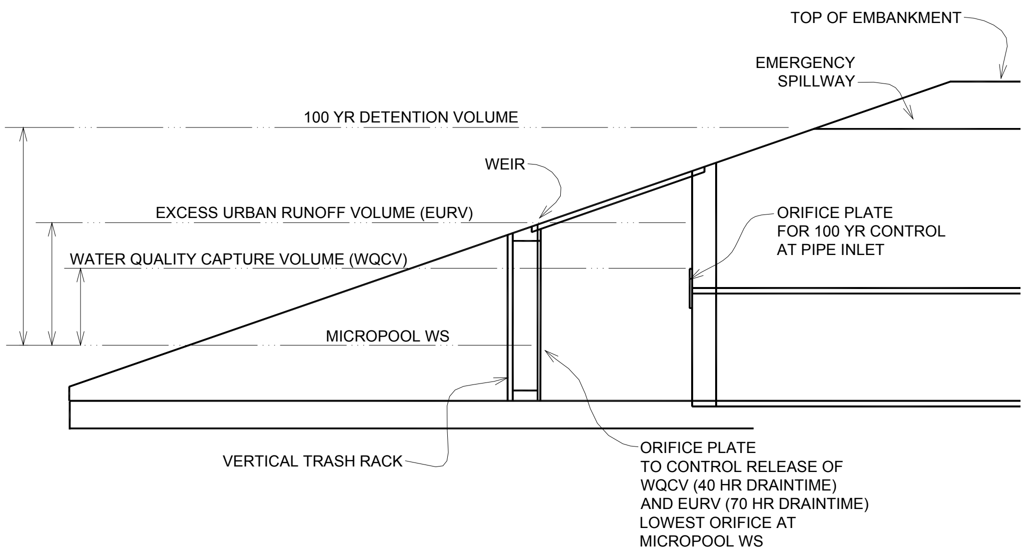


Figure 4. Excess Urban Runoff Volume for Hydrologic Soil Group C/D.

Controlling the Detention Release Rates

Stage-discharge relationships for each of the 50 detention basins were based on the outlet structure geometry seen in Figure 5. This relationship is given in Figure 6 for the 100-acre sub-watershed with Soil Group C/D. Detention basin stage-storage discharge relationships were developed for each combination of sub-watershed imperviousness and Soils Group. Orifice control was sized to release the *excess urban runoff volume* in approximately 70 hours, while maintaining approximately 40-hour drain time for the WQCV. The weir and pipe-inlet controls were adjusted until the simulated 100-year detained outflow was equal to the prescribed 100-year peak flow release rate of 1.0 cfs/acre for C/D Soils. Total basin geometry was also adjusted to maintain the 100-year stage between 7- and 8-feet.



EXAMPLE OUTLET STRUCTURE

Figure 5. Typical outlet structure conceptual profile for modeling *full-spectrum detention*. For details of this outlet download Ref. UDFCD (1992 & 1999)

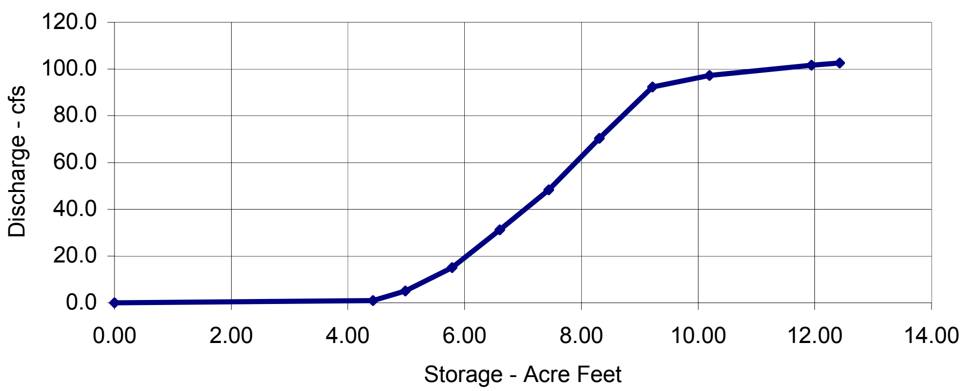


Figure 6. Storage-Discharge relationship for a single basin serving 100-acre sub-watershed with Soil Group C/D soils.

Sizing Relationships

The detention sizing volumes for the *WQCV*, *excess urban runoff volume* and the total 100-year detention for watershed imperviousness of up to 100% are summarized in Figure 7. The 100-year volume in this figure is a total volume that includes the *excess urban runoff* *volume*. A spreadsheet has been developed to calculate the design volumes and 100-year release rates for any watershed size, imperviousness and distribution of soil type (downloadable from the http://udfcd.org/techpapers.htm site). The spreadsheet finds the required size of the *WQCV*, *excess urban runoff volume* (which includes the *WQCV)*, and total basin volume (labeled as 100-year volume) based on the level of MDCIA used within the sub-watershed. The recommended CUHP infiltration parameters are calculated based on the area-weighted averages of each Soil Group.

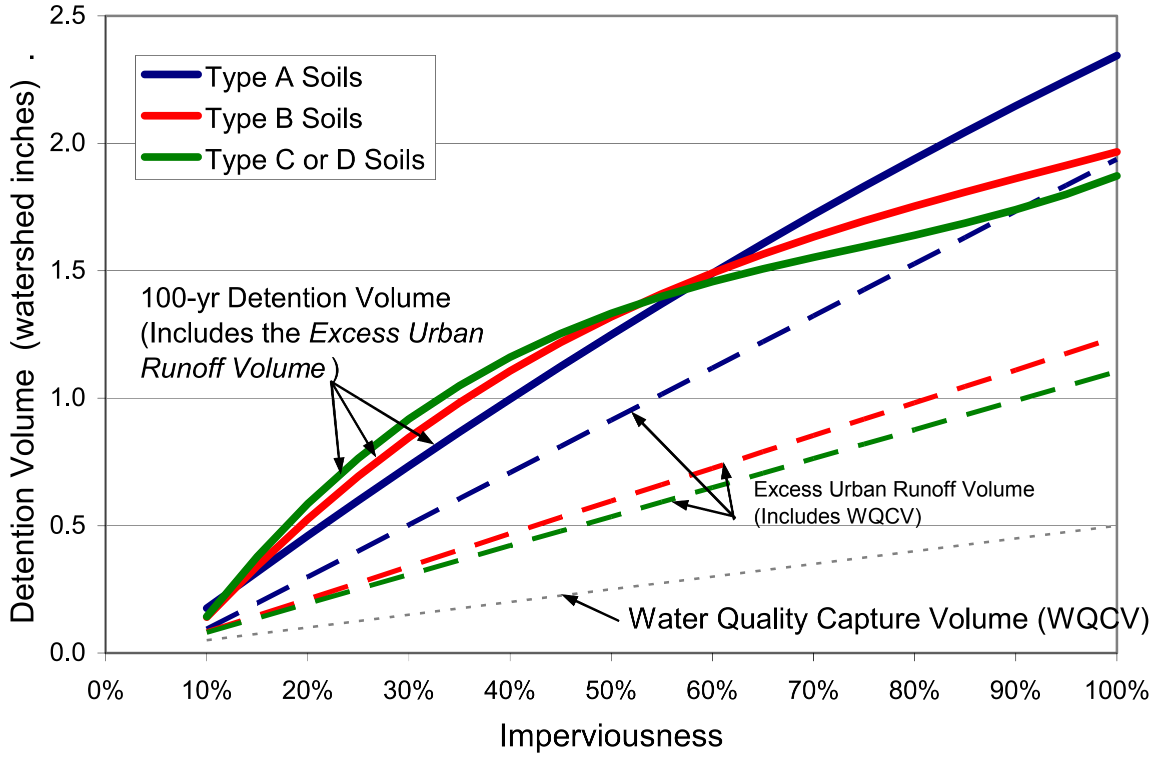


Figure 7. Sizing relationships for the tested *full-spectrum detention* concept.

Effectiveness of Full Spectrum Detention

Figure 8 summarizes the calculated peak flows for one sub-watershed and Figure 9 does the same for the cumulative peak flows along the major waterway when 50 sub-watersheds contribute to it when all the sub-watersheds are 50% impervious. The effectiveness of *full-spectrum detention* is clearly illustrated, especially for the 50 sub-watersheds, when compared to the pre-developed condition and the fully developed condition with no detention. Additional comparisons with the "10/100-year detention" and the "10/100-year detention plus WQCV" scenarios further illustrate the much greater effectiveness of the *full-spectrum detention* in controlling the peak flows over the entire range of design storm.

What is of particular interest to those trying to minimize the impacts of urbanization on receiving waters is the way that the peak flows with *full-spectrum detention* closely match pre-development flows for the smaller, more frequent, storms. This is seen not only downstream of one detention basin but also when large numbers of detention facilities operate concurrently. Similar comparisons are seen in Figures 10 and 11 for sub-watersheds that have 25% and 75% imperviousness.

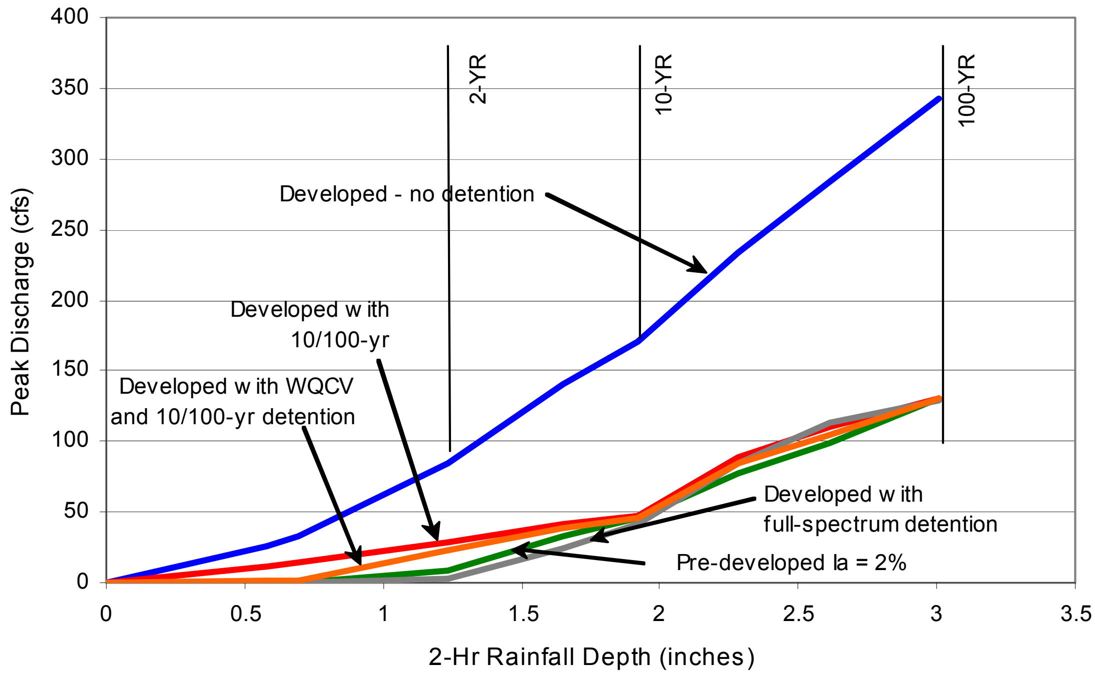


Figure 8. Peak flow rates from a single 100-acre tract (Developed Ia = 50%, C/D Soils).

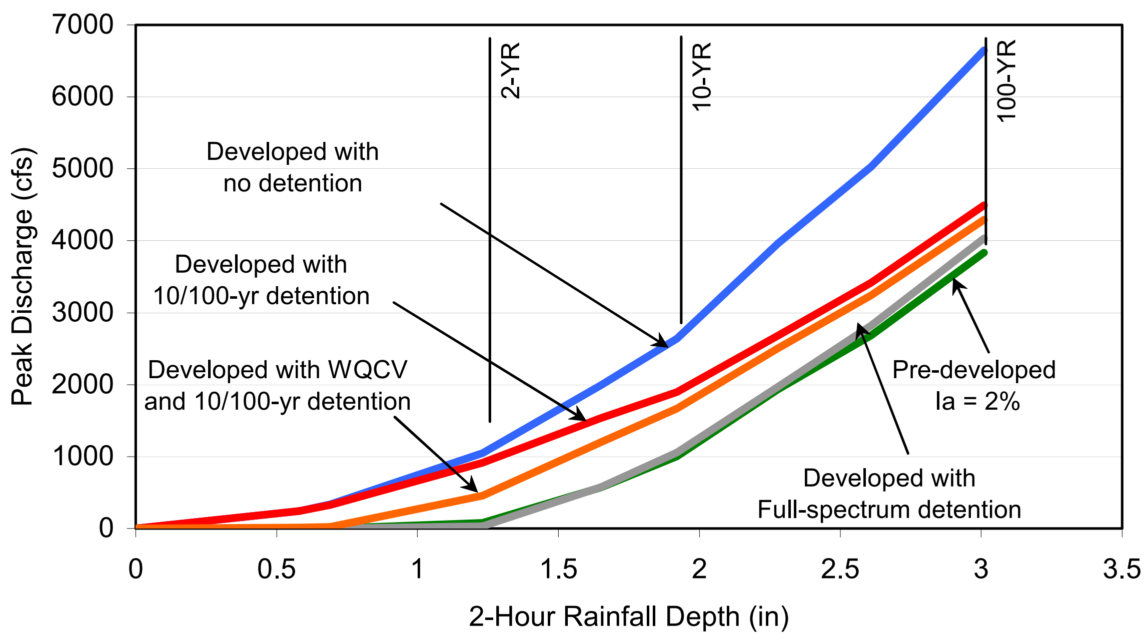


Figure 9. Peak flow rates from fifty 100-acre tracts (Ia = 50%, C/D Soils).

Another attractive feature of this design is its simplicity. Instead of attempting to size detention basins to match a variety of design storm sizes, this design has two simple volumes, the *excess urban runoff volume* and the total volume needed to control the 100-year peak rate of runoff. This means that the designer needs to design outlets for the two control situations only, one to drain the *excess urban runoff volume* in about 70 hours and the other to control the maximum release rate specified for the 100-year runoff event. In cases where the local jurisdiction has a flood detention policy other than the control of the 100-year peak flow, say a 10-year peak flow, similar volume sizing protocols, including the spreadsheet, can be developed.

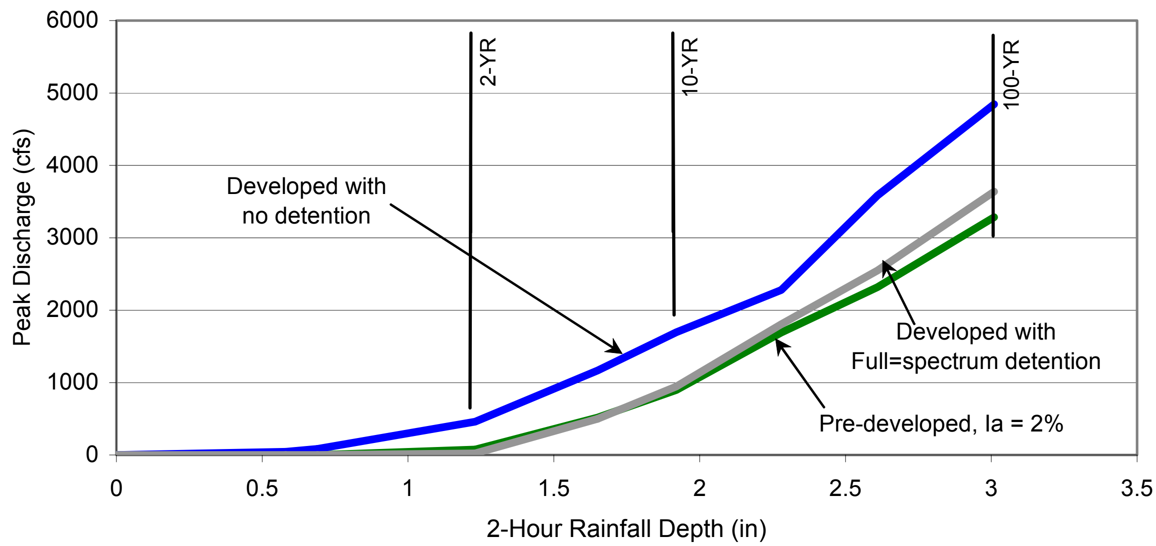


Figure 10. Peak flow rates from fifty 100-acre tracts (Ia = 25%, C/D Soils)

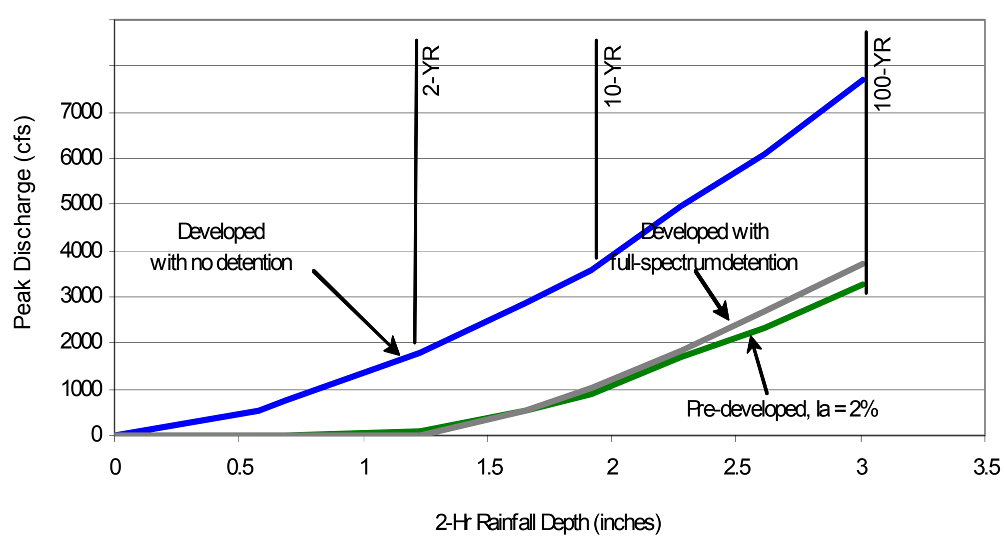


Figure 11. Peak flow rates from fifty 100-acre tracts (Ia = 75% and C/D Soils)

On-Site Detention and UDFCD 100-year Floodplain Management Policy

UDFCD has since 1969 been a national leader in promoting the use of detention for the purpose of reducing flooding and flood damages as areas urbanize. As described earlier, its USDCM provides technical guidance on how to size and design regional and smaller on-site detention basins. In addition, Volume 3 of the USDCM provides technical guidance for the sizing and design of BMPs to further reduce the increases in flow rates for the smaller storm events. While strongly promoting the use of stormwater detention as a practice, the UDFCD recognized the realities of how these types of facilities can, or will continue to, provide reliable control of peak flow rates along major drainageways for the 100-year regulatory floods.

While UDFCD has confidence in the ability of many on-site detention basins to control peak flow rates to predevelopment level for smaller watersheds, this is not the case for larger ones. The complexities of predicting where each on-site detention basin is going to be installed as areas urbanize, how it is going to be designed and built and then applying the detention routing technology on such an evolving and diffuse system of control facilities is beyond anyone's ability to do. In addition, the UDFCD has no ability or powers to insure that all on-site detention facilities will continue to be maintained and their function will not deteriorate over time. In fact, evidence suggest to the contrary (Prommersberger, 1984) that very few on-site detention facilities receive needed maintenance and that many do not provide the original design function after few years of operation. Many, in fact, have never been built as designed. In response to these questions, issues and findings, the UDFCD has adhered to the following policies when developing hydrology for the delineation and regulation of the 100-year flood hazard zones within its boundaries:

1. Hydrology has to be based on fully developed watershed condition as estimated to occur, at a minimum, over the next 50 years.
2. No on-site detention basin will be recognized in the development of hydrology unless:
   a. It serves a watershed that is larger than 130-acres, and
   b. It provides a regional function, and
   c. It is owned and maintained by a public agency, and
   d. The public agency has a commitment to maintain the detention basin so that it continues to operate in perpetuity as designed and built.

These policies are for the definition and administration of the 100-year floodplain and floodway zones. They are not intended to discourage communities from using on-site detention, including the *full-spectrum detention* concept discussed herein. On-site detention can be very beneficial for stormwater quality and quantity management, reducing the sizes of storm sewers and other conveyances, and providing a liability shield (defense) when needing to address the issue of keeping stormwater-related damages from increasing to downstream properties as lands are developed.

Conclusions

A new detention sizing concept is presented that appears to control the peak flows along the receiving waterways in a manner that closely matches the pre-development peak flows for a wide array of design storms. This approach was developed using the design storms and runoff models used in the Denver metropolitan area. As a result, the comparisons made in this paper based on the use of these hydrologic tools and analysis protocols and may or may not be the same for other regions and if other hydrologic and detention sizing protocols are used.

This new design procedure, which is termed *full spectrum detention*, is intended to add to the "toolbox" of methods available to engineers and communities trying to mitigate the effect of urbanization on receiving waters. When using the design protocols employed in the Denver area, this sizing and design concept does achieve the goal of matching pre-development peak flows along major waterways much better than other "simplified" design procedures recommended in USDCM and extends this control to design storms ranging from smaller than the 2-year to up to the 100-year design storm.

This design concept is based on "capturing" the *excess urban runoff volume* and releasing it slowly. In addition, the cases analyzed also included a control of the 100-year outflows to match allowable unit area release rates recommended in the USDCM for any mix of NRCS Hydrologic Soil Groups. This approach provides a relatively simple protocol for the actual sizing of detention volumes and outlets. To assist with the design of *full-spectrum detention*, an Excel™ spreadsheet has been prepared that calculates the needed design volumes and the 100-year release rates based on tributary watershed size, imperviousness, and distribution of soil types.

The outlet for the *excess urban runoff volume* is designed to drain the *excess urban runoff volume* in approximately 70 hours. A concern that has been expressed is that this outlet will be prone to clogging because the orifices in the perforated plate that provide this extended drain time are very small. That is a valid concern and is the same one that continues to be an issue with the 12- and 40-hour drain time outlets used to empty the WQCV recommended in Volume 3 of the USDCM. The design geometry of the 70-hour drain time outlet is virtually the same as used for the outlet providing a 40-hour drain time for the WQCV. The difference being that the perforated plate is taller and has more rows of orifices (see Figure 6a of the "Typical Structural BMP Details" chapter of Volume 3 of the USDCM). The key in preventing outlet clogging is use of the micro-pool just upstream of the perforated plate riser and in providing a properly sized trash rack. The outlet sizing curves currently suggested in Volume 3 of the USDCM will need to be expanded to assist the engineer with the design of outlets that drain the *excess urban runoff volume* in 70 hours.

Another concern that has been expressed is that this concept will increase mosquito-breeding habitat in urban areas. As long as the micro-pool is provided as part of the outlet design as discussed above, the mosquito-breeding environment will be no different than would exist for an extended detention basin recommended in the USDCM. What has been happening, however, is that this micro-pool is often not provided. As a result, many extended detention basins in the Denver area have become ideal mosquito breeding areas. The Tri-County Health Department (download their paper from: http://udfcd.org/techpapers.htm) conducted an inventory of many extended detention basins in Arapahoe and Adams Counties. They concluded that it was the lack of a micro-pool that was the largest contributor for creating worst mosquito breeding conditions. The other item to keep in mind is that on the average less than one event per year exceeds the *excess urban runoff volume*. Five days of standing shallow stagnant water are needed (i.e., not flowing and no wave action) for mosquitoes to hatch. When both conditions are taken together, is very unlikely that the full spectrum detention concept basins will increase mosquito breeding conditions or habitat.

Although excellent matching of pre-development peak flow rates using the design storms used in the Denver region was achieved, it is recommended that future studies of this concept be done for other regions of United States and in other countries to see if this concept has broad applicability. The authors do not claim that this concept is a "magic bullet" that will mitigate all of the stormwater-related impacts on receiving waters due to urbanization. It does appear to be more robust in mitigating the effects of hydrologic modifications than other "simplified" methods that are currently recommended in the USDCM. In addition, it is recommended that such studies also employ continuous simulation with locally calibrated rainfall-runoff-routing models; something that would answer many other remaining uncertainties about this concept's broader applicability.

Full spectrum detention is another "simplified" sizing and design methodology that appears to provide very robust control of stormwater peak flows over a large array of design storms. As a result, it appears to address at least one of the hydrologic modification issues of urbanization (i.e., increased flow rates) better than other detention sizing procedures for the Denver area. However, this control has a chance of working only if this concept uniformly implemented over 100 percent of the watershed and only if all facilities are designed, built and maintained in perpetuity for watersheds of up to a moderate size. In other word, this and other stormwater management concepts are only as good as their implementation and if they continue to function over time (i.e., are sustainable). Until such assurances can be made, it is unwise to suggest that the Urban Drainage and Flood Control District modify its policies on the development of hydrology for the purposes of long-term master planning and the delineation of 100-year flood hazard zones.

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We apologize if we missed anyone in this acknowledgement as many verbal comments and discussions took place that were not fully documented, but also helped shape the final version of this paper.

Request for Comments on the Full Spectrum Detention Concept

Written comments from the readers are requested on this concept, its potential merits and its shortcomings. As stated earlier, this concept was evaluated for the hydrologic conditions and analytical methods employed by the Urban Drainage and Flood Control District it is asked of the readers to keep this in mind when commenting on this paper. What is sought are comments on the concept and not the details of its evaluation, since this concept will need to be evaluated for merit at each location or region. Clearly much more work is needed to illustrate its broad applicability.

Please send your written comments to one or both of the authors:

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Appendix A. Representative Subwatershed and Channel Routing Parameters

Subwatershed Parameters	
Area	100 ac
Length	0.78 mi
Length to centroid	0.48 mi
Slope	0.7-percent (for 2% imperviousness)
Pervious storage	0.35 in
Impervious storage	0.10 in

Channel Routing Parameters	
Length	1000 ft
Slope	0.5-percent
N value	0.05
Bottom width	20 ft
Side slope	4 to 1