

POTENTIAL EFFECTIVENESS OF DETENTION POLICIES

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INTRODUCTION

Urbanization is a continuing phenomenon in the United States. Grasslands, farmlands, forests, swamps, etc. are being continually changed to residential subdivisions, commercial and industrial complexes, roads and streets, parking lots, shopping centers, and so on. One of the side effects of urbanization with which engineers and planners must deal with is the increase of peak flows and volumes of runoff from rainstorm events. As a result, the urban drainage and flood control systems must be designed to accommodate the peak flows from a variety of storms that may occur.

The approach to drainage until the early 1980's relied on swales, curb and gutter, inlets, storm sewers, and channels to carry away flow as quickly as possible. This approach has in recent years 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 since it has been widely embraced throughout the United States, Canada and many other countries throughout the world.

One approach to detention is the use of regional detention or retention facilities. Another approach to detention is to require developers to provide detention as a part of the development process. Such on-site detention facilities can take many forms in terms of size, shape, and location.

Although the concept of detention storage has been widely accepted, the questions regarding its effectiveness in managing stormwater runoff persist. 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 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 effectiveness of on-site detention is also affected by design criteria, which varies from one other regions.

BACKGROUND

The basic policy that most frequently guides the development of stormwater detention ordinances and design standards is the control of stormwater runoff peak discharges from a development. The peak flow, after development, is required not to exceed what would have occurred from the same storm under conditions existing prior to development (1). In the Denver area, the most commonly used policy among the various local general-purpose governments is to limit the 100-year peak flow after development to the pre-develop 100-year peak flow. However, there are several communities that require control of two recurrence frequencies such as 2-year and 100-year, 5-year and 100-year or 10-year and 100-year events.

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McCuen (1974) published reported the results of his modeling effort utilizing 17 sub-watersheds and two systems of detention storage. In one system he modeled 12 ponds and in another he modeled 17 ponds. He modeled ten storm events at the Gray Haven Watershed 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 article did not describe the design of individual detention facilities, McCuen reported that the 17 sub-watershed scenarios had a total of 22,000 cubic feet of storage. On the basis of his modeling results he suggested that,

"(1) That the "individual -size" approach to stormwater detention may actually create flooding problems 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."

Hardt and Burges (1976) report on their investigation of detention effects from an hypothetical 2000 acre watershed. Their investigation, utilizing SCS runoff model and a kinematic channel routing technique, was limited to three sub-watersheds; nevertheless it was one of the earlier attempts to look at the effects of detention systems. Their findings can be summarized in the following quote from their report:

"Restricting the outflow from a retention facility to 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."

Lindsey and Crawford (1974) 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, the cost of such modeling can be very expensive, and that the majority of design practitioners are not prepared to use continuous long term modeling in the design of stormwater detention facilities.

Walesh (1976 and 1979) 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 by McPherson (1977), Marsalek (1978) and Sieker (1978). This design storm controversy has not been resolved, however, the authors believe that there are definite applications, particularly where non-point source water quality is being considered, in which continuous simulation or quasi-continuous simulation should be used whenever rainfall data is 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 using properly developed design storms.

Urbonas (1979), 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. Once 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.

POLICY AND POTENTIAL EFFECTIVENESS

The objective of the Denver study reported herein was to assess the "potential effectiveness" of on-site detention by estimating how much on-site detention can reduce the peak flows along major drainageways. As stated earlier, many local governments require on-site detention; however, little work has been done to assess the effectiveness of on-site detention in controlling flows along major drainageways. The primary interest of the Urban Drainage and Flood Control District (District) is in the flooding along the "major drainageways". Thus, it was logical for the District to investigate the potential effectiveness of on-site detention policies in controlling flood levels along such drainageways.

Denver Area Setting

The Denver metropolitan area is located on the Colorado high plains immediately east of the Rocky Mountains at an elevation of 5,280 feet (1,600 m). Because it receives 15-inches (380 mm) of precipitation annually, it is considered to have a semiarid climate. Rainstorms in the spring and early fall often have an "upslope" character where easterly flow of moisture settles against the mountains. These types of rainstorms can have a duration that exceeds 6-hours and, although they may drop relatively large amounts of total precipitation, they are not very intense and are not normally associated with major urban flooding problems along major drainageways. In late spring and throughout the summer, the rainstorms often result from convective or frontal stimulated convective action. These type of storms are often less than 1- or 2-hours in duration; however, they can produce brief periods of high rainfall intensities.

Experience and rainfall/runoff data in the Denver area show that very little, if any, runoff occurs from low intensity storms such as "upslope" type storms and from the lesser convective storms when the land is not urbanized. As the land develops, streets, curbs and gutters, and storm drainage facilities are installed and runoff occurs from even very small rainstorms.

The terrain in the Denver area is rolling with moderate to steep slopes. Much of the area has high clay content with tight surface soils; however, there are also areas that have very free draining sandy soils. The native vegetation consists of dry land range grasses, which in some cases were replaced in the past by dry wheat or irrigated crops and are now being replaced by Kentucky Blue Grass as the area urbanizes. Since most of the land in new developments has residential land use, the detention study concentrated on an ultimate land use mix consisting of mostly residential with some light commercial.

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 square miles, a watershed length of 6.4 miles with an average watershed slope of 0.015. Its shape and drainage pattern is shown on 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 to be 38 percent impervious.

Runoff was modeled using 2-hour design storms for the 2-, 10-, and 100-year recurrence frequencies. These design storms were developed for the Denver area using the rainfall-runoff data collected by USGS since 1970 and the long term Denver Raingage record collected since 1896. Modeling was done using stationary storms and storms that moved across the watershed at six miles per hour upstream and downstream. In addition, runoff was modeled 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 were found to be similar. Namely, if a reduction in peak flow was calculated with detention for the stationary storm scenario, then a similar reduction was also observed for the a moving storm scenario when compared against the undetained moving storm condition.

Because the modeling was for a 7.85 square mile watershed, conclusions of this study should not be extrapolated much beyond 10 square mile watersheds. This seems like 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, controlling runoff from a 10 square mile or lesser watersheds may be very beneficial for flood control purposes in semi-arid climates.

The study watershed was subdivided into 56 sub-catchments 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 calculated for the pre and post-developed conditions. The control volume was estimated using a process illustrated in Figure 2, where the control volume was assumed to be equal to the cross-hatched portion of the runoff hydrograph.

The hydraulic characteristics of each pond's outlet were designed assuming that the outlet functioned as an orifice until the design control volume was filled. At that point the ponds were assumed to overflow and a broad-crested weir controlled the overflow. On the basis of trends observed in several individual designs, the outlet discharge versus storage volume relationship was reduced to a non-dimensional form for all ponds. This expedited the design of a large number of ponds under a variety of desired control conditions.

Figures 3 and 4 illustrate the design characteristics used for the 28 ponds in the model. In Figure 3 h represents the peak flow from an undeveloped sub-basin, Q_d represents the peak flow from a developed sub-basin, and V_T represents the design control volume of the pond. In Figure 4, Q_h and Q_d represent the historic and developed 100-year storm peak flows, V_T represents the 100-year control volume, and Q_i and V_i represent the historic peak flow and the required control volume for the 10-year storm.

While the pond is operating within orifice control, Equation 1 can express the discharge:

$$Q = C A (2gh)^{0.5} \tag{1}$$

- In which, Q = discharge-ft³/sec
 A = area of orifice-ft²
 h = water surface height above orifice-ft
 g = acceleration of gravity - 32.2 ft/sec²
 C = discharge coefficient

Equation I can be expressed for any given C and A as

$$Q = C h^{0.5} \tag{2}$$

For the individual ponds designed in the study, it was observed that the pond volume could be reasonably estimated by a power function of depth, which, after rearrangement was expressed as

$$h = C V^{0.92} \tag{3}$$

- In which, V = pond volume at any stage height
 C_2 = constant

Combining equations 2 and 3 gave

$$Q = KV^{0.46} \quad (4)$$

In which, $K = C_1 C_2^{0.5}$ (i.e. a constant).

To facilitate a large number of pond designs, the volume-discharge relationship was made non-dimensional by dividing the outflow by the discharge required at the full control volume and the volume by the full control volume. Equation 5 gives the non-dimensional relationship, while the pond is operating within the maximum control volume.

$$\frac{Q}{Q_T} = K \left(\frac{V}{V_T} \right)^{0.46} \quad (5)$$

In which $V_T =$ detention pond control volume V_T .

$Q_T =$ discharge desired at control volume V_T

The non-dimensional volume-discharge relationship for the entire range of pond operation is illustrated in Figures 3 and 4.

Results and Observations

Many of the results of the District's random detention study can be found in the Masters of Science Thesis by Mark Glidden (1981). A series of five figures (i.e., Figures 5, 6, 7, 8, and 9) summarize the generalized trends that were identified by the study. Each figure relates the size of the watershed to the non-dimensional peak flow. The non-dimensional peak flow was obtained by dividing the actual peak flow by its respective flow from the undeveloped watershed. Therefore, a value of "one" on the ordinate represents no change from the undeveloped condition and a value of "two" represent an increase in peak flows by a factor of two from the undeveloped condition. 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.

Figures 6 through 9 reveal the following trends for the soil and meteorological conditions modeled by the District's study:

1. The 2-year random detention pond design was effective in controlling the 2-year peak flows at individual pond sites only. As the number of ponds increased with an increasing tributary area, the 2-year design rapidly diminished in effectiveness. This trend is attributed to the fact that the 2-year storm volume increased many fold after development and, although the peaks were controlled at the individual sites, the resulting flat peaked outlet hydrographs from the ponds added directly as the flows progressed downstream. In contrast, prior to development the individual tributary hydrographs had small volumes and were out of phase with each other. The 2-year design somewhat reduced the 10-year and the 100-year storm runoff peaks when compared to the undetained condition.
2. The 10-year random detention pond designs were relatively effective in limiting runoff peaks along the major drainageways from the 10-year storms and were also somewhat effective in reducing the 100-year storm peaks. It was virtually ineffective in controlling the 2-year design storm 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 storm runoff, but was ineffective in controlling the 2-year storm runoff peaks. The two-frequency control design looked to be more effective in controlling the two design storms than the individual 10- or 100-year frequency designs were in controlling their respective individual recurrence runoff peaks.

The results of the District's study seem to verify some of the conclusions of Hard and Burges (1976). The one surprise, although predictable, was that the 2-year design was not very effective in controlling peak flows along the major drainageways from the smaller storms. It may be that McCuen's (1974) study, since it utilized recorded data, was limited to such smaller storms. It does not mean that the 2-year 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-year detention design effectiveness can be judged.

SIMPLIFIED CRITERIA EFFECTIVENESS

General

As a follow-up to the study of the "potential effectiveness" of detention policies for the Denver area, the District investigated the possibility of using simplified detention design criteria. Of great concern to designers is that simplified detention requirements take away the "creativity" in design and may result in detention sizing that is inappropriate for an individual site. These concerns are very valid. On the other hand, simple regional detention sizing requirements do offer advantages to the developer, the design engineer and the local government official that has to review large numbers of designs. Although simplified detention requirements may not permit "optimization" for each on-site detention facility, they offer the advantages of simplicity, uniformity and, from land developer's perspective, equal treatment. In other words, all developments know early on what the detention volumes and areas will have to be. It is also clear to everyone that all similar developments will be treated the same way. For these reasons, regional simple detention design criteria deserve to be considered by stormwater management professionals. A decision if they should be promulgated or rejected should then be made based on each community's needs, capabilities and political factors.

Preliminary Control Equations

Scrutinizing the "runoff vs. area" results of the earlier modeling effort revealed, two simplified trends for undeveloped runoff and detention control volume (see Equations 6, 7, 8, and 9):

$$V_{10} = (1.35 I + 2.70) (A/1000) \tag{6}$$

$$Q_{10} = 0.4 A \tag{7}$$

$$V_{100} = (2.07 I + 4.04) (A/1000) \tag{8}$$

$$Q_{100} = 1.25 A \tag{9}$$

In which,

V_{10}	=	Volume needed to control a 10-year storm in acre-feet
V_{100}	=	Volume needed to control a 100-year storm in acre-feet
Q_{10}	=	Average 10-year peak flow rate from undeveloped sub-basin in cubic feet per second

Q100 = Average 100-year peak flow rate from undeveloped sub-basin
in cubic feet per second

A = Tributary basin area in acres

I = Tributary basin imperviousness in percent

Equations 6 through 9 were used to size all of the 28 detention ponds in the study model for the 10- and 100-year storm runoff controls. These relationships provided pond designs that did not control the peak flows along major drainageways as well as the individually designed ponds during the earlier investigation.

Final Control Equations

After three trials, a set of simplified design equations (see Equations 10, 11, 12, and 13) were developed that produced peak flow trends along major drainageways similar to the ones obtained using the rigorous analysis of each detention site.

$$V_{10} = (0.95 I - 1.90) (A/1000) \quad (10)$$

$$Q_{10} = 0.24 A \quad (11)$$

$$V_{100} = (1.78 I - 0.002 I^2 - 3.56) (A/1000) \quad (12)$$

$$Q_{100} = 1.0A \quad (13)$$

OBSERVATIONS

The peak flow results obtained with detention ponds sized using equations 10 through 13 were reduced to a non-dimensional form and are depicted in Figures 10, 11, 12, 13, 14, and 15. These figures reveal the following trends:

1. The 10-year and 100-year designs based on Equation 10 through 13 controlled the peak flows along the major drainageways almost as well as the rigorous individual design scenarios.
2. The 10-year simplified design was less effective in controlling the 100-year peak storm flows than the rigorous 10-year design scenario.
3. The 100-year simplified design 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 simplified design was equivalent to the rigorous combined 10-year and 100-year in controlling both recurrence storm flow peaks.

Although the peak flow trends along the major drainageways were duplicated very well by the simplified design equations, there were a number of ponds in the system that overflowed. All ponds have the potential for overflowing since a storm larger than it was designed to control can and will occur. Thus, an infrequent overflow, by itself should not constitute a faulty design. It is up to the designer to insure that when an overflow occurs, property damages are not increased. Namely, a safe overflow path, free of structures, has to be provided for every detention pond regardless of control frequency design.

As a further comparison, Table 1 illustrates the differences in watershed detention storage requirements between the rigorous design approach and the simplified one. The comparison shows a trend towards less basin wide storage volume using the simplified approach as tested by the District.

Table 1. Comparison of Required Unit Volume Using Rigorous vs. Simplified Designs

		Unit Volume For 100-yr. Control (Acre-Feet/Acre)	
Percent Impervious	Rigorous	Simplified	% Difference
20	0.037	0.032	- 13
40	0.079	0.064	- 19
80	0.162	0.126	- 22
100	0.203	0.154	- 24

DESIGN ACCURACY AND EFFECTIVENESS

The topic of design accuracy was indirectly touched upon by 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 (ASCE, 1983) which can be obtained upon 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 as to the design accuracy or detention pond effectiveness. Although the questioning has merit and should not stop if technology is to move forward, it should not paralyze the designer into an endless analysis process. In the author's opinion, it is important that the designer recognizes the limitations in the accuracy of the rainfall input and move forward to design what are considered reasonably sized facilities in line with current state-of-the-art technology and practice.

Unlike many other fields of engineering, the statistics of hydrologic data have very wide bounds of design confidence. As an example, a USGS (1980) document provides regression equations and techniques for estimating flood peaks, volumes, and hydrographs on small streams in South Dakota. The range in the standard error of estimate is as much as +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 these kind of uncertainties all the time whether they know it or not. Thus, whenever we discuss accuracy or effectiveness, we need to remind ourselves of the randomness of the physical phenomenon which is involved, and the fact that the data that was used in developing all of the commonly available surface runoff calculating techniques is broadly scattered.

INSTITUTIONAL CONSTRAINTS

In their discussion, Jones and Jones (1982) 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 community's 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. They went on to say,

"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 insure 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 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 cannot be treated haphazardly. Thus, institutional arrangements in communities are just as important as sound design practices. In other words, communities need an institutional structure that insures sound design, and that the required detention ponds fit the system and are not used just to pacify local regulatory requirements.

Beyond this, an institutional structure is needed to insure 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 or policy is like trying to weigh candy with only one-half of a balance scale. Even though the product looks attractive, it is not possible to know how much there is of it. 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 under funded. Thus, the true effectiveness of detention systems or policies 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.

CONCLUSIONS

The effectiveness of on-site detention ponds was addressed from the quantity and institutional aspects. 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 that single design event.
- 2) Ponds designed to control peak flows of two separate recurrence frequency events 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 events.
- 3) Designs intended to control frequent events (e.g., 2-years) are effective in controlling the frequent event immediately downstream of each pond only. Control of frequent events appears to be less and less effective along the major drainageways as more and more ponds contribute to the system.
- 4) It appears feasible to develop simplified regional on-site detention sizing requirements. Ponds sized using such requirements have the potential of controlling peak flow rates along major drainageways just as effectively as ponds sized using rigorous, flood routed, design procedures. Finally, the effectiveness of random on-site detention policies is also constrained by the institutional structure that can insure adequate design, proper construction and long term operation and maintenance of detention facilities. Without knowing how effective the institutional structure is in providing and maintaining adequate facilities, we need to view the foregoing conclusions as representing Only the "potential effectiveness" of detention policies. The assessment of the actual effectiveness of random on-site detention will require studies beyond those conducted to date.

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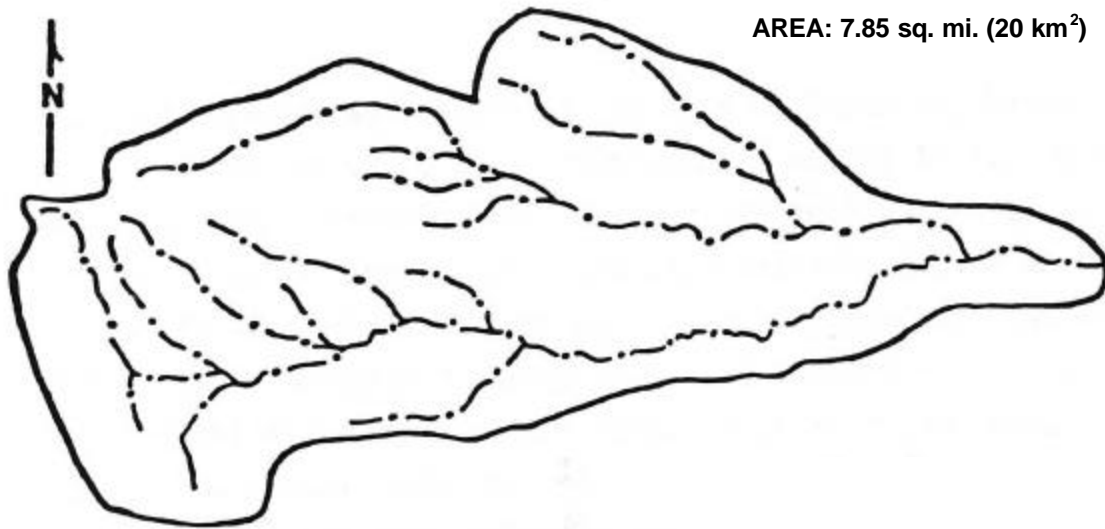


Figure 1. Study Catchment

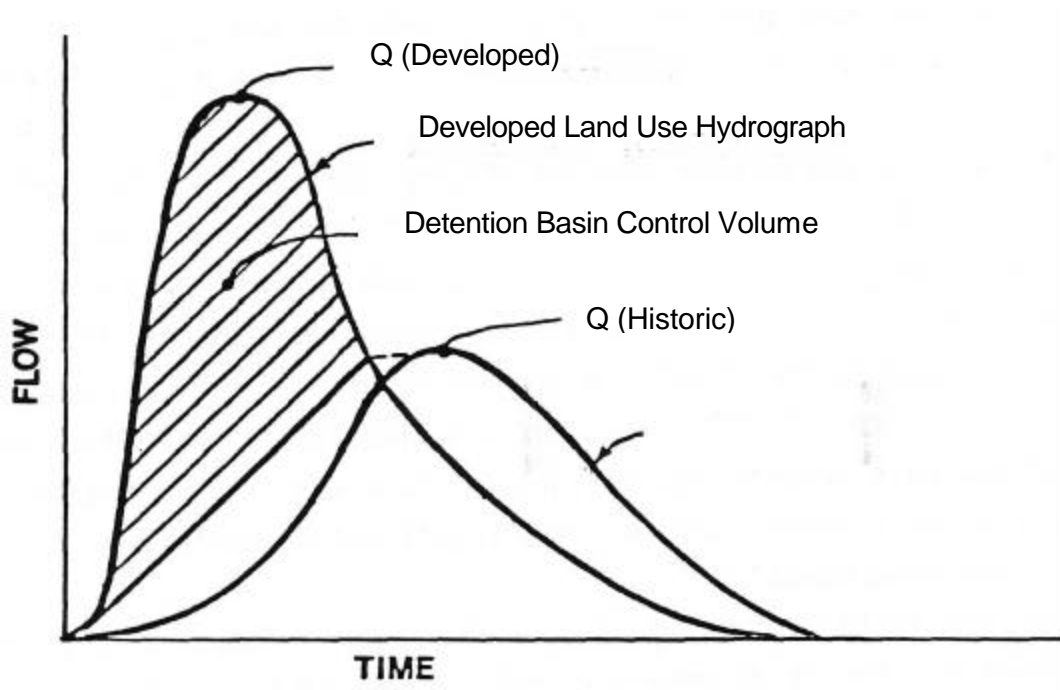


Figure 2. Determination of a Detention Pond Volume.

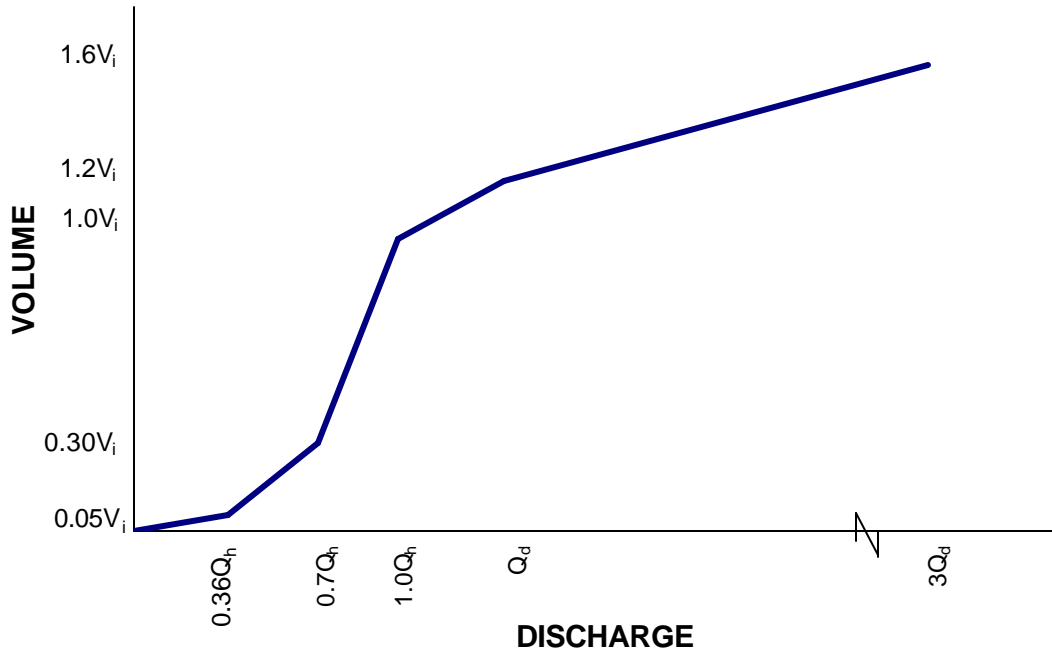


Figure 3. Volume vs. Discharge: 2-, 10- and 100-year Designs of Detention Basins.

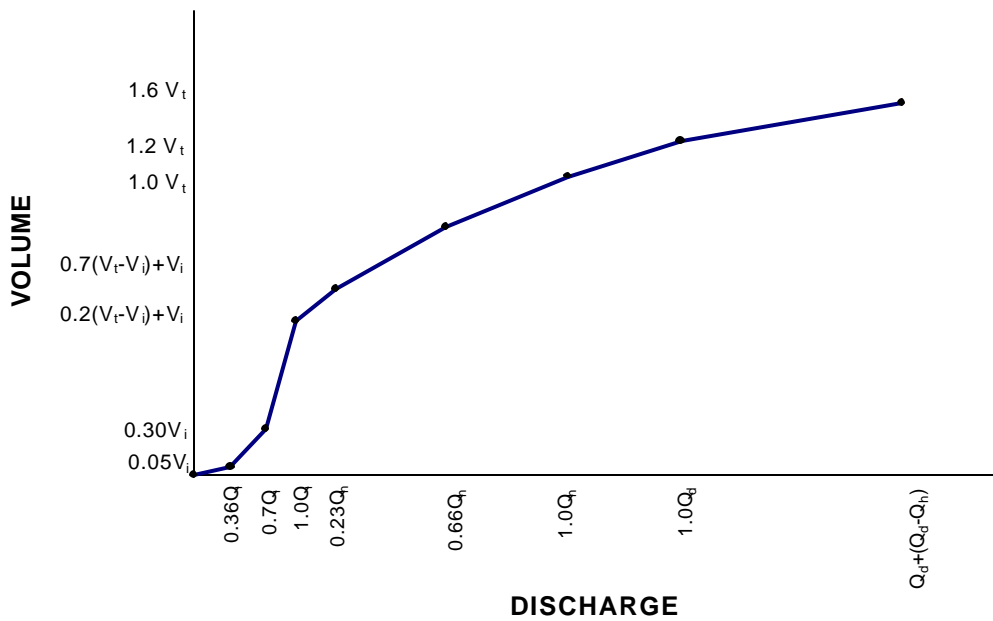


Figure 4. Volume vs. Discharge: 10- & 100-year Combination Designs of Detention Basins.

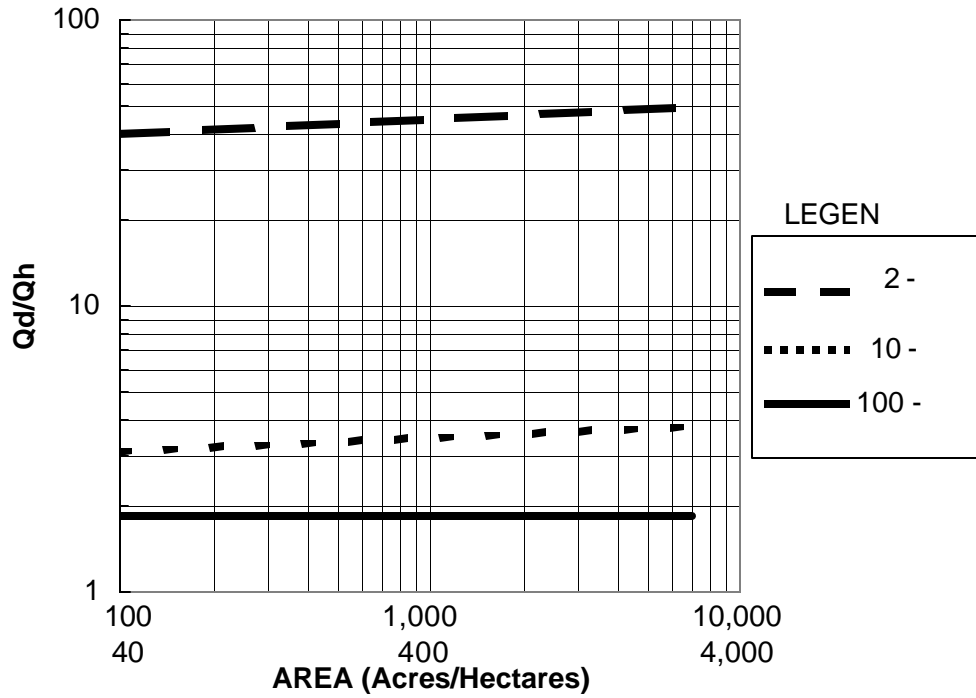


Figure 5. Urban Runoff Trends – Fully Urbanized Watershed Without Detention

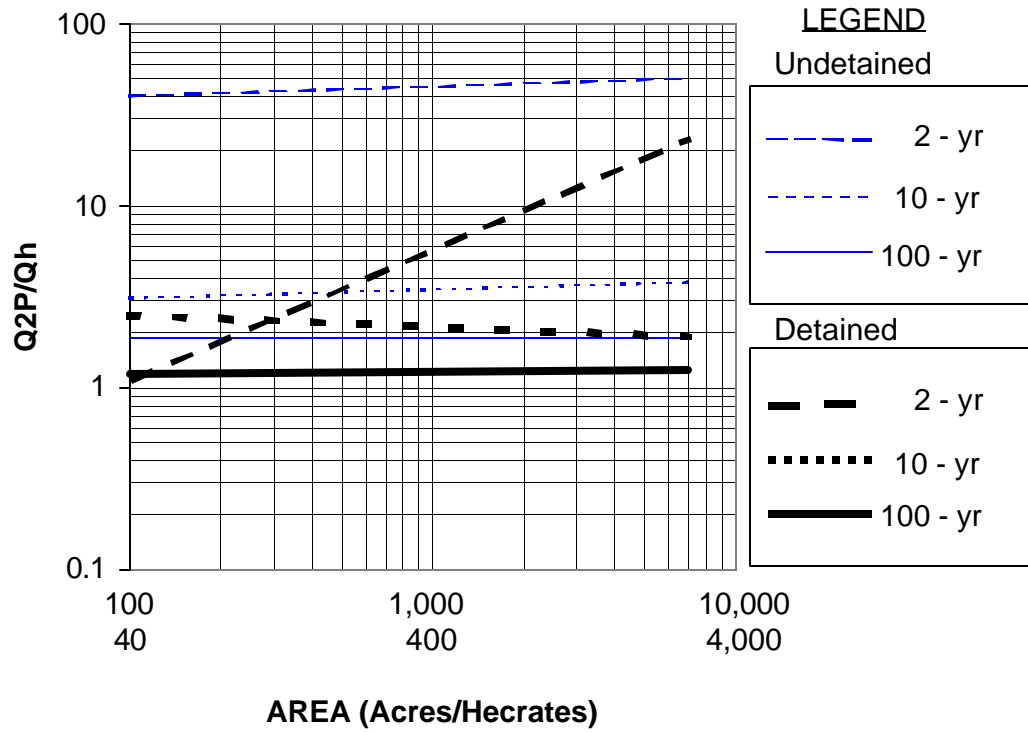


Figure 6. Effectiveness of 2-year Peak Flow Detention Design

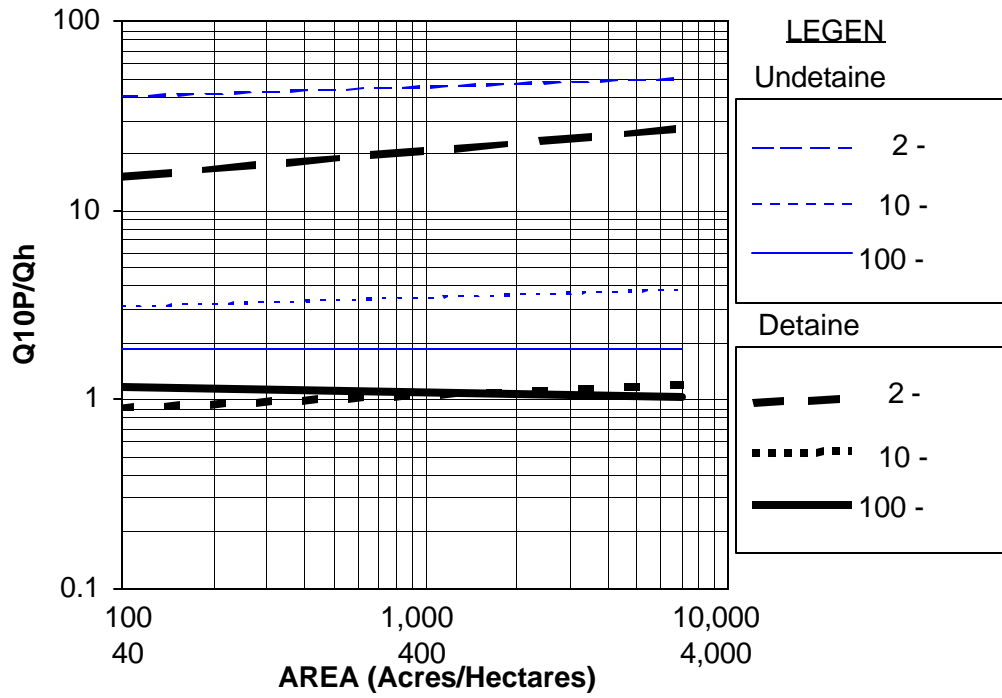


Figure 7. Effectiveness of 10-year Peak Flow Detention Design

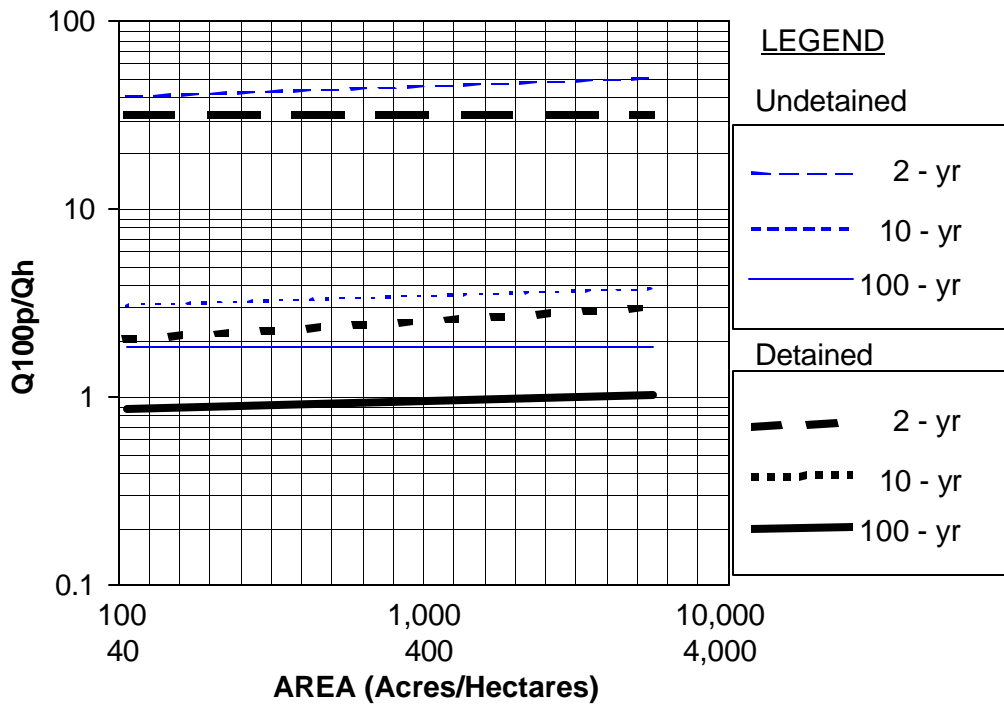


Figure 8. Effectiveness of 100-year Peak Flow Detention Design

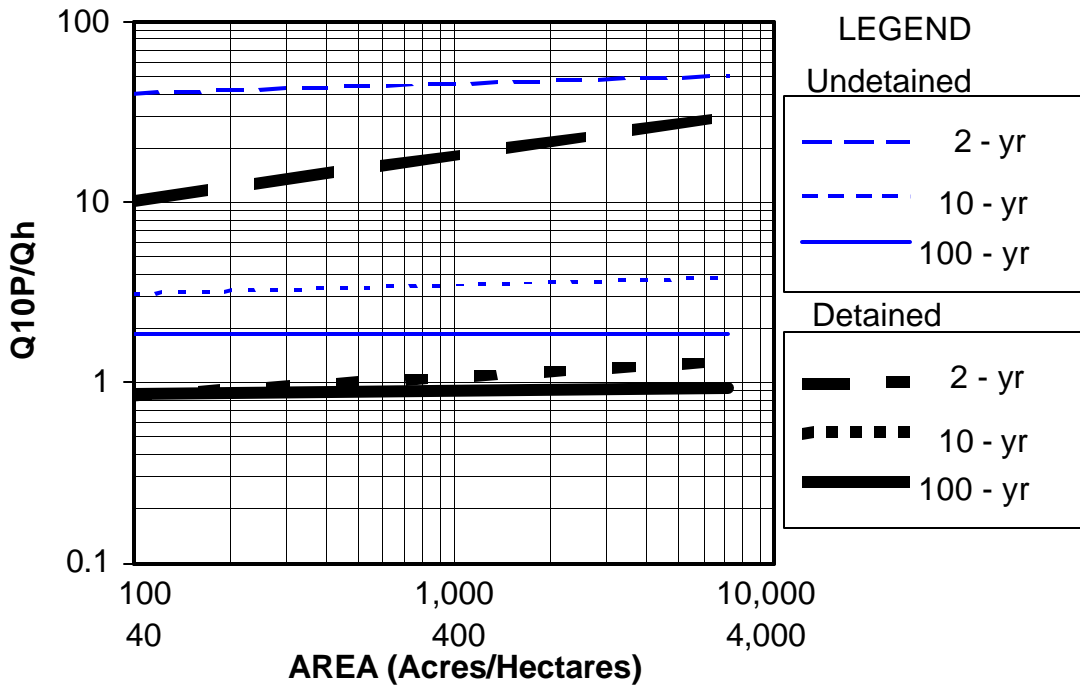


Figure 9. Effectiveness of 10- & 100-year Peak Flow Detention Design

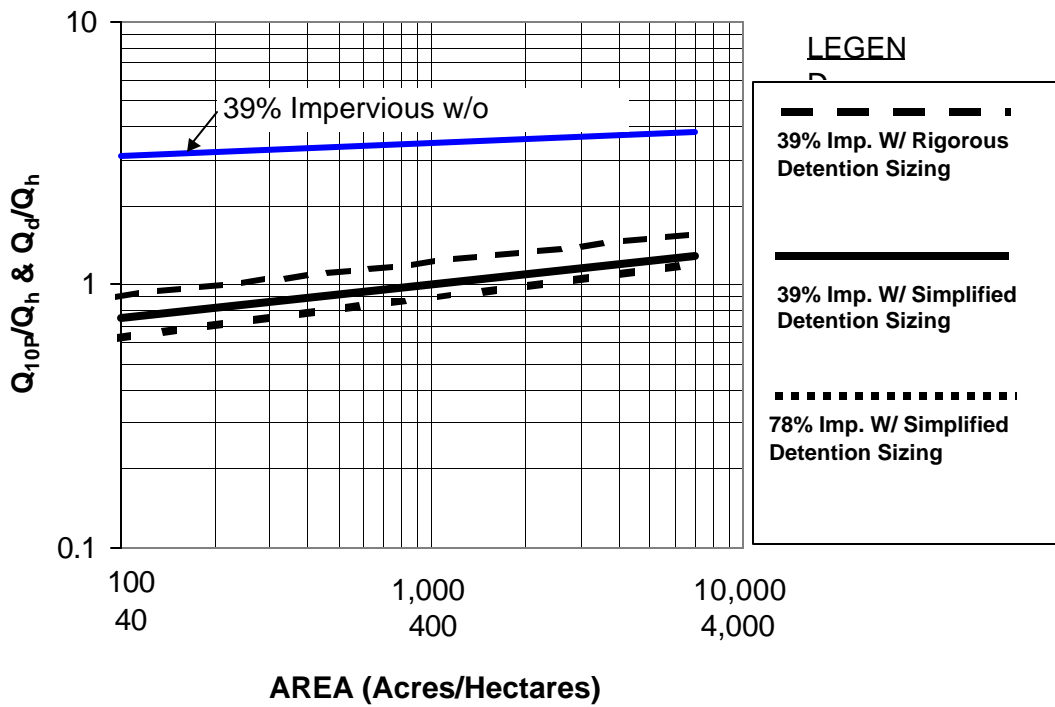


Figure 10. Effects of 10-year Simplified Detention Sizing on 10-year Runoff Peak Flows.

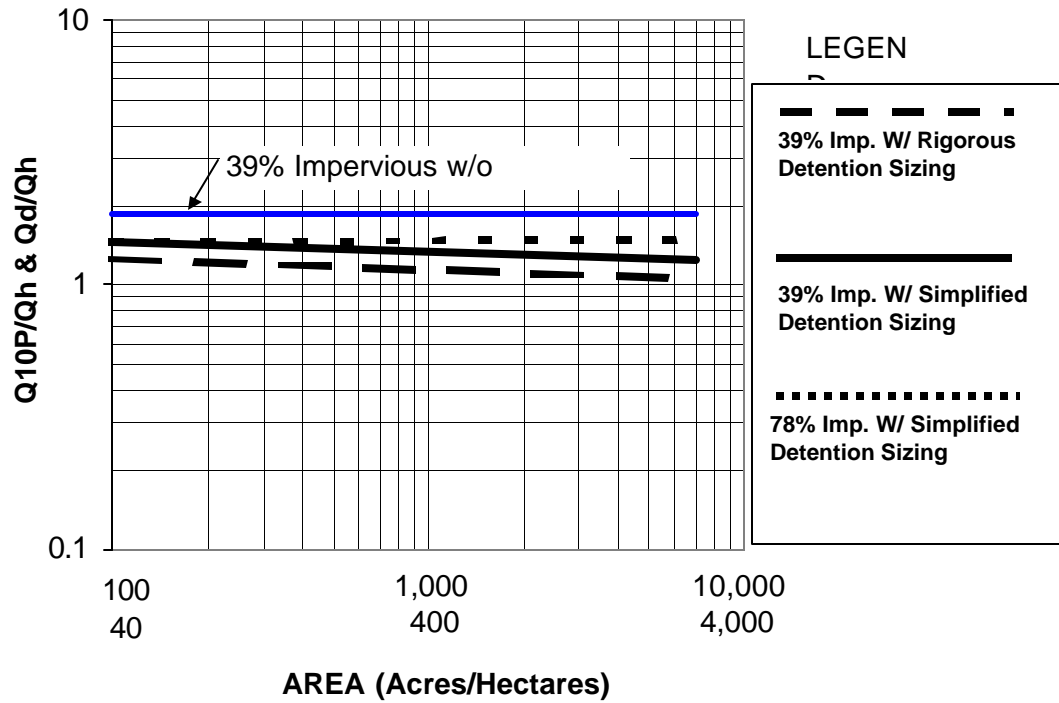


Figure 11. Effects of 10-year Simplified Detention Sizing on 100-year Runoff Peak Flows.

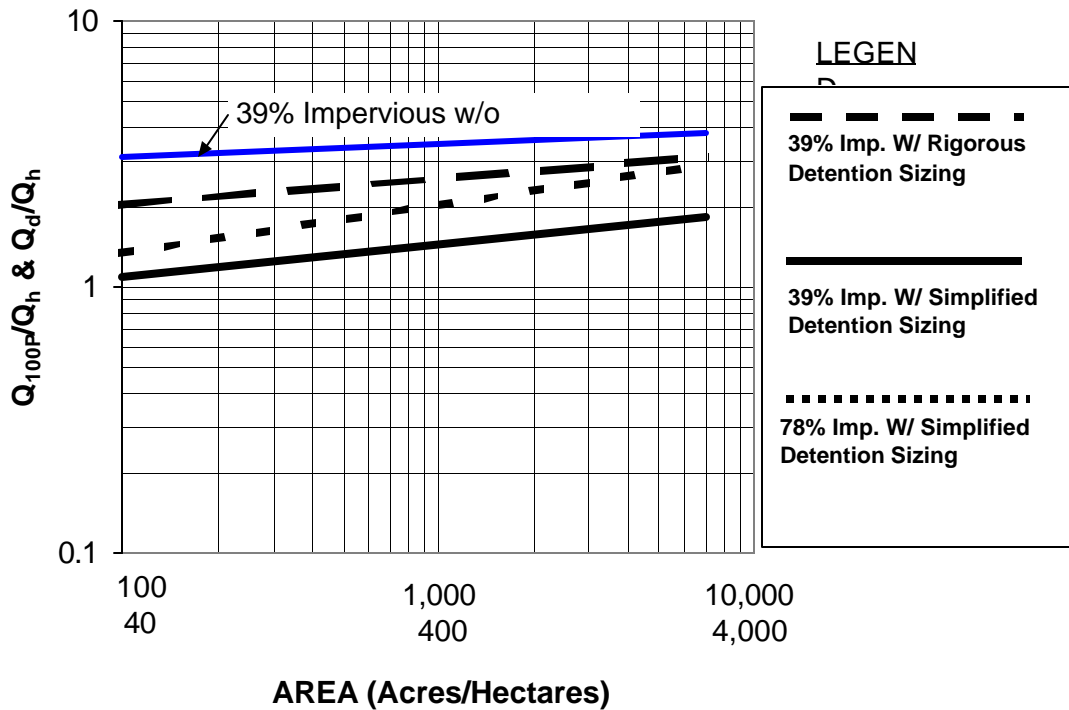


Figure 12. Effects of 100-year Simplified Detention Sizing on 10-year Runoff Peak Flows.

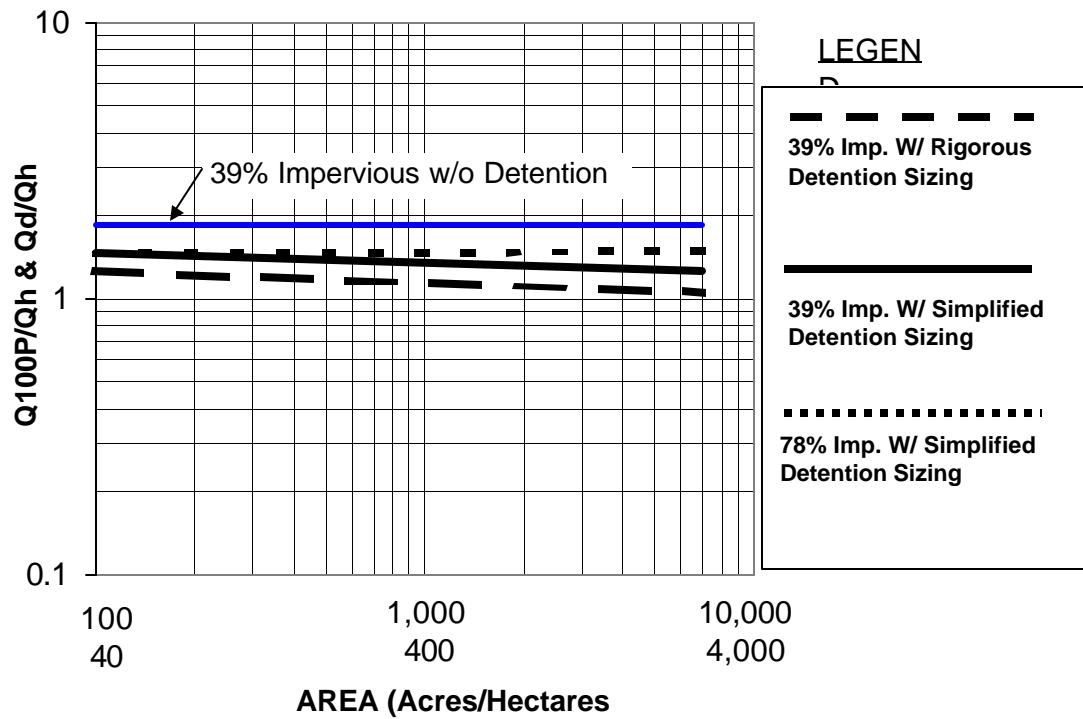


Figure 13. Effects of 100-year Simplified Detention Sizing on 100-year Runoff Peak Flows.

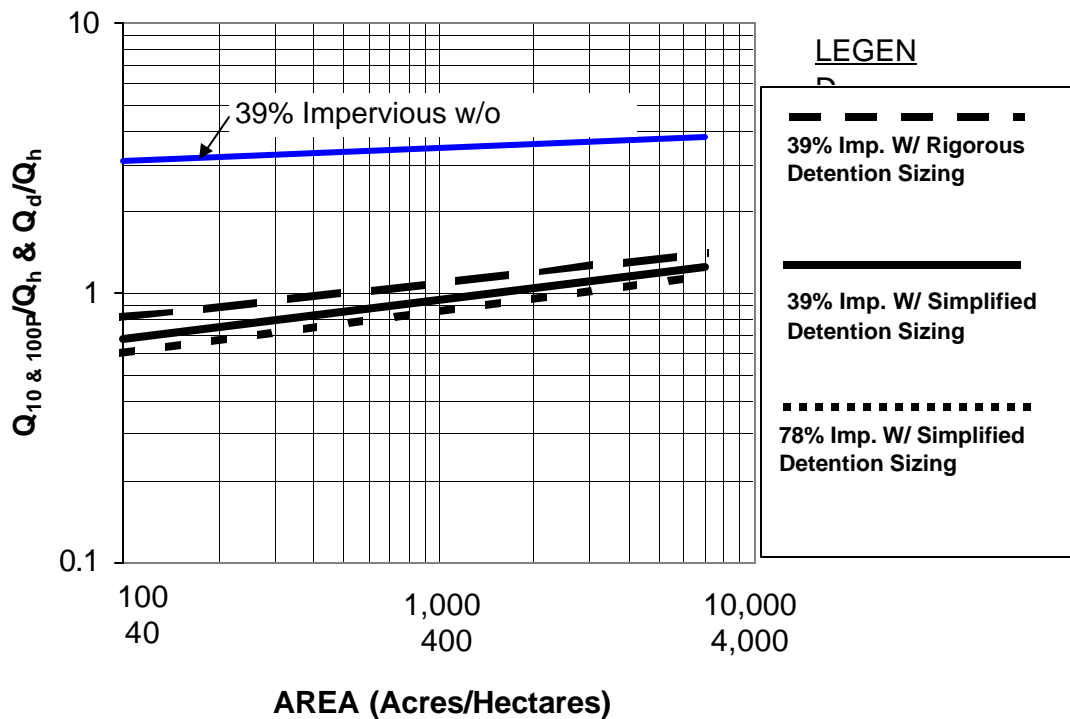


Figure 14. Effects of a Combined 10- & 100-year Simplified Detention Sizing on 10-year Peaks.

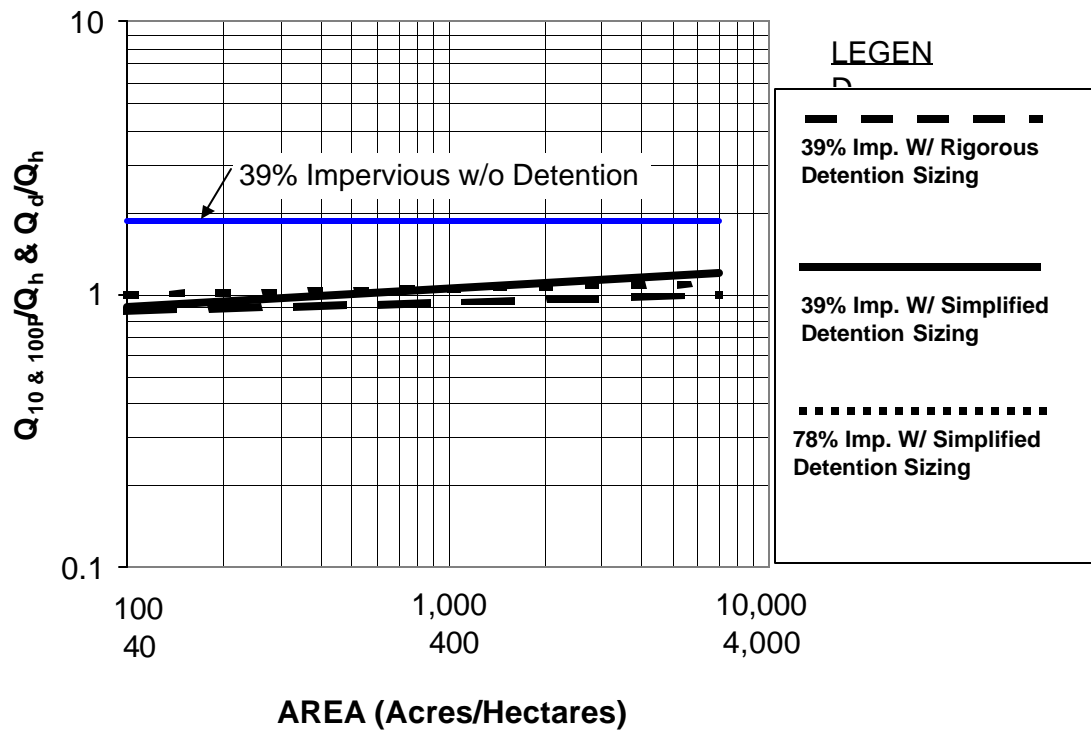


Figure 15. Effects of a Combined 10- & 100-year Simplified Detention Sizing on 100-year Peaks.