Impact of New Rainfall Patterns on Detention Pond Design

D. N. Powell[1]; A. A. Khan[2]; and N. M. Aziz[3]

Abstract: A new set of dimensionless rainfall hyetographs has been developed for the state of South Carolina. The new hyetographs show trends similar to those developed recently in other states and in general have milder intensities and lower peak rainfall than the Soil Conservation Service (SCS) rainfall hyetographs. This paper evaluates the impact the new hyetographs have on rainfall runoff and detention pond design and compares the results with those using the SCS hyetographs. Peak discharges for basin runoff were reduced up to approximately 20% of the predicted peak runoff rate using the current SCS hyetographs. Detention pond peak stage was also reduced by 25–50% of the predicted SCS stage. This analysis suggests that design hyetographs should be regularly updated to incorporate recent rainfall data.

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Introduction

Designing hydraulic structures that manage rainfall-runoff volume requires a time distribution of rainfall (hyetograph). A period of high intensity rainfall may produce a large volume of runoff in a short period of time. Runoff volume accumulation depends on the shape and intensity of the hyetograph. As a result, a detention pond's design will ultimately depend on the pattern of the selected hyetograph. That is, if the hyetograph has a high volume of rainfall concentrated in a short time with high peak intensity, a large volume of runoff has to be detained. Alternatively, the pond size will be smaller if a selected hyetograph has the same volume of rainfall spread over a longer time as the inflow and outflow rates from the pond may be the same. Thus, the rainfall distribution pattern plays a pivotal role in shaping the runoff hydrograph.

The state of South Carolina currently uses the Soil Conservation Service (SCS) Type II and III rainfall distributions. These curves, developed by the Soil Conservation Service (1986), were originally for a 24-h duration rainfall event. However, due to the nondimensional nature of these curves, they are usually scaled to other durations. This assumes that the rainfall of all durations has the same time-distribution pattern. However this assumption is questionable, as it is common knowledge that short and long duration storms behave differently. In addition, the rainfall patterns obtained from the SCS hyetograph peak at the middle of the duration, and 10% of the duration contains almost 60% of the total rainfall volume. This concentration of rainfall over a short period of time causes large runoff volumes to be generated and reach the detention pond during a short interval, leading to the need to manage large volumes of flow all at once.

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Development of Dimensionless Rainfall Patterns

The 15-min interval rainfall dataset (dating back to 1971) from EarthInfo, Inc. was selected for this study. To appropriately describe the rainfall event, an event with a minimum of six points was needed. With 15-min interval rainfall data, the minimum duration of rainfall that could be analyzed was 1.5 h. Durations up to 51 h were considered at a 15-min increment.

A storm started when the recorded rainfall was greater than 0.51 mm/h (based on a tipping bucket measurement per 15 min) and ended when the rainfall rate fell below 0.51 mm/h (0.02 in./h). Storms of different durations were separated from the recorded rainfall data using the duration percentage criterion (Powell et al. 2007). The storms of a given duration were separated using interevent time of 30% of its duration. This procedure incorporates short duration rain events into long duration events by using variable interevent time.

The storm events were then nondimensionalized using the storm duration and the total amount of rain in the storm. The storms generated were grouped into 1-h durations from 2 to 20 h. That is, the 2-h duration group contained all the storms less than 2 h duration (1.5–2 h). The 3-h group consisted of storms with duration higher than 2 h and less than or equal to 3 h, and so on. The last two groups were of storm durations up to 24 and 51 h. The minimum number of events in a grouping was set as 150 events, and the top 50 volume events (Pilgrim and Cordery 1975) were used in the pattern generation procedure. The top 50 storms in each group were used to determine a representative storm pattern using the method outlined by Pilgrim and Cordery (1975). Powell (2005) provides complete details of the derivation.

A representative storm pattern was derived for each group and these patterns are shown in Fig. 1. The patterns for duration of 7 h and less formed a group, while patterns for duration of 10 h and higher formed a separate group. The shorter durations show an early and high peak, while the longer durations show a more

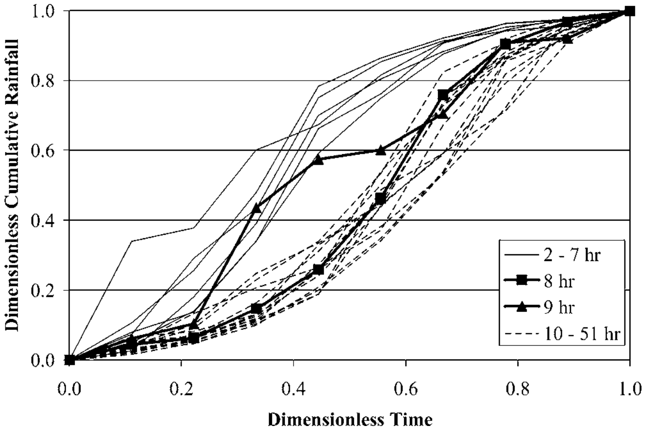

Fig. 1. Dimensionless rainfall patterns for all durations

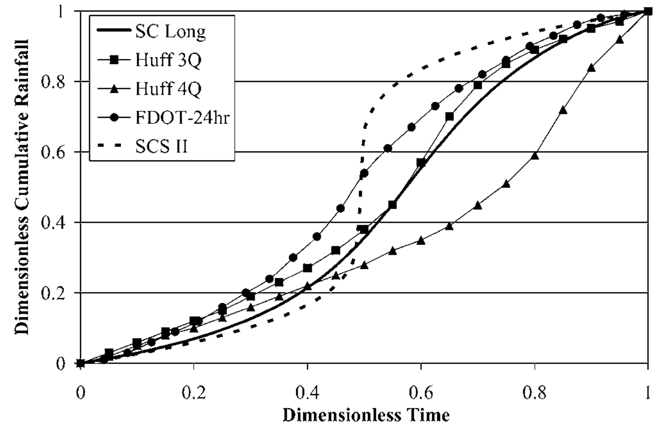

Fig. 3. Comparison of SC long pattern

delayed and lower peak. Representative patterns for the short durations (SC short) and long durations (SC long) were determined.

Figs. 2 and 3 compare the current SC short and long patterns with similar curves developed by the Florida Department of Transportation (FDOT) and Huff (1967) for Illinois along with the SCS Type II rainfall distribution pattern. The figures show that the new patterns are more similar to those derived for other states, but are quite different from the SCS hyetograph. The differences in the temporal distribution are expected to provide very different results for hydrologic performance.

Analysis of Impact

In an effort to determine the impact of the new hyetographs on runoff and pond design, hydrologic calculations were conducted using the TR-20 method which is built into the software HydroCAD (Applied Microcomputer Systems 2003). HydroCAD is a program for modeling the hydrology and hydraulics of stormwater runoff. The user can select the SCS Type I, IA, II, or III hyetograph, various updated hyetographs for different states, or provide a custom hyetograph, which in this study are entered as the SC short and SC long hyetographs. The TR-20 method uses the SCS runoff curve number (CN) method to compute runoff volume from a given rainfall event. The SCS methods of sheet flow and shallow concentrated flow are used to determine the travel time of runoff over different types of land surfaces. The runoff hydrograph resulting from the rainfall event is computed by the SCS dimensionless unit hydrograph. Detention pond routing with culverts and orifices as outflows is performed using the storage-indication (level pool) method within HydroCAD.

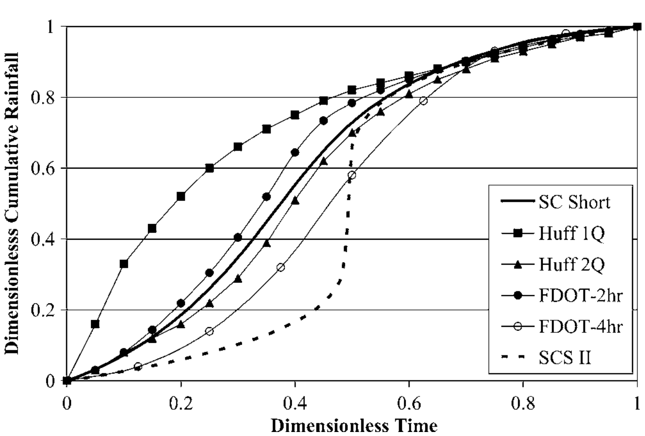

Fig. 2. Comparison of SC short pattern

To evaluate the impact of these new rainfall patterns in design practice, two sets of tests were conducted. The first set investigated the response of a basin runoff hydrograph and the second set evaluated pond response. The parameters investigated in the two tests are shown in Table 1.

Basin Tests

The first comparison looked directly at a sample drainage basin and its response to the different rainfall events. The basin was not created to mimic any existing piece of property. This example property was selected to be 8.1 hectares (20 acres) in size with an average CN of 79 (fair grassland covering, soil moisture Class C). Tests with larger area, up to 80.9 hectares (200 acres), showed results that were consistent with those reported in this paper. For the nondimensional comparisons, the rainfall duration and the basin's time of concentration were varied. Fig. 4 shows the runoff hydrograph from a 6-h duration rainfall event (SC short pattern) with 76.2 mm (3 in.) of rainfall and a 30-min time of concentration for the basin along with the response from the SCS Type II hyetograph for the same duration and time of concentration. The lower, broader peak runoff is the direct result of the longer, less intense peak rainfall in the SC short rainfall pattern. The peak of the hydrograph occurs earlier and significant runoff occurs before the peak. Fig. 4 also shows the runoff hydrograph for the same basin from an 18-h duration rainfall event (SC long pattern) and a 1-h time of concentration. The total amount of rain in this case is 127 mm (5 in.). The figure also shows the hydrograph produced by the SCS Type II hyetograph for the same parameters. The peak

Table 1. Evaluation Criteria for Basin and Pond Tests

Test type	Selected parameters	Comparison
Basin	Time of concentration (T_c)	Outlet pipe size
	Duration of event (D)	Event depth
Pond	Time to peak (T_p)	Runoff volume (RV)
	Peak flow (Q_p)	Peak storage volume (SV)
		Detention time (DT)

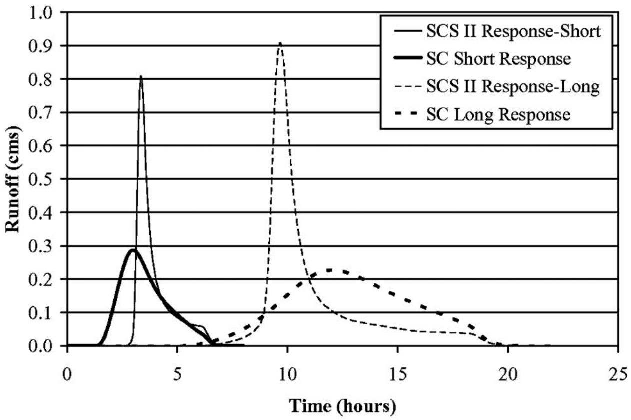

Fig. 4. Basin hydrograph comparisons—short and long events

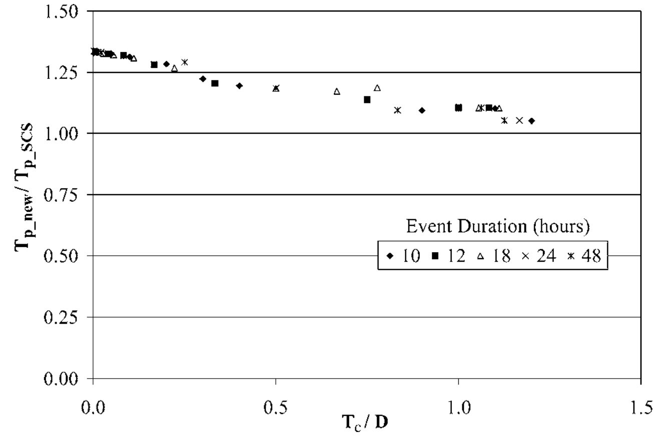

Fig. 6. Comparison of peak arrival time for SC long

of the hydrograph arrives later and is much lower than the peak of the hydrograph produced by the SCS hyetograph.

Figs. 5 and 6 show the ratio of time to peak of runoff hydrographs resulting from this study to those from the SCS pattern as a function of the time of concentration to event duration ratio. The duration of rainfall varied from 2 to 7 h for the short type event and from 10 to 48 h for the long type event. For each storm duration, the time of concentration is varied and the time to peak of the runoff hydrograph is calculated. In both cases, the peak arrival time using the new patterns approaches that of the SCS event as the time of concentration approaches the storm duration. For the ratio of time of concentration to the storm duration of less than one, the peak arrives earlier for the short pattern and later for the long pattern when compared to the peak arrival time based on the SCS event. Fig. 7 shows the variation of peak discharge ratio from the SC short to the SCS pattern. The SC long pattern has similar results but is slightly more pronounced. As with the time to peak, the peak discharge ratio also approaches unity as the time of concentration approaches the storm duration. However, the peak discharges from the new patterns are much lower than the predicted values from the SCS event for the ratio of concentration time to storm duration less than one. In summary, Figs. 4–7 show that peak arrival times and hydrograph peak flow rates derived using the new SC patterns approach those obtained using the SCS-type event when the time of concentration is equal to or exceeds the duration of the rainfall event (generally for large basins). When the time of concentration is less than the duration of the event, as it typically is for small basins, there is a pronounced difference between the predictions of the SCS hyetograph and the SC hyetographs.

Detention Pond Tests

The second test placed a sample inverted truncated pyramid pond ($7.62\ \text{m} \times 15.24\ \text{m}$ base, 2:1 side slope) at the basin outlet. The basin for this test was the same as for the first test. This case investigated the variation of pond stage with time and the impact of culvert size on storage volume. A horizontal outlet was always placed at the invert of the pond, and the entrance was a simple projecting reinforced concrete pipe (entrance loss of 0.2) with a Manning's n of 0.15. The outflow was a free discharge so tailwater effects would not be a factor in the analysis. As before, 76.2- and 127-mm rainfall depths for short and long rainfall patterns were used along with 30- and 60-min time of concentrations, respectively, for a direct comparison.

The pond stage variations versus time for SC short type and SC long type rainfall events are compared with those produced from the SCS event and are shown in Fig. 8. Rainfall durations of 6 and 18 h are chosen for the short type and long type patterns, respectively. Both cases use a 0.3-m-diameter (12-in.) outlet pipe. A difference of about 1 m occurs in the pond stage response in the short type pattern case. For the size of the outlet pipe used,

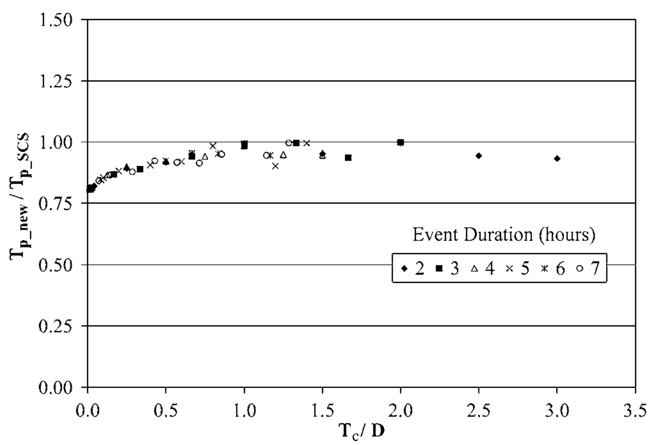

Fig. 5. Comparison of peak arrival time for SC short

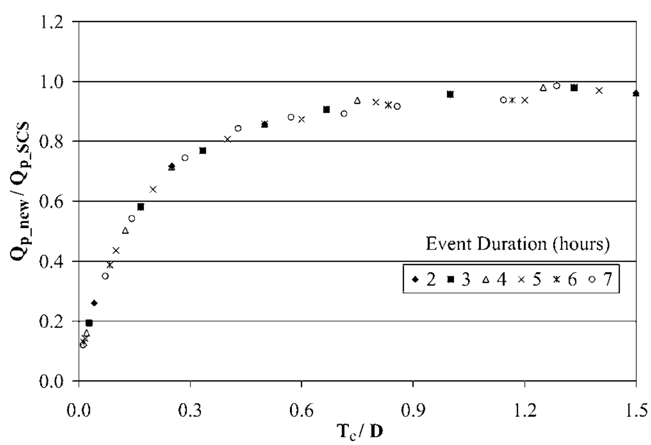

Fig. 7. Comparison of peak discharge for SC short

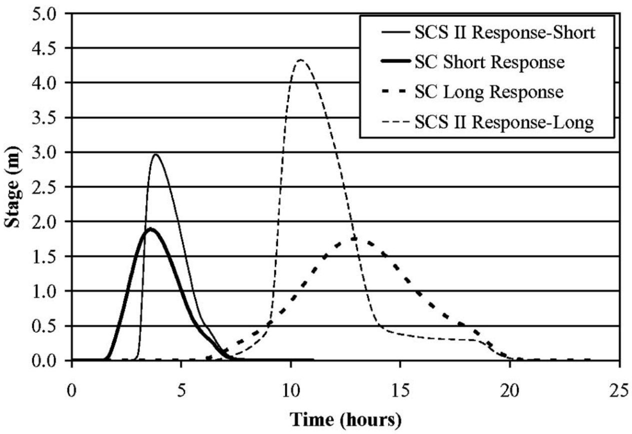

Fig. 8. Variation of pond stage—short and long

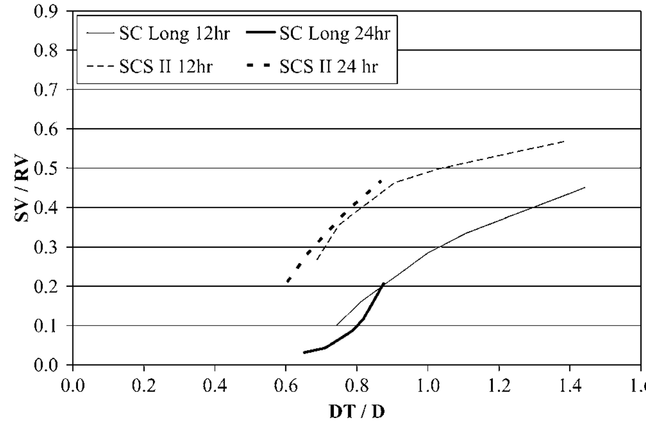

Fig. 10. Variation of ratio of storage volume to runoff volume for long type

not much storage volume is required for the long type event case. The new pattern response is more logical, as the buildup of runoff is more gradual and thus the pond response should be more gradual.

To quantify the impact of the new hyetographs on storage volume and detention time and compare it with the results from the SCS event, the variation of the ratio of storage volume to runoff volume versus the ratio of detention time (*DT*) to storm duration (*D*) is investigated. Figs. 9 and 10 show the results of this analysis for short type and long type events for an outlet pipe diameter of 0.3 m. These two figures show that the SCS and SC patterns behave similarly for the shorter durations with consistently higher storage volume from the SCS event. The wider divergence of the lines for the SC long type events leads to the observation that longer duration events have larger differences in storage volume. This makes sense, as most of the runoff volume from the SCS hyetograph will arrive in a short period of time, while the SC patterns tend to spread the runoff more evenly over the duration of the event, especially the SC long type. A pair of duration lines tends to converge as the *DT/D* ratio increases. This shows similar results to prior statements regarding the time of concentration and how both methods approach similar values for longer times.

Next, the storage volume ratio from the new events and the SCS rainfall pattern is compared for various rainfall amounts, rainfall durations, and outlet pipe sizes. Figs. 11 and 12 show the analyses for events with short type and long type patterns. In both figures, the storage volume based on the new hyetographs is less than that based on the SCS hyetograph.

In Figs. 11 and 12, the symbol type (open or filled) indicates the duration of an event, and similar symbol shapes indicate the same pipe size for multiple durations. When comparing the effects of the pipe sizes, it is shown that as the outlet size increases, the storage volume decreases at a faster rate for the new curves. Analysis of the values within the dataset revealed that when using the new SC patterns, the required peak storage volume changed markedly when the outlet size was increased. On the contrary, the required peak volume only decreased by a small factor when using the SCS type hyetographs despite the increase in the outlet area due to a large amount of concentrated rainfall in the middle of the hyetograph. For the same outlet size, the variation of storage volume for different storm durations reduces as the rainfall amount increases. In general, the new patterns show little deviation from the SCS response when using smaller outlets. However, larger outlets or smaller rainfall amounts could have marked reductions in storage requirements when using the new patterns. The 24-h event with 0.61-m (24-in.) outlet pipe is not shown in Fig. 12 as the water level remained below the pipe crest during routing.

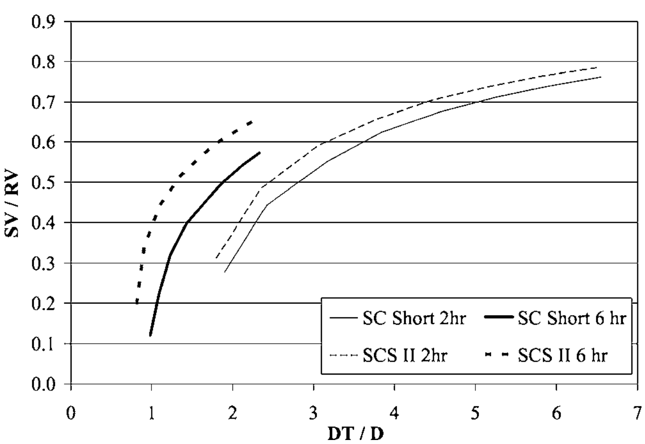

Fig. 9. Variation of ratio of storage volume to runoff volume for short type

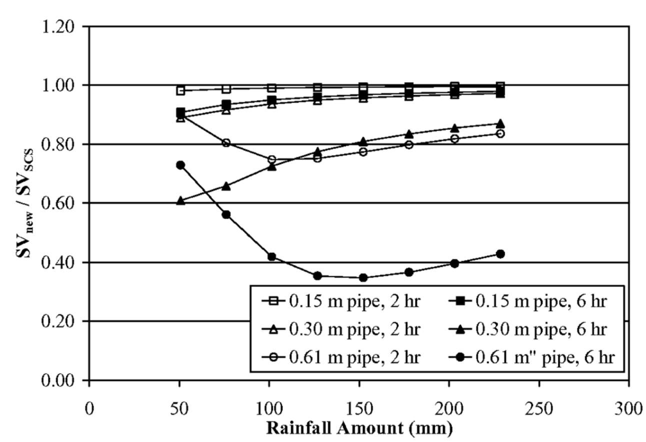

Fig. 11. Storage volume comparisons for SC short

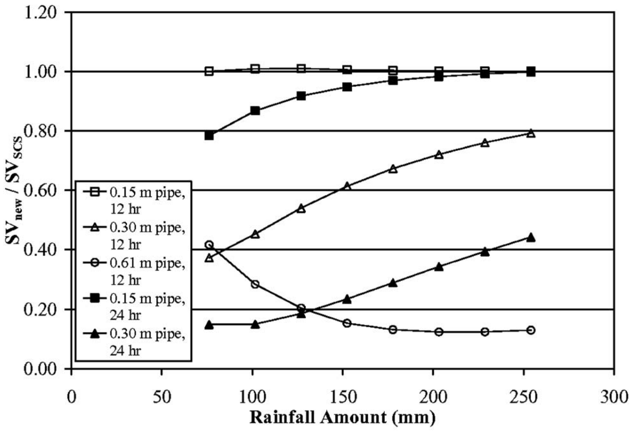

Fig. 12. Storage volume comparisons for SC long

Summary and Conclusions

The aim of the study is to assess the impact of new dimensionless rainfall patterns developed for the state of South Carolina by comparing the performance of the new patterns to that of the SCS Type II hyetograph for the design of hydraulic structures. There are two new general hyetographs for South Carolina, the SC short and the SC long, whose behavior is consistent with those of new patterns developed for other states. The SC short pattern is valid for storm durations up to 7 h, while the SC long pattern is valid for storm durations above 10 h. These new patterns are very different from the currently used SCS type patterns. The SCS peak intensity is almost four times the peak intensity of the SC short pattern and more than four times that of the SC long pattern. The location of the peak intensity is noticeably different as well, with the SC short peak filling most of the first half of the event and the SC long rising over the last half of the event, while the SCS event has its peak in a small period in the middle of the event. The new curves developed for this study compare well to those created through studies performed for the states of Florida and Illinois.

The basin test shows that the runoff hydrograph for the short pattern has lower, earlier peak runoff and the long pattern has lower, delayed peak runoff when compared to the runoff hydrograph generated using the SCS Type II hyetograph for the same event parameters. The hydrographs' time to peak based on the new patterns approach that of the SCS event as the time of concentration approaches the duration of the storm. The peak discharge follows the same trend. The required peak storage volume for detention is reduced with the new patterns as well. The less intense hyetograph allows water to leave the pond at a rate closer to the inflow rate, leading to a reduction in peak stage regardless of the time of concentration.

The new patterns appear to provide reduced peak discharge and reduced storage volume. It is believed that this is a direct result of using local and updated rainfall data. The analysis suggests that regular updates of hyetographs are necessary for rainfall-runoff design. This study is oriented towards small drainage basins where the time of concentration is less than the duration of the event and space for development is limited. In these basins, the peak discharge and storage volume are lower than those predicted using currently used hyetographs. In large drainage basins where the time of concentration approaches or exceeds the duration of the event, the peak discharge converges to the existing design value. In both cases, storage volume variations are where the largest impact can be made in the cost of the system. Lower required storage volumes mean smaller detention structures.

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