COMPARISON OF DISTRIBUTED VERSUS LUMPED HYDROLOGIC

SIMULATION MODELS USING STATIONARY AND MOVING

STORM EVENTS APPLIED TO SMALL SYNTHETIC

RECTANGULAR BASINS AND AN ACTUAL

WATERSHED BASIN

By

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ABSTRACT

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The University of Texas at Arlington, 2007

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The purpose of this investigation is to compare simulations using several artificial rectangular basins and a real drainage basin for distributed and lumped hydrologic models via results obtained with the U.S. Geological Survey Modular Modeling System (MMS). Impervious watershed conditions were assumed for each simulation. A critical objective of this investigation is to assess the performance of a physically-simple lumped model compared to a more physically-complex distributed model for various storm events. Knowledge gained from this investigation may be applied to the practical problem of determining when either a distributed or lumped model may be expected to function well given a set of hydrologic conditions.

The MMS was configured to simulate both distributed and lumped hydrologic models, and then combined with a kinematic wave technique to simulate overland and channel flow. Synthetic rectangular basins and a real drainage basin (Cowleech Fork Sabine River near Greenville, Texas) were investigated. Highlights of the methodology employed include: (1) synthetic rectangular drainage basins using three overland flow plane slopes and one channel slope developed based on a range of shape factors; (2) a real drainage basin for comparison of results; (3) specification of Manning's n coefficients which represent both natural overland flow and channel flow conditions; and (4) stationary and moving storm events applied to each drainage basin using the same total rainfall volumes.

Significant results for stationary rainfall events follow. Peak flow simulations were very similar for distributed rainfall applied as individual cases to the upper, middle, and lower part of each basin. However, peak flow magnitudes were much greater for the distributed cases when compared to the lumped cases. As for timing differences, downstream rains yielded earlier peak outflows when compared to peaks resulting from upstream rains. Peak flow comparisons for the distributed versus lumped cases generally ranged from 2.5 to 3.0 for the synthetic rectangular basins and 2.1 to 2.3 for the Greenville basin. These values dropped to 1.3 when the Greenville basin reached equilibrium conditions. Overall shapes of the dimensionless hydrographs differ when comparing distributed versus lumped cases. For the Greenville basin, the overall shapes

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of the dimensionless hydrographs also differ for equilibrium versus non-equilibrium conditions.

Significant results for moving storm events follow. For the synthetic rectangular basins, peak flows computed for both distributed and lumped rainfall scenarios were very similar. For storm systems moving upstream to downstream, peak flow magnitudes were slightly greater for the distributed cases when compared to the lumped cases. However, for storm systems moving in the opposite direction (downstream to upstream), peak flow magnitudes were slightly less for the distributed cases compared to the lumped case. For Greenville, this same general pattern occurred except the degree of magnitude between the distributed and lumped cases were either higher or lower for the upstream to downstream or downstream to upstream storm systems, respectively. Peak flows occurred later in time for storm systems moving from upstream to downstream when compared to storm systems moving in the opposite direction. Overall shapes of the dimensionless hydrographs were also different when comparing distributed versus lumped cases.

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CHAPTER 1

INTRODUCTION

Distributed modeling has great potential for the advancement of the hydrologic science. Because of this, distributed hydrologic models are currently being investigated as a means to improve hydrologic simulations over watershed drainage basins. For the past several decades, lumped hydrologic models have been used for these simulations. However, with recent technological advances, distributed hydrologic models are being explored as a means to improve the accuracy of the simulated hydrologic response when compared to the traditional lumped model.

Distributed models attempt to represent the hydrologic process of the watershed in more detail than lumped models. Because of this, they are viewed as being more accurate than lumped models. However, distributed models are generally more complex, thus requiring more data, more computational resources, larger computational algorithms, and more development time than a lumped modeling system.

Previous research studies have compared simulated results from both distributed and lumped modeling systems with observed streamflow data. Results from those investigations have been inconclusive. It is unclear whether a distributed or lumped model is the most efficient means for representing a watershed. Investigations will be

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conducted in this study to simulate the hydrologic response resulting from two such models with varying watershed characteristics and precipitation conditions.

The purpose of this investigation is to determine whether a lumped or distributed model performs best under a given set of drainage basin and rainfall conditions. The U.S. Geological Survey Modular Modeling System (MMS) was used to develop both lumped and distributed hydrologic models for (1) synthetic rectangular drainage basins and (2) an actual watershed drainage basin, Cowleech Creek Sabine River near Greenville, Texas.

This report is divided into several chapters. Chapter 1 (i.e. this chapter) provides an overall introduction to distributed versus lumped modeling. Chapter 2 discusses the research that has been investigated. Chapter 3 details the hydrologic indices which impact streamflow generation. Chapters 4 and 5 discuss the concepts of lumped models and distributed models, respectively. Chapter 6 describes the fundamental concepts of dynamic, diffusion, and kinematic wave theory and how they relate to distributed modeling. Chapter 7 outlines the Modular Modeling System (MMS), the research tool used for this investigation. Chapter 8 describes the methodology which was employed for the synthetic rectangular and actual drainage basins in conjunction with the stationary and moving storm events. Chapter 9 discusses the results of this investigation. Chapter 10 summarizes this research project. Chapter 11 provides a list of recommendations for additional research using distributed models.

CHAPTER 2

PROPOSED RESEARCH

The purpose of this research is to determine when a lumped model can be utilized without sacrificing the accuracy expected with a distributed model. A sensitivity analysis will be performed using both distributed and a lumped models to gain an understanding for the application of these models to given hydrologic conditions. Both the distributed and lumped hydrologic models will be applied to synthetic rectangular drainage basins consisting of various shapes and sizes. Stationary and moving storm systems will be applied in conjunction with each model to simulate runoff. Knowledge gained will then be applied to the practical problem of determining when a lumped model may perform as well as a fully distributed model.

An actual watershed headwater area will then be modeled using both a distributed model and a lumped model. From there, the sensitivity of a basin to spatially distributed model versus a lumped model can be determined.

In performing this analysis, the following questions should be kept in mind:

1. Under what set of watershed conditions is a distributed model more advantageous than a lumped model for simulating the hydrologic response over a watershed area?

2. How is discharge impacted by the location of stationary storm events in terms of peak discharge and lag time?

3. How does the direction of storm movement impact runoff production?

CHAPTER 3

HYDROLOGIC INDICES FOR STREAMFLOW GENERATION

Hydrologic indices vary in both space and time. Hydrologic indices are a function of topography, vegetation, land use, soils, geology, and the stream network across the drainage basin. These indices are related to the actual measurement of streamflow and include peak discharge, runoff volume, timing of runoff, and baseflow. The hydrologic properties which impact streamflow include interception, infiltration, evaporation, transpiration, and erosion. (Singh 1992)

This chapter deals with the hydrologic indices which impact streamflow generation. The first section discusses the physical characteristics of a watershed. The second section pertains to the precipitation and runoff processes for a drainage basin. The third section discusses the physical parameters which impact the shape of a hydrograph. The fourth section summarizes the chapter. It should be noted that the hydrologic indices discussed in this chapter apply to both distributed and lumped hydrologic models.

3.1 Characterizing the Watershed

A watershed is a system that is always in equilibrium. A watershed is a "natural laboratory of hydrology" where direct precipitation occurs within the confines of a watershed drainage basin and collects into a stream channel, flowing downhill to a common basin outlet. (Black 1970a) (Black 1996) (Singh 1992)

Watershed hydrology deals with the rainfall-runoff relationships across a drainage basin. Watershed characteristics include drainage basin characteristics, precipitation-runoff processes, and hydrograph shape.

3.1.1. Drainage Basin Characteristics

Drainage basin characteristics are various parameters used to describe the physical characteristics which pertain to a watershed. Gray (1961) states "the application of the principles of dimensional analysis to assist in developing relationships useful for hydrograph synthesis is not feasible unless careful consideration is given to the selection of watershed parameters." (Gray 1961)

Drainage basin characteristics pertain to both land and channel elements of the watershed. Land surface elements consist of drainage area, basin shape, elevation, slope, soil type, vegetation, land use, hydrogeology, and the drainage network, to name a few. Channel elements pertain to the hydraulic properties of the channel. Hydraulic properties

include channel order, size and shape of the cross-sections along a stream channel, channel slope, channel length, hydraulic roughness, and drainage density. (Singh 1992)

The physical characteristics of a drainage basin which affect the shape of the hydrograph are:

1. basin boundaries;

2. drainage area;

3. basin shape;

4. basin slope;

5. basin length;

6. elevation;

7. aspect;

8. orientation;

9. drainage network;

10. basin order and channel order;

11. drainage density;

12. soil type;

13. basin centroid;

14. drainage-basin similarity;

15. overland flow storage effects;

16. length of overland flow;

17. sheet flow;

18. overland flow plane roughness;

19. area-distance distribution; and

20. land-use.

3.1.1.1. Basin Boundaries

A drainage basin is the physical boundary between watersheds where the slope of the watershed diverts all surface runoff to the same drainage outlet. The boundary between watersheds is called a drainage divide. (Singh 1992)

3.1.1.2. Drainage Area

The drainage area of a watershed is the surface area located within the watershed basin boundary. A watershed drainage area can be very large, encompassing hundreds of thousands of square miles. It can also be quite small on the order of an acre. (Black 1996) The size of a drainage area has a significant impact on flood hydrographs. By increasing the size of the drainage area, the time base will be lengthened. Also, the peak ordinate will decrease with an increase in basin size. (Gray 1970) (Wisler 1959) (Bedient 1992)

The effective area is the drainage area which contributes directly to runoff for the basin. It is possible that the effective area may differ from the total basin area. For example, watersheds that are impacted by significant underground leakage between basins would have effective drainage areas different from the total drainage area. Also, areas of a watershed which have features that cause a closed drainage within its boundary

would have an effective drainage area smaller than the total basin area. (Singh 1992) (Strahler 1957)

Singh (1996) distinguishes the size of a watershed according to three general categories: small, medium, and large. A small watershed is considered to have an area less than 100 square miles. Medium watersheds have an area between 100 and 1000 square miles. A large area is considered to have an area greater than 1000 square miles. Although this classification is rather vague, watershed size is reflected in terms of spatial heterogeneity and the dampening of the hydrologic processes. (Black 1975) (Singh 1996)

From a hydrologic standpoint, large, medium, and small watersheds will behave similar providing they are spatially uniform. However, as the size of a watershed increases, the hydrologic processes begin to average out due to storage increases, effectively, linearizing watershed behavior. Also, as the drainage area increases, the peak rate of runoff, when expressed as a percentage of total runoff, decreases; the time base of the unit hydrograph increases; the rate of runoff per unit area at peak flow decreases; and, the average intensity of precipitation for a given storm event also decreases. (Black 1975) (Singh 1996)

Small watersheds tend to reside in the headwater areas of major river basins where channel systems are often lacking. Small watersheds are generally more homogenous in nature composed with similar basin characteristics. In these areas,

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rainfall amounts tend to be more significant than in the lower parts of the basin, resulting in greater depths of runoff. (Singh 1996) (Viessman 1977) (Viessman 1996) (Black 1996)

Small watersheds are highly sensitive to short-duration high-intensity rainfall and are more likely to receive precipitation over its entire drainage area. Overland flow is the principal hydrologic process; channel flow is less conspicuous. (Singh 1996) (Viessman 1977) (Viessman 1996) (Black 1996)

Large watersheds often cover entire river basins. As a result, large watersheds generally have more diverse basin attributes. Unfortunately, this generally makes it more difficult to describe a drainage area hydrologically due to complex multiple factors operating simultaneously. (Singh 1996) (Viessman 1977) (Viessman 1996) (Black 1996)

Large watersheds are typically less sensitive to short-duration high-intensity rainfall. Rainfall usually does not fall over the entire drainage area for a given storm event. Therefore, the entire drainage basin does not contribute to the production of runoff. Rainfall that falls in the upper reaches takes longer to travel to the basin outlet compared to rainfall that falls in the lower reach. Large watersheds have a dominant channel phase since they have a well defined network of channels; therefore, channel storage is dominant. (Singh 1996) (Viessman 1977) (Viessman 1996) (Black 1996)

3.1.1.3. Basin Shape

Basin shape is an important factor in the hydrologic response for a watershed. Watershed systems come in many different basin shapes. The most common is the pear shape. Rectangular, circular, and triangular shaped watersheds are also possible basin types. (Morisawa 1958)

In an early study, Sherman (1932) showed that the shape of unit hydrographs differed when derived from basins with different drainage basin characteristics. (Sherman 1932)

The shape of the drainage area has a direct impact on the rate surface runoff reaches the basin outlet. Basin tributaries which are compactly organized will allow flow from all parts of the basin to reach the outlet with higher peaks than flow from remote parts of a drainage. For example, flow from a semicircular basin will converge at the outlet much quicker than flow produced on a long, narrow basin of equal size. (Gray 1970) (Wisler 1959) (Bedient 1992)

Stream discharge characteristics are affected by the shape of the watershed. For a compact watershed, the hydrograph at the basin outlet will experience a sharper peak with a shorter duration time since the entire basin is more likely to be covered by local storm events. Long narrow watersheds, however, tend to have low flood peaks since it takes longer for the water to travel to the basin outlet. In this case, the basin is unlikely to be covered by an entire storm event. (Singh 1989) (Singh 1992)

Various dimensionless parameters are used to quantitatively define the shape of a watershed. These parameters include shape factor, form factor, elongation ratio, compactness coefficient, and the circularity ratio. The following equations are used to compute these parameters:

$$\text{Length/Width Ratio} = \frac{L}{W}$$

$$\text{Form Factor (F)} = \frac{A}{L^2}$$

$$\text{Shape Factor (S)} = \frac{L^2}{A} = \frac{L}{W}$$

$$\text{Elongation Ratio (E)} = \frac{1.128 A^{0.5}}{L}$$

$$\text{Circularity Ratio (C)} = \frac{12.57 A}{P^2}$$

$$\text{Compactness Coefficient} = \frac{0.2821 P}{A^{0.5}}$$

where L is the length of the watershed, W is the width of the watershed, A is the drainage area, and P is the wetted perimeter. (Singh 1992) (Horton 1932) (Schumm 1956)

It should be noted that as the watershed shape approaches that of a circle, the shape factor, elongation ratio, circularity ratio, and the compactness coefficient approach 1. This shape factor is greater than 1 for basins which are elongated along some characteristic length of the basin and less than 1 for basins which are elongated perpendicular to this characteristic length. In a study conducted by Smart (1967), two

basins had shape factors of 1.77 and 1.11. (Singh 1992) (Horton 1932) (Schumm 1956)
(Smart 1967)

3.1.1.4. Basin Slope

Basin slope greatly impacts the overland flow velocity, watershed erosion, and the
local wind systems. When the slope is coupled with the orientation of the basin, solar
radiation is affected, which in turn, influences the microclimate of the basin, snow melt,
and precipitation distribution. (Singh 1992) (Langbein 1947)

The equation used to compute basin slope is

$$\text{Basin Slope (s)} = \frac{h}{L}$$

where h is the change in elevation and L is the horizontal distance over this elevation
change.

Watershed slope directly impacts the travel time of runoff to the basin outlet.
Steeper hillslopes increase the velocity of overland flow, thus shortening the travel time
across the watershed basin. For small areas, overland flow has a major impact on the
time of concentration and hydrograph peaks. For large basins, however, the travel time
for overland flow is small compared to the flow in the actual channel. (Gray 1970)
(Wisler 1959) (Bedient 1992)

3.1.1.5. Basin Length

The basin length of a watershed is essentially the longest dimension which runs parallel to the primary drainage channel. The time of concentration of the flood peak is determined by dividing the length by the mean velocity of flow. (Singh 1992) (Schumm 1956) (Langbein 1947)

3.1.1.6. Elevation

Elevation is an important factor when it comes to the hydrologic processes on a watershed. Generally, higher elevations yield higher amounts of precipitation and runoff due to the orographic effect. Runoff also tends to be more "flashy" at higher elevations due to steeper terrain.

The elevation of the watershed has a direct impact on temperature and the type of precipitation. Temperature affects evapotranspiration, thereby impacting runoff. High elevation areas tend to receive snow, thereby affecting runoff processes. (Gray 1970) (Wisler 1959) (Bedient 1992)

Snowfall also occurs in the alpine and subalpine regions of a watershed. Runoff which results from snowmelt is typically smaller with a longer lag time than that resulting from rainfall. The depth of soil and the density of vegetation are also lower at higher elevations resulting in greater runoff.

3.1.1.7. Aspect

The aspect of a watershed is the direction of exposure from sunlight. South facing slopes are typically drier with greater evapotranspiration processes. North facing slopes are usually cooler and produce more runoff. (Black 1996)

3.1.1.8. Orientation

Orientation is a significant factor on basin runoff, especially when it is considered in conjunction with the direction of movement of a storm. Rainfall rarely falls uniformly both temporally and spatially over an entire drainage basin. Therefore, the orientation of a drainage basin in relation to the direction of the storm movement can have a major impact on the magnitude of peak flow and the duration of surface runoff. This is especially true for long elongated basins. A storm system that moves upstream will produce lower and much broader peaks since the system is moving in the opposite direction of runoff flowing downstream. A storm that moves downstream, however, will experience higher and steeper peaks, due in part to continued precipitation falling on top of the watershed runoff as it progresses downstream. (Gray 1970) (Wisler 1959) (Bedient 1992)

3.1.1.9. Drainage Network

A drainage network is the entire area of a watershed which drains water to a particular channel or set of channels and eventually through a single outlet. These channels form a drainage net and begin as small rills in the headwater reaches and

increase in size downstream to gullies, small streams, and eventually large river channels.

(Linsley 1949) (Leopold 1964) (Dunne 1978)

A drainage system with an efficient arrangement of stream channels reduces the

distance water must travel to the basin outlet. This allows runoff to reach the basin outlet

much quicker. (Gray 1970) (Wisler 1959) (Bedient 1992)

Several factors impact the development of a drainage system. These factors

include the natural landforms of a watershed which affect the direction of flow, pattern,

and the general nature of rivers and streams. The type of soil and the type of rock

material located within a basin also affect the development of a drainage system. Finally,

the climate also affects the drainage development. Drainage systems, even with identical

landforms, will differ between arid and humid climates. For example, evolution is slow

for areas located in arid climates. On the other extreme, major changes take place in

areas which periodically experience floods. (Linsley 1949)

Drainage patterns come in different sizes and shapes. Typically, stream patterns

are classified as dendritic (treelike), radial, centripetal, rectangular, and trellised. Each of

these drainage classifications is also associated with a treelike pattern. However,

different patterns resemble the branching of different kinds of trees. For example, these

branches can enter a main stream channel at right angles. Also, these branches can be

parallel to the main channel, thus entering the main stream segment at small angles. In

areas where the rock structure is homogenous, the drainage pattern is dendritic, or tree

like. In mountain valleys, small tributaries flow into larger streams, creating a pinnate leaf like structure. In areas where there are many rectangular joints and faults, the drainage pattern can form at right angles. Where dome mountains or volcanoes are present, the drainage system will radiate outward. For depression areas, the flow converges inward. (Linsley 1949) (Dunne 1978) (Horton 1945)

Drainage patterns when associated with drainage densities do not provide an adequate representation of the drainage network for a basin. River basins may consist of a variety of stream numbers, lengths, and orders, and yet, give the same drainage density. Because of this, Horton (1945) has listed the following criteria necessary to know the composition of a stream system: (1) drainage area, (2) the order of the main stream channel, (3) the bifurcation ratio, (4) the stream length ratio, and (5) the length of the main stream channel or preferably the average length of all first order streams. (Horton 1945)

3.1.1.10. Basin Order and Channel Order

Drainage areas are characterized by stream ordering, which is the position of the stream in a hierarchy of tributaries. Stream ordering is used to quantitatively compare the development of drainage nets of drainage basins of comparable size. However, its usefulness to compare basins is limited by the fact that stream systems generally increase in scope as the size of drainage areas increase.

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First-order streams are the smallest streams in the network and are located in the headwater areas. They have no tributaries and are dependant solely on localized surface overland flow. Second-order channels receive flow from two upstream first-order channels, local surface overland flow, and possibly from additional first order channels. The volume of flow is also greater for a second order than for a first order channel. Third-order channels receive flow from two second-order channels, local surface overland flow, and possibly additional first order or second order channels that flow directly into it. The ordering system for succeeding higher order channels continues in the same manner. Stream order increases in the downstream direction. Higher order channels carry more flow than lower order channels. (Singh 1989) (Singh 1992) (Dunne 1978) (Leopold 1964) (Leopold 1994) (Horton 1932) (Horton 1945) (Strahler 1957)

A word of caution needs to be mentioned in ordering streams. The definition of a first order stream is a function of the scale of the map used to derive stream orders. For example, a first order stream depicted from a small scale map may translate into a higher stream order, such as a fourth order stream, than on a larger scale map for the exact same tributary. Small scale maps offer more detail than large scale maps. (Leopold 1956).

3.1.1.11. Drainage Density

Drainage density is defined by the following equation

$$\text{Drainage Density (D}_\text{d}) = \frac{L}{A}$$

where L is the total length of all stream channels for all channel orders in the drainage basin and A is the drainage basin area.

Drainage density gives a strong indication as to how efficient the flow is from a river basin for both overland and channel flow. It is actually a measure of how close channels are spaced in a watershed. High drainage densities are usually associated with steep hill slopes and indicate a high percentage of precipitation that is translated into watershed runoff resulting in high flood peaks and high sediment production. Low drainage densities indicate a high degree of infiltration into the watershed, resulting in fewer channels which carry runoff. High infiltration occurs in sandy soil, especially with granite fragments, resulting in a low drainage density. Low infiltration occurs in clay soils, and to some degree, silty soils, indicating a high drainage density for the drainage area. In general, increases in drainage density results in decreases in the size of individual drainage units. (Singh 1989) (Singh 1992) (Dunne 1978) (Strahler 1957)

In a study conducted by Horton (1945), the poorly drained basin has a drainage density of 2.74; the well drained basin is 0.73, or one fourth as great. (Horton 1945) In another study conducted by Langbein (1947), drainage densities primarily for watershed basins in the northeastern United States ranged from 0.89 to 3.37 miles per square mile. (Langbein 1947)

Drainage density is typically higher in humid regions than in arid regions. Drainage density approaches a maximum in steep, rocky, humid regions; drainage

density approach zero in flat, sandy, desert watersheds. Generally, drainage density ranges from 1.5 to 2.0 for steep, impervious watersheds in areas subject to high amounts of precipitation. These densities drop towards 0 for permeable watersheds where all of the rainfall infiltrates into the soil. (Horton 1932)

In determining drainage density, perennial, intermittent, and ephemeral streams should be included in the computations. All of these stream types carry flood water; therefore, they should be included in determining the drainage density for a basin. Perennial streams are usually located in the lower reaches; intermittent and ephemeral streams are located near the headwaters above the groundwater table. (Horton 1945)

3.1.1.12. Soil Type

Runoff is greatly impacted by the type of soil over a drainage basin. For example, clay soils are less porous than sand, thereby causing infiltration to be lower and runoff to be higher. Also, clay has a high shrink-swell capacity. As the moisture content increases, clay soils tend to swell, reducing the porosity of the soil, thereby increasing runoff. (Gray 1970) (Wisler 1959) (Bedient 1992)

3.1.1.13. Basin Centroid

The centroid, otherwise known as the center of gravity, is the location, within a drainage basin, of a point which represents its weighted center. (Singh 1992)

3.1.1.14. Drainage-Basin Similarity

Drainage basin similarity can be depicted as three types. The first type is geometric similarity which deals in terms of basin area, basin shape, the slope of the main channel, and the topography of the basin. The second type is hydrologic similarity which deals in terms of the hydrologic processes occurring over a watershed. These processes include rainfall, snowfall, infiltration, runoff, and valley storage. The third type is geologic similarity which is derived from the parent geology over the drainage basin. This deals in terms of groundwater flow, soil erosion, porous media, sediment characteristics, and sediment transport. The hydrologic relations for a drainage basin can be transferred to another similar basin providing the basin similarity conditions are met. (Singh 1992)

3.1.1.15. Overland Flow Storage Effects

Storage of water occurs over both overland flow and channel flow. Storage typically decreases peak discharge while increasing the time base of the hydrograph. Storage typically occurs over flat areas, allowing flat rounded peaks with a long time period. Storage typically does not occur over steeper terrain where the peak discharge is greater and the time period is shorter. (Gray 1970) (Wisler 1959) (Bedient 1992)

3.1.1.16. Length of Overland Flow

Overland flow is the length of travel across a drainage basin as water flows down a slope toward a channel. (Singh 1989) (Singh 1992) (Horton 1945)

The average length of overland flow is usually equal to approximately half of the average distance between the stream channels. The average length of overland flow is also equivalent to half the reciprocal of the drainage density as shown in the following equations

$$l_o = \frac{1}{2D_d \sqrt{1-(\frac{s_c}{s_g})^2}}$$

or

$$l_o = \frac{1}{2D_d}$$

where l_o is the average length of overland flow, D_d is the drainage density, s_c is the channel slope, and s_g is the average ground slope. The second equation is generally used since the term s_c/s_g in the first equation is smaller than 1. (Horton 1932) (Horton 1945) (Singh 1992) (Schumm 1956)

Generally, as the length of overland flow increases, the amount of precipitation which infiltrates into the soil increases, thereby, decreasing the amount of surface runoff. (Horton 1932)

3.1.1.17. Sheet Flow

Sheet flow is a very thin layer of runoff which flows over an overland flow plane. Sheet flow can be considered as wide-open-channel flow. (Chow 1959)

Sheet flow can occur over an overland flow plane for a maximum distance of 300 feet. For distances greater than this, sheet flow usually concentrates into shallow flow. (Gupta 1989)

The travel time for sheet flow is given by the following equation

$$T_{t1} = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5} s^{0.4}}$$

where T_{t1} is the time in hours, n is the manning's n coefficient, L is the length, P_2 is the 2-year, 24-hour rainfall amount, and s is the slope. (Gupta 1989)

3.1.1.18. Overland Flow Plane Roughness

The overland flow-plane roughness applies to the roughness of sheet flow over and overland flow-plane. Manning's "n" coefficients for overland sheet flow are listed below. When selecting the "n" value, consider a 30 mm height of vegetative cover. Sheet flow is only obstructed by plant cover at this height.

Smooth asphalt   Manning's n: 0.011

Smooth concrete   Manning's n: 0.012

Range (natural)   Manning's n: 0.013

Short grass prairie   Manning's n: 0.15

Dense grass   Manning's n: 0.24

Bermuda grass   Manning's n: 0.41

Woods with light underbrush   Manning's n: 0.40

Woods with dense underbrush   Manning's n: 0.80

(FHA 2001)

3.1.1.19. Area-Distance Distribution

Runoff which occurs closer to the basin outlet should reach the outlet sooner than

runoff from remote areas of the watershed. Stream discharge at the outlet will also reach

greater flood peaks. Rainfall which occurs over a larger area of the basin will also

produce greater volumes of water. (Langbein 1947)

3.1.1.20. Land-Use

Land-Use is one of the most important factors which impacts runoff. Watersheds

can be classified into several different land-uses. These include urban, agricultural,

forest, mountainous, coastal, desert, and wetland watersheds. The hydrologic response

varies for each type of watershed.

Urban watersheds are associated with city and town environments which are dominated by buildings, roads, and parking lots. These features increase the impervious nature of the drainage area which reduces infiltration, thereby, increasing runoff. Runoff is generally greater over urban areas than over rural areas. Also, artificial drainage structures are quite often constructed which significantly alters the natural flow pattern across a watershed. (Singh 1992) (Gray 1970) (Wisler 1959) (Bedient 1992)

Agricultural watersheds undergo one of the most significant land-use changes. The land surface is tilled several times with crops growing several times each year. Cropping patterns along with the method of growing crops change. As a result, infiltration increases, erosion increases, while runoff decreases. It should also be noted that when the agricultural field is barren, falling raindrops have a tendency to compact the soil, thereby, reducing infiltration. Also, the organic material changes the soil texture, greatly altering the hydrologic process. (Singh 1992)

Forested watersheds have a much different hydrologic behavior than urban and agricultural watersheds. Interception by the forested canopy is significant. Runoff production is usually less in heavily vegetated forested areas than in lightly vegetated regions. Evapotranspiration is also a major component in the hydrologic budget. Also, the ground surface is often littered with vegetative matter such as leaves, stems, branches, and wood. During a period of rainfall, water is held in storage by both the trees and vegetative litter, allowing a greater opportunity for infiltration. This leads to the recharge of the groundwater aquifer and eventually groundwater flow into stream channels.

Because of these processes, surface runoff often has little to no contribution to streamflow, allowing for reduced peak discharges. (Singh 1992) (Gray 1970) (Wisler 1959) (Bedient 1992)

Mountainous watersheds receive considerable snowfall due to their high elevations. These watersheds usually have a substantial amount of vegetation allowing for significant interception. Evapotranspiration is also high. Infiltration, however, is usually low due to the steep watershed gradients and the relatively less porous nature of the soil. As a result, surface runoff is quite high, especially after a significant rainfall event. Flash floods are common. This is even more pronounced when rainfall falls on top of a snowpack. Generally, land-use is fairly static with little to no changes in land-use. During spring and summer, the water supply is regenerated due to melting snow. (Singh 1992)

Coastal watersheds are directly impacted by the sea. They may or may not be located in urban areas. The hydrologic system is affected by backwater caused by both wave and tidal influences. Rainfall amounts are high due to their location by the sea, making them vulnerable to severe, local flooding. The land gradient is small, allowing for slow drainages. Coastal watersheds also have high water tables and problems with saltwater intrusion into area aquifers. The coastal areas usually consist of sandy soil. Land-use changes are quite common. (Singh 1992)

Desert watersheds are marked by little annual rainfall. Virtually no vegetation exists in these areas. Whenever rainfall does occur, most of it is absorbed by the porous sandy soil.   If heavy localized rainfall does occur, local flooding may result. However, runoff from these events usually infiltrate into the soil as it travels downstream. As a result, these areas have very little stream development. Groundwater recharge is also minimal due to the limited amounts of rainfall in these areas. (Singh 1992)

Wetland areas are comprised of marshes, swamps, and water courses. These areas are relatively flat. Evaporation is a dominant hydrologic process in these environments. Rainfall amounts are typically high; infiltration is minimal. The majority of rainfall becomes runoff which discharges slowly across the watershed. As a result, flood hydrographs have a gradual peak and usually last for a long time. (Singh 1992)

3.1.2. Stream Channel Characteristics

The physical characteristics of a stream channel which affect the shape of the hydrograph are:

1. number of channels and their order;

2. channel length;

3. channel area;

4. channel profile;

5. channel slope;

6. channel roughness; and

7. channel flow storage effects.

<u>3.1.2.1. Number of Channels and their Order</u>

The number of channels of a given order located within a drainage basin is based on the land surface of the watershed. Basically, for basins which consist primarily of very permeable soil, fewer channels are present to transport runoff to the outlet. For basins which have a large number of channels, the drainage area is typically smaller which contributes more runoff to each channel order. (Singh 1992)

The bifurcation ratio is an index used to relate the total number of streams of a given order with the number of streams of the next higher order. This index is computed from the following equation:

$$R_b = \frac{N_w}{N_{w+1}}$$

where R_b is the bifurcation ratio and N_w is the number of streams of a given order w. (Singh 1992) (Schumm 1956) (Horton 1945)

According to a study conducted by Horton (1945), a bifurcation ratio of 2 equated to both flat and rolling drainage basins. A bifurcation ratio of 3 or 4 was found for both mountainous and highly dissected drainage basins. (Horton 1945) Schumm (1956) found the mean bifurcation ratio was 4.87 for the Perth Amboy Drainage, located in New Jersey. (Schumm 1956)

3.1.2.2. Channel Length

Channel length refers to the length of the channels of each order. First-order channels are channels with the shortest length. The length of a channel increases as the order increases. Channel length of a given order is a function of the soil type for a given basin. In general, as the length of a channel increases, the drainage becomes more permeable. (Singh 1989) (Singh 1992)

3.1.2.3. Channel Area

Channel area is the drainage area which contributes runoff to the channel segment of that order and all lower-order channels. (Singh 1992)

3.1.2.4. Channel Profile

Channel profile is a relationship between the altitude and horizontal distance within a given watershed. In general, the upper reaches of a drainage basin are typically steeper than the lower portion, especially when the watershed exhibits uniform geologic conditions. When the geology becomes nonuniform, differences in the erosional properties of the geologic strata distorts the uniform nature of the channel profile. This causes large variations in flow velocity along a stream channel. (Singh 1989) (Singh 1992) (Linsley 1949)

3.1.2.5. Channel Slope

Channel slope is the total change in elevation divided by the corresponding total length. Channel slope greatly impacts flow velocity within a river channel.   (Singh 1992) (Langbein 1947)

Channel slope has a direct impact on the travel time of water within its banks. By increasing channel slope, the velocity of the floodwave increases, thereby, decreasing its travel time. Also, peak discharge becomes steeper and the time duration of the hydrograph decreases at the outlet. (Gray 1970) (Wisler 1959) (Bedient 1992)

3.1.2.6. Channel Roughness

Channel roughness applies to the roughness of a stream channel. Channel roughness is a function of several factors including (1) channel bed material, (2) channel irregularities, (3) channel shape and size, (4) vegetation, (5) flow conditions, (6) channel obstructions, and (7) the degree of meandering in the channel. (Chow 1959) (Gupta 1989)

Manning's "n" roughness coefficient is used as a measure of channel roughness. Manning's "n" coefficients for a natural channel are listed below.

Natural Channel (minor streams, top width at flood stage < 100 feet)

    Fairly regular section   Manning's n: 0.03 - 0.07

    Irregular section with pools   Manning's n: 0.04 - 0.10

Gravel beds, straight	Manning's n: 0.025
Gravel beds with large boulders	Manning's n: 0.040
Earth, straight, with some grass	Manning's n: 0.026
Earth, winding, no vegetation	Manning's n: 0.030
Earth, winding	Manning's n: 0.050

(Chow 1959) (Gupta 1989) (FHA 2001) (Roberson 1998)

The reader is invited to refer to Chow (1959) for a detailed table and photographs showing Manning's "n" values for different stream channel conditions.

3.1.2.7. Channel Flow Storage Effects

Water storage occurs over both overland flow and channel flow. Storage typically decreases peak discharge while increasing the time base of the hydrograph. Storage typically occurs over flat areas, allowing flat rounded peaks with a long time period. Storage typically does not occur over steeper terrain where the peak discharge is greater and the time period is shorter. (Gray 1970) (Wisler 1959) (Bedient 1992)

3.2 Precipitation – Runoff Processes

The physical nature of a watershed impacts the movement of water to the basin outlet. (Dingman 1994) The drainage basin controls both the rate of and the degree of concentration of runoff off the watershed. Actual runoff is reflected in volume, peak discharge, and the shape and magnitude of the runoff hydrograph which results from a

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rainfall event. (Singh 1992) Precipitation is the "driving mechanism" which typically

translates into runoff.

3.2.1. Precipitation

Rainfall distribution across a watershed varies both spatially and temporally.

Spatial properties include both the location and amount of precipitation across the

watershed. Temporal properties include the time distribution of rainfall across the

drainage basin. Both spatial and temporal characteristics of rainfall can be determined

using precipitation gages and rainfall radar estimates.

Several climatic factors affect the runoff. These are:

1. rainfall intensity;

2. rainfall duration;

3. rainfall distribution on the drainage basin;

4. direction of storm movement;

5. type of storm;

6. type of precipitation;

7. soil moisture content and antecedent precipitation; and

8. other climatic conditions.

3.2.1.1. Rainfall Intensity

Rainfall intensity has a direct impact on the rate of peak flow and the amount of

runoff which is produced. Increasing rainfall intensity will increase both the peak

discharge and volume of runoff providing it is greater than the soil infiltration rate. Variations in rainfall intensity will have an impact on the hydrograph shape for small basins. However, this impact will be minimal for large basins.

3.2.1.2. Rainfall Duration

Rainfall duration has a direct impact on peak flow, the amount of surface runoff, and the time period of surface runoff. If the time duration of a storm is long, considerable runoff may be produced. Also, small basin watersheds may reach equilibrium for long duration storms whereby most of the precipitation becomes runoff. It should be noted that this condition is never reached on very large basins.

3.2.1.3. Rainfall Distribution on the Drainage Basin

Rainfall distribution on the drainage basin can greatly affect the shape of the hydrograph. If rainfall occurs in the upper reaches, the hydrograph at the basin outlet shows a lower and broader peak. However, if the rainfall occurs near the basin outlet, the hydrograph will have a rapid rise, a sharp "needle-nose" peak, followed by a rapid fall on the recession limb. Also, the size of the watershed impacts the hydrologic response. For large watershed basins, rainfall is very seldom uniformly distributed. High peak flows usually occur from several storms of lower intensities that cover large areas of the watershed. For small drainage basins, intense localized thunderstorms over smaller areas can create significant peak flows.

3.2.1.4. Direction of Storm Movement

Rainfall rarely falls uniformly both temporally and spatially over an entire drainage basin. Therefore, the direction of the storm movement in relation to the orientation of a drainage basin can have a major impact on the magnitude of peak flow and the duration of surface runoff. This is especially true for long elongated basins. A storm system that moves upstream will produce lower and much broader peaks since the system is moving in the opposite direction of runoff flowing downstream. A storm that moves downstream, however, will experience higher and steeper peaks, due in part to continued precipitation falling on top of the watershed runoff as it progresses downstream.

3.2.1.5. Type of Storm

The type of storm has an impact on the shape of the hydrograph. Thunderstorms are generally more localized and have a greater impact on small basins compared to large basins. Large cyclonic frontal-type storms have a greater affect on large basins than do thunderstorms.

3.2.1.6. Type of Precipitation

The type of precipitation influences the hydrograph response. Precipitation that falls in the form of rain impacts the watershed almost immediately, providing the rainfall intensity and magnitude is great enough to generate a runoff response. Snowfall, however, will have no impact on runoff until it begins to melt. Therefore, when compared to rainfall, a snowmelt hydrograph typically has lower and broader peaks.

3.2.1.7. Soil Moisture Content

The soil moisture content has a direct impact on the production of surface runoff and groundwater recharge. When the soil moisture content is high, surface runoff from the watershed is high due to the low capacity for infiltration. When the soil moisture content reaches field capacity, infiltration and percolation through the soil will increase causing increased groundwater discharge. During the summer months, evapotranspiration is high which depletes soil moisture. Rainfall which occurs during this time period is usually soaked up by the soil causing little if any surface runoff. However, if several rainfall events occur in succession over a very short time period, surface runoff may occur with the later events.

3.2.1.8. Other Climatic Conditions

Other climatic factors can impact the production of runoff. These components include temperature, annual precipitation, wind velocity, relative humidity, and average barometric pressure. Although these elements do not directly impact the runoff, they collectively impact the evapotranspiration processes from the watershed, and thus, soil moisture content and runoff. (Gray 1970) (Wisler 1959) Bedient 1992) (Black 1996)

3.2.2. Runoff

Watershed runoff is composed of three components: (1) surface runoff, (2) interflow, and (3) groundwater runoff (i.e. baseflow). Surface runoff flows over the surface of the watershed and downstream in stream channels to the watershed basin

outlet. Interflow is the portion of runoff that infiltrates into the upper soil layers of the watershed and moves laterally until it reaches the stream channel. Interflow moves slower than surface runoff, reaching the stream channel later in time. Baseflow percolates through the soil until it reaches the water table. From there it moves laterally until it reaches the stream. Baseflow is much slower than both surface runoff and interflow and has little to no impact on the flood peaks resulting from a storm. (Singh 1988)

Surface runoff is composed of two components: (1) overland flow and (2) channel flow. Overland flow is the portion of runoff which flows over the land surface to the stream channel. Overland flow occurs when the precipitation rate from a storm exceeds the interception capacity of the vegetative canopy, the infiltration capacity of the soil on the watershed, and surface storage. Channel flow is the translation of a flood wave as it moves downstream in a stream channel. As runoff moves across a watershed and then downstream to the outlet, it undergoes changes across both the overland flow plane and within the stream channel. (Singh 1988) (Wisler 1959)

It should be noted that overland flow may be turbulent, laminar, or a combination of these two flow conditions, where patches of laminar flow are interspersed with turbulent flow. (Horton 1945) Channel flow will also experience the same phenomena.

The spatial characteristics of soil and vegetation can be determined from a GIS database and field investigations. These spatial properties include the soil type and the type of vegetation located across the soil.

Surface runoff is impacted by both climatic and physiographic factors. The climatic factors include the intensity and duration of precipitation, the type of precipitation (i.e. convective, orographic, cyclonic), and the form of precipitation (i.e. rain, snow, sleet, hail). Vegetative cover, evapotranspiration, and the soil moisture content are also a function of the climate. The physiographic factors include the size, shape, average slope, soil type, land use, geologic structure, and the drainage network of the watershed. (Singh 1992) (Viessman 1977) (Viessman 1996) (Singh 1988) (Dunne 1978)

Based on a study conducted by Black (1970b), a deeper soil structure retards runoff, lowers the magnitude of flood peaks, and results in a longer sustained period of minimum flows. Also, steeper slopes cause the runoff to be more rapid, resulting in greater maximum peak flows with a shorter time of concentration and hydrograph decay time. Finally, Black found that drainage density is not a reliable index to measure drainage efficiency. Depending on the conditions, drainage patterns may mask the impact of this watershed parameters. (Black 1970b).

3.3. Hydrograph Shape

A streamflow hydrograph is the time distribution of water discharge at a specific point on a stream channel. A hydrograph is affected by both the characteristics of the watershed and the storm system causing the rainfall. The shape of the hydrograph is influenced by the rate water is transmitted across the drainage area to the basin outlet. Water is transmitted to the basin outlet by both overland flow and channel flow. The number of tributaries in the watershed system impacts the overall shape of the hydrograph. (Singh 1992)

Several factors affect the shape of a hydrograph. These factors are the drainage characteristics, soil type, vegetation type, land use, and rainfall distribution. (Singh 1992)

3.3.1. Drainage Characteristics

The parent geology of a drainage basin is a major factor governing streamflow at the basin outlet. Geology impacts the degree of perviousness, drainage pattern, and other hydrologic factors associated with the basin. (Singh 1992)

Basins which are highly pervious cause high infiltration rates resulting in low runoff and lower peak discharges. This results in a more "rounded" shaped hydrograph with gently rising limbs with longer recession times. In contrast to this, basins which are highly impervious cause low infiltration rates resulting in high-density drainage channels

with high runoff and higher peak discharges. This results in a more "peaked" shaped hydrograph with a relatively steep rising limb and shorter recession times. (Singh 1992)

Various drainage patterns occur over watersheds. The most common pattern is a dendritic type which is more treelike in appearance. Other pattern types include a rectangular or trellislike pattern. (Singh 1992)

3.3.2. Soil, Vegetation, and Land-Use

Soil type affects the shape of the hydrograph. Clay soils are highly impervious causing higher runoff and higher streamflow discharges compared to sand which is very pervious, resulting in lower runoff and lower streamflow discharges. Silt soil properties lie in between clay and sand, resulting in runoff which lies between these two soil types.

Vegetation also affects the shape of the hydrograph. A densely forested canopy increases the amount of rainfall which is intercepted and evaporated directly back into the atmosphere, resulting in lower runoff and lower streamflow at the basin outlet. In contrast, a sparsely covered grassland prairie decreases the amount of rainfall which is intercepted, resulting in higher runoff and higher streamflow at the basin outlet.

Land-use also affects the shape of the hydrograph. Land-use changes typically increase the amount of runoff resulting in higher streamflow discharges. Land use practices include urbanization, farming, and timber harvesting. Each of these practices

increase runoff. Land use practices such as building dams and diversions decrease

runoff. (Singh 1992)

3.3.3. Rainfall Distribution

The location of a storm system has a pronounced impact on the shape of a

hydrograph. Storm systems located near the basin outlet on the lower end of a basin

typically have higher peak discharges with steeper rising limbs with very a fast response.

This same storm system with an identical volume of water located in the upper end of the

drainage basin have lower peak discharges with more gradual rising limbs with a delayed

response. Finally, storm systems which occur over the entire drainage basin have

hydrograph shapes between those for the upper and lower storm systems. (Singh 1992)

3.4 Summary

This chapter discusses the hydrologic indices which impact streamflow

generation. These indices apply to both distributed and lumped hydrologic models and

include the physical characteristics of the watershed, precipitation and runoff processes,

and the shape of a hydrograph.   The next chapter discusses the principles associated

specifically with lumped models.

CHAPTER 4

LUMPED MODELS

Lumped models play an integral part of this investigation. Hydrologic

simulations were performed for both lumped and distributed models to see if distributed

models were more advantageous than the traditional lumped model using the kinematic

wave technique. This chapter deals with the fundamental concepts associated with

lumped models.

Smith (2004b) discusses that few studies have been conducted which specifically

address how distributed models show improvement over the traditional lumped model.

The hypothesis that distributed models, which use higher resolution data, are more

accurate than lumped models is largely untested. (Smith 2004b)

Lumped models have been used for over 50 years as a hydrologic technique to

estimate streamflow at a basin outlet. Unfortunately, this technique requires many

assumptions which tend to distort the overall hydrologic characteristics of a drainage

basin.

Lumped models are systems where all of the parameters which impact the

hydrologic response of a watershed are spatially averaged together to create uniformity

across the basin. (HEC 2000) (Johnson 1997) (Shah 1996a) Lumped models consider a

watershed catchment as one complete unit, characterized by a relative small number of

parameters and variables. (Refsgaard 1997)

Historically, hydrologic modeling has been conducted using a lumped modeling

approach. Unfortunately, there are many limitations when using this type of model.

Lumped models make the assumption that rainfall is uniformly distributed (i.e. mean

areal precipitation) over a watershed basin both spatially and temporally over a given

time period. Unfortunately, this never occurs in reality. Although there are a limited

number of cases where this may come close, in essence, it never happens. (Smith,

2004b) (Reed, 2004)

Lumped models also assume uniform soil types, vegetation types, and land-use

practices. Unfortunately, these parameters vary across a basin, sometimes very

significantly. Because of this, these parameters are averaged together across the basin

which results in uniform conditions, thus creating a lumped model.

Mean areal runoff for the drainage basin is computed by making abstractions from

the mean areal precipitation. Typically, this runoff is applied to a unit hydrograph to

determine the total streamflow at the basin outlet. In 1932, Sherman introduced the

concept of the unit hydrograph. The unit hydrograph is the runoff which results at the

downstream outlet of a drainage basin from a unit depth (i.e. 1 inch or 1 mm) of excess

rainfall for a storm of uniform intensity for a specified duration over an entire watershed drainage. (Sherman 1932)

It should be noted that the concept of a lumped model is based on uniformity of rainfall and hydrologic parameters across the basin. A lumped model can also be applied using a kinematic wave approach providing rainfall and the hydrologic parameters are assumed uniform across the basin.

In summary, the fundamental concepts associated with lumped models were discussed in this chapter. The next chapter deals with distributed modeling.

CHAPTER 5

DISTRIBUTED MODELS

Distributed models played an integral part of this investigation. Hydrologic simulations were performed for both distributed and lumped models to see if distributed models were more advantageous than the traditional lumped model using the kinematic wave technique.

Smith (2004b) discusses that few studies have been conducted which specifically address how distributed models show improvement over the traditional lumped model. The hypothesis that distributed models, which use higher resolution data, are more accurate than lumped models is largely untested. (Smith 2004b)

Distributed modeling is an active area of research in part due to the emergence of high resolution data sets, the increasing capabilities of GIS, and the increasing power of the modern day computer. (Smith 2004b) Until relatively recently, the use of distributed models was hindered by such factors as the inability of computers to efficiently process and store large amounts of data required to solve numerous and complex physics-based equations associated with these types of models. Also, from the perspective of operational forecasting, the implementation of distributed models has been hindered due to uncertainties in rainfall input, parameter errors, and model structure. A

number of questions remain as to how the variability of rainfall and drainage basin characteristics impact runoff, and thus, streamflow generation at the basin outlet.   (Smith 1999) (Smith 2004a) (Smith 2004b) (Carpenter 2004) (Woolhiser 1996)

The goal of distributed modeling is to better simulate the hydrologic response of a watershed by representing the spatial and temporal characteristics which govern the transformation of precipitation into runoff. (Vieux 2003b) Hydrologic distributed models explicitly consider the geographic spatial variations and processes across a watershed (HEC 2000). Hydrologic distributed models attempt to quantify the spatial variability of hydrologic parameters and use these parameters to analyze rainfall-runoff processes at desired locations within a watershed basin. (Smith 1993) Distributed models take into account (1) the spatial variability of both input and output of hydrologic variables for a given watershed, and (2) the hydrologic response at ungauged sites within the basin. (Smith 2004b)

Distributed models use parameters which are directly related to the physical characteristics of a watershed basin. These include topography, soil, vegetation, and geology. Distributed models also account for the spatial variability of the meteorological conditions of the drainage basin. (Refsgaard 1996) (Shultz 2006a)

This chapter deals with the fundamental concepts associated with distributed models. The first section discusses research investigations applicable to distributed modeling. The second section pertains to the distributed model intercomparison project.

The third section provides a brief description of several distributed models. The fourth section summarizes the chapter.

5.1. Distributed Model Research Investigations

Distributed model research investigations are currently being performed over a large number of sub-disciplines. These studies pertain to radar rainfall and rain gage networks, precipitation and runoff, watershed basin scale, grid cell, and watershed parameters. Other studies pertain to Hortonian (infiltration-excess) and Dunne (saturation-excess) runoff, complexity of distributed models, and distributed versus lumped model investigations. Also, a section is provided discussing river forecast applications using distributed models. Finally, a case example is provided which discusses the impact Tropical Storm Allison has over the development and calibration of a distributed model for a drainage basin located within Houston, Texas.

5.1.1. Radar Rainfall and Rain Gage Network Studies

Radar rainfall in conjunction with raingage network investigations are a very active area of research. Several research studies which have been conducted are discussed below.

Vieux (2003a) discusses that operational flood forecasts are critically dependent on accurate rainfall rates. (Vieux 2003a)   Rainfall information is determined using both the Weather Surveillance Radar – 1988 Dopplar (WSR-88D) and a network of raingages.

Rainfall estimates obtained from radar have distinct advantages over the measurements obtained from the traditional raingage network. Radar rainfall can estimate precipitations amounts with a high degree of spatial and temporal resolution over large areas. In contrast, a raingage measures precipitation amounts at a specific location. (Sharif 2002, 2004) It should be noted that raingage data is used to calibrate rainfall estimates obtained from the WSR-88D radar. This is critical to maintaining the accuracy of the radar estimates.

The geometry of the radar beam also affects the estimation of rainfall. Radar rainfall estimates need to be obtained for grid cells located below the atmospheric freezing level of precipitation. If the radar beam reflects back from an area of complex ice microphysics, radar reflectivity will be impacted by "bright banding" due to frozen precipitation, which results in the over estimation of rainfall. This often occurs with convective thunderstorm activity. However, if the radar beam overshoots the cloud tops, rainfall estimates will be underestimated, resulting in an under estimation of runoff. (Sharif 2002, 2004)

Rainfall estimates are also subject to error using the traditional raingage network. A study conduced by Shah (1996a) shows that spatial rainfall estimates obtained from measurements using a raingage network are subject to errors due to (1) the averaging of the spatial variability of rainfall and (2) the density of the raingage network. (Shah 1996a) Duncan (1993) also conducted a study which showed that raingage density had a

major impact on accurately estimating hydrograph parameters. Standard error was found to diminish as the raingage density increased. (Duncan 1993)

Bedient (2000) provides a general discussion on the applicability of the NEXRAD radar to hydrologic simulations within the Houston, Texas metropolitan area. The accuracy of rainfall radar is highly dependent on the raingage network. The raingage network is used to calibrate radar rainfall based on point rainfall data. Using NEXRAD radar estimates, Bedient showed the radar rainfall to be as accurate as raingage data. (Bedient 2000)

5.1.2. Precipitation and Runoff Studies

Precipitation and runoff investigations are an active area of research. A number of these investigations are discussed below.

An accurate portrayal of the spatial variation of rainfall across a watershed is necessary to accurately simulate stream discharge. In a study conducted by Beven (1982), different rainfall patterns across a basin have a highly significant impact in the timing of peak flows, have a smaller but still significant impact on peak flow, and have a relatively minor and insignificant impact on the distribution of storm flow volume. (Beven 1982)

Wilson (1979) concluded that the spatial distribution of rainfall has a major influence on the corresponding runoff hydrograph. In cases where precipitation is

accurately estimated and temporally recorded, errors may occur in total runoff volume, peak discharge, and the time-to-peak of the resulting hydrograph when the spatial pattern of the rainfall is not preserved. These errors will be more magnified for intense, short duration, localized, convective events as opposed to the frontal type. (Wilson 1979).

In another study, Ogden (1994) show that excess rainfall volumes decrease as the resolution of the rainfall data increases in relation to the scale of the characteristic basin length. (Ogden 1994)

In a case study by Guo (2004), runoff, followed by evapotranspiration, was the most sensitive to temporal and spatial distribution of precipitation when compared to the soil moisture of the basin. (Guo 2004) In another study conducted by Butts (2004), distributed routing and distributed rainfall were found to be the dominant process controlling the accuracy of the simulated hydrologic response for the test basin. (Butts 2004)

In another study, Troutman (1983) uses a stochastic model to discuss errors associated with spatial rainfall variability.   Runoff prediction using erroneous input is often over simulated for large events and under simulated for small events. For impervious basins, model output is usually more sensitive to changes in infiltration parameters associated with large storms. However, for pervious basins, model output is more sensitive to changes in pervious parameters for smaller storms. (Troutman 1983)

Finnerty (1997) has conducted research pertaining to the sensitivity of the Sacramento Soil Moisture Accounting Model (i.e. SAC-SMA) in relation to precipitation inputs. The SAC-SMA model is a conceptually based spatially lumped rainfall runoff model. In this study, the runoff components from the SAC-SMA model were found to be sensitive to precipitation inputs at both the spatial and temporal scales. As the model progresses to finer spatial scales while maintaining constant SAC-SMA parameters, the surface runoff, interflow, supplemental baseflow, and total channel inflow increased. As the time scale was decreased from a 6 hour to 1 hour model, while maintaining a constant spatial scale, the surface runoff, interflow, and total channel inflow increased significantly. However, for this same decrease in time scale, both the supplemental and primary baseflow decreased. (Finnerty 1997)

In a study by Ogden (1993), the spatial variability of rainfall is dominant when the duration of rainfall (t_r) is greater than the time of equilibrium (t_e). However, the temporal variability of rainfall is dominant when the duration of rainfall (t_r) is less than the time of equilibrium (t_e). As the duration of rainfall (t_r) increases beyond the time of equilibrium (t_e), the spatial sensitivity becomes quite small while the temporal sensitivity becomes quite large. (Ogden 1993)

Shah (1996b) discusses that runoff prediction errors are greater for "dry" catchment conditions than for "wet" catchment conditions. This suggests that runoff prediction is impacted by both the spatial variability of rainfall and soil moisture for a watershed basin. (Shah 1996b)

In another study conducted by Michaud (1994b), space-time averaged precipitation resulting from high intensity rainfall has a high impact on generated runoff while it was not particularly sensitive to low intensity rainfall. (Michaud 1994b)

Ogden (2000) conducted a study on the 1997 flash flood in Fort Collins, Colorado. On July 28, 1997, over 200 mm of torrential rainfall occurred over western Fort Collins, due to an unusually moist air mass, driven westward towards the foothills of the Rocky Mountains. From this study, Ogden concluded that accurate physically based runoff predictions with extreme rainfall over urban areas are contingent upon both accurate space-time rainfall information and accurate rainfall rate estimates. Ogden also concluded that spatially uniform soil properties or neglecting impervious areas had a considerably smaller effect than errors due to rainfall estimation and interpolation. (Ogden 2000)

5.1.3. Watershed Basin Scale Studies

Watershed scale is an active area of research and has implications on the hydrologic response of a watershed.

Bergstrom (1998) discuss the problem of scale and, in particular, the macro or continental scale watershed catchments. Bergstrom and Graham conclude that the magnitude of the scale is related to (1) the specific hydrologic problem which is being investigated, and (2) the scientific approach and prospective of the modeler. (Bergstrom

1998) Hayakawa (1995) point out that the hydrologic response for the subcatchment scale is dependent on the interrelation between the variations for both the channel network and the subcatchment geography. (Hayakawa 1995).

5.1.4. Grid Cell Size

Based on a case study, Refsgaard (1997) concluded that the maximum grid size for hydrologic simulating a catchment should be 1000 meters. (Refsgaard 1997) Vazquez (2002), however, concluded that, for another case study, the optimum grid resolution was 600 meters. (Vazquez 2002) Based on the counsel of the USGS, the maximum recommended size for a watershed plane is 1000 feet (i.e. approximately 300 meters) (Leavesley, 2006, personal communication).

5.1.5. Watershed Parameters

Distributed models consider spatial variations of watershed characteristics represented typically by a network of grid points for several parameters and variables. (Refsgaard 1997). Initial estimates for these indexes include topography, surface roughness, soil infiltration, and the distribution, duration, and intensity of precipitation across a watershed. (Ogden 1993) These estimates are then adjusted by calibration so simulated flows compare reasonably well to observed streamflow discharge at the watershed outlet. (Downer 2003)

5.1.6. Hortonian (Infiltration-Excess) and Dunne (Saturation-Excess) Runoff

Hydrologic distributed models depend on some type of process to generate runoff. The performance of these physically based models is highly dependent on the runoff production mechanism which is selected. The practitioner must consider the runoff mechanisms involved in the actual watershed when selecting an appropriate distributed model. Distributed models can be of the Hortonian (infiltration-excess) type or the Dunne (saturation-excess) type. (Downer 2002, 2004)

Hortonian (infiltration-excess) runoff is applicable to watershed conditions where the rate of precipitation is greater than the infiltration rate. (Horton 1933) For watersheds experiencing extreme rainfall with very low infiltration rates, the sensitivity of the spatial variability decreases as the runoff reaches equilibrium conditions. Because smaller watersheds reach its equilibrium condition sooner than larger basins, the sensitivity of Hortonian runoff to the spatial variability of rainfall or watershed characteristics diminish for small scales. (Downer 2002)

Dunne (saturation-excess) runoff is applicable to situations where overland flow results due to direct runoff falling on saturated areas. (Dunne 1970) Dunne type runoff is highly dependent on the condition of the hydraulics of the subsurface soil and groundwater strata. Typically rising water tables contribute to these saturated conditions. (Downer 2002)

In studies conduced by Sharif (2002, 2004), Hortonian runoff errors associated with radar rainfall errors decreased as the magnitude of the event increased. However, these errors increased significantly with range away from the radar, particularly beyond 80 km (128 miles). (Sharif 2002, 2004)

In another study conducted by Senarath (2000), a continuous distributed model based on the Hortonian runoff mechanism was found to simulate larger storms more accurately than small events. This indicates that, uncertainties in watershed parameters diminish for more extreme storm events. (Senarath 2000)

Winchell (1998) indicates there is a tendency to use the Hortonian infiltration-excess runoff mechanism as opposed to the Dunne saturation-excess type. In research conducted by Winchell (1998), the generation of runoff from infiltration-excess models is much more sensitive than from saturation-excess type models. Furthermore, runoff volume from infiltration-excess models decreases significantly when both the spatial and temporal resolution of the precipitation is decreased. (Winchell 1998). Koren (1999) also concludes that infiltration-excess models were the most sensitive while the saturation-excess models were less scale dependent. (Koren 1999)

Michaud (1994b) suspected that runoff simulations are highly sensitive to rainfall errors in large part due to the Hortonian runoff mechanism of the model used in their study. Michaud and Sorooshian (1994b) recommend that more research is needed

comparing the results from both Hortonian versus Dunne overland flow. (Michaud 1994b)

In a study conducted by Loague (1985) followed later by a re-evaluation of the initial study conducted by Loague (1990), a physically based distributed model based on the Hortonian mechanism did not show significant improvement for watershed basins which physically respond to a combination of Hortonian and Dunne overland flow. (Loague 1985, 1990)

Often times, it is inappropriate to classify a watershed as either Hortonian (infiltration-excess) or Dunne (saturation-excess) type basins. The particular meteorological event and recent climatic conditions ultimately decide which runoff production mechanism is appropriate at a given time for a watershed basin. For example, runoff typically produced by the saturation-excess (Dunne) mechanism under ordinary rainfall conditions may also produce infiltration-excess (Hortonian) runoff due to isolated convective events with extreme rainfall. (Downer 2002) Therefore, for high intensity highly convective rainfall events, a Hortonian model may be more appropriate. However, for stratiform rainfall events which typically results in a steady rainfall pattern over a long period of time, a Dunne model may be more appropriate.

Most studies showing the importance of spatial variability of rainfall were conducted using the Hortonian surface runoff generation mechanism. Although this is more applicable to basins where surface runoff is the more dominant process, in reality,

many basins are more complex in that a significant portion of runoff is generated from the slower responding subsurface runoff. Thus, the actual physical processes which may be at work in a basin may not be those predicted by a certain model. Because of this, much of the research which has been conducted may have emphasized the sensitivity of a particular model, not the actual processes at work in a basin. (Smith 2004b)

5.1.7. Complexity of Distributed Models

The complexity of distributed models is also an area of interest. In a study conducted by Michaud (1994a), a simple distributed model was as accurate as a complex distributed model, providing the models were calibrated. However, without calibration, the complex model proved to be more accurate than the simple distributed model. (Michaud 1994a).

Smith (2004b) points out the need for research regarding the level of model complexity needed to simulate the hydrologic response given the variability of rainfall and basin features for a watershed. Numerous studies exist pertaining to the sensitivity of runoff hydrographs to both spatial and temporal variations in precipitation and various basin characteristics. The results from these studies have provided mixed results. In some cases, the spatial distribution of rainfall was more dominant; in other cases, the temporal distribution had more impact. In others, the spatial pattern of rainfall had more impact while the global volume of rainfall with a variable pattern was more important. In another, representing the rainfall over the basin with sampling errors underestimated the

hydrologic basin response for small events while overestimating it for large events.
(Smith 2004b)

5.1.8. Distributed Versus Lumped Model Investigations

Various investigations have been conducted pertaining to distributed and lumped hydrologic models. Overall, conclusions resulting form research concerning the comparison of hydrologic simulations between distributed models and lumped models have been inconclusive. Indications are that distributed models may or may not provide any improvement over those conceived by a lumped model.

Smith (2004b) indicates that few studies have addressed the improvements distributed models can make over the traditional lumped model for flood forecasting at basin outlets.   Although predicting the hydrologic response at an interior point is a given, the use of distributed models to improve the hydrologic simulations at basin outlets is largely untested. (Smith 2004b)

Refsgaard (1997) also discusses that, in many cases, lumped models perform just as well as distributed models. However, distributed models may have advantages for predicting runoff in ungaged watersheds, simulating water quality parameters, and for predicting impacts due to changes in land use. (Refsgaard 1997).

Bergstrom (1998) point out that physically based distributed models are thought to be more superior to simpler conceptual lumped models. The distributed models are

perceived to be more theoretically exact, requiring less tuning of parameters. Lumped models, however, are often the only reasonable choice based on available data and operational applications. (Bergstrom 1998)

Despite the inconclusiveness between distributed versus lumped models, physically-based distributed models have distinct advantageous over the traditional lumped-based modeling approach. A distributed model has the ability to analyze runoff process details at small scales within a watershed, predict the rainfall-runoff response for ungaged and uncalibrated watersheds, and analyze the impact land-use changes have on the overall hydrologic response of a watershed. (Downer 2002) (Hayakawa 1995)

Refsgaard (1996) conducted a case study comparing three different models on three different basins in Zimbabwe. The three systems included a lumped conceptual model, a distributed physically based model, and an intermediate model between the lumped and distributed system. Based on this study, all models performed equally well when they were calibrated. The distributed model, however, performed marginally better for cases when the models were uncalibrated. (Refsgaard 1996)

In a study conducted by Boyle (2001), a semi-distributed model showed significant performance improvements over a lumped model when a watershed basin was partitioned into three sub basins. However, when the watershed was further subdivided into eight subbasins, no additional improvements were gained. (Boyle 2001)

In a case study by Krajewski (1991), the basin response was found to have a higher sensitivity to the temporal resolution of the rainfall data than to spatial resolution. Also, the lumped model tended to severely underestimate flood peaks compared to a distributed model. (Krajewski 1991)

A study conducted by Smith (1999) was unable to show a significant improvement using a simple semi-distributed approach with spatially uniform parameters when compared to a lumped model using sub-basins for several watersheds in the southern Great Plains of the U.S. (Smith 1999) In a separate study by Carpenter (2001), the results from a distributed model when compared to a lumped model were inconclusive. (Carpenter 2001)

Obled (1994) found that results from the use of distributed inputs were inconclusive. The semi-distributed representation when compared to a fully lumped model did not lead to improved hydrologic simulations. It is suspected that the saturated runoff mechanism used in this model may be responsible for the lack of improvement in the results. If the dominant runoff process is surface and subsurface runoff of the Dunne type, where most of the water infiltrates into the soil, the resulting local runoff will be smoothed as the movement of water is stored and delayed within the soil. Watershed basins which respond predominately to this type of subsurface physical runoff response may be much less sensitive to different rainfall patterns at the small catchment scale. (Obled 1994)

Reed (2004) indicates that depending on the characteristics for a drainage basin, a distributed or semi-distributed model may or may not improve the hydrologic simulations when compared to a lumped model. (Reed 2004)

5.1.9. River Forecasting Using Distributed Models

The National Weather Service West Gulf River Forecast Center in Fort Worth, Texas has been developing, calibrating, and implementing distributed hydrologic models into real time river forecast operations. At this time, results using distributed models versus the traditional lumped model have been inconclusive. Quite often the distributed models perform well compared to real time observed river flow data. At other times, results are less than desirable.

In a paper by Shultz (2006a), early indications show inconclusive results from distributed model simulations for several basins located at different locations in Texas. (Shultz 2006a) However, in another paper by Shultz (2006b), distributed model simulations performed well for five drainage basins located along the Texas Gulf Coast during the calibration phase using historical observed river flow data. Three of these basins are located in rural areas; two are located in the Houston metropolitan area. These models are currently being tested in real-time river flood operations. (Shultz 2006b)

5.1.10. Tropical Storm Allison – Houston, Texas (A Case Study)

Extreme flood events can also have a major impact in calibrating distributed models. In June, 2001, Tropical Storm Allison impacted many areas including the Texas

Gulf Coast over Houston. Heavy torrential rainfall occurred during the night of June 8-9, 2001 over the Houston metropolitan area causing catastrophic flooding. Rainfall amounts ranged from 2 to 20 inches from west to northeast Houston, with over 26 inches falling in a 10 hour period in east Houston over the Greens Bayou drainage. (NWS 2001)

A distributed model using kinematic wave principles was developed and calibrated by the National Weather Service West Gulf River Forecast Center for the Greens Bayou drainage. The calibration period was for an eight year time period from 1997 to 2005 which included Tropical Storm Allison. Overall, the calibrated simulations showed a very good comparison to historical observed streamflow for the overall calibration time period. However, during Allison, simulated peak flow discharge was much greater in magnitude than the observed peak flow. Also, the simulated hydrograph had a much steeper distinct peak with a narrow time base compared to the observed flow hydrograph which had a more attenuated and rounded peak with a wider time base. (Shultz 2006b)

Statistically, correlation coefficients were derived using simulated versus observed streamflow data. The correlation coefficients for each year generally ranged between 0.8 to 0.9. However, for the year 2001, the correlation coefficient fell to approximately 0.6. Also, the correlation coefficients for each month also ranged between 0.8 to 0.9. However, for the month of June, the correlation coefficient fell to approximately 0.6. These falls in correlation coefficients are attributed to Tropical Storm Allison which occurred in June, 2001. (Shultz 2006b)

Significant backwater issues occurred during Tropical Storm Allison. During Allison, extreme rainfall caused both significant sheet flow over the overland flow planes along with major backwater issues within the Greens Bayou stream channel. Unfortunately, the kinematic wave technique is not designed to physically simulate streamflow over flat terrain impacted by backwater. For extreme flood events such as Allison, a full dynamic wave model would more accurately simulate distributed flow impacted by significant backwater issues. (Shultz 2006b)

5.2. Distributed Model Intercomparison Project (DMIP)

The National Weather Service (NWS) Hydrology Laboratory (HL) recently embarked on a research project entitled the Distributed Model Intercomparison Project (DMIP). The purpose of DMIP was to compare, amongst themselves, various distributed models as well as the current lumped model used for NWS river forecast operations. The NWS is responsible for providing river and flash flood forecasts to the general public for the entire United States. To accomplish this mission, the NWS has 13 River Forecast Centers (RFC) and over 120 Weather Forecast Offices (WFO) across the country. The Hydrology Laboratory (HL) supports this mission by developing software, archiving historical data, and conducting scientific research. (Smith 2004b) (Reed 2004)

Ultimately, the main goal of DMIP is to provide guidance to the NWS concerning research and implementation directions using distributed models for operational river

forecasting. Also, many unresolved questions concerning rainfall and river basin

variability and its impact on the hydrologic response for river basins will be addressed.

Currently, the benefits which may be realized using a distributed model in an operational

setting are largely unknown. Because of this, DMIP was instituted as a means to try and

resolve some of these issues. (Smith 2004b) (Reed 2004)

5.2.1. DMIP Background Information

DMIP arose out of a combination of several factors. First, there is a real need to

infuse "state-of-the-art" science and technology into NWS river forecast operations.

Second, the continued increase in computer capabilities along with the proliferation of

high resolution geographic information systems (GIS) data has made it possible to

develop complex distributed hydrologic models. Finally, a major scientific objective of

DMIP is to see the impacts variable precipitation and basin properties have on the

hydrologic response of river basins and the level of model complexity which may be

required to improve these simulations. (Smith 2004b)

Numerous hydrologic distributed models exist. However, it is not clear which

modeling approach or distributed model would generate the best outlet simulations for a

watershed. Therefore, the NWS formulated DMIP as a means to help guide the research

and development efforts of this organization, capitalizing on the distributed modeling

research being conducted at various academic, governmental, and private institutions

from around the world. (Smith 2004b)

The DMIP project was conducted in two phases. Phase 1 was to investigate the application of distributed precipitation to individual subbasins for a drainage area, with each subbasin having its own lumped input. Phase 2 was to investigate various distributed models with distributed hydrologic parameters. In essence, Phase 1 addresses inputs into the distributed model; Phase 2 addresses the distributed model parameters. (Smith 1999)

To accomplish the objectives of DMIP, twelve entities, both public and private, participated in this project. These entities consisted of various academic, government, and private institutions. Each organization ran their own distributed model using a given test data set for several watersheds. From there, each simulation was compared with both observed streamflow and lumped model simulations using National Weather Service techniques as applied to the River Forecast Centers (RFCs). Also, calibrated versus uncalibrated simulations were assessed.   (Reed 2004)

5.2.2. Results and Conclusions of DMIP

The DMIP project showed that in most cases, the lumped model actually outperformed the distributed models. However, there are cases where a distributed model performs equal to or even better than a lumped model. In one particular case, the distributed model clearly demonstrated improvements over the lumped model. This basin is distinguishable from the other basins in shape, orientation, and soil characteristics. Finally, the DMIP project showed that calibrated distributed models show a significant improvement over the uncalibrated version of the same distributed model. (Reed 2004)

In summary, some of the key findings from DMIP are:

1. In most cases, the lumped model outperformed the distributed models. However, in some cases, the distributed models performed equal to or even better than the lumped model.

2. A calibrated distributed model performs better than the uncalibrated version of the same model.

3. A distributed model provided more accurate simulations than the lumped model for one of the test basins. The shape, orientation, and soil characteristics of this basin were much different than the other basins investigated as part of DMIP.

5.3. Available Distributed Models

The literature discusses a number of hydrologic distributed models which have been developed. These models range in complexity from physically based fully distributed models, semi-distributed models, and smaller scale conceptually lumped rainfall-runoff models. These models are built on a grid-based network, small sub-basins, and triangular irregular networks (TINs). (Koren 2004)

A number of organizations have developed distributed models. These models and organizations include:

1. Modular Modeling System (MMS) - U.S. Geological Survey

2. HLRMS - National Weather Service Hydrology Laboratory

3. Vflo^{TM} - University of Oklahoma

4. TOPMODEL - Department of Environmental Science, Institute of Environmental and Natural Sciences, Lancaster University, UK.

5. CASC2D - Colorado State University

6. MIKE-SHE - Danish Hydraulic Institute

7. Hydrologic Research Center Distributed Hydrologic Model (HRCDHM) - Hydrologic Research Center

8. Soil and Water Assessment Tool (SWAT) - US Department of Agriculture, Agriculture Research Service (USDA-ARS)

9. TIN-based Real-Time Integrated Basin Simulator (tRIBS) - Massachusetts Institute of Technology.

10. Variable Infiltration Capacity (VIC) - University of Washington

11. Gridded Surface/Subsurface Hydrologic Analysis (GSSHA)

Each of these models is physically-based, distributed hydrologic models. CASC2D, MIKE-SHE, HLRMS, Vflow, and tRIBS use a square grid-based GIS raster system in describing the meteorological, hydrological, and geological inputs into the system. MMS, HRCDHM, SWAT, and TOPMODEL use a catchment-based system. Most of these models use a kinematic wave channel routing approach. SWAT, however, uses the Muskingum routing method. MIKE-SHE uses the full dynamic wave approach.

These models are complex "state-of-the art" distributed hydrologic models. Each has their own unique characteristics. However, because the discussion of the technical intricacies of these models are outside the scope of this report, the reader is invited to refer to the user manual for each distributed model for further information. (Carpenter 2004) (Luzio 2004) (Ivanov 2004) (Koren 2004) (Vieux 2004) (Bandaragoda 2004) (Reed 2004) (Leavesley 1983, 2004)

5.4. Summary

The fundamental concepts associated with distributed models were discussed in this chapter of the report. Various research investigations which have been conducted over a large number of sub-disciplines associated with distributed modeling were provided. Also, the Distributed Model Intercomparison Project (DMIP) was discussed. Finally, a brief section showing a list of additional distributed models was provided.

The next chapter discusses dynamic, diffusion, and kinematic wave models. This chapter illustrates how kinematic wave models are applied to both overland flow planes and river channels.

CHAPTER 6

DYNAMIC, DIFFUSION, & KINEMATIC WAVE MODELS

Dynamic, diffusion, and kinematic wave models are for overland flow and channel flow applications. The dynamic wave takes into account the entire spectrum of physical processes involved with both overland and channel flow. The diffusion wave is an approximation of the dynamic wave. The kinematic wave is a further approximation of the dynamic wave.

The kinematic wave was used in this investigation as the computational process for both overland flow and channel flow as applied to distributed and lumped models.

This chapter deals with the differences between dynamic, diffusion, and kinematic wave models. The first section discusses dynamic wave models. The second section pertains to diffusion wave models. The third section discusses kinematic wave models. The fourth section provides a comparison between the three types of models. The fifth and sixth sections discuss the kinematic wave equations as applied to both overland flow and channel flow. The seventh section pertains to the finite-difference scheme, used to solve the kinematic wave equations. The eighth and final section summarizes the chapter.

6.1. Dynamic Wave Model

Dynamic wave models are based on one-dimensional gradually varied unsteady flow through open channels. Dynamic wave models are based on the Saint-Venant equations, two partial differential equations (continuity and momentum) developed in 1871 by Barre de Saint-Venant. These equations are also referred to as the shallow-water equations.

The Saint-Venant equations are based on physical concepts and are a function of local acceleration, convective acceleration, hydrostatic pressure forces, gravitational forces, and frictional forces. The Saint-Venant equations express the physical laws for both conservation of mass (continuity) and conservation of momentum (dynamic). The conservation of mass is described as inflow minus outflow and is equal to the change in storage over the change in time. The conservation of momentum is described as the time rate of change of linear momentum and is equal to the sum of all external forces acting on a system of particles.   (Alley 1982) (Fread 1988) (Chow 1988) (Wurbs 1985) (Wurbs 1986) (HEC 1990) (HEC 2002) (COE 1991) (Choi 1990) (McCuen 1989) (Stephenson 1986) (Shultz 1992) (Miller 1984) (Maidment 1993) (Mays 1996)

Important characteristics govern the use of the Saint-Venant equations. These are:

1. the water surface profile varies gradually;

2. the channel slope or flow plane slope is small;

3. the streamlines are more or less straight;

4. the pressure distribution is close to hydrostatic conditions;

5. The flow resistance is approximated by steady flow formulas;

6. The average velocity of the channel is used to solve the equations; and

7. Momentum due to lateral inflow is negligible.

(Stephenson 1986) (Overton 1976)

The dynamic wave model is based on both the continuity and momentum equations. These equations are shown below.

6.1.1. Continuity Equation

The continuity equation is based on the principle of the conservation of mass and is written as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

where Q is the discharge (cfs), A is the cross-sectional area (sq ft), q is the lateral inflow per unit length (cfs per ft), x is the space coordinate (ft), and t is the time (seconds).

6.1.2. Momentum Equation (Dynamic Wave Form)

The momentum equation is based on Newton's second law of motion and is written as

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0$$

Kinematic Wave

Diffusion Wave

Dynamic Wave
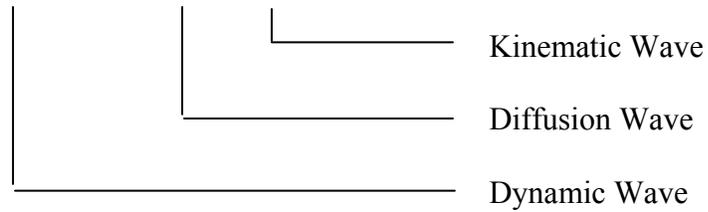
where y is the flow depth, V is the mean velocity, g is the gravitational acceleration, S_o is the bed slope, and S_f is the friction slope. (Chow 1988) (Mays 1996) (Singh 1996) (Shultz 1992) (HEC 1979) (HEC 2002)

6.2. Diffusion Wave Model

The diffusion wave model is based on both the continuity and a simplified form of the momentum equation. These equations are shown below.

6.2.1. Continuity Equation

The continuity equation is

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

where Q is equal to discharge, x is equal to distance, A is equal to the area, t is equal to time, and q is the lateral inflow.

6.2.2. Momentum Equation (Diffusion Wave Form)

The momentum equation is

$$\frac{\partial y}{\partial x} = S_o - S_f$$

where y is the flow depth, S_f is the friction slope, and S_o is the bed slope (gravity).

(Chow 1988) (Mays 1996) (Singh 1996) (Shultz 1992)

6.3. Kinematic Wave Model

The kinematic wave model is based on both the continuity and a simplified form of the momentum equation. These equations are shown below.

6.3.1. Continuity Equation

The continuity equation is

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

where Q is equal to discharge, x is equal to distance, A is equal to the area, t is equal to time, and q is the lateral inflow.

6.3.2. Momentum Equation (Kinematic Wave Form)

The momentum equation is

$$S_f = S_o$$

where S_f is the friction slope and S_o is the bed slope (gravity).

Friction slope can also be defined as the uniform flow formula, such as the Manning equation. Using the Manning equation, the momentum equation can be rewritten as

$$S_o = \left(\frac{Q^2 n^2}{2.21 R^{\frac{4}{3}} A^2} \right)$$

or as

$$Q = \frac{1.49 R^{\frac{2}{3}} S_o^{\frac{1}{2}} A}{n}$$

where n is manning's roughness (n coefficient), R is the hydraulic radius (i.e. area/wetted perimeter), A is the area, and S_o is the bed slope.

The power relationship can also be used as a more general expression for the uniform flow formula. The power relationship is given as

$$Q = \alpha A^m$$

where Q is discharge, A is area, and α and m are coefficients.

The kinematic wave equations are usually given by continuity and by the power relationship. The α and m are coefficients are two routing parameters in the power equation which are directly related to channel shape, boundary roughness, and either channel slope or the slope of the overland flow plane. (USGSNTC 2004) (Singh 1996) (Chow 1988) (Mays 1996) (Shultz 1992) (HEC 1979)

6.4. Comparison of the Kinematic, Diffusion, and Dynamic Wave Equations

The dynamic wave equations govern the movement of a flood wave traversing downstream in a channel when the dynamic forces (inertia or acceleration and pressure) are important factors in the solution scheme. This is especially true for river systems composed of long waves in shallow water bodies such as a flood wave in a wide river. The dynamic wave includes all of the terms found in the momentum equation. (CHOI 1990) (HEC 1980) (Overton 1976) (Ponce 1991) (HEC 1979) (HEC 2002) (Ponce 1978a) (COE 1991) (Shultz 1992) (USGSNTC 2004) (Singh 1996) (Mays 1996)

The diffusion wave equations simplify the full dynamic wave process. The diffusion wave applies to flow situations where the inertia (local and convective acceleration) forces are not important. The diffusion wave is based on gravity, friction, and pressure. The pressure term ($\partial y/\partial x$) is responsible for physical diffusion. (CHOI 1990) (HEC 1980) (Overton 1976) (Ponce 1991) (HEC 1979) (HEC 2002) (Ponce 1978a) (COE 1991) (Shultz 1992) (USGSNTC 2004) (Singh 1996) (Mays 1996)

Finally, the kinematic wave equations further simplify the full dynamic wave process, considering only gravity and friction while neglecting pressure and inertia (acceleration). With kinematic waves, the weight component (gravity) of the fluid is approximately balanced by resistive forces due to channel bed friction. Flow does not accelerate appreciably, remaining approximately uniform along the channel. Also, by neglecting pressure and inertia, the mechanism for flood wave peak attenuation is eliminated. In essence, the physical properties of the kinematic wave equations do not allow for attenuation of the flood wave (CHOI 1990) (HEC 1980) (Overton 1976) (Ponce 1991) (HEC 1979) (HEC 2002) (Ponce 1978a) (COE 1991) (Shultz 1992) (USGSNTC 2004) (Singh 1996) (Mays 1996)

The Froude number has been used as a measure to help distinguish between dynamic, diffusion, and kinematic waves. The Froude number is the ratio of the dynamic (inertial) force to the weight of the fluid. (Streeter 1979) The Froude number can also be considered as the ratio of the stream velocity to the wave velocity. (Henderson 1966) The Froude number is shown by the following equation

$$F = \frac{V}{\sqrt{gy}}$$

where F is the Froude number, V is the velocity of the fluid, and $\sqrt{gy}$ is the wave speed

(i.e. celerity) (Henderson 1966) (Streeter 1979).

A number of studies have been conducted to try and relate dynamic waves, diffusion waves, and kinematic waves. Singh 1996 and HEC 1979 discuss a study conducted in 1955 by Lighthill and Whitham. When the Froude number was less than 2, the kinematic wave began to dominate over the dynamic wave. As the Froude number became less than 1, the dynamic waves rapidly attenuated, allowing the kinematic waves to become even more dominant. Overton 1976 discusses that when the Froude number is greater than 2, the depth of flow will continue to increase allowing a surge or bore to develop. When the Froude number is exactly equal to 2, the kinematic waves prevailed over the dynamic waves. When the Froude number is less than 2, the dynamic waves dampen. (Overton 1976) (Singh 1996) (HEC 1979)

Singh also discusses the kinematic wave number as a criterion for measuring the goodness of the kinematic wave technique for modeling flow over an overland flow plane. The kinematic wave number (K) is shown by the following equation

$$K = \frac{S_o L}{hF^2}$$

where S_o is the bed slope (gravity), L is the length of the flow plane, h is the normal flow depth, and F is the Froude number.

Singh discusses a 1967 study conducted by Woolhiser and Liggett where the kinematic wave method was shown to be accurate for K > 20. (Singh 1996) Singh also discusses a 1980 study conducted by Morris and Woolhiser where for highly subcritical flow (F < 0.5) and $F^2K < 5$, the kinematic wave was found to be inadequate while the diffusion wave was adequate. (Singh 1996)

The diffusion wave model is possibly the most useful approximation of the full dynamic wave equations. The diffusion wave offers a balance between the accuracy of the dynamic wave model to the simplicity of the kinematic wave model for a wide range of field conditions. Application of the diffusion wave to overland flow modeling is relatively recent. At this time, little information has been reported on its validity, applicability limits, and other aspects as they relate to overland flow. (Mays 1996) (Singh 1996)

The kinematic wave model is best suited in urban environments where the channels are relatively steep, the channel reaches are uniform, and there are no overbank flow conditions. The kinematic wave is generally not used for floodplain applications. The kinematic wave only translates a flood wave and does not allow for attenuation. (HEC 1990)

Most watershed models have adopted the kinematic wave technique because of its simplicity. The kinematic wave becomes the dominant process when the dynamic wave component is small. However, for areas where dynamic impacts cannot be ignored, such as for flat slopes, the full dynamic wave model needs to be implemented. Terms in the dynamic wave equations, such as the acceleration components and pressure, become more important as the slope of the channel is decreased. For watersheds with steeper slopes, acceleration and pressure have less impact on the Saint Venant equations. Therefore, the kinematic wave method is more appropriate for channels with steeper slopes since it is based on the assumption that bed slope equals friction slope. (CHOI 1990) (Overton 1976) (Shultz 1992) (USGSNTC 2004)

The kinematic wave equations have three important characteristics when compared to the full dynamic wave equations. These are:

1. The kinematic wave model does not attenuate as it travels downstream;

2. The kinematic wave model may predict the rising stage of a hydrograph too late;

3. The kinematic wave model will not simulate backwater. (USGSNTC 2004)

<u>6.5. Overland Flow – Kinematic Wave Equations</u>

Overland flow planes are a major component of the watershed drainage network. The kinematic wave approximation is used to compute overland flow. Overland flow is computed using the equation

$$QR = PTN - FIN$$

where QR is the rainfall excess, PTN is net rainfall, and FIN is net infiltration for pervious areas.

For areas that are impervious, the net infiltration is zero; thus, rainfall excess is equal to net rainfall.

The partial differential equation used to solve each overland flow-plane segment is:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = re$$

where h is the flow depth (ft), q is the flow rate per unit width (cfs per ft), re is the rainfall excess inflow rate (ft/s), t is time (s), and x is the length of the plane (ft).

A general power relationship used to relate h and q is:

$$q = \alpha h^m$$

where α and m are functions of overland flow-plane characteristics.

Alpha (α) and m are computed using equations for selected overland flow-plane and channel-segment characteristics. These equations are outlined in Table 2 in the PRMS users manual. These equations may also be overridden by user-defined values for alpha and m. The numerical technique used to compute the kinematic wave component of overland flow is described in Dawdy, Schaake, and Alley (1978). (Leavesley 1983)

6.6. Channel Flow – Kinematic Wave Equations

Channel segments are a major component of the watershed drainage network. Each channel segment receives inflow from two sources: (1) upstream channels and (2) overland flow planes.

Channel-flow routing uses the same computational approach as that which was used for overland-flow computations. This approach consists of the continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

where A is the area of flow (sq ft), Q is the flow rate (cfs), q is the later inflow per unit length of the channel (cfs per ft), t is the time (seconds), and x is the distance down the channel (ft).

Channel flow routing also uses the power relationship

$$Q = \alpha A^m$$

where A is the area in flow (sq ft), Q is the flow rate (cfs), and α and m are kinematic wave parameters.

Alpha and m are computed from the equations for selected channel segment characteristics and are given in table 2 of the users manual. User-defined values of alpha and m can be used to override these equations. The numerical technique used to solve the kinematic wave approximations are described by Dawdy, Schaake, and Alley (1978). (Leavesley 1983)

6.7. Finite – Difference Scheme

The kinematic wave equations for both overland and channel flow are solved using the finite-difference scheme. The finite-difference technique uses a network of computational cells based on a four-point grid system. A schematic diagram of this grid system is shown below. (Shultz 1992) (Garbrecht 1991) (Ponce 1978b)

```
    c                              d
(i, j+1)                      (i+1, j+1)
        │                 │
────────┼─────────────────┼────────
        │                 │
        │                 │
        │                 │
        │                 │
        │                 │
────────┼─────────────────┼────────
    a   │                 │   b
 (i,j)  │                 │ (i+1,j)
```
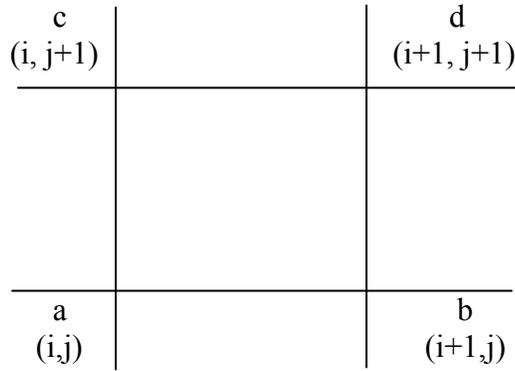
Figure 6.1. Finite Difference Grid Scheme

The individual points located on this four-point grid system are represented as a, b, c, and d. Both discharge and area are known at points a, b, and c. The finite-difference scheme is used to compute both area and discharge at point d. (Alley 1982)

The finite difference numerical procedure introduces a numerical dampening which attenuates to some degree, a flood wave as it propagates downstream. Unfortunately, the physical properties of the kinematic wave equations do not allow for attenuation of the flood wave. Therefore, the numerical dampening introduced by the finite difference technique is in direct contrast to what is actually being simulated using the kinematic wave technique. (Mays 1996)

The finite-difference scheme consists of two types: explicit and implicit. These schemes are discussed below.

6.7.1. Explicit Finite – Difference Scheme

The explicit method results in a set of two finite-difference linear algebraic equations where the unknown variables can be computed directly without the use of iterative computations. (Overton 1976) The model selects the appropriate equation at each point along the four-point grid network in order to keep the computational errors small while maintaining unconditional stability in the numerical solution.

The decision as to which equation to use depends on the stability parameter (θ) as shown by the following equation

$$\theta = \frac{\alpha}{q\Delta x}\left[(q\Delta t + A_a)^m - A_a^m\right]$$

for q $\neq$ 0, and

$$\theta = \alpha m A_a^{m-1} \frac{\Delta t}{\Delta x} = m \frac{Q_a}{A_a}\frac{\Delta t}{\Delta x}$$

for q = 0. The stability parameter is an expression which represents the path of the characteristic curve; it defines whether the characteristic curve passes above or below the diagonal line which connects the points a and d in the computational grid.

If the stability parameter (θ) is greater than or equal to unity, the finite-difference equations use the grid points a, c, and d. These equations consist of the continuity equation and power relationship and are represented below.

Continuity Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

$$\frac{A_c - A_a}{\Delta t} + \frac{Q_d - Q_c}{\Delta x} = q$$

$$\frac{Q_d - Q_c}{\Delta x} = q - \frac{A_c - A_a}{\Delta t}$$

$$Q_d = Q_c + q\Delta x - \frac{\Delta x}{\Delta t}(A_c - A_a)$$

Power Relationship:

$$Q_d = \alpha A_d^m$$

$$A_d = \left(\frac{Q_d}{\alpha}\right)^{\frac{1}{m}}$$

If the stability parameter (θ) is less than unity, the finite-difference equations use

the grid points a, b, and d. These equations consist of the continuity equation and power

relationship and are represented below.

Continuity Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

$$\frac{A_d - A_b}{\Delta t} + \frac{Q_b - Q_a}{\Delta x} = q$$

$$\frac{A_d - A_b}{\Delta t} = q - \frac{Q_b - Q_a}{\Delta x}$$

$$A_d = A_b + q\Delta t - \frac{\Delta t}{\Delta x}(Q_a - Q_b)$$

Power Relationship:

$$Q_d = \alpha A_d^m$$

$$Q_d = \alpha A^m$$

These equations are solved by beginning upstream (i.e. for both the overland flow plane and channel) where x = 0 and continuing downstream in Δx increments until x = L. Initial values for both Area (A) and Discharge (Q) are given along the entire x-axis. When the initial time step is equal to zero (i.e. t=0), both A and Q are set to 0 everywhere in the model. During the solution scheme, the upstream boundary condition for inflow (i.e. Q) is given. The corresponding value for area (i.e. A) is computed using the power relationship. (Dawdy 1978) (Alley 1982)

6.7.2. Implicit Finite – Difference Scheme

The implicit finite-difference scheme is a four-point formulation which uses and iterative procedure to numerically solve for the unknown flow area. The explicit method is used to obtain the initial estimate of the flow area for use in the implicit method.

The implicit finite-difference scheme uses a weighting function (W), a value between 0.5 and 1.0 specified by the user, for the space derivative in the numerical solution. The implicit method uses the continuity equation and power relationship and is represented below.

Continuity Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

$$\frac{W(Q_d - Q_c) + (1-W)(Q_b - Q_a)}{\Delta x} + \frac{(A_d - A_b) + (A_c - A_a)}{2\Delta t} = q$$

Power Relationship:

$$Q_d = \alpha A_d^m$$

The continuity equation has two unknown values, Q_d and A_d. However, the power relationship is substituted into the continuity equation resulting in the final form of the equation for the implicit finite-difference technique as shown below:

$$\alpha A_d^m + \frac{\Delta x}{2W\Delta t} A_d + \frac{\Delta x}{2W\Delta t}[(A_c - A_a) - A_b] + \frac{(1-W)}{W}(Q_b - Q_a) - Q_c - \frac{q\Delta x}{W} = 0$$

The final equation can also be further simplified as follows:

$$C_0 A_d^m + C_1 A_d + C_2 = 0$$

where

$$C_0 = \alpha$$

$$C_1 = \frac{\Delta x}{2W\Delta t}$$

$$C_2 = C_1 \left[(A_c - A_a) - A_b \right] + \frac{(1-W)}{W} (Q_b - Q_a) - Q_c - \frac{q\Delta x}{W}$$

The roots for these nonlinear equations are found by using Newton's second order iterative procedure. To speed up the process, the first estimate is obtained using the solution found in the explicit method. From there, this procedure converges rapidly to a correct solution. (Alley 1982)

6.7.3. Comparison of Explicit and Implicit Finite – Difference Schemes

The explicit finite-difference technique allows unknown values in linear algebraic equations to be evaluated directly without using iterative computations. The implicit method, however, solves non-linear algebraic equations where the unknown values are computed using iterative techniques. (Overton 1976)

The explicit technique is a much simpler technique than the implicit method, making it much easier to program, and with fewer computer resources. However, certain conditions (i.e. the courant condition) must be met before this technique is considered numerically stable. Unfortunately, this restricts the size of the computational time interval, making this technique inefficient for the analyses of unsteady flows for large river systems with long time durations. Numerical stability is the property where small computational errors will not increase in magnitude as the solution progresses, thus causing the true solution to be masked by errors. These errors are a function of the size of each time and distance step in the solution. A drawback to the explicit technique is

that a trial and error approach is necessary to establish numerical stability criteria. (Overton 1976) (Roberson 1998) (Fread 1974)

The implicit finite-difference technique is unconditionally stable when compared to the explicit scheme. The numerical computational process is more efficient. There are no restrictions on the size of the time and distance steps in the numerical solutions. Thus, the numerical scheme used in the finite-difference technique is more stable. However, for the implicit scheme to be highly accurate, the computational time step should be nearly equal to the time step determined from the courant conditions. Unfortunately, a drawback to the implicit method is that it is more difficult to program. (Overton 1976) (Roberson 1998) (Fread 1974)

To summarize, the major difference between the implicit and explicit schemes is that the implicit technique is numerically stable for all time steps. The explicit method is stable only for time steps which meet the requirements of the courant condition. (Chow 1988) One thing to note, the explicit method is superior to the implicit method for hydrologic simulations consisting of very sharp peaks. In these cases, the use of small time steps is necessary. The implicit method requires more effort to determine the computational time step than the explicit method. (Roberson 1998)

6.8. Summary

Dynamic, diffusion, and kinematic wave models were discussed in this chapter. The dynamic wave considers the physical processes involved with both overland and channel flow. The diffusion wave is an approximation of the dynamic wave. The kinematic wave is a further approximation of the dynamic wave.

This chapter also illustrates how kinematic wave models are applied to both overland flow planes and river channels. In addition, the finite-difference computational scheme used to solve the kinematic wave equations was included.

The next chapter discusses the research model which was used in this investigation, the Modular Modeling System (MMS).

CHAPTER 7

INVESTIGATIVE RESEARCH MODEL

The USGS Modular Modeling System (MMS) was used as the research model for

this investigation. The hydrologic response was simulated for both distributed and

lumped rainfall for stationary and moving storm events using MMS.

MMS was developed as part of the U.S. Geological Survey (USGS) National

Research Program (NRP) Precipitation-Runoff Modeling Project. Initially, MMS began

as a cooperative project between the USGS and the University of Colorado's Center for

Advanced Decision Support for Water and Environmental Systems (CADSWES). As

MMS continued to develop, many national and international agencies and organizations

have developed interest in this software. (Leavesley 2004).

MMS is an integrated system of computer software modules designed to address

water resources related issues. Within MMS is the Precipitation-Runoff Modeling

System (PRMS) module which was a major component used for this investigation.

PRMS was originally designed as a stand-alone computer program. As MMS evolved,

PRMS was integrated into MMS as a module.

For this investigation, MMS in conjunction with PRMS were used as research tools to compare hydrologic simulations between both distributed and lumped models. Both stationary and moving storm events were simulated using the kinematic wave theory.

This chapter discusses the fundamental concepts which pertain to both MMS and PRMS. The first section deals with the Modular Modeling System (MMS). The second section discusses the Precipitation-Runoff Modeling System (PRMS). The third section summarizes the chapter.

7.1. Modular Modeling System (MMS)

MMS is a modeling framework used to develop, support, and apply dynamic models to water resource applications. MMS is not a specific model but is actually a modeling system consisting of various components.

MMS consists of a module library with various water resource applications. A module is a set of computer source code used to simulate a variety of physical processes related to water, energy, chemical and biological situations. A given process can actually be represented by several different library modules, each representing an alternative means to conceptualize a solution to a given problem.

An MMS model is created by coupling the most appropriate modules together to develop the most optimal application for a given water resource situation. MMS is designed with flexibility in order to develop the most desirable modeling approach given a set of user needs and water resource conditions.

MMS is comprised of three major components: pre-process, model, and post-process. The pre-process component includes various tools used to input, analyze, and prepare spatial and time-series data for use in model applications. The model component is actually the core of the system and includes various tools to develop and apply MMS. The post-process component provides a variety of tools to display and analyze model results.

7.2. Precipitation – Runoff Modeling System (PRMS)

PRMS is a module which is contained within the MMS system. PRMS is a physically based module which evaluates the hydrologic impacts resulting from a wide combination of precipitation, climate, sediment yields, land use, and general basin hydrology. The modular design of PRMS provides a flexible framework for hydrologic modeling research and development.

PRMS is used to simulate the hydrologic response of a drainage basin due to normal and extreme rainfall and snowmelt conditions over various combinations of land use and watershed conditions. Changes in flood peaks and volumes, flow regimes, water-

balance relationships, soil and water relationships, sediment yields, and ground-water recharge are evaluated.

Within PRMS, each component of the hydrologic cycle is expressed in terms of known physical laws or empirical relationships. These laws and relationships have some physical interpretation based on measurable characteristics over watershed basins. This reproduces the physical reality of the hydrologic system to actual watershed conditions as closely as possible.

PRMS is designed to provide a flexible modeling capability. Subroutines are maintained in a computer-system library which defines each component of the hydrologic system. Each of these subroutines is compatible and can be linked to each other. These subroutines were obtained by modularizing both a daily flow rainfall-snowmelt-runoff model and an event driven distributed routing rainfall-runoff model. New algorithms were also developed for processes and procedures which were not available in these earlier models.

PRMS is designed to function either as a lumped-parameter or distributed-parameter type model. PRMS will simulate both mean daily flows and storm flow hydrographs. Drainage basins are partitioned into units based on watershed characteristics such as slope, aspect, vegetation type, soil type, and precipitation distribution. Each unit is called a hydrologic-response unit (HRU) and is considered homogeneous with respect to its hydrologic response characteristics. Partitioning the

watershed into sub areas provides the ability to impose various land-use schemes or climatic changes on all or part of the entire watershed area. As a result, the hydrologic impacts for each HRU and the total watershed can be evaluated.

The watershed characteristics for each HRU are input into the PRMS model. These parameters include the physiography, vegetation, soils, and other hydrologic characteristics of each subbasin. Climate variations and land-use changes over the drainage are also input into the model. From there, rainfall distributions with a 60 minute time interval or less are applied to the model. Finally, streamflow simulations are generated for the basin. (Leavesley 1983)

7.2.1. Conceptual Watershed System

PRMS was designed based on the concept of the hydrologic cycle. The hydrologic cycle is based on the following processes: precipitation, interception, evaporation, transpiration, snow accumulation, infiltration, percolation, snowmelt, overland flow, lake storage, streamflow, and groundwater discharge. (Dunne and Leopold, 1978)

7.2.2. Watershed Partitioning

The distributed model is developed by partitioning the watershed into "homogeneous" units, based on slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. By partitioning the watershed, spatial and temporal variations based on physical and hydrologic characteristics of the drainage basin, climatic variables,

and system response can be accounted for. Also, land-use or climatic changes can be imposed on parts or all of a basin. From there, the impact of these changes on the hydrology of each unit and the entire basin can be evaluated.

The watershed can be partitioned into two distinct levels. The first level divides the basin into homogeneous hydrologic response units (HRUs) based on some or all of the physical characteristics mentioned above. This allows for the definition of each conceptual watershed system for each HRU. It should be noted that for most small watershed areas, the groundwater zone is defined for the entire watershed while each soil zone is defined for each HRU. The second level of partitioning is designed mainly for storm hydrograph simulation. The drainage area is conceptualized as a series of interconnected flow-planes and channel segments. Surface runoff is routed as overland flow over the flow planes into the channel segments. From there, channel flow is routed downstream through the watershed channel system. An HRU is either the equivalent of a flow plane or a number of flow planes. (Leavesley 1983)

7.2.3. Designing a PRMS Model

The PRMS model is designed to allow great flexibility in designing a watershed schematic. Different sizes and shapes of channels and overland flow planes can be used to properly define a drainage basin. Each overland flow segment is configured as a rectangular shape. The dimensions of the rectangular shapes can vary to adequately depict the complex uneven topography of the overland flow planes. Finally, watersheds with very flat slopes are very difficult to model due to the physical limitations of the

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kinematic wave method. For very flat slopes, the complete Saint Venant equations are required to simulate all of the physical hydraulic characteristics for unsteady flow. It should be noted that the PRMS model is not designed to model cascading overland flow planes. (Alley 1982) (USGSNTC 2004)

A PRMS model consists of four types of segments which describe the drainage characteristics of a watershed basin. Four types of segments are implemented in a basin design. These segments are (1) overland-flow, (2) channel, (3) reservoir, and (4) nodal.

7.2.3.1. Overland-flow segments

Overland flow segments are used as basic building blocks to design watershed schematics. Each overland flow plane receives a uniformly distributed amount of excess rainfall. Each overland flow plane is also assumed to be rectangular with a given length, slope, roughness, and percent impervious areas.

7.2.3.2. Channel Segments

Channel segments are also used as basic building blocks to design watershed schematics. Each channel segment represents the natural conveyance of a river system. Each segment may receive inflow from as many as three upstream segments and can be combinations of other channel segments, reservoir segments, and nodal segments. Lateral inflow can also be received from overland-flow segments.

7.2.3.3. Reservoir Segments

Reservoir segments are used to describe on-channel storage behind a reservoir, culvert, or other detention structure.

7.2.3.4. Nodal Segments

Nodal segments are used to form junctions between channel segments. The user may also use this feature as a way to input a hydrograph or contant discharge for each storm event.

7.2.4. Assumptions in the PRMS Model

Several assumptions are applicable to the PRMS model. These assumptions are:

1. Excess rainfall is uniformly distributed over a drainage basin;

2. Pervious and impervious areas are uniformly distributed over a drainage basin;

3. Overland flow planes are used to approximate the complex uneven topography of the drainage basin;

4. Excess rainfall does not infiltrate as it moves overland;

5. Infiltration ceases when rainfall ceases;

6. Base flow is considered negligible;

7. Lateral inflow into a river system is uniformly distributed; and

8. Changes from laminar to turbulent flow do not occur. (USGSNTC-2004)

7.2.5. Daily and Storm Modes

A PRMS model is designed to simulate basin hydrology based on either a daily or a storm event time scale. The daily mode simulates the hydrologic response by computing mean daily streamflow. The storm mode uses much smaller time intervals to simulate the hydrologic response from selected rainfall events.

The model initially begins in the daily mode. When a storm occurs, the model then shifts into storm mode, continuing in this mode until the storm period is over. At that time, the model shifts back into its daily mode operation. (Leavesley 1983)

7.2.6. Theoretical Development of System Library Components

A MMS library consisting of water resource modules has been developed to simulate the various components of the hydrologic cycle. Module components include temperature, precipitation, solar radiation, impervious area, interception, soil-moisture accounting, evapotranspiration, infiltration, overland flow, subsurface flow, ground water, channel flow, reservoir routing, sediment, and snow.

7.2.7. Channel and Overland Flow Segments

MMS utilizes a hydraulic approach for routing water across watersheds and downstream channels. This reduces the surface runoff problem to a hydraulic unsteady flow problem consisting of uniform channels and planes. Complex watershed topography and geometry is subdivided into many small elemental overland flow planes

and channels. Each plane or channel is then considered a single segment which characterizes the watershed catchment into a distributed model. (USGSNTC 2004)

There are two principal advantages for using a hydraulic approach for a distributed model. First, hydraulic routing results in a nonlinear formulation for the hydrologic response of a watershed. This can be an improvement over the traditional linear formulation such as the unit hydrograph method. Second, the hydraulic approach is actually a more deterministic model since the various parameters are based on a more physical representation of the watershed. This provides a clear advantage in the modeling capability for situations when only minimum data is available. (USGSNTC 2004)

7.3. Summary

The Modular Modeling System (MMS) is a powerful set of integrated computer system software designed to address water resource issues. The Precipitation-Runoff Modeling System (PRMS) is a module within MMS which expresses each component of the hydrologic cycle in the form of known physical laws or empirical relationships. This reproduces the physical reality of the watershed basin as closely as possible.

The purpose of this chapter was to discuss the fundamental concepts of the MMS and the PRMS module. MMS, in conjunction with PRMS, was used for this investigation as a research tool to compare hydrologic simulations between both

distributed and lumped models. Both of these models were applied to stationary and

moving storm systems using the kinematic wave theory. The next chapter discusses the

methodology which was used for this research project.

CHAPTER 8

METHODOLOGY

This chapter describes the methodology which was used in this investigation to compare hydrologic basin simulations resulting from both distributed versus lumped rainfall events. The first phase of the project was to simulate runoff response resulting from storm events applied to synthetic rectangular drainage basins. The second phase was to apply the same general storm scenarios over an actual river basin. Both stationary and moving storm events were used for this project. The U.S. Geological Survey Modular Modeling System (MMS) was used as a research tool for this investigation.

Hydrologic processes which govern basin response are highly complex. Because of this, impervious basins were assumed for both the rectangular and actual drainage watersheds to simplify the problem for this investigation. This allowed for a better understanding as to how the actual location of and movement of rainfall across a basin for both stationary and moving storm events impacted the hydrologic response of the basin for both distributed and lumped models.

8.1. Synthetic Rectangular Drainage Basins

V-shaped synthetic rectangular shaped drainage basins were developed for this part of this investigation. The actual synthetic basin configurations for each case scenario, slope, Manning's n roughness coefficient for both the overland flow plane and channel, and the hypothetical rainfall scenarios which were applied to each basin case configuration are discussed below.

8.1.1. Basin Configurations

V-shaped synthetic rectangular shaped drainage basins were bisected in half along its length by a major drainage channel creating two overland flow planes. The length of the basin was then subdivided into 10 increments creating a total of 20 overland flow planes. The subdivisions of a typical rectangular drainage basin are shown below in figure 8-1.

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Basin Outlet

Figure 8-1. Synthetic Rectangular Drainage Basin

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The rectangular dimensions for each basin were based on typical watershed shape factors of 1, 2, 3, 4, and 5. Shape factor is the length to width ratio of a drainage basin. Shape factor was used to establish various length to width dimensions for the rectangular basins.

A shape factor of 1 was used to develop a "pivot" basin. The dimensions of the "pivot" basin are 2000 feet by 2000 feet and were used as a reference to develop the other basins. From there, the length and widths of the remaining basins were developed based on these dimensions in conjunction with shape factors 2, 3, 4, and 5.

For each individual shape factor, three basin configurations were developed based on constant area, constant width, and constant length. Because the "pivot" basin with a shape factor of 1 is exactly the same for each of the three basin configurations, a total of 13 synthetic rectangular basins were developed for this investigation. Shape factor 1 has one rectangular basin; shape factors 2, 3, 4, and 5 each have three rectangular basin. These basin configurations are shown below in Table 8-1.

It should be noted that no literature was available which indicated a maximum length of an overland flow plane which should be implemented in a watershed model. However, based on the experience and recommendation of the U.S. Geological Survey Precipitation Modeling Branch, a maximum length of 1000 feet for the overland flow plane was used as a rule of thumb in designing these watershed models for this investigation. (George Leavesley, 2006, personal communication)

8.1.1.1. Constant Area

The area of the "pivot" basin (shape factor 1) was used to determine the length to width dimensions for the rectangular basins with shape factors 2, 3, 4, and 5. The drainage area was set constant for each basin. As the shape factor increases, the basin length increases while the basin width decreases. The configurations for these basins are shown below in Table 8-1.

8.1.1.2. Constant Width

The width of the "pivot" basin (shape factor 1) was used to determine the length of the rectangular basins with shape factors 2, 3, 4, and 5. The width was set constant for each basin. As the shape factor increases, both the length and area of each basin increase. The configurations for these basins are shown below in Table 8-1.

8.1.1.3. Constant Length

The length of the "pivot" basin (shape factor 1) was used to determine the width of the rectangular basins with shape factors 2, 3, 4, and 5. The length was set constant for each basin. As the shape factor increases, both the width and area of each basin decrease. The configurations for these basins are shown below in Table 8-1.

Table 8-1. Rectangular Basin Size and Configuration

	Shape Factor	Length (feet)	Width (feet)	Area (acres)
Constant Area	1	2000	2000	91.83
(Case 1)	2	2828	1414	91.83
	3	3464	1166	91.83
	4	4000	1000	91.83
	5	4472	894	91.83
Constant Width	1	2000	2000	91.83
(Case 2)	2	4000	2000	183.65
	3	6000	2000	275.48
	4	8000	2000	367.31
	5	10000	2000	459.14
Constant Length	1	2000	2000	91.83
(Case 3)	2	2000	1000	45.91
	3	2000	667	30.61
	4	2000	500	22.96
	5	2000	400	18.37

<u>8.1.2. Slope (Overland Flow Plane and Channel)</u>

Each rectangular basin is designed to represent a moderately steep overland flow plane flowing into a flat channel, which is typical of many of the basins located across the State of Texas. Three overland flow plane slopes were selected for this investigation. These slopes are (1) 16.22%, (2) 9.12%, and (3) 4.05%. These slopes were computed from the kinematic wave equation alpha parameters (i.e. 4, 3, and 2) for overland flow. A slope of 1.55 percent was used for the channel.

<u>8.1.3. Manning's n Roughness Coefficients (Overland Flow Plane and Channel)</u>

Manning's n roughness coefficients were also required to simulate the hydrologic response of the watershed models. These coefficients were selected based on typical

roughness factors associated with drainage areas located in north central Texas. A Manning's n coefficient of 0.15 was selected to represent tall grass vegetation for an overland flow plane. A Manning's n coefficient of 0.05 was also selected to represent the main stream channel in its natural condition. (FHA 2001)

8.1.4. Hypothetical Rainfall Scenarios

Precipitation scenarios were applied to each rectangular basin configuration using both distributed and lumped (mean areal precipitation) rainfall consisting of both stationary and moving storm events. Rainfall amounts typical of North Texas were selected for this investigation.

A hypothetical rainfall amount of 1 inch uniformly distributed over a 10 minute time period was selected as the basis for this investigation. This is approximately equal to a 2 year-10 minute storm intensity frequency as outlined in NOAA Technical Memorandum NWS HYDRO-35. (NOAA 1977)

The 1 inch base rainfall amount was first applied as distributed precipitation for the test case scenarios for the stationary storm events. From there, lumped (mean areal) precipitation was computed and applied to each basin. Finally, this rainfall was also configured for both distributed and lumped rainfall and applied to each basin for the moving storm events.

Each rainfall scenario resulted in a mean areal runoff of 0.2 inches for each basin. For these cases, each basin was assumed to have an impervious surface, thereby causing runoff to equal the precipitation over the basin. Distributed and lumped rainfall for both the stationary and moving storm events are discussed below.

8.1.4.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved placing distributed rainfall over the upper 20%, middle 20%, and lower 20% of the rectangular drainage basin. The fourth event involved placing lumped rainfall uniformly over the entire basin.

Each of these four events was applied to each rectangular basin case study. These case studies included shape factors 1, 2, 3, 4, 5 for the constant area, width, and length basin scenarios.

Distributed rainfall consisting of a 1 inch amount over a 10 minute time period was applied to the upper 20%, middle 20%, and lower 20% of each drainage basin. Lumped rainfall consisting of 0.2 inches over a 10 minute time period was also applied uniformly over the entire basin. The total volume of runoff which occurred over the entire basin for each of the three distributed cases and the single lumped case was 0.2 inches.

8.1.4.1.1. Distributed Rainfall

Three hypothetical distributed rainfall events of 1 inch over a 10 minute time period was applied over the upper 20%, middle 20%, and lower 20% of each basin. The volume of runoff which resulted was 0.2 inches.

8.1.4.1.1.1. Upper 20%

A rainfall event of 1 inch over a 10 minute time period was applied over the upper 20% for each basin configuration. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-2 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-2 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Basin Outlet

Shaded Area = 1 inch of uniform rainfall over 10 minutes
Unshaded Area = no rainfall

Figure 8-2. Stationary Storm – Distributed Rainfall (Upper 20%)

Table 8-2. Stationary Storm – Distributed Rainfall (Upper 20%)

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
1	0.10	0.10	0	0	0	0	0	0	0	0
2	0.10	0.10	0	0	0	0	0	0	0	0
3	0.10	0.10	0	0	0	0	0	0	0	0
4	0.10	0.10	0	0	0	0	0	0	0	0
5	0.10	0.10	0	0	0	0	0	0	0	0
6	0.10	0.10	0	0	0	0	0	0	0	0
7	0.10	0.10	0	0	0	0	0	0	0	0
8	0.10	0.10	0	0	0	0	0	0	0	0
9	0.10	0.10	0	0	0	0	0	0	0	0
10	0.10	0.10	0	0	0	0	0	0	0	0
Total	1.00	1.00	0	0	0	0	0	0	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.1.1.2. Middle 20%

A rainfall event of 1 inch over a 10 minute time period was applied over the middle 20% for each basin. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-3 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-3 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Basin Outlet

Shaded Area = 1 inch of uniform rainfall over 10 minutes
Unshaded Area = no rainfall

Figure 8-3. Stationary Storm – Distributed Rainfall (Middle 20%)

Table 8-3. Stationary Storm – Distributed Rainfall (Middle 20%)

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
1	0	0	0	0	0.10	0.10	0	0	0	0
2	0	0	0	0	0.10	0.10	0	0	0	0
3	0	0	0	0	0.10	0.10	0	0	0	0
4	0	0	0	0	0.10	0.10	0	0	0	0
5	0	0	0	0	0.10	0.10	0	0	0	0
6	0	0	0	0	0.10	0.10	0	0	0	0
7	0	0	0	0	0.10	0.10	0	0	0	0
8	0	0	0	0	0.10	0.10	0	0	0	0
9	0	0	0	0	0.10	0.10	0	0	0	0
10	0	0	0	0	0.10	0.10	0	0	0	0
Total	0	0	0	0	1.00	1.00	0	0	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.1.1.3. Lower 20%

A rainfall event of 1 inch over a 10 minute time period was applied over the lower 20% for each basin. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-4 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-4 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Basin Outlet

Shaded Area = 1 inch of uniform rainfall over 10 minutes
Unshaded Area = no rainfall

Figure 8-4. Stationary Storm – Distributed Rainfall (Lower 20%)

Table 8-4. Stationary Storm – Distributed Rainfall (Lower 20%)

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
1	0	0	0	0	0	0	0	0	0.10	0.10
2	0	0	0	0	0	0	0	0	0.10	0.10
3	0	0	0	0	0	0	0	0	0.10	0.10
4	0	0	0	0	0	0	0	0	0.10	0.10
5	0	0	0	0	0	0	0	0	0.10	0.10
6	0	0	0	0	0	0	0	0	0.10	0.10
7	0	0	0	0	0	0	0	0	0.10	0.10
8	0	0	0	0	0	0	0	0	0.10	0.10
9	0	0	0	0	0	0	0	0	0.10	0.10
10	0	0	0	0	0	0	0	0	0.10	0.10
Total	0	0	0	0	0	0	0	0	1.00	1.00

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.1.2. Lumped Rainfall

A rainfall event of 0.2 inch over a 10 minute time period was applied over the entire basin. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-5 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-5 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Basin Outlet

Shaded Area = 0.2 inch of uniform rainfall over 10 minutes

Figure 8-5. Stationary Storm - Lumped Rainfall (Entire Basin)

Table 8-5. Stationary Storm – Lumped Rainfall (Entire Basin)

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.2. Moving Storms

Two moving storm systems with both a constant uniform velocity and a constant

rate of rainfall were applied to each rectangular basin case scenario. These storm systems

either moved from the upstream to downstream or from the downstream to upstream

direction across the basin. For each storm system, both distributed and lumped rainfall

was applied for each storm case, making a total of four scenarios where rainfall was

applied to each rectangular basin configuration.

8.1.4.2.1. Upstream to Downstream

A storm system moving from upstream to downstream was applied to each

rectangular basin case scenario. Both distributed and lumped rainfall was simulated.

8.1.4.2.1.1. Distributed Rainfall

Distributed rainfall was applied over each basin as the storm system moved from

the upstream to downstream direction across the drainage. Initially, rain fell in the upper

reaches of the basin. At the 10 minute time period, the storm system had moved across

the basin so that rainfall was occurring over the entire drainage. As the storm system

continued to move across the basin, rainfall ceased in the upper reaches and was only

occurring in the lower reaches at the latter time periods. At 20 minutes, the entire storm

system had moved out of the basin. A total of 0.2 inch of distributed rainfall with a 10

minute time duration was applied to each part of the basin at some point within the 20

minute storm event. The entire storm event produced a total volume of rainfall for the

entire basin of 0.2 inch. The hydrologic response of this rainfall was computed at the

outlet for each basin. Figure 8-6 shows a diagram of the rainfall distribution across each rectangular basin. Table 8-6 shows the actual amount of rainfall applied to each overland flow plane at each time increment.
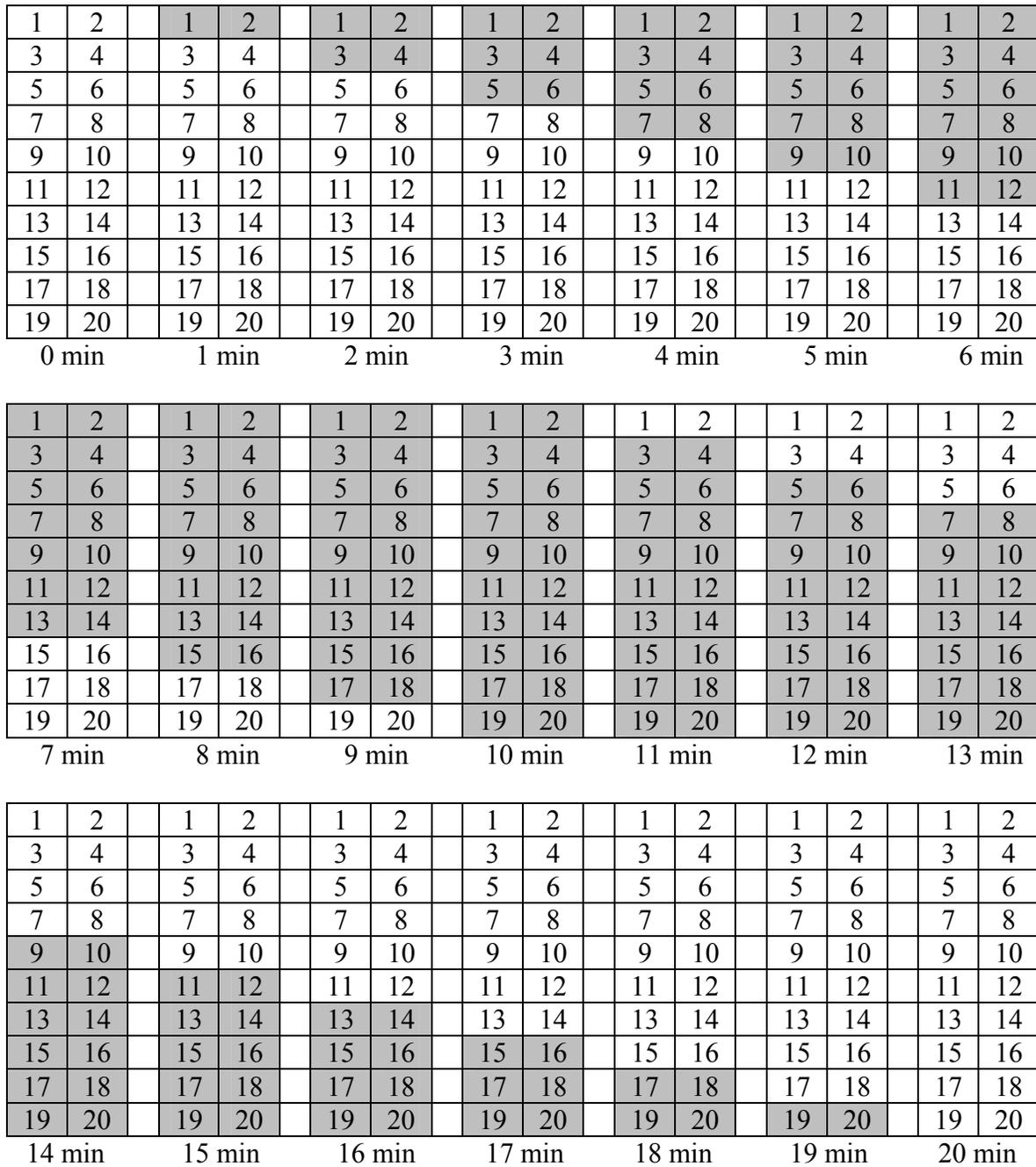
Figure 8-6. Moving Storm – Upstream to Downstream – Distributed Rainfall

Table 8-6. Moving Storm – Upstream to Downstream – Distributed Rainfall

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
0	0	0	0	0	0	0	0	0	0	0
1	0.02	0	0	0	0	0	0	0	0	0
2	0.02	0.02	0	0	0	0	0	0	0	0
3	0.02	0.02	0.02	0	0	0	0	0	0	0
4	0.02	0.02	0.02	0.02	0	0	0	0	0	0
5	0.02	0.02	0.02	0.02	0.02	0	0	0	0	0
6	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0	0
7	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0
8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0	0
9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0
10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
11	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
12	0	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
13	0	0	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02
14	0	0	0	0	0.02	0.02	0.02	0.02	0.02	0.02
15	0	0	0	0	0	0.02	0.02	0.02	0.02	0.02
16	0	0	0	0	0	0	0.02	0.02	0.02	0.02
17	0	0	0	0	0	0	0	0.02	0.02	0.02
18	0	0	0	0	0	0	0	0	0.02	0.02
19	0	0	0	0	0	0	0	0	0	0.02
20	0	0	0	0	0	0	0	0	0	0
Total	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.2.1.2. Lumped Rainfall

Lumped rainfall was also applied over each basin as the storm system moved from the upstream to downstream direction across the drainage. The rainfall pattern was exactly the same as in the distributed rainfall scenario for the storm system moving in the same direction. However, for the lumped rainfall event, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 minute ordinate during the entire storm event. The entire storm event produced a total

volume of rainfall for the entire basin of 0.2 inch. The hydrologic response of this

rainfall was computed at the outlet for each basin. Figure 8-7 shows a diagram of the

rainfall distribution across the rectangular basin. Table 8-7 shows the actual amount of

rainfall applied to each overland flow plane at each time increment.

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
0 min			1 min			2 min			3 min			4 min			5 min			6 min	

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
7 min			8 min			9 min			10 min			11 min			12 min			13 min	

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
14 min			15 min			16 min			17 min			18 min			19 min			20 min	

Figure 8-7. Moving Storm – Upstream to Downstream – Lumped Rainfall

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Table 8-7. Moving Storm – Upstream to Downstream – Lumped Rainfall

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
0	0	0	0	0	0	0	0	0	0	0
1	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
2	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
3	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
4	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
5	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
6	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
7	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
8	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
9	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
10	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
11	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
12	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
13	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
14	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
15	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
16	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
17	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
18	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
19	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
20	0	0	0	0	0	0	0	0	0	0
Total	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.1.4.2.2. Downstream to Upstream

A storm system moving from downstream to upstream was applied to each rectangular basin case scenario. Both distributed and lumped rainfall was simulated.

8.1.4.2.2.1. Distributed Rainfall

Distributed rainfall was applied over each basin as the storm system moved from the downstream to upstream direction across the drainage. The rainfall pattern was

exactly the same as the previous storm system except that this system was moving in the opposite direction from downstream to upstream. At the 10 minute time period, the storm system had moved across the basin so that rainfall was occurring over the entire drainage. As the storm system continued to move across the basin, rainfall ceased in the lower reaches and was only occurring in the upper reaches at the latter time periods. At 20 minutes, the entire storm system had moved out of the basin. As in the previous case, a total of 0.2 inch of distributed rainfall with a 10 minute time duration was applied to each part of the basin at some point within the 20 minute storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.2 inch. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-8 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-8 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

Figure 8-8. Moving Storm – Downstream to Upstream – Distributed Rainfall

Each cell grid contains the numbers 1–20 arranged in two columns:

1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20

Row 1 grids: 0 min, 1 min, 2 min, 3 min, 4 min, 5 min, 6 min

Row 2 grids: 7 min, 8 min, 9 min, 10 min, 11 min, 12 min, 13 min

Row 3 grids: 14 min, 15 min, 16 min, 17 min, 18 min, 19 min, 20 min

Table 8-8. Moving Storm – Downstream to Upstream – Distributed Rainfall

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0.02
2	0	0	0	0	0	0	0	0	0.02	0.02
3	0	0	0	0	0	0	0	0.02	0.02	0.02
4	0	0	0	0	0	0	0.02	0.02	0.02	0.02
5	0	0	0	0	0	0.02	0.02	0.02	0.02	0.02
6	0	0	0	0	0.02	0.02	0.02	0.02	0.02	0.02
7	0	0	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8	0	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
9	0	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
10	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
11	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0
12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0	0
13	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0
14	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0	0
15	0.02	0.02	0.02	0.02	0.02	0	0	0	0	0
16	0.02	0.02	0.02	0.02	0	0	0	0	0	0
17	0.02	0.02	0.02	0	0	0	0	0	0	0
18	0.02	0.02	0	0	0	0	0	0	0	0
19	0.02	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
Total	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.4.1.2.2.2. Lumped Rainfall

Lumped rainfall was applied over each basin as the storm system moved from the downstream to upstream direction across the drainage. The rainfall pattern was exactly the same as the distributed rainfall scenario for the storm system moving in the same direction. However, for the lumped case, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 minute ordinate during the entire storm event. The entire storm event produced a total volume of

rainfall for the entire basin of 0.2 inch. The hydrologic response of this rainfall was computed at the outlet for each basin. Figure 8-9 shows a diagram of the rainfall distribution across the rectangular basin. Table 8-9 shows the actual amount of rainfall applied to each overland flow plane at each time increment.

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
0 min			1 min			2 min			3 min			4 min			5 min			6 min	

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
7 min			8 min			9 min			10 min			11 min			12 min			13 min	

1	2		1	2		1	2		1	2		1	2		1	2		1	2
3	4		3	4		3	4		3	4		3	4		3	4		3	4
5	6		5	6		5	6		5	6		5	6		5	6		5	6
7	8		7	8		7	8		7	8		7	8		7	8		7	8
9	10		9	10		9	10		9	10		9	10		9	10		9	10
11	12		11	12		11	12		11	12		11	12		11	12		11	12
13	14		13	14		13	14		13	14		13	14		13	14		13	14
15	16		15	16		15	16		15	16		15	16		15	16		15	16
17	18		17	18		17	18		17	18		17	18		17	18		17	18
19	20		19	20		19	20		19	20		19	20		19	20		19	20
14 min			15 min			16 min			17 min			18 min			19 min			20 min	

Figure 8-9. Moving Storm – Downstream to Upstream – Lumped Rainfall

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Table 8-9. Moving Storm – Downstream to Upstream – Lumped Rainfall

Time (min)	OFP 1, 2	OFP 3, 4	OFP 5, 6	OFP 7, 8	OFP 9, 10	OFP 11, 12	OFP 13, 14	OFP 15, 16	OFP 17, 18	OFP 19, 20
0	0	0	0	0	0	0	0	0	0	0
1	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
2	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
3	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
4	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
5	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
6	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
7	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
8	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
9	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
10	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
11	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
12	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
13	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014
14	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
15	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
16	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
17	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
18	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
19	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
20	0	0	0	0	0	0	0	0	0	0
Total	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.2. Actual Drainage Basin

The Cowleech Fork Sabine River near Greenville, Texas drainage basin was
selected for this part of this investigation. This drainage area is located in North Texas
approximately 50 miles northeast of Dallas, near the town of Greenville. The topography
of this basin is generally flat with some rolling hills. The vegetation cover consists
primarily of timber, shrubs, and grasses. The soil type in this region is primarily clay.

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The Greenville basin configuration, slope, Manning's n roughness coefficient for both the

overland flow plane and channel, and the hypothetical rainfall scenarios which were

applied to this basin are discussed below.

8.2.1. Basin Configuration

The Greenville basin is somewhat rectangular in shape. The average length to

width ratio is approximately 11 units to 4 units, respectively, correlating to a shape factor

of 2.75 for the entire basin. Shape factor is the length to width ratio of a drainage basin.

A general map of the Greenville Basin is shown below in Figure 8-10.
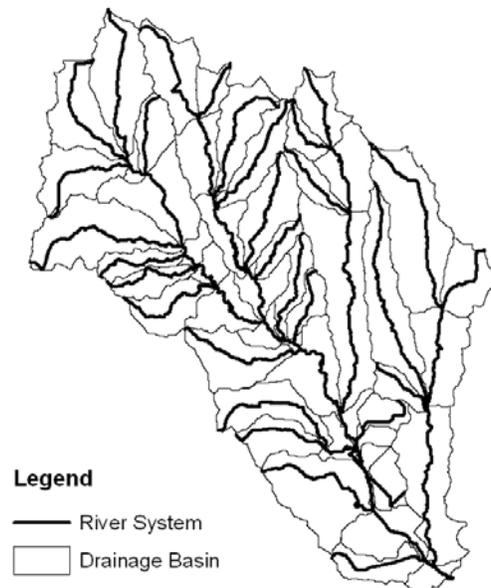
Figure 8-10. Drainage Basin – Cowleech Fork Sabine River near Greenville, Texas

The Greenville basin was subdivided into 102 subbasins with 51 interconnecting river segments using Geographic Information Systems (GIS). These individual subbasins and river segments vary in drainage area, slope, length, width, and Manning's n roughness coefficients. This information is summarized in Table 8-10. More detailed information for each subbasin is provided in Table F.1, located in Appendix F.

Table 8-10. Drainage Basin Configuration (General Summary)
Cowleech Fork Sabine River near Greenville, Texas

Number of Subbasins (i.e. Overland Flow Planes)	102
Number of Channel Segments	51
Overland Flow Planes (Subbasins)	
Drainage Area	19.1 to 1880.8 acres
Length	75.7 to 3443.3 feet
Width	2495 to 34482 feet
Slope	0.008 to 0.047
Manning's n Roughness Coefficient	0.13 (Bare Soil), 0.4 (Shrubs), Trees (0.6)
Soil Type	Clay
Channel Segments	
Length	2495 to 34482 feet
Slope	0.001 to 0.009
Manning's n Roughness Coefficient	0.05

8.2.2. Slope (Overland Flow Plane and Channel)

The slope of each individual subbasin and river segment varies. The slope of the overland flow planes range from approximately 0.01 to 0.04. The slope of the channel segments range from approximately 0.001 to 0.009.

8.2.3. Manning's n Roughness Coefficients (Overland Flow Plane and Channel)

Manning's n roughness coefficients also vary for each subbasin and river segment. Manning's n values for the overland flow planes were selected based on predominate vegetation types across each basin. A Manning's n value of 0.6 was used for timbered areas with moderately dense under brush, 0.4 for shrubs, and 0.13 for bare soil conditions. A Manning's n value of 0.07 was selected for the river segments based on natural river channel conditions. (FHA 2001)

8.2.4. Hypothetical Rainfall Scenario (1 Inch in 5 Hours)

A hypothetical storm event with a rainfall intensity of 1 inch with a 5 hour time duration was applied over the Greenville drainage. This rainfall was applied as both distributed and lumped rainfall in conjunction with stationary and moving storm events. It should be noted that this rainfall amount occurs quite frequently over North Texas. The rainfall frequency Atlas of the United States, NOAA Technical Paper No. 40, was consulted as a guide in selecting this storm. (NOAA 1961)

The 1 inch base rainfall amount was first applied to the Greenville drainage as distributed precipitation for the stationary storm events. From there, lumped precipitation was computed and applied to the basin. This rainfall was configured for both distributed and lumped rainfall for the moving storm events.

Each rainfall scenario resulted in a mean areal runoff of approximately 0.22 inches for the Greenville drainage. For the purpose of this investigation, the Greenville

drainage was assumed to have an impervious surface, thereby causing basin runoff to equal the precipitation over the basin. This would allow a more direct comparison of the hydrologic response of the Greenville drainage with the synthetic rectangular drainage basins, which were also impervious. Distributed and lumped rainfall for both the stationary and moving storm events are discussed below.

8.2.4.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved placing distributed rainfall over an approximate area of the upper 22%, middle 22%, and lower 22% of the Greenville basin. The fourth event involved placing lumped rainfall uniformly over the entire basin.

Distributed rainfall consisting of a 1 inch amount over a 5 hour time period was applied to approximately the upper 22%, middle 22%, and lower 22% of the Greenville drainage. Lumped rainfall consisting of 0.22 inches over a 5 hour time period was also applied uniformly over the entire basin. The total volume of runoff which occurred over the entire basin for each of the three distributed cases and the single lumped case was 0.22 inches.

8.2.4.1.1. Distributed Rainfall

Three hypothetical distributed rainfall events of 1 inch over a 5 hour time period was applied over the upper 22%, middle 22%, and lower 22% of the Greenville basin. The volume of basin runoff which resulted was 0.22 inches.

8.2.4.1.1.1. Upper 22%

A rainfall event of 1 inch over a 5 hour time period was applied over the upper 22% of the Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-11 shows the actual location rainfall was placed over the basin. Table 8-11 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
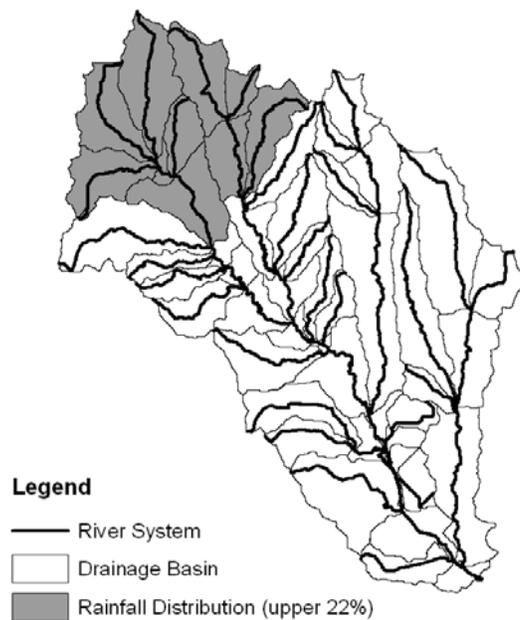
Figure 8-11. Stationary Storm – Distributed Rainfall (Upper 22%)

Table 8-11. Stationary Storm – Distributed Rainfall (Upper 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
1	0.20	0	0	0	0
2	0.20	0	0	0	0
3	0.20	0	0	0	0
4	0.20	0	0	0	0
5	0.20	0	0	0	0
Total	1.00	0	0	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.1.1.2. Middle 22%

A rainfall event of 1 inch over a 5 hour time period was applied over the middle 22% of the Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-12 shows the actual location rainfall was placed over the basin. Table 8-12 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

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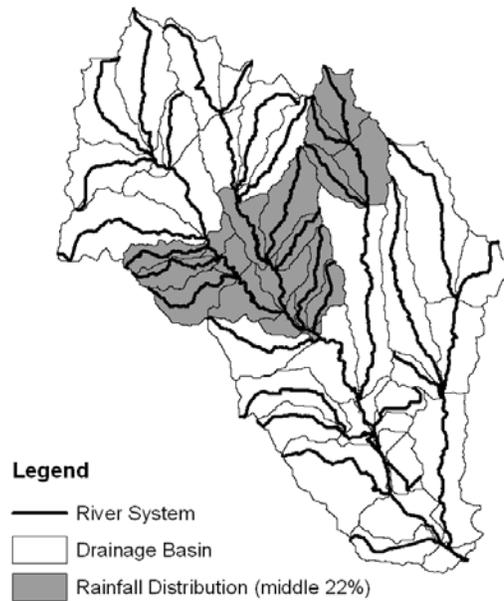
Figure 8-12. Stationary Storm – Distributed Rainfall (Middle 22%)

Table 8-12. Stationary Storm – Distributed Rainfall (Middle 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
1	0	0	0.20	0	0
2	0	0	0.20	0	0
3	0	0	0.20	0	0
4	0	0	0.20	0	0
5	0	0	0.20	0	0
Total	0	0	1.00	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.1.1.3. Lower 22%

A rainfall event of 1 inch over a 5 hour time period was applied over the lower

22% of the Greenville drainage. The hydrologic response of this rainfall was computed

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at the basin outlet. Figure 8-13 shows the actual location rainfall was placed over the

basin. Table 8-13 shows the actual amount of rainfall which was applied to each region

of the basin at each time increment.
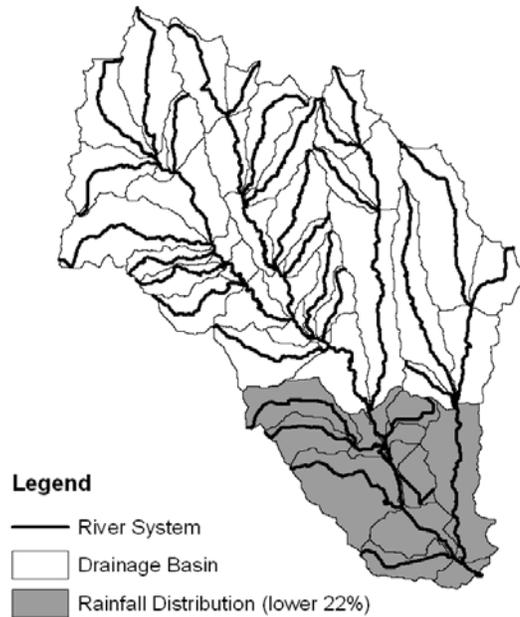
Figure 8-13. Stationary Storm – Distributed Rainfall (Lower 22%)

Table 8-13. Stationary Storm – Distributed Rainfall (Lower 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
1	0	0	0	0	0.20
2	0	0	0	0	0.20
3	0	0	0	0	0.20
4	0	0	0	0	0.20
5	0	0	0	0	0.20
Total	0	0	0	0	1.00

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.1.2. Lumped Rainfall

A rainfall event of 0.22 inch over a 5 hour time period was applied over the entire Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-14 shows the actual location rainfall was placed over the basin. Table 8-14 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
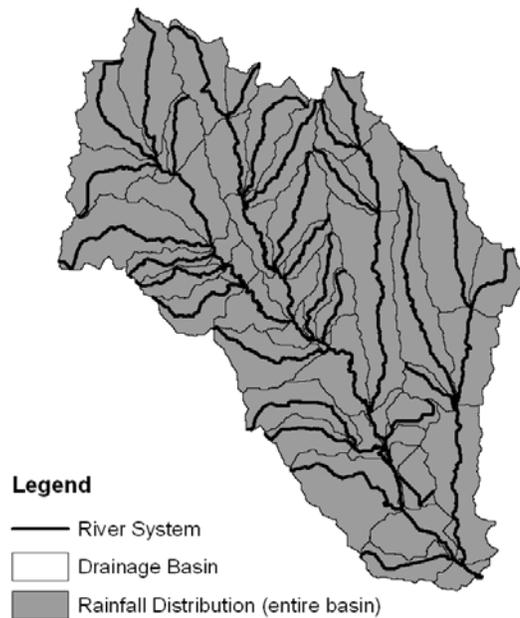
Figure 8-14. Stationary Storm – Lumped Rainfall (Entire Basin)

Table 8-14. Stationary Storm – Lumped Rainfall (Entire Basin)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
1	0.044	0.044	0.044	0.044	0.044
2	0.044	0.044	0.044	0.044	0.044
3	0.044	0.044	0.044	0.044	0.044
4	0.044	0.044	0.044	0.044	0.044
5	0.044	0.044	0.044	0.044	0.044
Total	0.220	0.220	0.220	0.220	0.220

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.2. Moving Storms

Two moving storm systems with both a constant uniform velocity and a constant rate of rainfall were applied to the Greenville basin. These storm systems either moved from the upstream to downstream or from the downstream to upstream direction across the basin. For each storm system, both distributed and lumped rainfall was applied for each storm case.

8.2.4.2.1. Upstream to Downstream

A storm system moving from upstream to downstream was applied to the Greenville drainage. Both distributed and lumped rainfall was simulated.

8.2.4.2.1.1. Distributed Rainfall

Distributed rainfall was applied over the Greenville basin as the storm system moved from the upstream to downstream direction across the drainage. Initially, rain fell in the upper reaches of the basin. At the 5 hour time period, the storm system had moved across the basin so that rainfall was occurring over the entire drainage. As the storm

system continued to move across the basin, rainfall ceased in the upper reaches and was only occurring in the lower reaches at the latter time periods. At 10 hours, the storm system had moved out of the basin. A total of 0.22 inch of distributed rainfall with a 5 hour time duration was applied to each part of the basin at some point within the 10 hour storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-15 shows the actual location rainfall was placed over the basin. Table 8-15 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.


| 0 hour | 1 hour | 2 hour | 3 hour | 4 hour |

| 5 hour | 6 hour | 7 hour | 8 hour | 9 hour |

10 hour
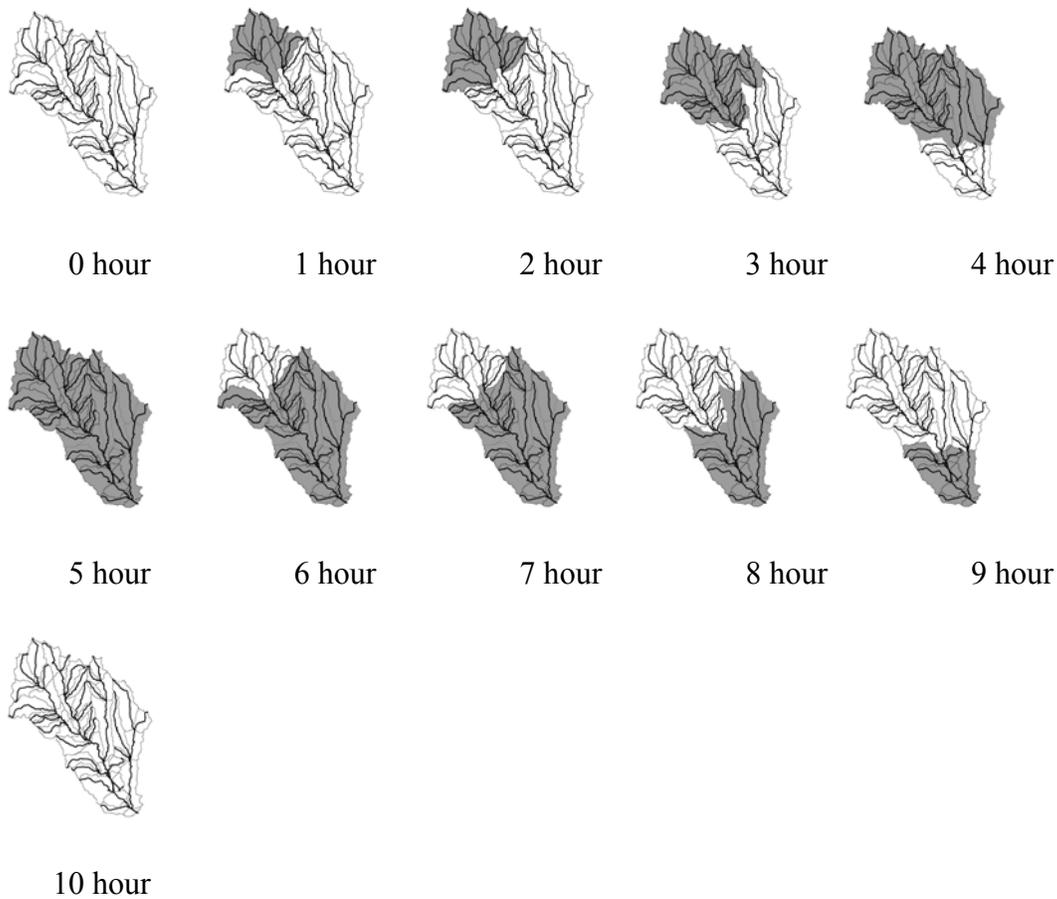
Figure 8-15. Moving Storm – Upstream to Downstream – Distributed Rainfall

Table 8-15. Moving Storm – Upstream to Downstream
Distributed Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
0	0	0	0	0	0
1	0.044	0	0	0	0
2	0.044	0.044	0	0	0
3	0.044	0.044	0.044	0	0
4	0.044	0.044	0.044	0.044	0
5	0.044	0.044	0.044	0.044	0.044
6	0	0.044	0.044	0.044	0.044
7	0	0	0.044	0.044	0.044
8	0	0	0	0.044	0.044
9	0	0	0	0	0.044
10	0	0	0	0	0
Table	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.2.1.2. Lumped Rainfall

Lumped rainfall was applied over the Greenville basin as the storm system moved from the upstream to downstream direction across the drainage. For the lumped rainfall event, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 hour ordinate during the entire storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-16 shows the actual location rainfall was placed over the basin. Table 8-16 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

| 0 hour | 1 hour | 2 hour | 3 hour | 4 hour |

| 5 hour | 6 hour | 7 hour | 8 hour | 9 hour |

10 hour
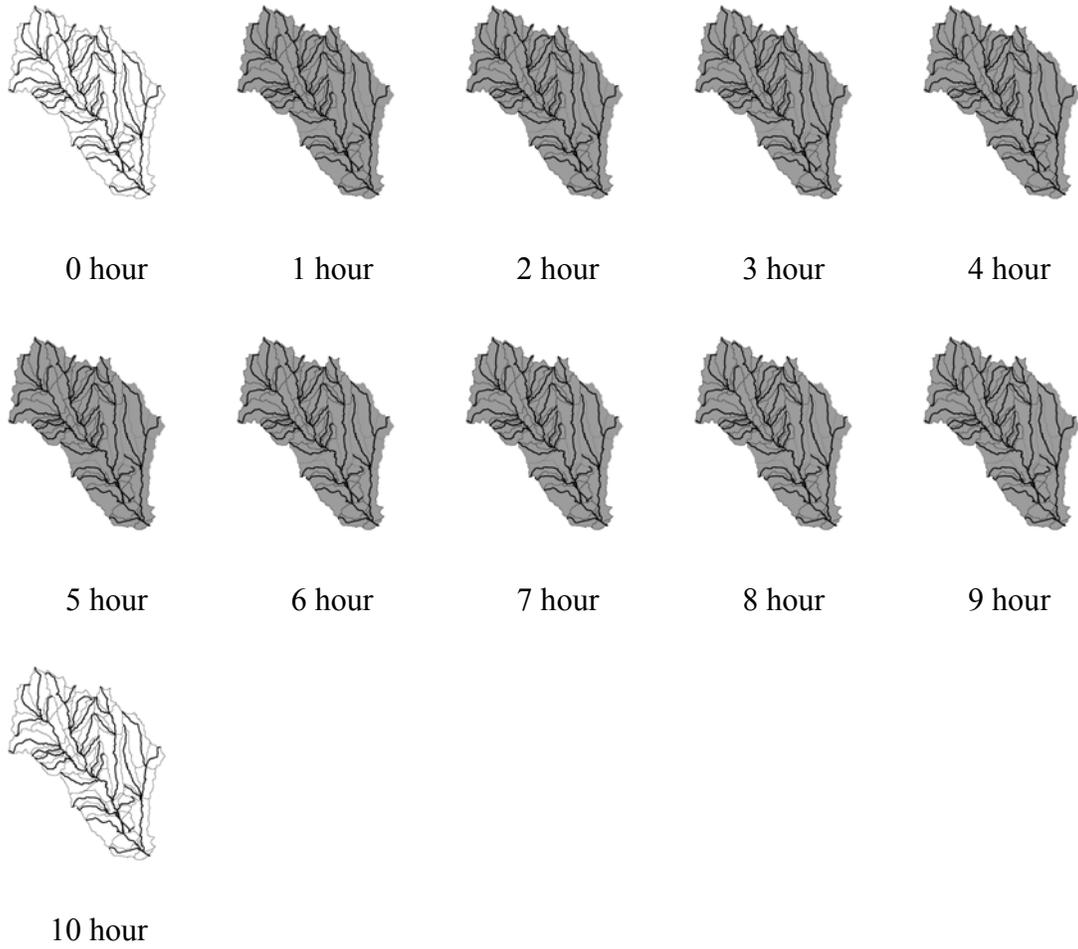
Figure 8-16. Moving Storm – Upstream to Downstream – Lumped Rainfall

Table 8-16. Moving Storm – Upstream to Downstream
Lumped Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
0	0	0	0	0	0
1	.0088	.0088	.0088	.0088	.0088
2	.0176	.0176	.0176	.0176	.0176
3	.0264	.0264	.0264	.0264	.0264
4	.0352	.0352	.0352	.0352	.0352
5	.0440	.0440	.0440	.0440	.0440
6	.0352	.0352	.0352	.0352	.0352
7	.0264	.0264	.0264	.0264	.0264
8	.0176	.0176	.0176	.0176	.0176
9	.0088	.0088	.0088	.0088	.0088
10	0	0	0	0	0
Total	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.2 inches

8.2.4.2.2. Downstream to Upstream

A storm system moving from downstream to upstream was applied to the Greenville drainage. Both distributed and lumped rainfall was simulated.

8.2.4.2.2.1. Distributed Rainfall

Distributed rainfall was applied over the Greenville basin as the storm system moved from the downstream to upstream direction across the drainage. Initially, rain fell in the lower reaches of the basin. At the 5 hour time period, the storm system had moved across the basin so that rainfall was occurring over the entire drainage. As the storm system continued to move across the basin, rainfall ceased in the lower reaches and was only occurring in the upper reaches at the latter time periods. At 10 hours, the storm system had moved out of the basin. A total of 0.22 inch of distributed rainfall with a 5

hour time duration was applied to each part of the basin at some point within the 10 hour storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-17 shows the actual location rainfall was placed over the basin. Table 8-17 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

| 0 hour | 1 hour | 2 hour | 3 hour | 4 hour |

| 5 hour | 6 hour | 7 hour | 8 hour | 9 hour |

10 hour
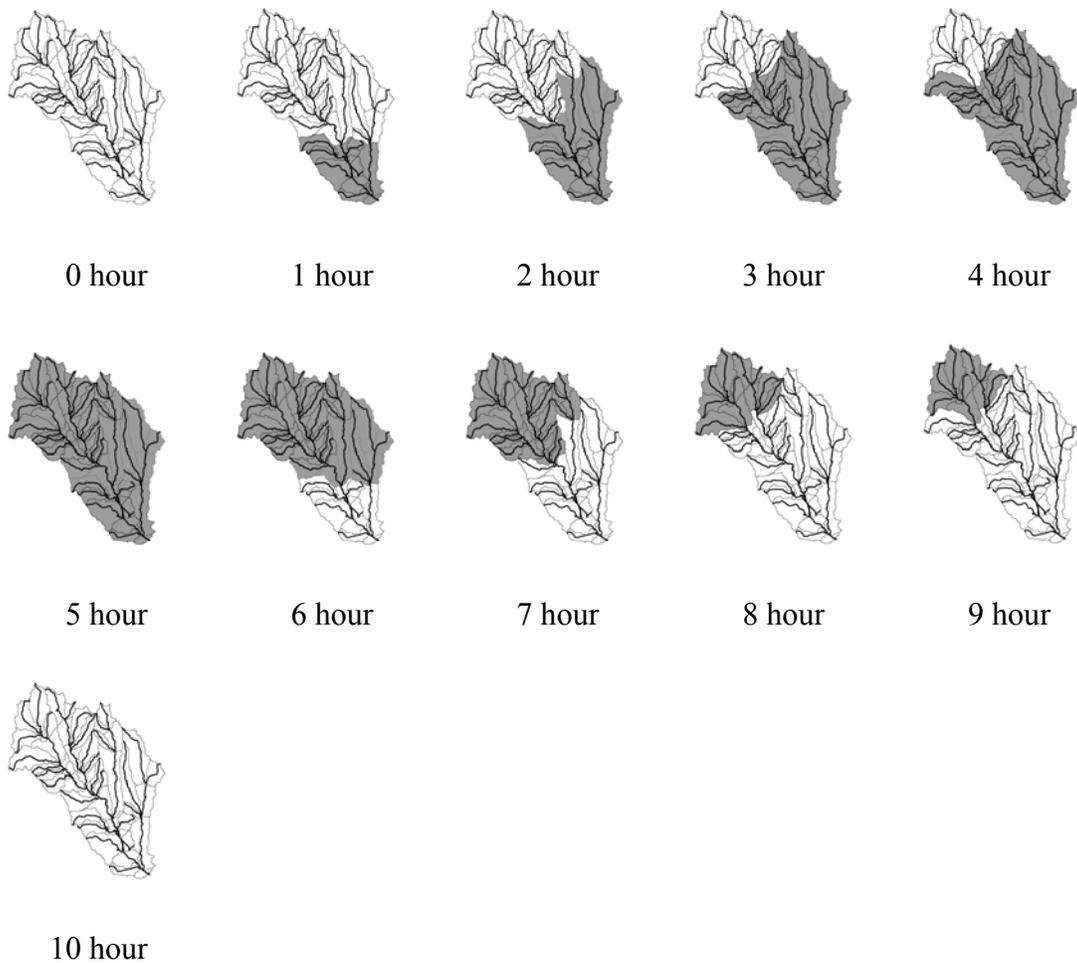
Figure 8-17. Moving Storm – Downstream to Upstream – Distributed Rainfall

Table 8-17. Moving Storm – Downstream to Upstream
Distributed Rainfall

Time (hr)	Area 6	Area 7	Area 8	Area 9	Area 10
0	0	0	0	0	0
1	0	0	0	0	0.044
2	0	0	0	0.044	0.044
3	0	0	0.044	0.044	0.044
4	0	0.044	0.044	0.044	0.044
5	0.044	0.044	0.044	0.044	0.044
6	0.044	0.044	0.044	0.044	0
7	0.044	0.044	0.044	0	0
8	0.044	0.044	0	0	0
9	0.044	0	0	0	0
10	0	0	0	0	0
Total	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.4.2.2.2. Lumped Rainfall

Lumped rainfall was applied over the Greenville basin as the storm system moved from downstream to upstream across the drainage. For the lumped rainfall event, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 hour ordinate during the entire storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-18 shows the actual location rainfall was placed over the basin. Table 8-18 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

| 0 hour | 1 hour | 2 hour | 3 hour | 4 hour |

| 5 hour | 6 hour | 7 hour | 8 hour | 9 hour |

10 hour
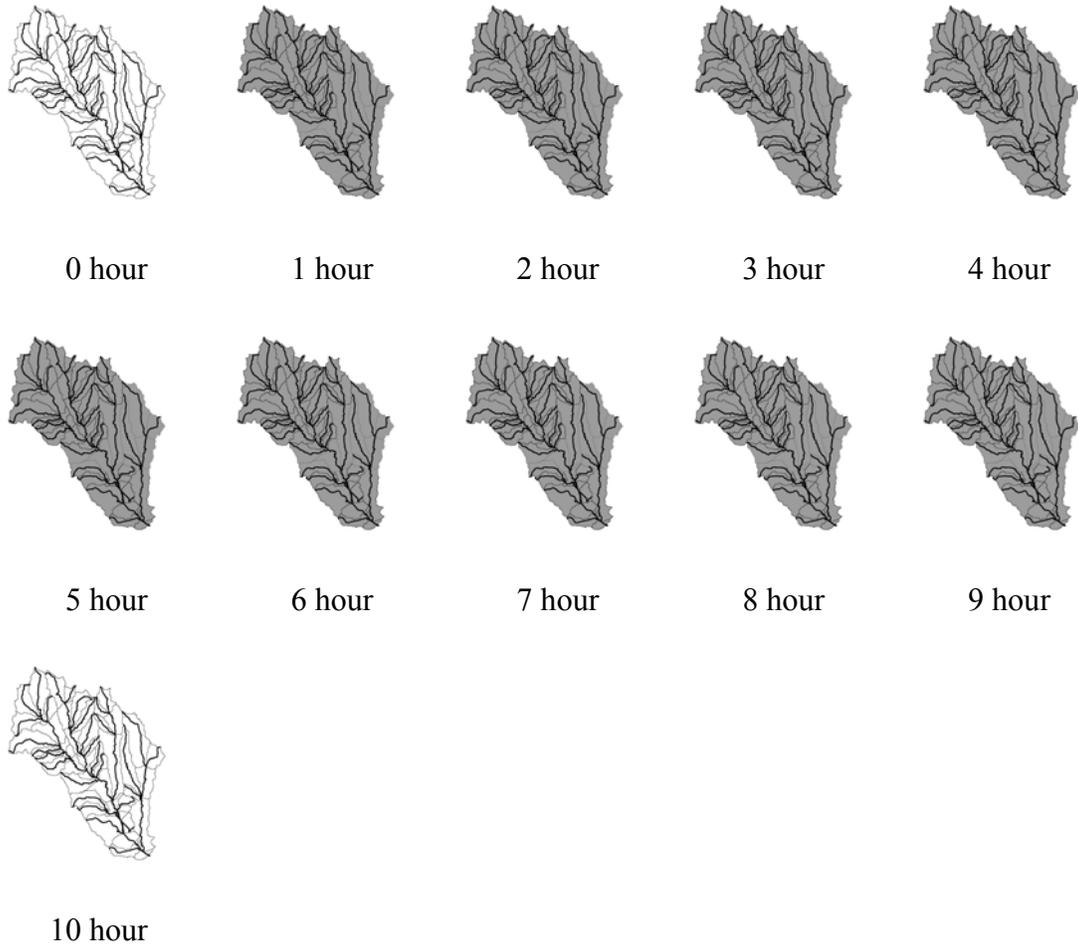
Figure 8-18. Moving Storm – Downstream to Upstream – Lumped Rainfall

Table 8-18. Moving Storm – Downstream to Upstream
Lumped Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5
0	0	0	0	0	0
1	.0088	.0088	.0088	.0088	.0088
2	.0176	.0176	.0176	.0176	.0176
3	.0264	.0264	.0264	.0264	.0264
4	.0352	.0352	.0352	.0352	.0352
5	.0440	.0440	.0440	.0440	.0440
6	.0352	.0352	.0352	.0352	.0352
7	.0264	.0264	.0264	.0264	.0264
8	.0176	.0176	.0176	.0176	.0176
9	.0088	.0088	.0088	.0088	.0088
10	0	0	0	0	0
Total	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5. Hypothetical Rainfall Scenario (1 Inch in 10 Hours)

A hypothetical storm event with a rainfall intensity of 1 inch with a 10 hour time duration was applied over the Greenville drainage. This rainfall was applied as both distributed and lumped rainfall in conjunction with stationary and moving storm events. It should be noted that this rainfall amount occurs quite frequently over North Texas. The rainfall frequency Atlas of the United States, NOAA Technical Paper No. 40, was consulted as a guide in selecting this storm. (NOAA 1961)

The 1 inch base rainfall amount was first applied to the Greenville drainage as distributed precipitation for the stationary storm events. From there, lumped precipitation was computed and applied to the basin. This rainfall was configured for both distributed and lumped rainfall for the moving storm events.

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Each rainfall scenario resulted in a mean areal runoff of approximately 0.22 inches for the Greenville drainage. For the purpose of this investigation, the Greenville drainage was assumed to have an impervious surface, thereby causing basin runoff to equal the precipitation over the basin. This would allow a more direct comparison of the hydrologic response of the Greenville drainage with the synthetic rectangular drainage basins, which were also impervious. Distributed and lumped rainfall for both the stationary and moving storm events are discussed below.

8.2.5.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved placing distributed rainfall over an approximate area of the upper 22%, middle 22%, and lower 22% of the Greenville basin. The fourth event involved placing lumped rainfall uniformly over the entire basin.

Distributed rainfall consisting of a 1 inch amount over a 10 hour time period was applied to approximately the upper 22%, middle 22%, and lower 22% of the Greenville drainage. Lumped rainfall consisting of 0.22 inches over a 10 hour time period was also applied uniformly over the entire basin. The total volume of runoff which occurred over the entire basin for each of the three distributed case and the single lumped case was 0.22 inches.

8.2.5.1.1. Distributed Rainfall

Three hypothetical distributed rainfall events of 1 inch over a 10 hour time period was applied over the upper 22%, middle 22%, and lower 22% of the Greenville basin. The volume of basin runoff which resulted was 0.22 inches.

8.2.5.1.1.1. Upper 22%

A rainfall event of 1 inch over a 10 hour time period was applied over the upper 22% of the Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-19 shows the actual location rainfall was placed over the basin. Table 8-19 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
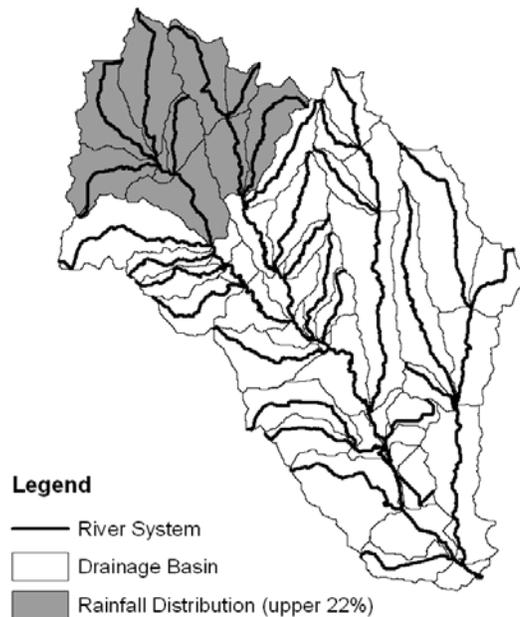

Figure 8-19. Stationary Storm – Distributed Rainfall (Upper 22%)

Table 8-19. Stationary Storm – Distributed Rainfall (Upper 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
1	0.10	0.10	0	0	0	0	0	0	0	0
2	0.10	0.10	0	0	0	0	0	0	0	0
3	0.10	0.10	0	0	0	0	0	0	0	0
4	0.10	0.10	0	0	0	0	0	0	0	0
5	0.10	0.10	0	0	0	0	0	0	0	0
6	0.10	0.10	0	0	0	0	0	0	0	0
7	0.10	0.10	0	0	0	0	0	0	0	0
8	0.10	0.10	0	0	0	0	0	0	0	0
9	0.10	0.10	0	0	0	0	0	0	0	0
10	0.10	0.10	0	0	0	0	0	0	0	0
Total	1.00	1.00	0	0	0	0	0	0	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.1.1.2. Middle 22%

A rainfall event of 1 inch over a 10 hour time period was applied over the middle 22% of the Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-20 shows the actual location rainfall was placed over the basin. Table 8-20 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
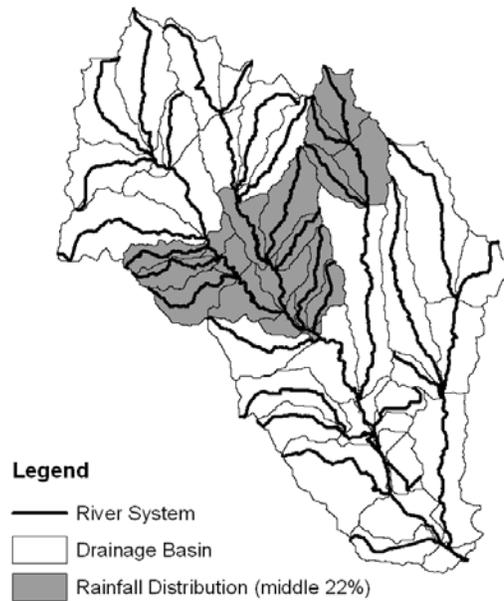
Figure 8-20. Stationary Storm – Distributed Rainfall (Middle 22%)

Table 8-20. Stationary Storm – Distributed Rainfall (Middle 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
1	0	0	0	0.10	0.10	0	0	0	0	0
2	0	0	0	0.10	0.10	0	0	0	0	0
3	0	0	0	0.10	0.10	0	0	0	0	0
4	0	0	0	0.10	0.10	0	0	0	0	0
5	0	0	0	0.10	0.10	0	0	0	0	0
6	0	0	0	0.10	0.10	0	0	0	0	0
7	0	0	0	0.10	0.10	0	0	0	0	0
8	0	0	0	0.10	0.10	0	0	0	0	0
9	0	0	0	0.10	0.10	0	0	0	0	0
10	0	0	0	0.10	0.10	0	0	0	0	0
Total	0	0	0	1.00	1.00	0	0	0	0	0

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.1.1.3. Lower 22%

A rainfall event of 1 inch over a 10 hour time period was applied over the lower 22% of the Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-21 shows the actual location rainfall was placed over the basin. Table 8-21 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
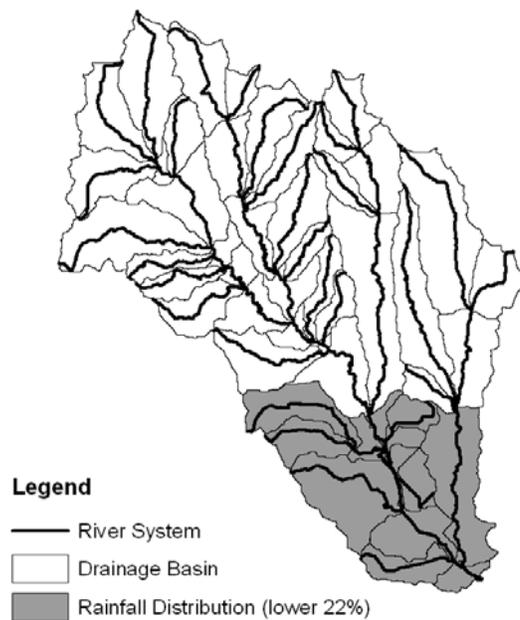

Figure 8-21. Stationary Storm – Distributed Rainfall (Lower 22%)

Table 8-21. Stationary Storm – Distributed Rainfall (Lower 22%)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
1	0	0	0	0	0	0	0	0.10	0.10	0.10
2	0	0	0	0	0	0	0	0.10	0.10	0.10
3	0	0	0	0	0	0	0	0.10	0.10	0.10
4	0	0	0	0	0	0	0	0.10	0.10	0.10
5	0	0	0	0	0	0	0	0.10	0.10	0.10
6	0	0	0	0	0	0	0	0.10	0.10	0.10
7	0	0	0	0	0	0	0	0.10	0.10	0.10
8	0	0	0	0	0	0	0	0.10	0.10	0.10
9	0	0	0	0	0	0	0	0.10	0.10	0.10
10	0	0	0	0	0	0	0	0.10	0.10	0.10
Total	0	0	0	0	0	0	0	1.00	1.00	1.00

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.1.2. Lumped Rainfall

A rainfall event of 0.22 inch over a 10 hour time period was applied over the entire Greenville drainage. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-22 shows the actual location rainfall was placed over the basin. Table 8-22 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.
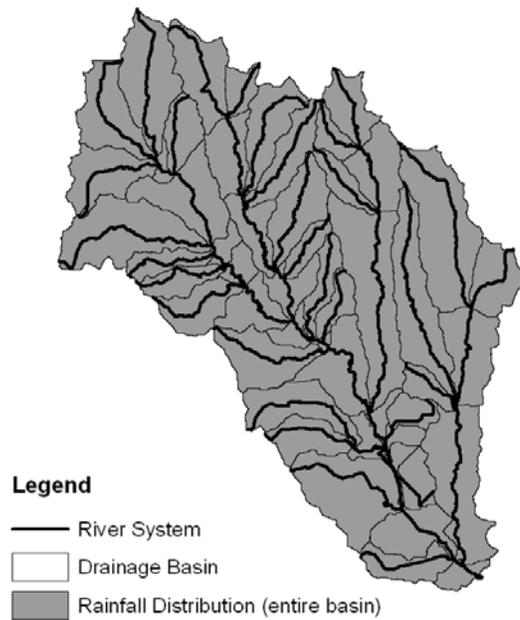
Figure 8-22. Stationary Storm – Lumped Rainfall (Entire Basin)

Table 8-22. Stationary Storm – Lumped Rainfall (Entire Basin)

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
1	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
2	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
3	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
4	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
5	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
6	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
7	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
8	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
9	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
10	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
Total	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches

Mean Areal Basin Precipitation = 0.22 inches

8.2.5.2. Moving Storms

Two moving storm systems with both a constant uniform velocity and a constant rate of rainfall were applied to the Greenville basin. These storm systems either moved from the upstream to downstream or from the downstream to upstream direction across the basin. For each storm system, both distributed and lumped rainfall was applied.

8.2.5.2.1. Upstream to Downstream

A storm system moving from upstream to downstream was applied to the Greenville drainage. Both distributed and lumped rainfall was simulated.

8.2.5.2.1.1. Distributed Rainfall

Distributed rainfall was applied over the Greenville basin as the storm system moved from the upstream to downstream direction across the drainage. Initially, rain fell in the upper reaches of the basin. At the 10 hour time period, the storm system had moved across the basin so that rainfall was occurring over the entire drainage. As the storm system continued to move across the basin, rainfall ceased in the upper reaches and was only occurring in the lower reaches. At 20 hours, the storm system had moved out of the basin. A total of 0.22 inch of distributed rainfall with a 10 hour time duration was applied to each part of the basin at some point within the 20 hour storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-23 shows the actual location rainfall was placed over the basin. Table 8-23 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

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0 hour   1 hour   2 hour   3 hour   4 hour

5 hour   6 hour   7 hour   8 hour   9 hour

10 hour   11 hour   12 hour   13 hour   14 hour

15 hour   16 hour   17 hour   18 hour   19 hour

20 hour
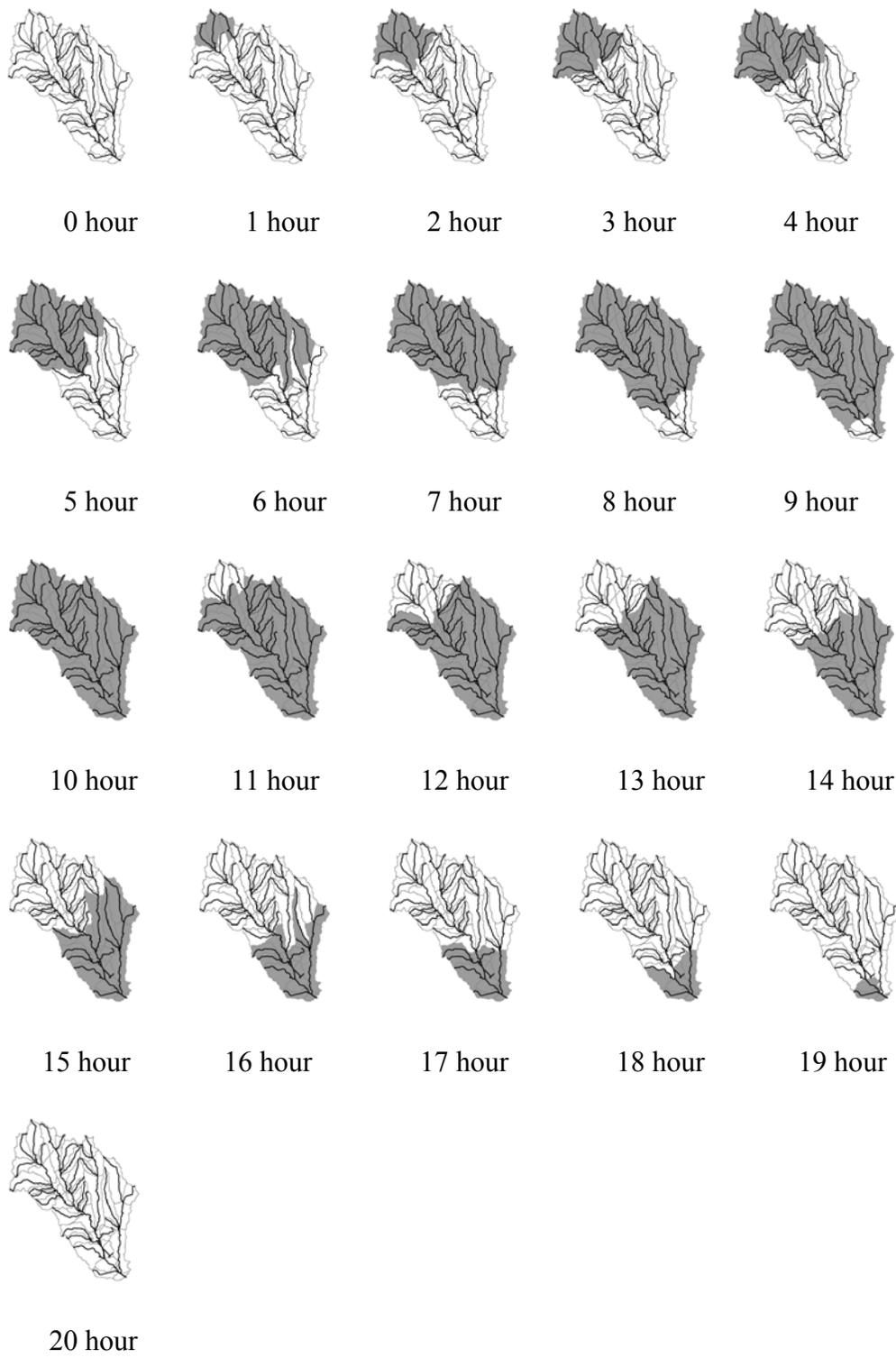
Figure 8-23. Moving Storm – Upstream to Downstream – Distributed Rainfall

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Table 8-23. Moving Storm – Upstream to Downstream – Distributed Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
0	0	0	0	0	0	0	0	0	0	0
1	0.022	0	0	0	0	0	0	0	0	0
2	0.022	0.022	0	0	0	0	0	0	0	0
3	0.022	0.022	0.022	0	0	0	0	0	0	0
4	0.022	0.022	0.022	0.022	0	0	0	0	0	0
5	0.022	0.022	0.022	0.022	0.022	0	0	0	0	0
6	0.022	0.022	0.022	0.022	0.022	0.022	0	0	0	0
7	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0	0	0
8	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0	0
9	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0
10	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
11	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
12	0	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
13	0	0	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022
14	0	0	0	0	0.022	0.022	0.022	0.022	0.022	0.022
15	0	0	0	0	0	0.022	0.022	0.022	0.022	0.022
16	0	0	0	0	0	0	0.022	0.022	0.022	0.022
17	0	0	0	0	0	0	0	0.022	0.022	0.022
18	0	0	0	0	0	0	0	0	0.022	0.022
19	0	0	0	0	0	0	0	0	0	0.022
20	0	0	0	0	0	0	0	0	0	0
Table	0.22	0.22	0.22	0.22						0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.2.1.2. Lumped Rainfall

Lumped rainfall was applied over the Greenville basin as the storm system moved from upstream to downstream across the drainage. For the lumped rainfall event, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 hour ordinate during the entire storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-24 shows the actual location rainfall was placed over the basin. Table 8-24 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

| 0 hour | 1 hour | 2 hour | 3 hour | 4 hour |

| 5 hour | 6 hour | 7 hour | 8 hour | 9 hour |

| 10 hour | 11 hour | 12 hour | 13 hour | 14 hour |

| 15 hour | 16 hour | 17 hour | 18 hour | 19 hour |

20 hour
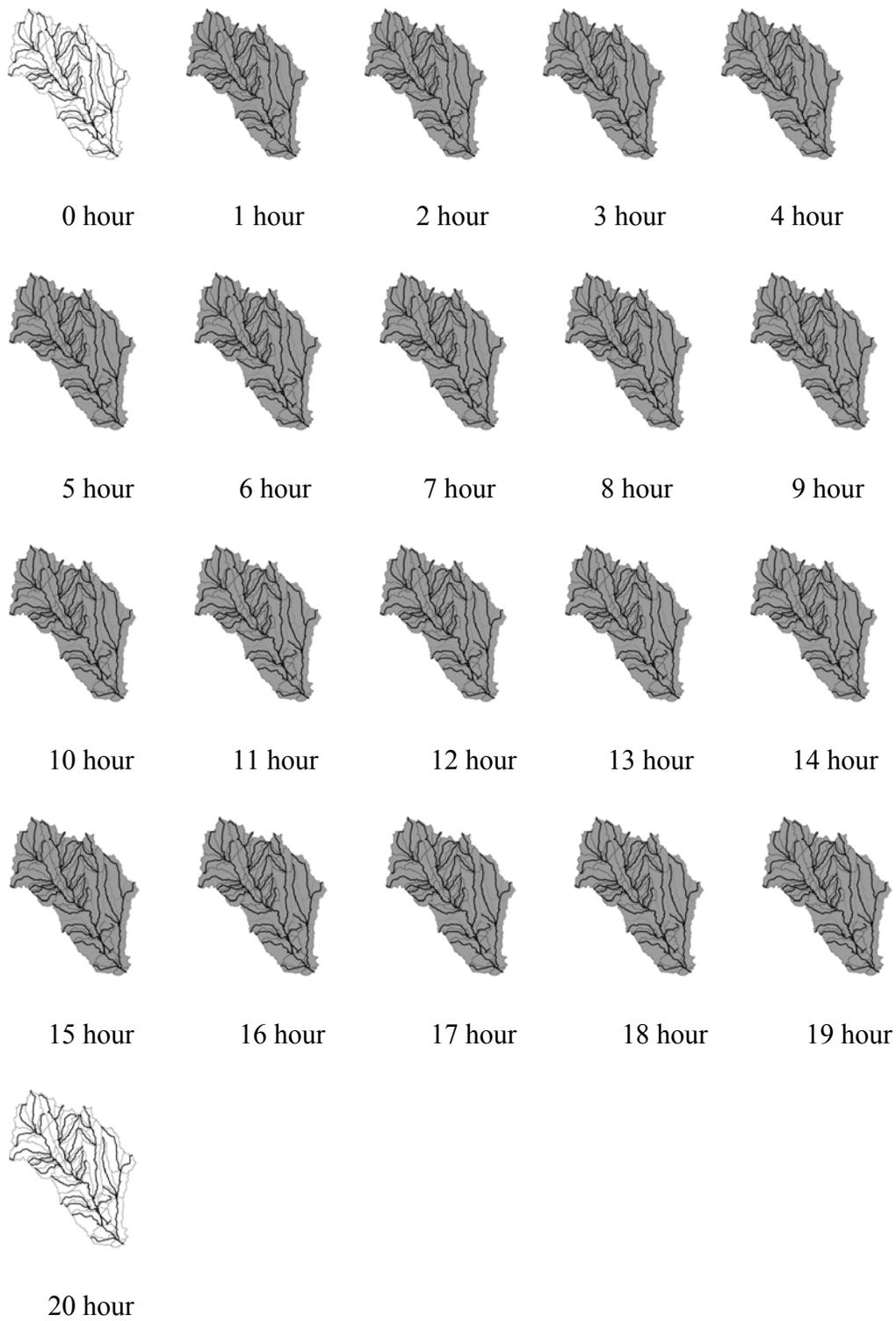
Figure 8-24. Moving Storm – Upstream to Downstream – Lumped Rainfall

Table 8-24. Moving Storm – Upstream to Downstream – Lumped Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
0	0	0	0	0	0	0	0	0	0	0
1	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022
2	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044
3	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066
4	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088
5	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110
6	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132
7	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154
8	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176
9	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198
10	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220
11	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198
12	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176
13	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154
14	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132
15	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110
16	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088
17	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066
18	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044
19	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022
20	0	0	0	0	0	0	0	0	0	0
Total	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.2.2. Downstream to Upstream

A storm system moving from downstream to upstream was applied to the

Greenville drainage. Both distributed and lumped rainfall was simulated.

8.2.5.2.2.1. Distributed Rainfall

Distributed rainfall was applied over the Greenville basin as the storm system

moved from the downstream to upstream direction across the drainage. Initially, rain fell

in the lower reaches of the basin. At the 10 hour time period, the storm system had

moved across the basin so that rainfall was occurring over the entire drainage. As the storm system continued to move across the basin, rainfall ceased in the lower reaches and was only occurring in the upper reaches at the latter time periods. At 20 hours, the storm system had moved out of the basin. A total of 0.22 inch of distributed rainfall with a 10 hour time duration was applied to each part of the basin at some point within the 20 hour storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-25 shows the actual location rainfall was placed over the basin. Table 8-25 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

0 hour   1 hour   2 hour   3 hour   4 hour

5 hour   6 hour   7 hour   8 hour   9 hour

10 hour   11 hour   12 hour   13 hour   14 hour

15 hour   16 hour   17 hour   18 hour   19 hour

20 hour
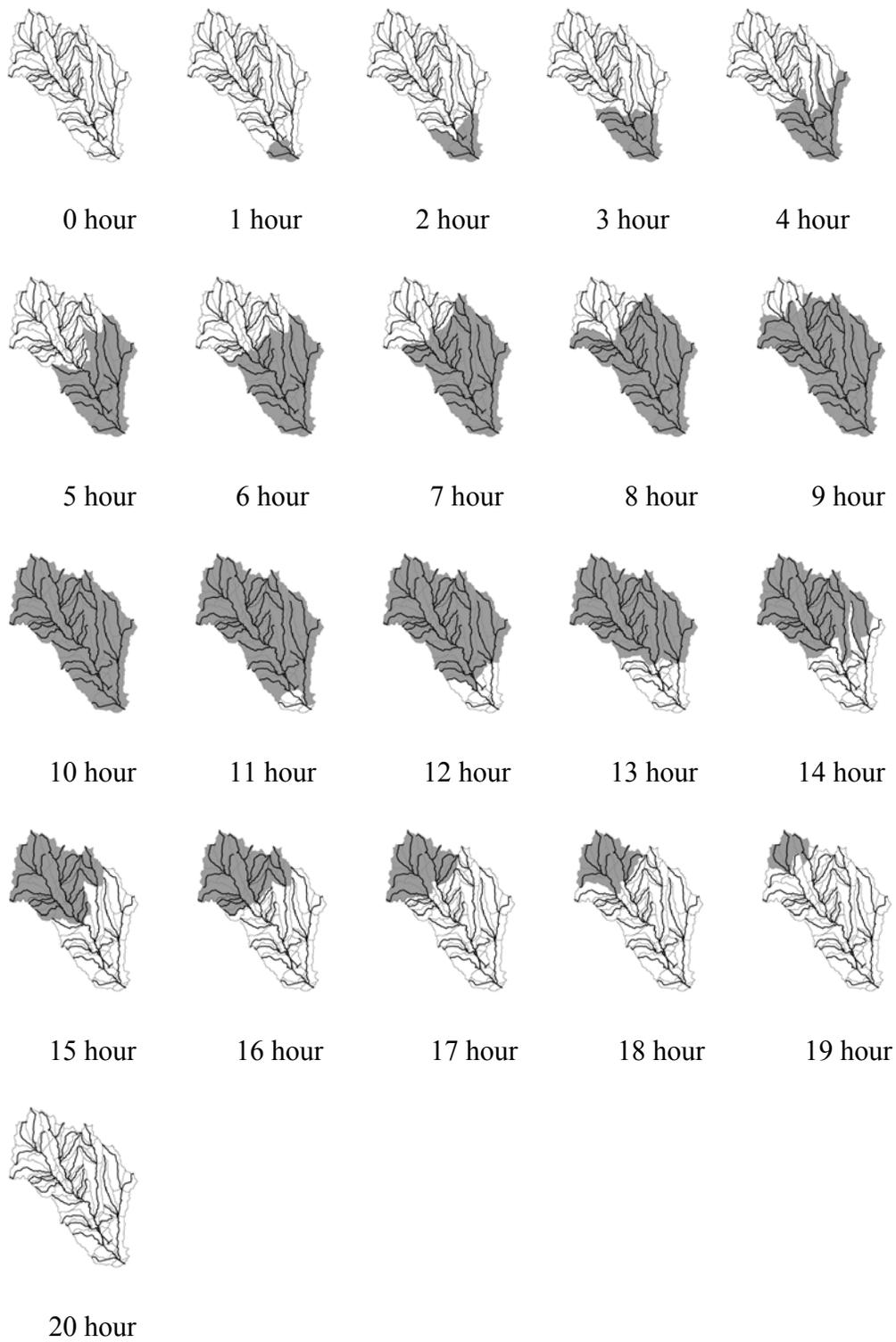
Figure 8-25. Moving Storm – Downstream to Upstream – Distributed Rainfall

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Table 8-25. Moving Storm – Downstream to Upstream – Distributed Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0.022
2	0	0	0	0	0	0	0	0	0.022	0.022
3	0	0	0	0	0	0	0	0.022	0.022	0.022
4	0	0	0	0	0	0	0.022	0.022	0.022	0.022
5	0	0	0	0	0	0.022	0.022	0.022	0.022	0.022
6	0	0	0	0	0.022	0.022	0.022	0.022	0.022	0.022
7	0	0	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022
8	0	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
9	0	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
10	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
11	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0
12	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0	0
13	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0	0	0
14	0.022	0.022	0.022	0.022	0.022	0.022	0	0	0	0
15	0.022	0.022	0.022	0.022	0.022	0	0	0	0	0
16	0.022	0.022	0.022	0.022	0	0	0	0	0	0
17	0.022	0.022	0.022	0	0	0	0	0	0	0
18	0.022	0.022	0	0	0	0	0	0	0	0
19	0.022	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
Table	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.2.5.2.2.2. Lumped Rainfall

Lumped rainfall was applied over the Greenville basin as the storm system moved from downstream to upstream across the drainage. For the lumped rainfall event, mean areal precipitation was computed and applied as uniform lumped precipitation over the entire drainage at each 1 hour ordinate during the entire storm event. The entire storm event produced a total volume of rainfall for the entire basin of 0.22 inch. The hydrologic response of this rainfall was computed at the basin outlet. Figure 8-26 shows the actual location rainfall was placed over the basin. Table 8-26 shows the actual amount of rainfall which was applied to each region of the basin at each time increment.

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0 hour 1 hour 2 hour 3 hour 4 hour

5 hour 6 hour 7 hour 8 hour 9 hour

10 hour 11 hour 12 hour 13 hour 14 hour

15 hour 16 hour 17 hour 18 hour 19 hour

20 hour
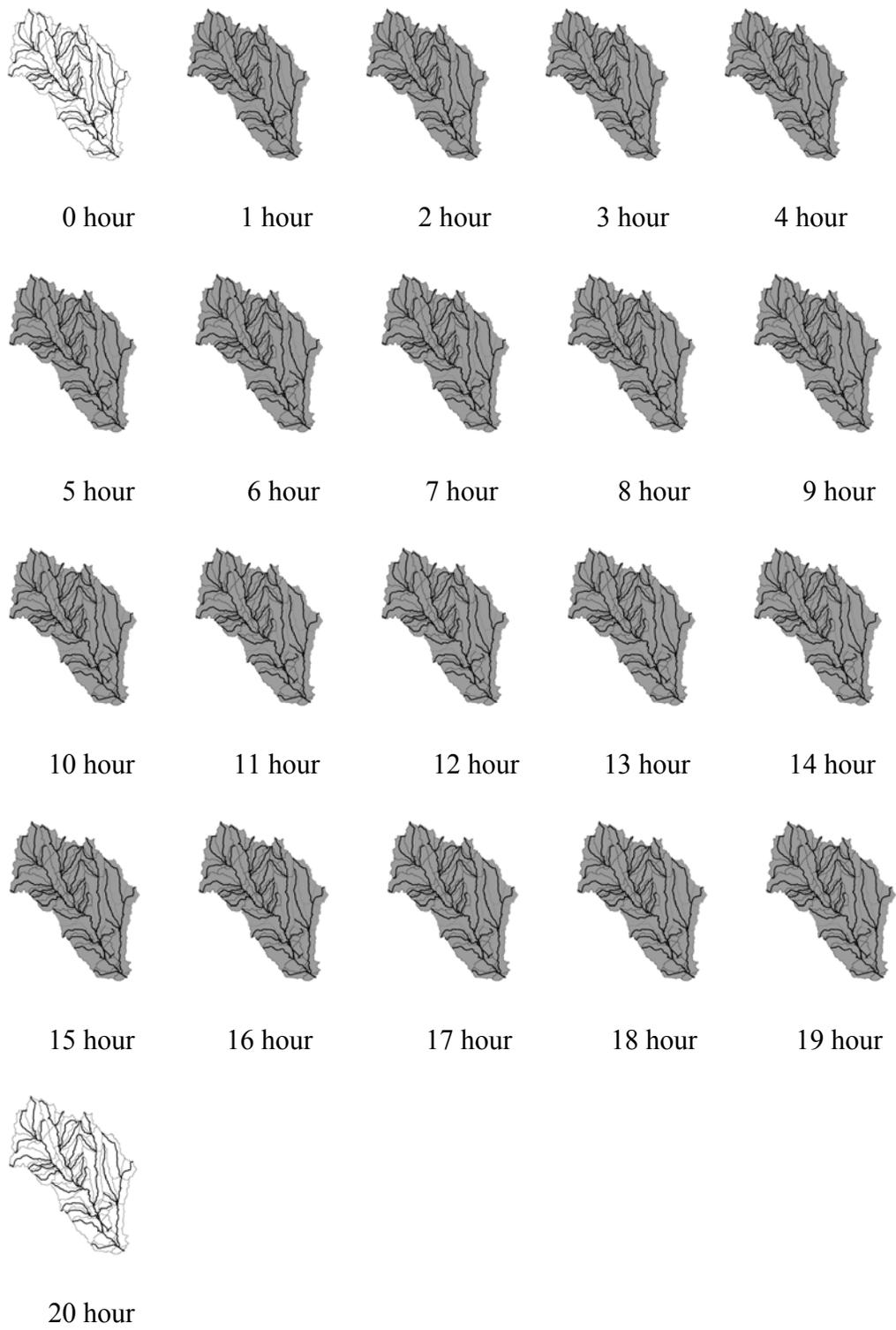
Figure 8-26. Moving Storm – Downstream to Upstream – Lumped Rainfall

Table 8-26. Moving Storm – Downstream to Upstream – Lumped Rainfall

Time (hr)	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8	Area 9	Area 10
0	0	0	0	0	0	0	0	0	0	0
1	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022
2	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044
3	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066
4	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088
5	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110
6	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132
7	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154
8	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176
9	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198
10	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220	.0220
11	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198	.0198
12	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176	.0176
13	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154	.0154
14	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132	.0132
15	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110	.0110
16	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088	.0088
17	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066	.0066
18	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044	.0044
19	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022	.0022
20	0	0	0	0	0	0	0	0	0	0
Total	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Precipitation is in inches
Mean Areal Basin Precipitation = 0.22 inches

8.3. Summary

This chapter described the methodology which was used in this investigation. The U.S. Geological Survey Modular Modeling System (MMS) was used as a research tool.

The first phase of the project was to simulate runoff response resulting from storm events applied to synthetic rectangular drainage basins. The second phase was to apply

the same general storm scenarios over an actual river basin. For both phases, rainfall was

applied to each basin as both distributed and lumped rainfall in conjunction with

stationary and moving storm events. Hydrologic basin simulations were then compared

between the distributed versus lumped cases.

The next chapter discusses the results of the hydrologic simulations which

occurred for each drainage basin for both the distributed versus lumped rainfall events.

CHAPTER 9

RESULTS

Hydrologic simulations were generated using the kinematic wave technique for both synthetic rectangular drainage basins and an actual drainage basin located in North Texas. Precipitation was applied as both distributed versus lumped rainfall to stationary and moving storm scenarios.

Hydrologic processes which govern basin response are highly complex. Because of this, impervious basins were used to simplify the problem for this investigation. This allowed for a better understanding as to how the actual location of and movement of rainfall across a basin for both stationary and moving storm events impacted the hydrologic response of the basin for both distributed and lumped models.

This chapter deals with the results obtained from this investigation. The first section discusses the results obtained using the synthetic rectangular drainage basins. The second section discusses the results which were obtained using an actual drainage basin. The third section summarizes the chapter. It should be noted that three different overland flow plane slopes were used to simulate the hydrologic response for the synthetic basins. Watershed parameters for the actual drainage basin were derived using geographic information systems.

9.1. Synthetic Rectangular Drainage Basins

Hydrologic simulations were generated for synthetic rectangular drainage basins using three different overland flow plane slopes (i.e. 16.22%, 9.12%, and 4.05%). These slopes were computed from the kinematic wave equation alpha parameters (i.e. 4, 3, and 2) for overland flow.

Both distributed and lumped rainfall scenarios in conjunction with stationary and moving storm events across the watershed plane were applied to each test case. Dimensionless graphical plots (q/qp versus t/tp) were developed comparing these overland flow plane slopes in conjunction with shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. Although the actual hydrograph shape varies between shape factor and basin configuration, the same general pattern applies to every case. As the overland flow plane slope becomes steeper, the actual plot becomes more acute with a narrower time base. As the slope becomes flatter, the resulting plot becomes more attenuated with a wider time base. These plots are presented in Appendix 1a – 40a.

9.1.1. Overland Flow Plane (Slope = 16.22%)

Hydrologic simulations were generated for the rectangular basins with 16.22% overland flow plane slopes using the kinematic wave routing technique. Both distributed and lumped rainfall scenarios were applied to each test case scenario, in conjunction with stationary and moving storm events across the watershed plane.

<u>9.1.1.1. Stationary Storms</u>

Four stationary rainfall events were investigated as part of this study. Three of these events involved applying distributed rainfall over the upper 20%, middle 20%, and lower 20% of the rectangular drainage basin. The fourth event involved applying lumped rainfall uniformly over the entire basin.

<u>9.1.1.1.1. Distributed Rainfall</u>

Distributed rainfall was applied over the upper 20%, middle 20%, and lower 20% of each rectangular basin. Results from this study show that for each stationary rainfall event, the simulated peak discharge is approximately the same for each individual basin configuration and shape factor. However, travel times vary due to the distance the storm system is located from the basin outlet. If the storm system is located in the upper 20% of the basin, the travel time to the basin outlet is greater when compared to the case where rainfall is located in the lower 20% of the basin where the travel time is shorter. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are presented for each shape factor and basin case scenario in Tables 9-1, 9-2, and 9-3.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. Although there is some difference, in most cases, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are illustrated in Appendix 1b – 3b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 1c – 3c.

9.1.1.1.2. Lumped Rainfall

Lumped rainfall was uniformly applied over the entire rectangular drainage basin. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-1, 9-2, and 9-3.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. As the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 4b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs

for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 4c.

9.1.1.1.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between the three distributed (upper, middle, and lower) versus the lumped rainfall scenarios for stationary storm systems. The ratios comparing peak discharges, time to peak flow, and the time widths at the 50% and 75% peak flow interval are discussed below. A general description of the dimensionless hydrographs comparing distributed versus lumped rainfall is also provided.

Peak discharge ratios (distributed versus lumped) generally ranged from 1.8 to 3.0, with the majority of the cases being 2.6-2.9. The few values which were small were associated with the very small drainage basins. This shows that simulated peak discharge magnitudes at the basin outlet are much greater for distributed rainfall events than for lumped rainfall events. Peak discharge ratios for each basin scenario are listed in Tables 9-1, 9-2, and 9-3.

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Time to peak flow ratios (distributed versus lumped) generally ranged from 0.4 to 0.8. This indicates that the travel time for the peak flow to reach the basin outlet is shorter for the distributed cases than for the lumped case. The time to peak flow ratios for each basin scenario are listed in Tables 9-1, 9-2, and 9-3.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow intervals generally ranged from 0.3 to 0.4. This shows that the width of the time base of the hydrograph is narrower for the distributed cases than for the lumped cases. Although there are a few cases with higher ratios, these values were associated with the very small rectangular basins with faster hydrologic response times. It is suspected that for these basins, the 1 minute time increment used for these simulations may be inadequate and may need to be refined to smaller 1 second time increments to better capitalize on the hydrologic response of these small basins. Time width ratios for each basin scenario are listed in Tables 9-1, 9-2, and 9-3.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs resulting from distributed and lumped rainfall scenarios for each basin configuration for each shape factor (i.e. 1-5). The overall shapes of the three distributed cases are similar. However, the rising limb began sooner for rainfall applied over the lower 20% than when rainfall was applied over the upper 20%. The falling limbs of the three hydrographs are very similar. For the lumped case, the rising limbs typically began at approximately the same time as the distributed lower 20% case. The falling limb of the lumped case occurred much later in time than the three distributed cases. Finally, the

dimensionless hydrographs for the three distributed cases are more acute with a narrower

time base when compared with the lumped case which is more attenuated with a wider

time base. These plots are presented in Appendix 1d – 5d.

Table 9-1. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Stationary Storm – Constant Area (Case 1)

Factor	Length	Width	Area	Rainfall Shape Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	50.12	13	2.922	0.684	37.59	10	2.922	0.333	25.06	15	2.922	0.326
2	2828	1414	91.83	upper 20%	68.13	13	2.834	0.684	51.10	6	2.834	0.300	34.07	10	2.834	0.313
3	3464	1155	91.83	upper 20%	78.66	14	2.726	0.700	59.00	4	2.726	0.267	39.33	9	2.726	0.346
4	4000	1000	91.83	upper 20%	86.71	14	2.680	0.700	65.03	4	2.680	0.333	43.36	8	2.680	0.348
5	4472	894	91.83	upper 20%	92.27	14	2.661	0.700	69.20	4	2.661	0.364	46.14	8	2.661	0.381
Distributed																
1	2000	2000	91.83	middle 20%	50.12	12	2.922	0.632	37.59	10	2.922	0.333	25.06	16	2.922	0.348
2	2828	1414	91.83	middle 20%	68.61	12	2.854	0.632	51.46	7	2.854	0.350	34.31	12	2.854	0.375
3	3464	1155	91.83	middle 20%	79.97	12	2.771	0.600	59.98	6	2.771	0.400	39.99	10	2.771	0.385
4	4000	1000	91.83	middle 20%	87.37	12	2.701	0.600	65.53	5	2.701	0.417	43.69	8	2.701	0.348
5	4472	894	91.83	middle 20%	92.32	12	2.663	0.600	69.24	5	2.663	0.455	46.16	8	2.663	0.381
Distributed																
1	2000	2000	91.83	lower 20%	50.10	11	2.921	0.579	37.58	9	2.921	0.300	25.05	16	2.921	0.348
2	2828	1414	91.83	lower 20%	68.33	11	2.842	0.579	51.25	6	2.842	0.300	34.17	12	2.842	0.375
3	3464	1155	91.83	lower 20%	79.16	11	2.743	0.550	59.37	5	2.743	0.333	39.58	10	2.743	0.385
4	4000	1000	91.83	lower 20%	85.92	11	2.656	0.550	64.44	5	2.656	0.417	42.96	9	2.656	0.391
5	4472	894	91.83	lower 20%	91.13	10	2.628	0.500	68.35	5	2.628	0.455	45.57	9	2.628	0.429
Lumped																
1	2000	2000	91.83	entire basin	17.15	19			12.86	30			8.58	46		
2	2828	1414	91.83	entire basin	24.04	19			18.03	20			12.02	32		
3	3464	1155	91.83	entire basin	28.86	20			21.65	15			14.43	26		
4	4000	1000	91.83	entire basin	32.35	20			24.26	12			16.18	23		
5	4472	894	91.83	entire basin	34.67	20			26.00	11			17.34	21		

Note: d = distributed, l = lumped

Table 9-2. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Stationary Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	50.12	13	2.922	0.684	37.59	10	2.923	0.333	25.06	15	2.921	0.326
2	4000	2000	183.65	upper 20%	99.91	14	2.920	0.636	74.93	9	2.919	0.310	49.96	15	2.920	0.326
3	6000	2000	275.48	upper 20%	149.75	15	2.928	0.625	112.31	8	2.928	0.296	74.88	15	2.927	0.333
4	8000	2000	367.31	upper 20%	196.91	17	2.899	0.654	147.68	8	2.899	0.308	98.46	14	2.899	0.311
5	10000	2000	459.14	upper 20%	247.12	17	2.927	0.607	185.34	7	2.927	0.280	123.56	14	2.927	0.311
Distributed																
1	2000	2000	91.83	middle 20%	50.12	12	2.922	0.632	37.59	10	2.923	0.333	25.06	16	2.921	0.348
2	4000	2000	183.65	middle 20%	99.86	13	2.918	0.591	74.90	9	2.918	0.310	49.93	16	2.918	0.348
3	6000	2000	275.48	middle 20%	149.62	13	2.925	0.542	112.22	10	2.925	0.370	74.81	15	2.925	0.333
4	8000	2000	367.31	middle 20%	199.27	14	2.934	0.538	149.45	9	2.934	0.346	99.64	15	2.934	0.333
5	10000	2000	459.14	middle 20%	248.92	14	2.949	0.500	186.69	10	2.948	0.400	124.46	15	2.949	0.333
Distributed																
1	2000	2000	91.83	lower 20%	50.10	11	2.921	0.579	37.58	9	2.922	0.300	25.05	16	2.920	0.348
2	4000	2000	183.65	lower 20%	100.04	11	2.923	0.500	75.03	9	2.923	0.310	50.02	16	2.923	0.348
3	6000	2000	275.48	lower 20%	149.23	11	2.917	0.458	111.92	10	2.918	0.370	74.62	17	2.917	0.378
4	8000	2000	367.31	lower 20%	199.07	12	2.931	0.462	149.30	10	2.931	0.385	99.54	17	2.931	0.378
5	10000	2000	459.14	lower 20%	248.91	12	2.948	0.429	186.68	10	2.948	0.400	124.46	16	2.949	0.356
Lumped																
1	2000	2000	91.83	entire basin	17.15	19			12.86	30			8.58	46		
2	4000	2000	183.65	entire basin	34.22	22			25.67	29			17.11	46		
3	6000	2000	275.48	entire basin	51.15	24			38.36	27			25.58	45		
4	8000	2000	367.31	entire basin	67.92	26			50.94	26			33.96	45		
5	10000	2000	459.14	entire basin	84.42	28			63.32	25			42.21	45		

Note: d = distributed, l = lumped

Table 9-3. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Stationary Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	50.12	13	2.922	0.684	37.59	10	2.923	0.333	25.06	15	2.921	0.326
2	2000	1000	45.91	upper 20%	43.46	13	2.596	0.765	32.60	5	2.596	0.385	21.73	8	2.596	0.348
3	2000	667	30.62	upper 20%	34.13	13	2.191	0.813	25.60	4	2.190	0.500	17.07	7	2.191	0.438
4	2000	500	22.96	upper 20%	27.09	13	1.942	0.867	20.32	4	1.943	0.667	13.55	6	1.941	0.462
5	2000	400	18.37	upper 20%	22.45	12	1.818	0.800	16.84	4	1.819	0.800	11.23	6	1.817	0.545
Distributed																
1	2000	2000	91.83	middle 20%	50.12	12	2.922	0.632	37.59	10	2.923	0.333	25.06	16	2.921	0.348
2	2000	1000	45.91	middle 20%	43.05	12	2.572	0.706	32.29	5	2.571	0.385	21.53	10	2.572	0.435
3	2000	667	30.62	middle 20%	34.30	11	2.202	0.688	25.73	5	2.201	0.625	17.15	8	2.202	0.500
4	2000	500	22.96	middle 20%	27.10	11	1.943	0.733	20.33	4	1.944	0.667	13.55	7	1.941	0.538
5	2000	400	18.37	middle 20%	22.03	11	1.784	0.733	16.52	5	1.784	1.000	11.02	7	1.783	0.636
Distributed																
1	2000	2000	91.83	lower 20%	50.10	11	2.921	0.579	37.58	9	2.922	0.300	25.05	16	2.920	0.348
2	2000	1000	45.91	lower 20%	43.59	10	2.604	0.588	32.69	5	2.603	0.385	21.80	9	2.605	0.391
3	2000	667	30.62	lower 20%	34.78	10	2.232	0.625	26.09	5	2.232	0.625	17.39	8	2.232	0.500
4	2000	500	22.96	lower 20%	27.31	10	1.958	0.667	20.48	5	1.958	0.833	13.66	9	1.957	0.692
5	2000	400	18.37	lower 20%	22.11	10	1.790	0.667	16.58	6	1.790	1.200	11.06	8	1.790	0.727
Lumped																
1	2000	2000	91.83	entire basin	17.15	19			12.86	30			8.58	46		
2	2000	1000	45.91	entire basin	16.74	17			12.56	13			8.37	23		
3	2000	667	30.62	entire basin	15.58	16			11.69	8			7.79	16		
4	2000	500	22.96	entire basin	13.95	15			10.46	6			6.98	13		
5	2000	400	18.37	entire basin	12.35	15			9.26	5			6.18	11		

Note: d = distributed, l = lumped

Two moving storm systems both having constant uniform velocity and rainfall rates were applied to each rectangular basin scenario. These storm systems moved either upstream to downstream or downstream to upstream across the basin. For each storm system, both distributed and lumped rainfall was applied to each storm system, making a total of four scenarios for the application of rainfall to each rectangular basin.

9.1.1.2.1. Distributed Rainfall

Distributed rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. Results from this study show that as the storm system moves from upstream to downstream, the peak discharge is greater when compared to an identical storm system which moves downstream to upstream for each individual basin configuration and shape factor. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin scenario in Tables 9-4, 9-5, and 9-6.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm systems, as the shape factor increases, the actual plot becomes more acute with a narrower time base.   It should be noted that the rising limb has a very steep slope for the upstream to downstream cases compared to

the downstream to upstream cases where the slope is more gradual. These plots are presented in Appendix 5b and 7b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 5c and 7c.

9.1.1.2.2. Lumped Rainfall

Lumped rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. It should be noted that because of the symmetry of the rectangular basin in conjunction with both the uniform rate of movement and rainfall rate of the storm system, the lumped rainfall patterns for both the upstream to downstream and downstream to upstream storm systems are identical. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin scenario in Tables 9-4, 9-5, and 9-6.

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Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm systems, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are illustrated in Appendix 6b and 8b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 6c and 8c.

9.1.1.2.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between the distributed and lumped rainfall for moving storm systems. These systems moved either upstream to downstream or downstream to upstream across the drainage basin.

Peak discharge ratios (distributed versus lumped) are generally slightly greater than 1 for storm systems which moved upstream to downstream. However, peak

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discharge ratios are generally slightly less than 1 for storm system which moved downstream to upstream. This indicates that simulated peak discharge magnitudes at the basin outlet are similar for both the distributed and lumped rainfall events. Although there are a few cases where these ratios are somewhat higher (upstream to downstream) or lower (downstream to upstream), these values were associated with the very small rectangular basins with faster hydrologic response times. Peak discharge ratios for each basin scenario are listed in Tables 9-4, 9-5, and 9-6.

Time to peak flow ratios (distributed versus lumped) generally ranged from 0.8 to 0.9 for the upstream to downstream systems. This indicates that the travel time for peak flow to reach the basin outlet is shorter for the distributed cases than for the lumped case. However, time to peak flow ratios generally ranged from 1.0 to 1.2 for the downstream to upstream systems. This indicates that the travel time for peak flow to reach the basin outlet is longer for the distributed cases when compared to the lumped case. The time to peak flow ratios for each basin scenario are listed in Tables 9-4, 9-5, and 9-6.

Examination of time width ratios (distributed versus lumped) at the 50% and 75% peak flow intervals yielded mixed results. Values were typically very close to 1 indicating that the width of the hydrographs is very similar for both distributed and lumped rainfall. Time width ratios for each basin scenario are listed in Tables 9-4, 9-5, and 9-6.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs resulting from distributed and lumped rainfall scenarios for each basin configuration with each shape factor (i.e. 1-5). For the upstream to downstream storm system, both the rising and falling limbs of the distributed cases typically begins later than for the lumped cases. For the downstream to upstream storm system, both the rising and falling limbs of the distributed cases begins earlier than the lumped cases. These graphs are presented in Appendix 6d – 10d.

Table 9-4. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Moving Storm – Constant Area (Case 1)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	17.16	20	1.003	0.769	12.87	32	1.003	1.067	8.58	47	1.003	1.000
2	2828	1414	91.83	up to down	24.26	21	1.021	0.808	18.20	21	1.021	1.050	12.13	32	1.021	1.000
3	3464	1155	91.83	up to down	29.66	21	1.048	0.840	22.25	16	1.048	1.067	14.83	25	1.048	0.926
4	4000	1000	91.83	up to down	34.10	21	1.083	0.840	25.58	13	1.083	1.000	17.05	21	1.083	0.913
5	4472	894	91.83	up to down	37.86	22	1.124	0.846	28.40	11	1.124	0.917	18.93	19	1.124	0.864
Lumped																
1	2000	2000	91.83	up to down	17.11	26			12.83	30			8.56	47		
2	2828	1414	91.83	up to down	23.77	26			17.83	20			11.89	32		
3	3464	1155	91.83	up to down	28.29	25			21.22	15			14.15	27		
4	4000	1000	91.83	up to down	31.50	25			23.63	13			15.75	23		
5	4472	894	91.83	up to down	33.68	26			25.26	12			16.84	22		
Distributed																
1	2000	2000	91.83	down to up	16.99	27	0.993	1.038	12.74	28	0.993	0.933	8.50	47	0.993	1.022
2	2828	1414	91.83	down to up	22.85	27	0.961	1.038	17.14	19	0.961	0.950	11.43	34	0.961	1.063
3	3464	1155	91.83	down to up	26.10	28	0.923	1.120	19.58	16	0.923	1.067	13.05	30	0.923	1.111
4	4000	1000	91.83	down to up	27.75	29	0.881	1.160	20.81	15	0.881	1.154	13.88	28	0.881	1.217
5	4472	894	91.83	down to up	28.61	29	0.849	1.115	21.46	14	0.849	1.167	14.31	27	0.849	1.227
Lumped																
1	2000	2000	91.83	down to up	17.11	26			12.83	30			8.56	46		
2	2828	1414	91.83	down to up	23.77	26			17.83	20			11.89	32		
3	3464	1155	91.83	down to up	28.29	25			21.22	15			14.15	27		
4	4000	1000	91.83	down to up	31.50	25			23.63	13			15.75	23		
5	4472	894	91.83	down to up	33.68	26			25.26	12			16.84	22		

Note: d = distributed, l = lumped

Table 9-5. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Moving Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	17.16	20	1.003	0.769	12.87	32	1.003	1.067	8.58	47	1.002	1.000
2	4000	2000	183.65	up to down	34.32	23	1.007	0.793	25.74	30	1.007	1.034	17.16	46	1.007	1.000
3	6000	2000	275.48	up to down	51.46	26	1.012	0.867	38.60	29	1.012	1.074	25.73	46	1.011	1.000
4	8000	2000	367.31	up to down	68.56	27	1.016	0.844	51.42	28	1.016	1.077	34.28	45	1.016	1.000
5	10000	2000	459.14	up to down	85.61	29	1.021	0.853	64.21	27	1.021	1.038	42.81	44	1.021	0.978
Lumped																
1	2000	2000	91.83	up to down	17.11	26			12.83	30			8.56	47		
2	4000	2000	183.65	up to down	34.08	29			25.56	29			17.04	46		
3	6000	2000	275.48	up to down	50.87	30			38.15	27			25.44	46		
4	8000	2000	367.31	up to down	67.49	32			50.62	26			33.75	45		
5	10000	2000	459.14	up to down	83.82	34			62.87	26			41.91	45		
Distributed																
1	2000	2000	91.83	down to up	16.99	27	0.993	1.038	12.74	28	0.993	0.933	8.50	47	0.993	1.022
2	4000	2000	183.65	down to up	33.61	30	0.986	1.034	25.21	27	0.986	0.931	16.81	47	0.987	1.022
3	6000	2000	275.48	down to up	49.81	32	0.979	1.067	37.36	26	0.979	0.963	24.91	47	0.979	1.044
4	8000	2000	367.31	down to up	65.60	35	0.972	1.094	49.20	26	0.972	1.000	32.80	47	0.972	1.044
5	10000	2000	459.14	down to up	80.87	36	0.965	1.059	60.65	25	0.965	0.962	40.44	47	0.965	1.044
Lumped																
1	2000	2000	91.83	down to up	17.11	26			12.83	30			8.56	46		
2	4000	2000	183.65	down to up	34.08	29			25.56	29			17.04	46		
3	6000	2000	275.48	down to up	50.87	30			38.15	27			25.44	45		
4	8000	2000	367.31	down to up	67.49	32			50.62	26			33.75	45		
5	10000	2000	459.14	down to up	83.82	34			62.87	26			41.91	45		

Note: d = distributed, l = lumped

Table 9-6. Distributed versus Lumped Summary Table; OFP Slope = 16.22%; Moving Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	17.16	20	1.003	0.769	12.87	32	1.003	1.067	8.58	47	1.002	1.000
2	2000	1000	45.91	up to down	17.09	20	1.048	0.870	12.82	15	1.048	1.071	8.55	22	1.048	0.917
3	2000	667	30.62	up to down	16.77	19	1.139	0.905	12.58	9	1.139	1.000	8.39	14	1.140	0.824
4	2000	500	22.96	up to down	15.92	18	1.226	0.857	11.94	6	1.226	0.750	7.96	11	1.225	0.786
5	2000	400	18.37	up to down	15.08	18	1.322	0.900	11.31	5	1.321	0.714	7.54	9	1.320	0.692
Lumped																
1	2000	2000	91.83	up to down	17.11	26			12.83	30			8.56	47		
2	2000	1000	45.91	up to down	16.31	23			12.23	14			8.16	24		
3	2000	667	30.62	up to down	14.72	21			11.04	9			7.36	17		
4	2000	500	22.96	up to down	12.99	21			9.74	8			6.50	14		
5	2000	400	18.37	up to down	11.41	20			8.56	7			5.71	13		
Distributed																
1	2000	2000	91.83	down to up	16.99	27	0.993	1.038	12.74	28	0.993	0.933	8.50	47	0.993	1.022
2	2000	1000	45.91	down to up	14.96	25	0.917	1.087	11.22	14	0.917	1.000	7.48	26	0.917	1.083
3	2000	667	30.62	down to up	12.16	24	0.826	1.143	9.12	12	0.826	1.333	6.08	22	0.826	1.294
4	2000	500	22.96	down to up	9.81	24	0.755	1.143	7.36	12	0.756	1.500	4.91	21	0.755	1.500
5	2000	400	18.37	down to up	7.99	25	0.700	1.250	5.99	12	0.700	1.714	4.00	21	0.701	1.615
Lumped																
1	2000	2000	91.83	down to up	17.11	26			12.83	30			8.56	46		
2	2000	1000	45.91	down to up	16.31	23			12.23	14			8.16	24		
3	2000	667	30.62	down to up	14.72	21			11.04	9			7.36	17		
4	2000	500	22.96	down to up	12.99	21			9.74	8			6.50	14		
5	2000	400	18.37	down to up	11.41	20			8.56	7			5.71	13		

Note: d = distributed, l = lumped

9.1.2. Overland Flow Plane (Slope = 9.12%)

Hydrologic simulations were generated for the rectangular basins with 9.12% overland flow plane slopes using the kinematic wave routing technique. Both distributed and lumped rainfall patterns were applied to each test scenario in conjunction with stationary and moving storm events across the watershed plane.

9.1.2.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved applying distributed rainfall over the upper 20%, middle 20%, and lower 20% of the rectangular drainage basin. The fourth event involved applying lumped rainfall uniformly over the entire basin.

9.1.2.1.1. Distributed Rainfall

Distributed rainfall was applied over the upper 20%, middle 20%, and lower 20% of each rectangular basin. Results from this study show that for each stationary rainfall event, the simulated peak discharge is approximately the same for each individual basin configuration and shape factor. However, travel times vary due to the distance the storm system is located from the basin outlet. If the storm system is located in the upper 20% of the basin, the travel time to the basin outlet is greater when compared to the case where rainfall is located in the lower 20% of the basin where the travel time is shorter. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-7, 9-8, and 9-9.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. Although there is some difference, in most cases, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 9b – 11b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 9c – 11c.

9.1.2.1.2. Lumped Rainfall

Lumped rainfall was uniformly applied over the entire rectangular drainage basin. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-7, 9-8, and 9-9.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 with each other for each rectangular basin configuration. As the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 12b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for shape factor equal to 1 is shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for each case scenario for shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 12c.

9.1.2.1.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between the three distributed (upper, middle, and lower) versus the lumped rainfall for stationary storm systems. The ratios comparing peak discharges, time to peak flow, and the time widths at the 50% and 75% peak flow interval are discussed below. A general description of the dimensionless hydrographs comparing distributed versus lumped rainfall is also provided.

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Peak discharge ratios (distributed versus lumped) generally ranged from 2.1 to 3.0, with the majority of the cases being 2.8-2.9. The few values which were small were associated with the very small drainage basins. This shows that simulated peak discharge magnitudes at the basin outlet are much greater for distributed rainfall events than for lumped rainfall events. Peak discharge ratios for each basin scenario are listed in Tables 9-7, 9-8, and 9-9.

Time to peak flow ratios (distributed versus lumped) generally ranged from 0.4 to 0.8. This indicates that the travel time for the peak flow to reach the basin outlet is shorter for the distributed cases than for the lumped cases. The time to peak flow ratios for each basin scenario are listed in Tables 9-7, 9-8, and 9-9.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow intervals generally ranged from 0.3 to 0.4. This shows that the width of the time base of the hydrograph is narrower for the distributed cases than for the lumped cases. Although there are a few cases with higher ratios, these values were associated with the very small rectangular basins with faster hydrologic response times. It is suspected that for these basins, the 1 minute time increment used for these simulations may be inadequate and may need to be refined to a smaller 1 second time increment to better capture the hydrologic response of these small basins. Time width ratios for each basin scenario are listed in Tables 9-7, 9-8, and 9-9.

Dimensionless plots (q/q_p versus t/t_p) were also developed comparing hydrographs resulting from distributed and lumped rainfall scenarios for each basin configuration for each shape factor (i.e. 1-5). The overall shapes of the three distributed cases are similar. However, the rising limb began sooner for rainfall applied over the lower 20% than for rainfall applied over the upper 20%. The falling limbs of the three hydrographs are very similar. For the lumped case, the rising limbs typically began at approximately the same time as the distributed lower 20% case. The falling limb of the lumped case occurred much later in time than the three distributed cases. Finally, the dimensionless hydrographs for the three distributed cases are more acute with a narrower time base when compared with the lumped case which is more attenuated with a wider time base. These plots are presented in Appendix 11d – 15d.

Table 9-7. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Stationary Storm – Constant Area (Case 1)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	37.77	14	2.935	0.667	28.33	13	2.935	0.317	18.89	20	2.935	0.323
2	2828	1414	91.83	upper 20%	52.89	14	2.917	0.636	39.67	8	2.917	0.308	26.45	14	2.917	0.326
3	3464	1155	91.83	upper 20%	63.19	14	2.874	0.636	47.39	7	2.874	0.350	31.60	12	2.874	0.343
4	4000	1000	91.83	upper 20%	70.46	15	2.827	0.682	52.85	5	2.827	0.294	35.23	10	2.827	0.333
5	4472	894	91.83	upper 20%	76.79	15	2.825	0.652	57.59	5	2.825	0.333	38.40	9	2.825	0.333
Distributed																
1	2000	2000	91.83	middle 20%	37.75	13	2.933	0.619	28.31	14	2.933	0.341	18.88	22	2.933	0.355
2	2828	1414	91.83	middle 20%	52.71	13	2.907	0.591	39.53	9	2.907	0.346	26.36	15	2.907	0.349
3	3464	1155	91.83	middle 20%	63.20	13	2.874	0.591	47.40	7	2.874	0.350	31.60	12	2.874	0.343
4	4000	1000	91.83	middle 20%	71.06	13	2.852	0.591	53.30	6	2.852	0.353	35.53	11	2.852	0.367
5	4472	894	91.83	middle 20%	77.15	13	2.838	0.565	57.86	6	2.838	0.400	38.58	9	2.838	0.333
Distributed																
1	2000	2000	91.83	lower 20%	37.79	11	2.936	0.524	28.34	13	2.936	0.317	18.90	22	2.936	0.355
2	2828	1414	91.83	lower 20%	52.94	11	2.920	0.500	39.71	8	2.920	0.308	26.47	16	2.920	0.372
3	3464	1155	91.83	lower 20%	63.59	11	2.892	0.500	47.69	7	2.892	0.350	31.80	13	2.892	0.371
4	4000	1000	91.83	lower 20%	71.50	11	2.869	0.500	53.63	6	2.869	0.353	35.75	12	2.869	0.400
5	4472	894	91.83	lower 20%	77.49	11	2.851	0.478	58.12	5	2.851	0.333	38.75	11	2.851	0.407
Lumped																
1	2000	2000	91.83	entire basin	12.87	21			9.65	41			6.44	62		
2	2828	1414	91.83	entire basin	18.13	22			13.60	26			9.07	43		
3	3464	1155	91.83	entire basin	21.99	22			16.49	20			11.00	35		
4	4000	1000	91.83	entire basin	24.92	22			18.69	17			12.46	30		
5	4472	894	91.83	entire basin	27.18	23			20.39	15			13.59	27		

Note: d = distributed, l = lumped

Table 9-8. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Stationary Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	37.77	14	2.935	0.667	28.33	13	2.936	0.317	18.89	20	2.933	0.323
2	4000	2000	183.65	upper 20%	75.50	15	2.937	0.600	56.63	13	2.937	0.333	37.75	20	2.935	0.328
3	6000	2000	275.48	upper 20%	113.18	16	2.939	0.593	84.89	12	2.939	0.324	56.59	20	2.938	0.328
4	8000	2000	367.31	upper 20%	151.49	17	2.956	0.567	113.62	11	2.957	0.306	75.75	20	2.957	0.333
5	10000	2000	459.14	upper 20%	187.66	19	2.939	0.594	140.75	11	2.938	0.314	93.83	20	2.939	0.333
Distributed																
1	2000	2000	91.83	middle 20%	37.75	13	2.933	0.619	28.31	14	2.934	0.341	18.88	22	2.932	0.355
2	4000	2000	183.65	middle 20%	75.43	13	2.934	0.520	56.57	13	2.934	0.333	37.72	21	2.933	0.344
3	6000	2000	275.48	middle 20%	113.23	14	2.940	0.519	84.92	13	2.940	0.351	56.62	20	2.940	0.328
4	8000	2000	367.31	middle 20%	150.79	15	2.943	0.500	113.09	13	2.943	0.361	75.40	20	2.943	0.333
5	10000	2000	459.14	middle 20%	188.51	15	2.952	0.469	141.38	13	2.952	0.371	94.26	20	2.952	0.333
Distributed																
1	2000	2000	91.83	lower 20%	37.79	11	2.936	0.524	28.34	13	2.937	0.317	18.90	22	2.935	0.355
2	4000	2000	183.65	lower 20%	75.49	12	2.936	0.480	56.62	13	2.937	0.333	37.75	22	2.935	0.361
3	6000	2000	275.48	lower 20%	113.24	12	2.941	0.444	84.93	14	2.941	0.378	56.62	21	2.940	0.344
4	8000	2000	367.31	lower 20%	150.92	12	2.945	0.400	113.19	14	2.945	0.389	75.46	21	2.945	0.350
5	10000	2000	459.14	lower 20%	188.32	12	2.949	0.375	141.24	14	2.949	0.400	94.16	22	2.949	0.367
Lumped																
1	2000	2000	91.83	entire basin	12.87	21			9.65	41			6.44	62		
2	4000	2000	183.65	entire basin	25.71	25			19.28	39			12.86	61		
3	6000	2000	275.48	entire basin	38.51	27			28.88	37			19.26	61		
4	8000	2000	367.31	entire basin	51.24	30			38.43	36			25.62	60		
5	10000	2000	459.14	entire basin	63.86	32			47.90	35			31.93	60		

Note: d = distributed, l = lumped

Table 9-9. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Stationary Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	37.77	14	2.935	0.667	28.33	13	2.936	0.317	18.89	20	2.933	0.323
2	2000	1000	45.91	upper 20%	35.93	13	2.822	0.684	26.95	6	2.822	0.333	17.97	10	2.821	0.333
3	2000	667	30.62	upper 20%	31.23	13	2.560	0.722	23.42	4	2.560	0.364	15.62	7	2.561	0.333
4	2000	500	22.96	upper 20%	25.60	13	2.250	0.765	19.20	4	2.248	0.500	12.80	6	2.250	0.375
5	2000	400	18.37	upper 20%	21.18	13	2.060	0.765	15.89	4	2.061	0.571	10.59	6	2.060	0.429
Distributed																
1	2000	2000	91.83	middle 20%	37.75	13	2.933	0.619	28.31	14	2.934	0.341	18.88	22	2.932	0.355
2	2000	1000	45.91	middle 20%	35.99	12	2.827	0.632	26.99	6	2.826	0.333	18.00	11	2.826	0.367
3	2000	667	30.62	middle 20%	30.85	12	2.529	0.667	23.14	4	2.529	0.364	15.43	8	2.530	0.381
4	2000	500	22.96	middle 20%	25.44	12	2.236	0.706	19.08	5	2.234	0.625	12.72	7	2.236	0.438
5	2000	400	18.37	middle 20%	21.29	11	2.071	0.647	15.97	5	2.071	0.714	10.65	7	2.072	0.500
Distributed																
1	2000	2000	91.83	lower 20%	37.79	11	2.936	0.524	28.34	13	2.937	0.317	18.90	22	2.935	0.355
2	2000	1000	45.91	lower 20%	35.76	11	2.809	0.579	26.82	6	2.808	0.333	17.88	11	2.807	0.367
3	2000	667	30.62	lower 20%	30.95	10	2.537	0.556	23.21	5	2.537	0.455	15.48	9	2.538	0.429
4	2000	500	22.96	lower 20%	26.00	10	2.285	0.588	19.50	5	2.283	0.625	13.00	8	2.285	0.500
5	2000	400	18.37	lower 20%	21.67	10	2.108	0.588	16.25	5	2.108	0.714	10.84	8	2.109	0.571
Lumped																
1	2000	2000	91.83	entire basin	12.87	21			9.65	41			6.44	62		
2	2000	1000	45.91	entire basin	12.73	19			9.55	18			6.37	30		
3	2000	667	30.62	entire basin	12.20	18			9.15	11			6.10	21		
4	2000	500	22.96	entire basin	11.38	17			8.54	8			5.69	16		
5	2000	400	18.37	entire basin	10.28	17			7.71	7			5.14	14		

Note: d = distributed, l = lumped

Two moving storm systems both having constant a uniform velocity and rainfall rate were applied to each rectangular basin scenario. These storm systems moved either upstream to downstream or downstream to upstream across the basin. For each storm system, both distributed and lumped rainfall was applied to each storm case, making a total of four scenarios for the application of rainfall to each rectangular basin.

9.1.2.2.1. Distributed Rainfall

Distributed rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. Results from this study show that as the storm system moves from upstream to downstream, the peak discharge is greater when compared to an identical storm system which is moving from downstream to upstream for each individual basin configuration and shape factor. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% peak flow are listed for each shape factor and basin scenario in Tables 9-10, 9-11 and 9-12.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm movement, as the shape factor increases, the actual plot becomes more acute with a narrower time base. It should be noted that the rising limb has a very steep slope for the upstream to downstream cases compared to

the downstream to upstream cases where the slope is more gradual. These plots are presented in Appendix 13b and 15b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 13c and 15c.

9.1.2.2.2. Lumped Rainfall

Lumped rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. It should be noted that because of the symmetry of the rectangular basin in conjunction with both the uniform rate of movement and rainfall rate of the storm system, the lumped rainfall patterns for both the upstream to downstream and downstream to upstream storm systems are identical. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-10, 9-11, and 9-12.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm movement, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 14b and 16b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 14c and 16c.

9.1.2.2.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between distributed and lumped rainfall for moving storm systems. These systems moved either upstream to downstream or downstream to upstream across the drainage basin.

Peak discharge ratios (distributed versus lumped) are generally slightly greater than 1 for storm systems which moved upstream to downstream. However, peak

discharge ratios are generally slightly less than 1 for storm system which moved downstream to upstream. This indicates that simulated peak discharge magnitudes at the basin outlet are similar for both the distributed and lumped rainfall events. Although there are a few cases where these ratios are somewhat higher (upstream to downstream) or lower (downstream to upstream), these values were associated with the very small rectangular basins with faster hydrologic response times. Peak discharge ratios for each basin scenario are listed in Tables 9-10, 9-11, and 9-12.

Time to peak flow ratios (distributed versus lumped) generally ranged from 0.8 to 0.9 for the upstream to downstream systems. This indicates that the travel time for peak flow to reach the basin outlet is shorter for the distributed cases than for the lumped cases. However, time to peak flow ratios generally ranged from 1.0 to 1.2 for the downstream to upstream systems. This indicates that the travel time for peak flow to reach the basin outlet is longer for the distributed cases than for the lumped cases. The time to peak flow ratios for each basin scenario are listed in Tables 9-10, 9-11, and 9-12.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow intervals were generally mixed results. These values were typically very close to 1 indicating that the width of the hydrographs are very similar for both distributed and lumped rainfall. Time width ratios for each basin scenario are listed in Tables 9-10, 9-11, and 9-12.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs resulting from distributed and lumped rainfall scenarios for each basin configuration with each shape factor (i.e. 1-5). For the upstream to downstream storm system, both the rising and falling limbs for the distributed cases typically begin later than for the lumped cases. For the downstream to upstream storm system, both the rising and falling limbs for the distributed cases begin earlier than the lumped cases. These graphs are presented in Appendix 16d – 20d.

Table 9-10. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Moving Storm – Constant Area (Case 1)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	12.87	22	1.001	0.786	9.65	43	1.001	1.024	6.44	63	1.001	1.016
2	2828	1414	91.83	up to down	18.20	23	1.008	0.821	13.65	28	1.008	1.037	9.10	43	1.008	0.977
3	3464	1155	91.83	up to down	22.27	23	1.023	0.821	16.70	22	1.023	1.048	11.14	34	1.023	0.971
4	4000	1000	91.83	up to down	25.65	24	1.044	0.857	19.24	18	1.044	1.000	12.83	29	1.044	0.935
5	4472	894	91.83	up to down	28.56	24	1.069	0.857	21.42	15	1.069	1.000	14.28	26	1.069	0.929
Lumped																
1	2000	2000	91.83	up to down	12.86	28			9.65	42			6.43	62		
2	2828	1414	91.83	up to down	18.05	28			13.54	27			9.03	44		
3	3464	1155	91.83	up to down	21.76	28			16.32	21			10.88	35		
4	4000	1000	91.83	up to down	24.56	28			18.42	18			12.28	31		
5	4472	894	91.83	up to down	26.71	28			20.03	15			13.36	28		
Distributed																
1	2000	2000	91.83	down to up	12.83	29	0.998	1.036	9.62	39	0.998	0.951	6.42	63	0.998	1.016
2	2828	1414	91.83	down to up	17.74	30	0.983	1.071	13.31	25	0.983	0.926	8.87	44	0.983	1.023
3	3464	1155	91.83	down to up	20.85	30	0.958	1.071	15.64	20	0.958	1.000	10.43	37	0.958	1.057
4	4000	1000	91.83	down to up	22.82	31	0.929	1.107	17.12	17	0.929	1.000	11.41	34	0.929	1.097
5	4472	894	91.83	down to up	23.95	31	0.897	1.107	17.96	17	0.897	1.133	11.98	32	0.897	1.143
Lumped																
1	2000	2000	91.83	down to up	12.86	28			9.65	41			6.43	62		
2	2828	1414	91.83	down to up	18.05	28			13.54	27			9.03	43		
3	3464	1155	91.83	down to up	21.76	28			16.32	20			10.88	35		
4	4000	1000	91.83	down to up	24.56	28			18.42	17			12.28	31		
5	4472	894	91.83	down to up	26.71	28			20.03	15			13.36	28		

Note: d = distributed, l = lumped

Table 9-11. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Moving Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	12.87	22	1.001	0.786	9.65	43	1.000	1.024	6.44	63	1.002	1.016
2	4000	2000	183.65	up to down	25.74	26	1.003	0.839	19.31	41	1.003	1.051	12.87	62	1.002	1.016
3	6000	2000	275.48	up to down	38.61	29	1.005	0.853	28.96	40	1.005	1.081	19.31	61	1.005	1.000
4	8000	2000	367.31	up to down	51.46	31	1.007	0.861	38.60	39	1.007	1.083	25.73	60	1.007	1.000
5	10000	2000	459.14	up to down	64.28	33	1.010	0.868	48.21	38	1.010	1.086	32.14	59	1.010	0.983
Lumped																
1	2000	2000	91.83	up to down	12.86	28			9.65	42			6.43	62		
2	4000	2000	183.65	up to down	25.67	31			19.25	39			12.84	61		
3	6000	2000	275.48	up to down	38.43	34			28.82	37			19.22	61		
4	8000	2000	367.31	up to down	51.09	36			38.32	36			25.55	60		
5	10000	2000	459.14	up to down	63.64	38			47.73	35			31.82	60		
Distributed																
1	2000	2000	91.83	down to up	12.83	29	0.998	1.036	9.62	39	0.997	0.951	6.42	63	0.998	1.016
2	4000	2000	183.65	down to up	25.54	33	0.995	1.065	19.16	37	0.995	0.949	12.77	62	0.995	1.016
3	6000	2000	275.48	down to up	38.09	35	0.991	1.029	28.57	35	0.991	0.946	19.05	62	0.991	1.016
4	8000	2000	367.31	down to up	50.48	38	0.988	1.056	37.86	34	0.988	0.944	25.24	60	0.988	1.000
5	10000	2000	459.14	down to up	62.63	40	0.984	1.053	46.97	34	0.984	0.971	31.32	61	0.984	1.017
Lumped																
1	2000	2000	91.83	down to up	12.86	28			9.65	41			6.43	62		
2	4000	2000	183.65	down to up	25.67	31			19.25	39			12.84	61		
3	6000	2000	275.48	down to up	38.43	34			28.82	37			19.22	61		
4	8000	2000	367.31	down to up	51.09	36			38.32	36			25.55	60		
5	10000	2000	459.14	down to up	63.64	38			47.73	35			31.82	60		

Note: d = distributed, l = lumped

Table 9-12. Distributed versus Lumped Summary Table; OFP Slope = 9.12%; Moving Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	12.87	22	1.001	0.786	9.65	43	1.000	1.024	6.44	63	1.002	1.016
2	2000	1000	45.91	up to down	12.86	20	1.024	0.800	9.65	20	1.024	1.111	6.43	31	1.024	1.000
3	2000	667	30.62	up to down	12.80	20	1.085	0.870	9.60	12	1.085	1.000	6.40	20	1.085	0.952
4	2000	500	22.96	up to down	12.65	18	1.170	0.818	9.49	8	1.170	0.889	6.33	15	1.170	0.882
5	2000	400	18.37	up to down	12.29	19	1.263	0.864	9.22	6	1.263	0.750	6.15	11	1.263	0.733
Lumped																
1	2000	2000	91.83	up to down	12.86	28			9.65	42			6.43	62		
2	2000	1000	45.91	up to down	12.56	25			9.42	18			6.28	31		
3	2000	667	30.62	up to down	11.80	23			8.85	12			5.90	21		
4	2000	500	22.96	up to down	10.81	22			8.11	9			5.41	17		
5	2000	400	18.37	up to down	9.73	22			7.30	8			4.87	15		
Distributed																
1	2000	2000	91.83	down to up	12.83	29	0.998	1.036	9.62	39	0.997	0.951	6.42	63	0.998	1.016
2	2000	1000	45.91	down to up	12.01	27	0.956	1.080	9.01	17	0.956	0.944	6.01	32	0.957	1.032
3	2000	667	30.62	down to up	10.37	26	0.879	1.130	7.78	13	0.879	1.083	5.19	25	0.880	1.190
4	2000	500	22.96	down to up	8.73	26	0.808	1.182	6.55	12	0.808	1.333	4.37	22	0.808	1.294
5	2000	400	18.37	down to up	7.33	26	0.753	1.182	5.50	12	0.753	1.500	3.67	22	0.754	1.467
Lumped																
1	2000	2000	91.83	down to up	12.86	28			9.65	41			6.43	62		
2	2000	1000	45.91	down to up	12.56	25			9.42	18			6.28	31		
3	2000	667	30.62	down to up	11.80	23			8.85	12			5.90	21		
4	2000	500	22.96	down to up	10.81	22			8.11	9			5.41	17		
5	2000	400	18.37	down to up	9.73	22			7.30	8			4.87	15		

Note: d = distributed, l = lumped

9.1.3. Overland Flow Plane (Slope = 4.05%)

　　Hydrologic simulations were generated for the rectangular basins with 4.05%

overland flow plane slopes using the kinematic wave routing technique. Both distributed

and lumped rainfall scenarios in conjunction with stationary and moving storm events

across the watershed plane were applied to each test scenario.

9.1.3.1. Stationary Storms

　　Four stationary rainfall events were investigated as part of this study. Three of

these events involved applying distributed rainfall over the upper 20%, middle 20%, and

lower 20% of the rectangular drainage basin. The fourth event involved applying lumped

rainfall uniformly over the entire basin.

9.1.3.1.1. Distributed Rainfall

　　Distributed rainfall was applied over the upper 20%, middle 20%, and lower 20%

of each rectangular basin. Results from this study show that for each stationary rainfall

event, the simulated peak discharge is approximately the same for each individual basin

configuration and shape factor. However, travel times vary due to the distance the storm

system is located from the basin outlet. If the storm system is located in the upper 20%

of the basin, the travel time to the basin outlet is greater when compared to the case

where rainfall is located in the lower 20% of the basin where the travel time is shorter.

Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the

50% and 75% of peak flow are listed for each shape factor and basin case scenario in

Tables 9-13, 9-14, and 9-15.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. Although there is some difference, in most cases, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 17b – 19b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 17c – 19c.

9.1.3.1.2. Lumped Rainfall

Lumped rainfall was uniformly applied over the entire rectangular drainage basin. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-13, 9-14, and 9-15.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 with each other for each rectangular basin configuration. As the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 20b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for shape factor equal to 1 is shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for each case scenario for shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 20c.

9.1.3.1.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between the three distributed (upper, middle, and lower) versus the lumped rainfall for stationary storm systems. The ratios comparing peak discharges, time to peak flow, and the time widths at the 50% and 75% peak flow interval are discussed below. A general description of the dimensionless hydrographs comparing distributed versus lumped rainfall is also provided.

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Peak discharge ratios (distributed versus lumped) generally ranged from 2.5 to 3.0. The few smaller values were associated with the very small drainage basins. This shows that simulated peak discharge magnitudes at the basin outlet are much greater for distributed rainfall events than for lumped rainfall events. Peak discharge ratios for each basin scenario are listed in Tables 9-13, 9-14, and 9-15.

Time to peak flow ratios (distributed versus lumped) generally ranged from 0.4 to 0.7. This indicates that the travel time for the peak flow to reach the basin outlet is shorter for the distributed cases than for the lumped cases. The time to peak flow ratios for each basin scenario are listed in Tables 9-13, 9-14, and 9-15.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow intervals generally ranged from 0.3 to 0.4. This shows that the width of the hydrograph is narrower for the distributed cases than for the lumped cases which are wider. Time width ratios for each basin scenario are listed in Tables 9-13, 9-14, and 9-15.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs resulting from distributed and lumped rainfall scenarios for each basin configuration for each shape factor (i.e. 1-5). The overall shapes of the three distributed cases are similar. However, the rising limb began sooner for rainfall applied over the lower 20% than when rainfall was applied over the upper 20%. The falling limbs of the three hydrographs are very similar. For the lumped case, the rising limbs typically began at approximately the same time as the distributed lower 20% case. The falling limb of

the lumped case occurred much later in time than the three distributed cases. Finally, the

dimensionless hydrographs for the three distributed cases are more acute with a narrower

time base when compared with the lumped case which is more attenuated with a wider

time base. These plots are presented in Appendix 21d – 25d.

Table 9-13. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Stationary Storm – Constant Area (Case 1)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	25.22	15	2.939	0.625	18.92	21	2.939	0.333	12.61	31	2.939	0.330
2	2828	1414	91.83	upper 20%	35.59	15	2.936	0.600	26.69	14	2.936	0.333	17.80	22	2.936	0.338
3	3464	1155	91.83	upper 20%	43.39	16	2.932	0.615	32.54	10	2.932	0.313	21.70	17	2.932	0.327
4	4000	1000	91.83	upper 20%	49.79	16	2.937	0.615	37.34	8	2.937	0.308	24.90	15	2.937	0.333
5	4472	894	91.83	upper 20%	55.07	16	2.939	0.593	41.30	7	2.939	0.318	27.54	13	2.939	0.325
Distributed																
1	2000	2000	91.83	middle 20%	25.22	13	2.939	0.542	18.92	21	2.939	0.333	12.61	32	2.939	0.340
2	2828	1414	91.83	middle 20%	35.60	14	2.937	0.560	26.70	14	2.937	0.333	17.80	22	2.937	0.338
3	3464	1155	91.83	middle 20%	43.41	14	2.933	0.538	32.56	12	2.933	0.375	21.71	18	2.933	0.346
4	4000	1000	91.83	middle 20%	49.79	14	2.937	0.538	37.34	9	2.937	0.346	24.90	15	2.937	0.333
5	4472	894	91.83	middle 20%	55.16	14	2.943	0.519	41.37	8	2.943	0.364	27.58	14	2.943	0.350
Distributed																
1	2000	2000	91.83	lower 20%	25.22	12	2.939	0.500	18.92	21	2.939	0.333	12.61	33	2.939	0.351
2	2828	1414	91.83	lower 20%	35.62	12	2.939	0.480	26.72	14	2.939	0.333	17.81	23	2.939	0.354
3	3464	1155	91.83	lower 20%	43.43	12	2.934	0.462	32.57	11	2.934	0.344	21.72	19	2.934	0.365
4	4000	1000	91.83	lower 20%	49.76	12	2.936	0.462	37.32	10	2.936	0.385	24.88	16	2.936	0.356
5	4472	894	91.83	lower 20%	55.04	12	2.937	0.444	41.28	9	2.937	0.409	27.52	14	2.937	0.350
Lumped																
1	2000	2000	91.83	entire basin	8.58	24			6.44	63			4.29	94		
2	2828	1414	91.83	entire basin	12.12	25			9.09	42			6.06	65		
3	3464	1155	91.83	entire basin	14.80	26			11.10	32			7.40	52		
4	4000	1000	91.83	entire basin	16.95	26			12.71	26			8.48	45		
5	4472	894	91.83	entire basin	18.74	27			14.06	22			9.37	40		

Note: d = distributed, l = lumped

Table 9-14. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Stationary Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	25.22	15	2.939	0.625	18.92	21	2.938	0.333	12.61	31	2.939	0.330
2	4000	2000	183.65	upper 20%	50.44	17	2.939	0.586	37.83	19	2.939	0.317	25.22	30	2.939	0.323
3	6000	2000	275.48	upper 20%	75.66	18	2.941	0.545	56.75	19	2.940	0.328	37.83	30	2.939	0.326
4	8000	2000	367.31	upper 20%	100.83	20	2.941	0.571	75.62	19	2.941	0.333	50.42	30	2.942	0.330
5	10000	2000	459.14	upper 20%	126.02	21	2.944	0.553	94.52	18	2.945	0.327	63.01	29	2.944	0.319
Distributed																
1	2000	2000	91.83	middle 20%	25.22	13	2.939	0.542	18.92	21	2.938	0.333	12.61	32	2.939	0.340
2	4000	2000	183.65	middle 20%	50.44	15	2.939	0.517	37.83	21	2.939	0.350	25.22	31	2.939	0.333
3	6000	2000	275.48	middle 20%	75.65	16	2.940	0.485	56.74	21	2.940	0.362	37.83	31	2.939	0.337
4	8000	2000	367.31	middle 20%	100.87	16	2.943	0.457	75.65	20	2.942	0.351	50.44	31	2.943	0.341
5	10000	2000	459.14	middle 20%	126.07	17	2.946	0.447	94.55	20	2.945	0.364	63.04	31	2.946	0.341
Distributed																
1	2000	2000	91.83	lower 20%	25.22	12	2.939	0.500	18.92	21	2.938	0.333	12.61	33	2.939	0.351
2	4000	2000	183.65	lower 20%	50.44	13	2.939	0.448	37.83	22	2.939	0.367	25.22	32	2.939	0.344
3	6000	2000	275.48	lower 20%	75.66	13	2.941	0.394	56.75	22	2.940	0.379	37.83	33	2.939	0.359
4	8000	2000	367.31	lower 20%	100.87	13	2.943	0.371	75.65	21	2.942	0.368	50.44	33	2.943	0.363
5	10000	2000	459.14	lower 20%	126.05	14	2.945	0.368	94.54	21	2.945	0.382	63.03	33	2.945	0.363
Lumped																
1	2000	2000	91.83	entire basin	8.58	24			6.44	63			4.29	94		
2	4000	2000	183.65	entire basin	17.16	29			12.87	60			8.58	93		
3	6000	2000	275.48	entire basin	25.73	33			19.30	58			12.87	92		
4	8000	2000	367.31	entire basin	34.28	35			25.71	57			17.14	91		
5	10000	2000	459.14	entire basin	42.80	38			32.10	55			21.40	91		

Note: d = distributed, l = lumped

Table 9-15. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Stationary Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P$_x$)	Peak Time (t$_x$)	Ratio P$_d$/P$_l$	Ratio t$_d$/t$_l$	75% Peak Flow (P$_{75}$)	75% Time Width (t$_{75}$)	75% Ratio P$_{75d}$/P$_{75l}$	75% Ratio t$_{75d}$/t$_{75l}$	50% Peak Flow (P$_{50}$)	50% Time Width (t$_{50}$)	50% Ratio P$_{50d}$/P$_{50l}$	50% Ratio t$_{50d}$/t$_{50l}$
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	upper 20%	25.22	15	2.939	0.625	18.92	21	2.938	0.333	12.61	31	2.939	0.330
2	2000	1000	45.91	upper 20%	24.98	14	2.922	0.636	18.74	9	2.924	0.310	12.49	15	2.918	0.326
3	2000	667	30.62	upper 20%	23.86	14	2.837	0.667	17.90	5	2.837	0.294	11.93	10	2.834	0.333
4	2000	500	22.96	upper 20%	21.47	14	2.647	0.700	16.10	4	2.648	0.333	10.74	8	2.645	0.348
5	2000	400	18.37	upper 20%	19.68	14	2.589	0.737	14.76	3	2.589	0.300	9.84	7	2.589	0.368
Distributed																
1	2000	2000	91.83	middle 20%	25.22	13	2.939	0.542	18.92	21	2.938	0.333	12.61	32	2.939	0.340
2	2000	1000	45.91	middle 20%	24.97	13	2.920	0.591	18.73	9	2.922	0.310	12.49	16	2.918	0.348
3	2000	667	30.62	middle 20%	23.74	12	2.823	0.571	17.81	6	2.823	0.353	11.87	11	2.819	0.367
4	2000	500	22.96	middle 20%	21.90	12	2.700	0.600	16.43	5	2.702	0.417	10.95	8	2.697	0.348
5	2000	400	18.37	middle 20%	19.52	12	2.568	0.632	14.64	5	2.568	0.500	9.76	7	2.568	0.368
Distributed																
1	2000	2000	91.83	lower 20%	25.22	12	2.939	0.500	18.92	21	2.938	0.333	12.61	33	2.939	0.351
2	2000	1000	45.91	lower 20%	25.01	11	2.925	0.500	18.76	9	2.927	0.310	12.51	17	2.923	0.370
3	2000	667	30.62	lower 20%	23.87	11	2.838	0.524	17.90	6	2.837	0.353	11.94	11	2.836	0.367
4	2000	500	22.96	lower 20%	21.48	11	2.649	0.550	16.11	5	2.650	0.417	10.74	9	2.645	0.391
5	2000	400	18.37	lower 20%	19.35	10	2.546	0.526	14.51	5	2.546	0.500	9.68	9	2.547	0.474
Lumped																
1	2000	2000	91.83	entire basin	8.58	24			6.44	63			4.29	94		
2	2000	1000	45.91	entire basin	8.55	22			6.41	29			4.28	46		
3	2000	667	30.62	entire basin	8.41	21			6.31	17			4.21	30		
4	2000	500	22.96	entire basin	8.11	20			6.08	12			4.06	23		
5	2000	400	18.37	entire basin	7.60	19			5.70	10			3.80	19		

Note: d = distributed, l = lumped

Two moving storm systems both having a constant uniform velocity and rainfall rates were applied to each rectangular basin scenario. These storm systems moved either upstream to downstream or downstream to upstream across the basin. For each storm system, both distributed and lumped rainfall was applied to each storm case, making a total of four scenarios for the application of rainfall to each rectangular basin.

9.1.3.2.1. Distributed Rainfall

Distributed rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. Results from this study show that as the storm system moves from upstream to downstream, the peak discharge is greater when compared to an identical storm system which is moving from downstream to upstream for each individual basin configuration and shape factor. Simulated peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of peak flow are listed for each shape factor and basin case scenario in Tables 9-16, 9-17, and 9-18.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm movement, as the shape factor increases, the actual plot becomes more acute with a narrower time base.   It should be noted that the rising limb has a very steep slope for the upstream to downstream cases compared to

the downstream to upstream cases where the slope is more gradual. These plots are
presented in Appendix 21b and 23b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin
configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs
for a shape factor equal to 1 are shown for informational purposes only. A shape factor
of 1 was used as a reference basin to develop the basin dimensions for the scenarios
having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the
hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a
narrower time base. However, the largest rectangular basin (i.e. constant width) is more
attenuated with a wider time base. The constant area case lies between the constant
length and constant width cases. These plots are illustrated in Appendix 21c and 23c.

9.1.3.2.2. Lumped Rainfall

Lumped rainfall was applied over the basin as the storm system moved either
upstream to downstream or downstream to upstream across the drainage. It should be
noted that because of the symmetry of the rectangular basin in conjunction with both the
uniform rate of movement and rainfall rate of the storm system, the lumped rainfall
patterns for both the upstream to downstream and downstream to upstream storm systems
are identical. Simulated peak discharge, time to peak flow, and the hydrograph time
widths at both the 50% and 75% of peak flow are listed for each shape factor and basin
scenario in Tables 9-16, 9-17, and 9-18.

Dimensionless plots (q/qp versus t/tp) were developed comparing shape factors 1, 2, 3, 4, and 5 for each rectangular basin configuration. For both the upstream to downstream and downstream to upstream storm movement, as the shape factor increases, the actual plot becomes more acute with a narrower time base. These plots are presented in Appendix 22b and 24b.

Dimensionless plots (q/qp versus t/tp) were also developed comparing each basin configuration with each shape factor (i.e. 1-5). It should be noted that the hydrographs for a shape factor equal to 1 are shown for informational purposes only. A shape factor of 1 was used as a reference basin to develop the basin dimensions for the scenarios having shape factors 2 through 5. For each individual shape factor (i.e. 2-5), the hydrograph for the smallest rectangular basin (i.e. constant length) is more acute with a narrower time base. However, the largest rectangular basin (i.e. constant width) is more attenuated with a wider time base. The constant area case lies between the constant length and constant width cases. These plots are presented in Appendix 22c and 24c.

9.1.3.2.3. Distributed versus Lumped Rainfall Comparison

Comparisons of the simulated hydrologic basin response were made between distributed and lumped rainfall for moving storm systems. These systems moved either upstream to downstream or downstream to upstream across the drainage basin.

Peak discharge ratios (distributed versus lumped) are generally slightly greater than 1 for storm systems which moved upstream to downstream. However, peak

discharge ratios are generally slightly less than 1 for storm system which moved

downstream to upstream. This indicates that simulated peak discharge magnitudes at the

basin outlet are similar for both the distributed and lumped rainfall events. Although

there are a few cases where these ratios are somewhat higher (upstream to downstream)

or lower (downstream to upstream), these values were associated with the very small

rectangular basins with faster hydrologic response times. Peak discharge ratios for each

basin scenario are listed in Tables 9-16, 9-17, and 9-18.

Time to peak flow ratios (distributed versus lumped) generally ranged from 0.8 to

0.9 for the upstream to downstream systems. This indicates that the travel time for peak

flow to reach the basin outlet is shorter for the distributed cases than for the lumped

cases. However, time to peak flow ratios generally ranged from 1.0 to 1.2 for the

downstream to upstream systems. This indicates that the travel time for peak flow to

reach the basin outlet is longer for the distributed cases than for the lumped cases. The

time to peak flow ratios for each basin scenario are listed in Tables 9-16, 9-17, and 9-18.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow

intervals were generally mixed results. These values were typically close to 1 indicating

that the width of the hydrographs is very similar for both distributed and lumped rainfall.

Time width ratios for each basin scenario are listed in Tables 9-16, 9-17, and 9-18.

Dimensionless plots (q/qp versus t/tp) were also developed comparing

hydrographs resulting from distributed and lumped rainfall scenarios for each basin

configuration with each shape factor (i.e. 1-5). For the upstream to downstream storm system, both the rising and falling limbs for the distributed cases typically begin later than for the lumped cases. For the downstream to upstream storm system, both the rising and falling limbs for the distributed cases begin earlier than the lumped cases. These graphs are presented in Appendix 26d – 30d.

Table 9-16. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Moving Storm – Constant Area (Case 1)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	8.58	26	1.000	0.813	6.44	65	1.000	1.032	4.29	94	1.000	1.000
2	2828	1414	91.83	up to down	12.14	27	1.002	0.844	9.11	43	1.002	1.049	6.07	65	1.002	1.000
3	3464	1155	91.83	up to down	14.86	27	1.007	0.844	11.15	34	1.007	1.063	7.43	53	1.007	1.019
4	4000	1000	91.83	up to down	17.14	28	1.017	0.875	12.86	28	1.017	1.077	8.57	45	1.017	1.000
5	4472	894	91.83	up to down	19.12	28	1.029	0.875	14.34	24	1.029	1.043	9.56	39	1.029	0.951
Lumped																
1	2000	2000	91.83	up to down	8.58	32			6.44	63			4.29	94		
2	2828	1414	91.83	up to down	12.11	32			9.08	41			6.06	65		
3	3464	1155	91.83	up to down	14.75	32			11.06	32			7.38	52		
4	4000	1000	91.83	up to down	16.86	32			12.65	26			8.43	45		
5	4472	894	91.83	up to down	18.58	32			13.94	23			9.29	41		
Distributed																
1	2000	2000	91.83	down to up	8.58	32	1.000	1.000	6.44	60	1.000	0.952	4.29	94	1.000	1.000
2	2828	1414	91.83	down to up	12.06	33	0.996	1.031	9.05	39	0.996	0.951	6.03	66	0.996	1.015
3	3464	1155	91.83	down to up	14.54	34	0.986	1.063	10.91	31	0.986	0.969	7.27	54	0.986	1.019
4	4000	1000	91.83	down to up	16.37	35	0.971	1.094	12.28	26	0.971	1.000	8.19	47	0.971	1.044
5	4472	894	91.83	down to up	17.71	35	0.953	1.094	13.28	22	0.953	0.957	8.86	43	0.953	1.075
Lumped																
1	2000	2000	91.83	down to up	8.58	32			6.44	63			4.29	94		
2	2828	1414	91.83	down to up	12.11	32			9.08	41			6.06	65		
3	3464	1155	91.83	down to up	14.75	32			11.06	32			7.38	53		
4	4000	1000	91.83	down to up	16.86	32			12.65	26			8.43	45		
5	4472	894	91.83	down to up	18.58	32			13.94	23			9.29	40		

Note: d = distributed, l = lumped

Table 9-17. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Moving Storm – Constant Width (Case 2)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	8.58	26	1.000	0.813	6.44	65	1.000	1.032	4.29	94	1.000	1.000
2	4000	2000	183.65	up to down	17.16	31	1.001	0.861	12.87	63	1.001	1.050	8.58	93	1.000	1.000
3	6000	2000	275.48	up to down	25.74	34	1.001	0.872	19.31	61	1.002	1.034	12.87	92	1.001	1.000
4	8000	2000	367.31	up to down	34.32	37	1.002	0.881	25.74	60	1.002	1.053	17.16	91	1.002	1.000
5	10000	2000	459.14	up to down	42.89	39	1.003	0.886	32.17	58	1.003	1.055	21.45	90	1.003	0.989
Lumped																
1	2000	2000	91.83	up to down	8.58	32			6.44	63			4.29	94		
2	4000	2000	183.65	up to down	17.15	36			12.86	60			8.58	93		
3	6000	2000	275.48	up to down	25.71	39			19.28	59			12.86	92		
4	8000	2000	367.31	up to down	34.25	42			25.69	57			17.13	91		
5	10000	2000	459.14	up to down	42.76	44			32.07	55			21.38	91		
Distributed																
1	2000	2000	91.83	down to up	8.58	32	1.000	1.000	6.44	60	1.000	0.952	4.29	94	1.000	1.000
2	4000	2000	183.65	down to up	17.13	37	0.999	1.028	12.85	58	0.999	0.967	8.57	94	0.999	1.011
3	6000	2000	275.48	down to up	25.66	41	0.998	1.051	19.25	56	0.998	0.949	12.83	93	0.998	1.011
4	8000	2000	367.31	down to up	34.14	44	0.997	1.048	25.61	55	0.997	0.965	17.07	91	0.996	1.000
5	10000	2000	459.14	down to up	42.56	46	0.995	1.045	31.92	53	0.995	0.964	21.28	91	0.995	1.000
Lumped																
1	2000	2000	91.83	down to up	8.58	32			6.44	63			4.29	94		
2	4000	2000	183.65	down to up	17.15	36			12.86	60			8.58	93		
3	6000	2000	275.48	down to up	25.71	39			19.28	59			12.86	92		
4	8000	2000	367.31	down to up	34.25	42			25.69	57			17.13	91		
5	10000	2000	459.14	down to up	42.76	44			32.07	55			21.38	91		

Note: d = distributed, l = lumped

Table 9-18. Distributed versus Lumped Summary Table; OFP Slope = 4.05%; Moving Storm – Constant Length (Case 3)

Shape Factor	Length	Width	Area	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
	(feet)	(feet)	(acres)		(cfs)	(min)			(cfs)	(min)			(cfs)	(min)		
Distributed																
1	2000	2000	91.83	up to down	8.58	26	1.000	0.813	6.44	65	1.000	1.032	4.29	94	1.000	1.000
2	2000	1000	45.91	up to down	8.58	23	1.007	0.793	6.44	30	1.008	1.034	4.29	45	1.007	0.978
3	2000	667	30.62	up to down	8.57	22	1.035	0.815	6.43	19	1.035	1.056	4.29	29	1.036	0.967
4	2000	500	22.96	up to down	8.54	21	1.081	0.840	6.41	13	1.081	1.000	4.27	21	1.081	0.913
5	2000	400	18.37	up to down	8.46	20	1.143	0.833	6.35	9	1.144	0.900	4.23	16	1.143	0.800
Lumped																
1	2000	2000	91.83	up to down	8.58	32			6.44	63			4.29	94		
2	2000	1000	45.91	up to down	8.52	29			6.39	29			4.26	46		
3	2000	667	30.62	up to down	8.28	27			6.21	18			4.14	30		
4	2000	500	22.96	up to down	7.90	25			5.93	13			3.95	23		
5	2000	400	18.37	up to down	7.40	24			5.55	10			3.70	20		
Distributed																
1	2000	2000	91.83	down to up	8.58	32	1.000	1.000	6.44	60	1.000	0.952	4.29	94	1.000	1.000
2	2000	1000	45.91	down to up	8.40	30	0.986	1.034	6.30	27	0.986	0.931	4.20	46	0.986	1.000
3	2000	667	30.62	down to up	7.81	29	0.943	1.074	5.86	17	0.944	0.944	3.91	33	0.944	1.100
4	2000	500	22.96	down to up	6.98	28	0.884	1.120	5.24	14	0.884	1.077	3.49	28	0.884	1.217
5	2000	400	18.37	down to up	6.14	28	0.830	1.167	4.61	13	0.831	1.300	3.07	26	0.830	1.368
Lumped																
1	2000	2000	91.83	down to up	8.58	32			6.44	63			4.29	94		
2	2000	1000	45.91	down to up	8.52	29			6.39	29			4.26	46		
3	2000	667	30.62	down to up	8.28	27			6.21	18			4.14	30		
4	2000	500	22.96	down to up	7.90	25			5.93	13			3.95	23		
5	2000	400	18.37	down to up	7.40	24			5.55	10			3.70	19		

Note: d = distributed, l = lumped

9.2. Actual Drainage Basin
Cowleech Fork Sabine River near Greenville, Texas

Hydrologic simulations were conducted on the Cowleech Fork Sabine River near Greenville, Texas drainage basin. The Greenville drainage area is located in North Texas approximately 50 miles northeast of Dallas near the town of Greenville.

Two hypothetical storm events were applied over the Greenville drainage. Rainfall intensities for these storm events are (1) a 1 inch storm with a 5 hour duration and (2) a 1 inch storm with a 10 hour duration. These two rainfall events were each applied as both distributed and lumped rainfall scenarios in conjunction with stationary and moving storm patterns over the Greenville drainage.

9.2.1. Storm Event – 1 Inch in 5 Hours

Rainfall intensities of 1 inch in 5 hours were applied to the Greenville drainage. Both stationary and moving storm events were applied to this drainage with both distributed and lumped rainfall configurations.

9.2.1.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved placing distributed rainfall over the upper 22%, middle 22%, and lower 22% of the Greenville drainage basin. The fourth event involved placing lumped rainfall uniformly over the entire basin.

Distributed Rainfall

Distributed rainfall was applied over the upper 22%, middle 22%, and lower 22% of the Greenville drainage. The hydrologic response at the basin outlet shows hydrographs with definite peak flows for rainfall distributions located over the upper and middle 22% of the basin. This indicates that the basin has not reach equilibrium for this rainfall intensity. However, for the lower 22% case, the hydrograph has a lower peak flow rate, indicating that the equilibrium may be occurring for the basin. Equilibrium is the point where the storm duration time period is either equal to or greater than the time it takes for runoff to travel to the basin outlet from its furthest most point on the watershed.

Peak discharges resulting from the upper 22%, middle 22%, and lower 22% distributed rainfall distributions are similar in magnitude. Although there are some variations, these differences in peak discharge are relatively small when compared between the three distributed cases. These differences are most likely attributable to the various shapes and drainage configurations of the upper 22%, middle 22%, and lower 22% of the drainage basin. Also, peak discharge is slightly higher for the upper 22% case than for the lower 22%. The peak discharge for the middle 22% lies between the upper and lower distributed cases. Peak discharges are listed in Table 9-19.

The time to peak flow also varies due to the distance that the distributed storm systems are located from the basin outlet. If the storm system is located in the upper 22% of the basin, the time to peak is greater when compared to the case where rainfall is located in the lower 22%. Time to peak flow values are listed in Table 9-19.

The time width of the dimensionless hydrographs at both the 50% and 75% peak

flow level vary for the upper 22%, middle 22%, and lower 22% cases. Generally, at both

the 50% and 75% interval, the time width for the upper 22% case is smaller while the

time width for the lower 22% case is larger. This indicates that the dimensionless

hydrograph has a slightly more "peaked" response for rainfall located in the upper basin

than for the lower. The 50% and 75% time width intervals are listed in Table 9-19.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville

drainage. Dimensionless hydrographs for the three distributed rainfall cases show

hydrographs with a more acute appearance with a fairly rapid rise and fall. Although

there are differences in timing, the three distributed cases are generally similar in

appearance. These plots are presented in Appendix 1e.

9.2.1.1.2. Lumped Rainfall

Lumped rainfall was uniformly applied over the entire Greenville drainage. The

hydrologic response at the basin outlet shows a typical rising and falling hydrograph with

a definite peak flow, indicating that the basin has not reached equilibrium. Simulated

peak discharge, time to peak flow, and the hydrograph time widths at both the 50% and

75% of peak flow are discussed in Table 9-19.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville

drainage.   The dimensionless hydrograph resulting for the lumped rainfall case has a

gradual rise and fall with a more "rounded" peak flow. This plot is presented in

Appendix 1e.

9.2.1.1.3. Distributed versus Lumped Rainfall Comparison

Simulated hydrologic basin response comparisons were made between the three

distributed (upper, middle, and lower) versus the lumped rainfall events for the stationary

storm systems. The ratios comparing peak discharges, time to peak flow, and the time

widths at the 50% and 75% peak flow interval are discussed below. A general

description of the dimensionless hydrographs comparing distributed versus lumped is

also provided.

Peak discharge ratios comparing the three distributed cases (upper, middle, and

lower) to the lumped case generally ranged from 2.1 to 2.3, with the highest value

attributable to the upper distributed case. This indicates that simulated peak discharge

magnitudes at the basin outlet are much greater for distributed rainfall events than for

lumped rainfall events. Peak discharge ratios for the Greenville drainage are shown in

Table 9-19.

Time to peak flow ratios comparing the three distributed cases (upper, middle,

and lower) to the lumped case ranged from 0.5 to 0.8, with the highest value attributable

to the upper distributed case. This indicates that the travel time for peak flow to reach the

basin outlet is shorter for the distributed cases when compared to the lumped case. The

time to peak flow ratios for each basin scenario are listed in Table 9-19.

Time width ratios at the 50% and 75% peak flow intervals comparing the three distributed cases (upper, middle, and lower) to the lumped case ranged from 0.25 to 0.75. These ratios indicate that the width of the hydrograph is narrower for the distributed cases compared to the wider lumped case. Time width ratios at the 50% and 75% peak flow interval are listed in Table 9-19.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs which resulted between distributed and lumped rainfall scenarios. The rising limb began earlier and the falling limb occurred later in time for the lumped case than for the three distributed cases. For the lumped case, the hydrograph has a gradual rising and falling limb, a wider time base, and a more "rounded" peak flow. For the three distributed cases, the hydrographs have steeper rising and falling limbs, narrower time bases, and a more acute peak flow. The only exception may be distributed rainfall which is occurring in the lower 22% of the basin. The hydrograph has a flatter peak flow, indicating that the equilibrium may be occurring for the basin. The dimensionless hydrographs are presented in Appendix 1e.

9.2.1.2. Moving Storms

Two moving storm systems with both a constant uniform velocity and rainfall rate were applied to the Greenville drainage. These storm systems moved either upstream to downstream or downstream to upstream across the basin. For each storm system, both distributed and lumped rainfall was applied to the Greenville drainage.

9.2.1.2.1. Distributed Rainfall

Distributed rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the Greenville drainage.

Peak discharges were higher for storm systems moving upstream to downstream. Also, because the storm system was moving in the same direction as the flood wave, additional rainfall creates even higher peak flows than the already moving flood wave. In contrast, peak discharges are lower for storm systems moving downstream to upstream. Because the storm system moves in the opposite direction as the flood wave, additional rainfall does not create higher peak flows than the already moving flood wave. However, the total time duration of the flood wave is longer. Peak discharges are listed in Table 9-19.

The time to peak flow is shorter for the storm system moving upstream to downstream. In contrast the time to peak flow is longer for the storm system moving downstream to upstream. The time to peak values are listed in Table 9-19.

The time width of the dimensionless hydrographs at both the 50% and 75% peak flow level are much smaller for the storm system moving from the upstream to downstream. The time width is larger for the storm system moving downstream to upstream. The 50% and 75% time width intervals are listed in Table 9-19.

Dimensionless plots (q/qp versus t/tp) were developed for upstream to downstream moving storm systems. The dimensionless hydrograph shows an acute shape at peak flow with rapid rising and falling limbs and a narrow time base. Because the storm system moves in the same direction as the already generated flood wave, additional rainfall creates higher peak flows to the already moving flood wave.

Dimensionless plots (q/qp versus t/tp) were also developed for downstream to upstream moving storm systems. The dimensionless hydrograph shows a more "rounded" shape at peak flow with rapid rising and falling limbs with a wider time base. Because the storm system moves in the opposite direction as the flood wave, additional rainfall does not contribute to higher peak flows to the already moving flood wave. However, the total time duration of the flood wave is longer. Also, several minor peak fluctuations occur on the rising limb of the hydrograph. This is most likely due to various subbasin and drainage geometry of the lower part of the basin which has a more immediate impact on the hydrologic response when compared to the upper basin. This is definitely more noticeable as the storm system moves upstream away from the basin outlet. In contrast, when the storm system moves from upstream to downstream, these fluctuations are "dampened" out due to added rainfall falling on top of the already generated flood wave. Dimensionless plots are presented in Appendix 2e.

9.2.1.2.2. Lumped Rainfall

Lumped rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. The rainfall rate across the basin was constant as the storm systems moved across the basin at a uniform rate. The only difference was the direction of movement of the storm systems.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville drainage. The dimensionless hydrograph resulting for the lumped rainfall case has a somewhat gradual rise and fall with a somewhat more "rounded" peak flow. This dimensionless hydrograph is presented in Appendix 2e.

9.2.1.2.3. Distributed versus Lumped Rainfall Comparison

Simulated hydrologic basin response comparisons were made between distributed and lumped rainfall for moving storm systems. These systems moved either upstream to downstream or downstream to upstream across the drainage basin.

The peak discharge ratio (distributed versus lumped) for the storm system moving upstream to downstream is 1.69. This indicates that the simulated peak discharge magnitude at the basin outlet is greater for distributed rainfall than for the lumped. In contrast, the peak discharge ratio for the storm system moving in the opposite direction, downstream to upstream, is 0.69. This indicates that the simulated peak discharge is smaller for distributed rainfall than for the lumped. Peak discharge ratios for the Greenville drainage are listed in Table 9-19.

Time to peak flow ratios (distributed versus lumped) for the storm system moving upstream to downstream is 0.83. This indicates that the travel time is shorter for distributed rainfall than for the lumped. In contrast, the time to peak flow ratio for the storm system moving in the opposite direction, downstream to upstream, is 1.25. This indicates that the travel time is longer for distributed rainfall than for the lumped. The time to peak flow ratios for the Greenville drainage are listed in Table 9-19.

Time width ratios at the 50% and 75% peak flow intervals for the storm system moving upstream to downstream were 0.5 for both intervals. This indicates that the width of the hydrograph is narrower for the distributed rainfall compared to the lumped. In contrast, time width ratios at the 50% and 75% interval for the storm system moving in the opposite direction, downstream to upstream, were 1.75 and 2.25, respectively. This indicates that the width of the hydrograph is wider for distributed rainfall compared to the lumped. These ratios are listed in Table 9-19.

Dimensionless plots (q/qp versus t/tp) were developed for upstream to downstream moving storm systems. For distributed rainfall, the hydrograph has a rising limb which began later in time, is more acute in appearance, and has a narrower time base. For the lumped case, the hydrograph has a rising limb which begins earlier in time, is more "rounded", and has a wider time base.

Dimensionless plots (q/qp versus t/tp) were also developed for downstream to upstream moving storm systems. For distributed rainfall, the hydrograph has a rising limb which began earlier in time, is more "rounded", and has a wider time base. In comparison, the lumped case began later in time and has a narrower time base. Also, the distributed case shows several minor peak fluctuations on the rising limb of the hydrograph. This is most likely due to various subbasin and drainage configurations of the lower part of the basin which has a more immediate impact on the hydrologic response when compared to the upper basin. This is more noticeable as the storm system moves upstream away from the basin outlet. These dimensionless hydrographs are presented in appendix 2e.

9.2.2. Storm Event – 1 Inch in 10 Hours

Rainfall intensities of 1 inch in 10 hours were applied to the Greenville drainage. Both stationary and moving storm events were applied to this drainage with both distributed and lumped rainfall configurations.

9.2.2.1. Stationary Storms

Four stationary rainfall events were investigated as part of this study. Three of these events involved placing distributed rainfall over the upper 22%, middle 22%, and lower 22% of the Greenville drainage basin. The fourth event involved placing lumped rainfall uniformly over the entire basin.

9.2.2.1.1. Distributed Rainfall

Distributed rainfall was applied over the upper 22%, middle 22%, and lower 22% of the Greenville drainage. The hydrologic response at the basin outlet shows hydrographs with a rising limb, flat peak, and falling limb for every distributed case scenario. This indicates that the basin has reached equilibrium conditions for this rainfall intensity. Equilibrium is the point where the storm duration time period is either equal to or greater than the time it takes for runoff to travel to the basin outlet from its furthest most point on the watershed. When the basin reaches equilibrium, the hydrograph has a flat peak. Once rainfall ceases, the hydrograph then begins to recede.

Peak discharges resulting from the upper 22%, middle 22%, and lower 22% distributed rainfall distributions are similar in magnitude. Although there are some variations, these differences in peak discharge are relatively small when compared between the three distributed cases. These differences are most likely attributable to the various shapes and drainage configurations of the upper 22%, middle 22%, and lower 22% of the drainage basin. Also, peak discharge is slightly higher for the upper 22% case than for the lower 22%. The peak discharge for the middle 22% lies in between the upper and lower distributed cases. Peak discharges are listed in Table 9-20.

The time to peak flow also varies due to the distance that the distributed storm systems are located from the basin outlet. If the storm system is located in the upper 22% of the basin, the time to peak is greater when compared to the case where rainfall is located in the lower 22%. Time to peak flow values are listed in Table 9-20.

The time width of the dimensionless hydrographs at both the 50% and 75% peak

flow level vary for the upper 22%, middle 22%, and lower 22% cases. Generally, at both

the 50% and 75% interval, the time width for the upper 22% case is smaller while the

time width for the lower 22% case is larger. This indicates that the dimensionless

hydrograph has a slightly more "peaked" response for rainfall located in the upper basin

than the lower. The 50% and 75% time width intervals are listed in Table 9-20.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville

drainage. Dimensionless hydrographs for the three distributed rainfall cases show fairly

rapid rising and falling limbs. However, because equilibrium was reached, the peak flow

has a flat appearance. These plots are presented in Appendix 3e.

9.2.2.1.2. Lumped Rainfall

Lumped rainfall was uniformly applied over the entire Greenville drainage. The

hydrologic response at the basin outlet shows a typical rising and falling hydrograph with

a definite peak flow, indicting the basin has not reached equilibrium. Simulated peak

discharge, time to peak flow, and the hydrograph time widths at both the 50% and 75% of

peak flow are listed in Table 9-20.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville

drainage. The dimensionless hydrograph resulting for the lumped rainfall case has a

gradual rise and fall with a more "rounded" peak flow. This plot is presented in Appendix 3e.

9.2.2.1.3. Distributed versus Lumped Rainfall Comparison

Simulated hydrologic basin response comparisons were made between the three distributed (upper, middle, and lower) versus the lumped rainfall events for the stationary storm systems. The ratios comparing peak discharges, time to peak flow, and the time widths at the 50% and 75% peak flow interval are discussed below. A general description of the dimensionless hydrographs comparing distributed versus lumped is also provided.

Peak discharge ratios comparing the three distributed cases (upper, middle, and lower) to the lumped case were approximately 1.3. This indicates that simulated peak discharge magnitudes at the basin outlet are greater for distributed rainfall events than for lumped rainfall events. Peak discharge ratios for the Greenville drainage are listed in Table 9-20.

Time to peak flow ratios comparing the three distributed cases (upper, middle, and lower) to the lumped case ranged from approximately 0.6 to 0.9, with the highest value attributable to the upper distributed case. This indicates that the travel time for peak flow to reach the basin outlet is shorter for the distributed cases when compared to the lumped case. The time to peak flow ratios for each basin scenario are listed in Table 9-20.

Time width ratios at the 50% and 75% peak flow intervals comparing the three distributed cases (upper, middle, and lower) to the lumped case ranged from 1.2 to 1.4 for the 75% case, and from 0.8 to 0.9 for the 50% case. Because of the inconsistency of these values, further investigation is warranted before drawing any conclusions. It is suspected that the 1 minute time periods used in these simulations may be inadequate and may need to be refined to smaller 1 second time periods to better analyze this situation for watershed equilibrium conditions. Time width ratios at the 50% and 75% peak flow interval are listed in Table 9-20.

Dimensionless plots (q/qp versus t/tp) were also developed comparing hydrographs which resulted between distributed and lumped rainfall scenarios. The rising limb of the hydrograph began at the same time for both lumped rainfall and distributed rainfall located in the lower 22%. However, the rising limb of the hydrograph began later in time for the distributed cases located in the upper 22% and middle 22% of the basin. For the lumped case, the rising limb has a more gradual rise and fall with a rounded peak flow. The three distributed cases, however, have reached equilibrium, which is noticeable due to the flat crest at the peak ordinate of the hydrograph. The falling limb occurred slightly later in time for the lumped case compared to the distributed cases. These dimensionless hydrographs are presented in Appendix 3e.

9.2.2.2. Moving Storms

Two moving storm systems with both a constant uniform velocity and rainfall rate were applied to the Greenville drainage. These storm systems moved either upstream to downstream or downstream to upstream across the basin. For each storm system, both distributed and lumped rainfall was applied to the Greenville drainage.

9.2.2.2.1. Distributed Rainfall

Distributed rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the Greenville drainage.

Peak discharges are higher for storm systems moving upstream to downstream. Also, because the storm system is moving in the same direction as the flood wave, additional rainfall creates even higher peak flows to the already moving flood wave. In contrast, peak discharges are lower for storm systems moving downstream to upstream. Because the storm system moves in the opposite direction as the flood wave, additional rainfall does not create higher peak flows to the already moving flood wave. However, the total time duration of the flood wave is longer. Peak discharges are listed in Table 9-20.

The time to peak flow is shorter for the storm system moving upstream to downstream. In contrast the time to peak flow is longer for the storm system moving downstream to upstream. The time to peak values are listed in Table 9-20.

The time width of the dimensionless hydrographs at both the 50% and 75% peak flow level are much smaller for the storm system moving from the upstream to downstream. The time width is larger for the storm system moving downstream to upstream. The 50% and 75% time width intervals are listed in Table 9-20.

Dimensionless plots (q/qp versus t/tp) were developed for upstream to downstream moving storm systems. The dimensionless hydrograph shows a very "rounded" peak flow with rapid rising and falling limbs with a narrow time base. It is suspected that this very "rounded" peak may be due to the basin reaching equilibrium conditions for this rainfall intensity. Further research is required. Also, because the storm system moves in the same direction as the already generated flood wave, additional rainfall creates higher peak flows to the already moving flood wave.

Dimensionless plots (q/qp versus t/tp) were also developed for downstream to upstream moving storm systems. The dimensionless hydrograph shows a more "rounded" shape at peak flow with a more gradual rising and falling limb with a wider time base. Because the storm system moves in the opposite direction as the flood wave, additional rainfall does not create higher peak flows to the already moving flood wave. However, the total time duration of the flood wave is longer. Also, several minor peak fluctuations occur on the rising limb of the hydrograph. This is most likely due to various subbasin and drainage geometry of the lower part of the basin which has a more immediate impact on the hydrologic response when compared to the upper basin. This is definitely more noticeable as the storm system moves upstream away from the basin

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outlet. In contrast, when the storm system moves from upstream to downstream, these fluctuations are "dampened" out due to added rainfall falling on top of the already generated flood wave. Dimensionless plots are presented in Appendix 4e.

9.2.2.2.2. Lumped Rainfall

Lumped rainfall was applied over the basin as the storm system moved either upstream to downstream or downstream to upstream across the drainage. The rainfall rate across the basin was constant as the storm systems moved across the basin at a uniform rate. The only difference was the direction of movement of the storm systems.

Dimensionless plots (q/qp versus t/tp) were developed for the Greenville drainage. The dimensionless hydrograph resulting for the lumped rainfall case has a somewhat gradual rise and fall with a somewhat more "rounded" peak flow. This dimensionless hydrograph plot is presented in Appendix 2e.

9.2.2.2.3. Distributed versus Lumped Rainfall Comparison

Simulated hydrologic basin response comparisons were made between distributed and lumped rainfall for moving storm systems. These systems moved either upstream to downstream or downstream to upstream across the drainage basin.

The peak discharge ratio (distributed versus lumped) for the storm system moving upstream to downstream is 1.44. This indicates that the simulated peak discharge magnitude at the basin outlet is greater for distributed rainfall than for the lumped. In

contrast, the peak discharge ratio for the storm system moving in the opposite direction, downstream to upstream, is 0.70. This indicates that the simulated peak discharge is smaller for distributed rainfall than for the lumped. Peak discharge ratios for the Greenville drainage are listed in Table 9-20.

Time to peak flow ratios (distributed versus lumped) for the storm system moving upstream to downstream is 0.94. This indicates that the travel time is shorter for distributed rainfall than for the lumped. In contrast, the time to peak flow ratio for the storm system moving in the opposite direction, downstream to upstream, is 1.24. This indicates that the travel time is longer for distributed rainfall than for the lumped. The time to peak flow ratios for the Greenville drainage are listed in Table 9-20.

Time width ratios at the 50% and 75% peak flow intervals for the storm system moving upstream to downstream are 0.58 and 0.83, respectively. This indicates that the width of the hydrograph is narrower for the distributed rainfall compared to the lumped. In contrast, time width ratios at the 50% and 75% interval for the storm system moving in the opposite direction, downstream to upstream, were 1.83 and 1.5, respectively. This indicates that the width of the hydrograph is wider for distributed rainfall compared to the lumped. These ratios are listed in Table 9-20.

Dimensionless plots (q/qp versus t/tp) were developed for upstream to downstream moving storm systems. For distributed rainfall, the hydrograph has a rising limb which began later in time and has a narrower time base. The hydrograph is very

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"rounded" at the peak flow, which may be due to the basin reaching equilibrium conditions. Further research is required. For the lumped case, the hydrograph has a rising limb which begins earlier in time, is "rounded", and has a wider time base.

Dimensionless plots (q/qp versus t/tp) were also developed for downstream to upstream moving storm systems. For distributed rainfall, the hydrograph has a rising limb which began earlier in time, is more "rounded", and has a wider time base. In comparison, the lumped case began later in time and has a narrower time base. Also, the distributed case shows several minor peak fluctuations on the rising limb of the hydrograph. This is most likely due to various subbasin and drainage configurations of the lower part of the basin which has a more immediate impact on the hydrologic response when compared to the upper basin. This is definitely more noticeable as the storm system moves upstream away from the basin outlet. These dimensionless hydrographs are presented in appendix 4e.

Table 9-19. Distributed versus Lumped Summary Table; Cowleech Fork Sabine River near Greenville, Texas; Rainfall Rate = 1 inch in 5 hours

	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
		(cfs)	(hours)			(cfs)	(hours)			(cfs)	(hours)		
Stationary Storm													
Distributed	upper 22%	2474	8	2.282	0.8	1856	1	2.283	0.25	1237	3	2.282	0.375
Distributed	middle 22%	2319	7	2.139	0.7	1739	2	2.139	0.50	1160	4	2.140	0.5
Distributed	lower 22%	2308	5	2.129	0.5	1731	3	2.129	0.75	1154	4	2.129	0.5
Lumped	entire basin	1084	10			813	4			542	8		
Moving Storm													
Distributed	up to down	1722	10	1.690	0.833	1292	2	1.691	0.5	861	4	1.688	0.5
Lumped	up to down	1019	12			764	4			510	8		
Distributed	Down to up	702	15	0.689	1.250	527	9	0.690	2.25	351	14	0.688	1.75
Lumped	Down to up	1019	12			764	4			510	8		

Table 9-20. Distributed versus Lumped Summary Table; Cowleech Fork Sabine River near Greenville, Texas; Rainfall Rate = 1 inch in 10 hours

	Rainfall Location	Peak Flow (P_x)	Peak Time (t_x)	Ratio P_d/P_l	Ratio t_d/t_l	75% Peak Flow (P_{75})	75% Time Width (t_{75})	75% Ratio P_{75d}/P_{75l}	75% Ratio t_{75d}/t_{75l}	50% Peak Flow (P_{50})	50% Time Width (t_{50})	50% Ratio P_{50d}/P_{50l}	50% Ratio t_{50d}/t_{50l}
		(cfs)	(hours)			(cfs)	(hours)			(cfs)	(hours)		
Stationary Storm													
Distributed	upper 22%	1195	11	1.350	0.917	896	6	1.349	1.200	598	8	1.350	0.8
Distributed	middle 22%	1160	9	1.311	0.750	870	6	1.310	1.200	580	8	1.309	0.8
Distributed	lower 22%	1155	7	1.305	0.583	866	7	1.304	1.400	578	9	1.305	0.9
Lumped	entire basin	885	12			664	5			443	10		
Moving Storm													
Distributed	up to down	1118	16	1.439	0.941	839	5	1.439	0.833	559	7	1.437	0.583
Lumped	up to down	777	17			583	6			389	12		
Distributed	Down to up	540	21	0.695	1.235	405	11	0.695	1.833	270	18	0.694	1.5
Lumped	Down to up	777	17			583	6			389	12		

9.3. Summary

This chapter discussed the results which were obtained from this investigation. Hydrologic simulations were conducted using the kinematic wave technique for both synthetic rectangular drainage basins and an actual drainage basin located in North Texas. Precipitation was applied as both distributed versus lumped rainfall to stationary and moving storm systems.

The first section of this chapter discusses the results obtained using synthetic rectangular drainage basins. The second section discusses the results obtained using an actual drainage basin. The next chapter presents conclusions from this investigation.

CHAPTER 10

CONCLUSIONS

Hydrologic simulations were conducted using the kinematic wave technique via the U.S. Geological Survey Modular Modeling System (MMS). Hydrologic simulations were generated for both synthetic rectangular drainage basins and an actual drainage basin (Cowleech Fork Sabine River near Greenville, Texas). Both stationary storms and moving storms were applied to the basin events as either distributed or lumped precipitation.

Due to the complexity of the hydrologic processes, impervious basins were used for this study. This allowed for a better understanding of how the actual location of and movement of rainfall across a basin for both stationary and moving storms impacted the hydrologic response of the basin for both distributed and lumped models.

This chapter discusses the conclusions which can be drawn from this investigation. The first section deals with the stationary storms. The second section deals with moving storms. The third section discusses the major findings which resulted from this investigation. The fourth section summarizes the study and provides some final comments.

10.1 Stationary Storm Events

Stationary storms using both distributed and lumped rainfall were applied to the synthetic rectangular drainage basins. Three overland flow planes slopes were used as part of this investigation. These slopes are 16.22%, 9.12%, and 4.05%. Distributed rainfall of 1 inch over a 10 minute time period was applied over the upper 20%, middle 20%, and lower 20% of each synthetic rectangular basin, equivalent to a mean areal basin precipitation of 0.2 inch. Lumped rainfall of 0.2 inch over a 10 minute time period was also applied uniformly over the entire basin.

Stationary storm events using both distributed and lumped rainfall were also applied to the Cowleech Fork Sabine River near Greenville, Texas drainage basin. Two hypothetical storms were selected: (1) a 1 inch storm with a 5 hour duration, and (2) a 1 inch storm with a 10 hour duration. Distributed rainfall was applied over the upper 22%, middle 22%, and lower 22% of the basin for each storm, equivalent to a mean areal basin precipitation of 0.22 inch. Lumped rainfall of 0.22 inch was also applied uniformly over the entire basin for each storm.

Peak flow simulations were conducted for both the synthetic rectangular drainage areas (all three overland flow plane slopes) and the Greenville drainage area. For every test case for these runoff scenarios, distributed rainfall applied over the upper, middle, and lower region which resulted in approximately the same simulated peak flows at the

basin outlet. These simulated flows did not attenuate as the flood wave traveled downstream. Also, simulated peak flow was also higher for the distributed cases than the lumped cases.

Peak flow ratios (distributed versus lumped) for the rectangular basins typically ranged from 1.8 to 3.0, with the majority of the cases ranging from 2.5-3.0. The few values which were small were associated with the very small rectangular drainage basins. For the Greenville drainage area, these ratios ranged from 2.1-2.3 for the 5 hour storm event and were approximately 1.3 for the 10 hour event. This indicates that the magnitude of the simulated peak discharges are much greater for distributed rainfall than for lumped rainfall events. Also, there is more variation among the peak flow ratios for the 5 hour event than for the 10 hour event. Peak flows for the lumped and distributed cases are close in magnitude for the 10 hour event. It should be noted that equilibrium conditions were reached for the 10 hour event. Also, rainfall intensity is higher for the 5 hour event than it is for the 10 hour event.

Time to peak flow ratios (distributed versus lumped) for the rectangular basins ranged from 0.4 to 0.8. For the Greenville drainage, these ratios ranged from 0.5 to 0.8 for the 5 hour storm duration and from 0.6 to 0.9 for the 10 hour storm duration. This indicates that the travel time for peak flow to reach the basin outlet is shorter for the distributed cases when compared to the lumped cases.

Time width ratios (distributed versus lumped) at the 50% and 75% peak flow levels ranged from 0.3 to 0.4 for the rectangular basins. For the Greenville drainage, these ratios ranged from 0.25 to 0.75 for the 5 hour storm for both the 50% and 75% intervals. This indicates that the width of the hydrographs is narrower for the distributed cases compared to the wider lumped case. However, for the 10 hour storm, these ratios ranged from 1.2-1.4 for the 75% level and 0.8-0.9 for the 50% level. Because these results are mixed, further investigation is warranted before drawing any conclusions. Watershed equilibrium was reached with the 10 hour storm. Also, 1 minute time periods may need to be refined to smaller 1 second intervals to better simulate watershed equilibrium. At this time, results are inconclusive.

Dimensionless hydrographs were also generated for the synthetic rectangular drainage basins. For all three distributed rainfall cases, the overall shapes of the dimensionless hydrographs are very similar. However, there is some difference in the rate of rise and timing of the rising limb of the hydrograph. For rainfall applied in the lower 20% of the basin, the rise begins earlier and is not as steep when compared to rainfall applied over the upper 20%, which has a delayed rise that is much steeper. The receding limbs for all three distributed cases are very similar. When the distributed cases are compared to the lumped case, the hydrograph for the lumped case has a wider time base. The rising limb of the lumped case is also similar to the distributed case applied over the lower 20% of the basin. Finally, the receding limb of the lumped case occurs later than the three distributed cases.

Dimensionless hydrographs were also developed for the Cowleech Fork Sabine River near Greenville, Texas. The overall shape of the rising and receding limbs of the dimensionless hydrographs is similar for the three distributed rainfall cases. The only major difference is the rate of rise and the timing of the rising limb of the hydrograph. For both the 5 hour and 10 hour storm duration, rainfall applied in the lower 22% began earlier than for the upper 22%, which has a delayed rise. The shape of the falling limb of the hydrographs is very similar. The shape of the hydrograph at peak flow conditions varied between the two storm durations. For the shorter 5 hour duration, the hydrograph has a "rounded" hydrograph peak. For the longer 10 hour duration, the peak flow is constant indicating that the basin has reached equilibrium. Also, for the 10 hour event, the receding limb begins sooner when rainfall is applied to the lower 22% of the basin, rather than the upper 22%.

10.2. Moving Storm Events

Two moving storm systems with both a constant uniform velocity and rainfall rate were applied to each rectangular basin and the Cowleech Fork Sabine River near Greenville, Texas. These storm systems moved either from the upstream to downstream or from the downstream to upstream direction across each drainage basin.

For the rectangular basins, both distributed and lumped rainfall was applied to each drainage area. These storm events consisted of mean areal rainfall volumes of 0.2

inch. For the Greenville drainage area, these storm events consisted of mean areal rainfall volumes of 0.22 inch.

Peak discharges are higher for storm systems moving upstream to downstream when compared to storms moving in the opposite direction. Because the storm system is moving in the same direction as the flood wave, additional rainfall contributes to even higher peak flow rates for the already moving flood wave. In contrast, peak discharges are lower for storm systems moving downstream to upstream. Because the storm system moves in the opposite direction as the flood wave, additional rainfall does not contribute to higher peak flow rates for the already moving flood wave. However, the total time duration of the flood wave is longer.

Peak flow ratios (distributed versus lumped) for the upstream to downstream moving storm systems applied to the rectangular basins were generally slightly greater than 1. This indicates that simulated peak discharge magnitudes at the basin outlet are similar for both the distributed and lumped rainfall events. For the Greenville drainage area, these ratios were 1.69 and 1.44 for the 5 hour and 10 hour storm durations, respectively. This indicates that simulated peak discharges are higher for distributed rainfall compared to lumped rainfall.

Peak flow ratios (distributed versus lumped) for the downstream to upstream moving storm systems for the rectangular basins were generally slightly less than 1. This

indicates that simulated peak discharges at the basin outlet are similar for both the distributed and lumped rainfall events. For the Greenville drainage area, these ratios were 0.69 and 0.70 for the 5 hour and 10 hour storm durations, respectively. This indicates that simulated peak discharges are lower for the distributed rainfall compared to the lumped rainfall.

Time to peak flow ratios (distributed versus lumped) for the upstream to downstream moving storm system for the rectangular basins ranged from 0.8 to 0.9. For Greenville, these ratios were 0.83 and 0.94 for the 5 hour and 10 hour storm durations, respectively. This indicates that the travel time for peak flow to reach the basin outlet is shorter for the distributed cases when compared to the lumped cases.

Time to peak flow ratios (distributed versus lumped) for the downstream to upstream moving storm systems for the rectangular basins ranged from 1.0 to 1.2. For Greenville, these ratios were 1.25 and 1.24 for the 5 hour and 10 hour storm durations, respectively. This indicates that the travel time for peak flow to reach the basin outlet is longer for the distributed cases when compared to the lumped cases.

Time to width ratios (distributed versus lumped) at the 50% and 75% peak flow levels for the upstream to downstream moving storm systems for the rectangular basins were generally mixed results. These values were typically close to 1 indicating that the width of the hydrographs is very similar for both distributed and lumped rainfall. For

Greenville, these ratios were 0.5 for both the 50% and 75% levels with the 5 hour storm duration. These ratios were also 0.58 and 0.83 for both the 50% and 75 % levels for the 10 hour storm duration. This indicates that the width of the hydrograph is narrower for the distributed rainfall compared to the lumped.

Time to width ratios (distributed versus lumped) at the 50% and 75% peak flow levels for the downstream to upstream moving storm systems with rectangular basins yielded mixed results. Ratios were typically close to 1 indicating that the width of the hydrographs is similar for both distributed and lumped rainfall. For Greenville, these ratios were 1.75 and 2.25 for the 50% and 75% levels, respectively, with the 5 hour storm duration. These ratios were 1.83 and 1.50 for the 10 hour storm duration. This indicates that the hydrograph is wider for the distributed rainfall than for the lumped.

Dimensionless hydrographs were also generated for storm systems moving from upstream to downstream. For the synthetic rectangular drainage basins, the rising limb for distributed rainfall begins later in time compared to the lumped case. The receding limb also has a delayed response. For Greenville, the rising limb with distributed rainfall also begins later in time compared to the lumped case. The receding limb, however, is approximately the same for both distributed and lumped rainfall.

Dimensionless hydrographs were also generated for storm systems moving from downstream to upstream. For the synthetic rectangular drainage basins, the rising limb

for distributed rainfall begins earlier compared to the lumped case. However, the receding limb is approximately the same for both the distributed and lumped cases. For Greenville, the rising limb for distributed rainfall also begins earlier compared to the lumped case. The receding limb is approximately the same for both the distributed and lumped cases.

10.3. Major Findings

Several major findings can be concluded from this report. These include:

1. Simulated peak flows did not attenuate as the flood wave progressed downstream. This is a deficiency of the kinematic wave technique and may impose significant limitations when applied to distributed modeling. Actual flood hydrographs typically attenuate as they progress downstream. The physical characteristics governing the kinematic wave approach do not allow for attenuation. Therefore, the kinematic wave technique may have significant limitations when used for distributed modeling of large scale river basins.

2. Peak flow ratios (distributed versus lumped) are typically much higher for stationary events than for moving storm events.

3. Peak flow ratios (distributed versus lumped) for stationary storm systems are much greater than 1.

4. Peak flow ratios (distributed versus lumped) for upstream to downstream moving storm systems are greater than 1.

5. Peak flow ratios (distributed versus lumped) for downstream to upstream moving storm systems are less than 1.

6. Peak flow ratios (distributed versus lumped) are greater for high intensity rainfall events. This is observed on the Cowleech Fork Sabine River near Greeenville, Texas drainage area.

7. Time to peak ratios (distributed versus lumped) for stationary storm systems were less than 1.

8. Time to peak ratios (distributed versus lumped) for upstream to downstream moving storm systems are less than 1.

9. Time to peak ratios (distributed versus lumped) for downstream to upstream moving storm systems are greater than 1.

10. Time width ratios (distributed versus lumped) at the 50% and 75% peak flow rate levels for stationary storm events were less than 1 in most cases. However, for Greenville, these values were greater than 1 at the 75% interval with the 10 hour storm duration which met equilibrium conditions.

11. Time width ratios (distributed versus lumped) at the 50% and 75% peak flow rate levels for upstream to downstream moving storm systems over synthetic rectangular basins were inconclusive. For the Greenville drainage area, these ratios were less than 1 for both the 5 and 10 hour storm durations.

12. Time width ratios (distributed versus lumped) at the 50% and 75% peak flow rate levels for downstream to upstream moving storm systems over synthetic rectangular basins were inconclusive. For Greenville, these ratios were greater than 1 for both the 5 and 10 hour storm durations.

13. Dimensionless hydrograph shapes differ between drainage basins that reach equilibrium conditions compared to those that do not.

14. The hydrologic response of distributed and lumped models is highly dependent on storm location and whether the storm system is moving or stationary.

10.4. Final Comments

Distributed hydrologic modeling is often viewed as the future direction of the hydrologic sciences. Traditionally, hydrologic investigations have been conducted using lumped models. However, with recent technological advances, distributed models are seen as a way to capture the various hydrologic conditions across drainage areas and ultimately the hydrologic basin response.

Most distributed models are based on the kinematic wave theory for both the overland flow planes and channel routing. However, the kinematic wave is limited in its ability to adequately simulate the hydrologic response over large scale river basins. The kinematic wave method is based strictly on gravity and friction, which does not allow for the attenuation of a flood wave. Although minor attenuations may occur as the flood wave is routed downstream, this is due to the numerical properties of the finite difference scheme used to solve equations of kinematic wave theory, not the actual physical mechanisms.

The limitations of the kinematic wave method are quite noticeable with stationary storm. However, the impact of this method becomes difficult to distinguish for moving storm events in conjunction with flood wave translation down a river system.

The kinematic wave has been very beneficial for developing the foundations of distributed modeling. However, techniques such as the diffusion wave technique which allow for flood wave attenuation should be investigated as a means to further advance the application of distributed modeling. For more complex hydraulic situations where backwater conditions exist, the full dynamic wave technique may need to be implemented.

Distributed modeling has great potential for revolutionizing the hydrologic sciences. Additional research is needed to further enhance the capabilities of hydrologic distributed modeling.

CHAPTER 11

RECOMMENDATIONS FOR FURTHER RESEARCH

Distributed modeling implementation is a relatively new concept in the

hydrologic sciences. Many unknowns exist concerning distributed modeling. Because of

this, research needs to continue with the goal of finding ways to effectively implement

distributed modeling for enhanced hydrologic simulation of drainage basins. Some

suggested areas for further research are discussed below.

11.1. Diffusion Wave Models

An area of research which may improve distributed modeling is the application of

diffusion wave models. The impact of distributed models using this method is largely

unknown.

Distributed modeling has its roots based in the full dynamic wave (i.e. Saint

Venant) equations. The full dynamic wave is physically based and is a function of both

local and convective acceleration, hydrostatic pressure forces, gravitational forces, and

frictional forces. The diffusion wave is a simplified form of the full dynamic wave and is

based on the physical concepts of hydrostatic pressure, gravity, and friction. The

kinematic wave further simplifies the full dynamic process and is based on gravity and friction.

Most distributed models have adopted the kinematic wave due to its simplicity. Unfortunately, the kinematic wave has limitations which adversely impact hydrologic simulations. The kinematic wave is best suited for urban environments with relatively steep, uniform channel reaches with no overbank flow conditions. The kinematic wave only translates a flood wave; it does not allow for the attenuation of a flood wave.

Diffusion wave models have an additional physical component beyond what is included in the kinematic wave, i.e. hydrostatic pressure. This added component allows for the attenuation of a flood wave as it translates across overland flow planes and downstream. The diffusion wave is still simpler than the full dynamic wave, making it easier to apply to hydrologic situations.

11.2. Diffusion Wave and Kinematice Wave Models in Conjunction with Full Dynamic Wave Models

An additional areal of research would be to integrate a full dynamic wave for stream channels in conjunction with the diffusion wave for overland flow. During flood events, especially over flat terrain, backwater can significantly impact streamflow. With this in mind, the full dynamic wave model will take into account backwater issues in

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stream channels, where as, the diffusion wave will attenuate flow over the overland flow plane.

11.3. Rainfall Areal Coverage Applied to Synthetic Rectangular and an Actual Drainage Basin

An area of research which may improve the understanding of distributed modeling is to apply various hypothetical rainfall coverage patterns as both distributed and lumped rainfall to impervious synthetic rectangular and an actual drainage basin. For example, distributed rainfall could be applied over the upper, middle, and lower 10%, 25%, and 40% of each basin and compared with the hydrologic simulations generated using lumped rainfall. From there, ratios (distributed versus lumped) for peak flow, time to peak, and time width ratios could be compared for each areal rainfall coverage pattern.

11.4. Investigation of Distributed Modeling for Actual Drainage Basins

An additional area of research is to investigate distributed models for actual drainage basins. These studies would incorporate different basin shapes, more complex drainage patterns, different soil types, different vegetation types, and different land use patterns across a watershed. In addition, research needs to be conducted for basins where the runoff production mechanism is either Hortonian (Infiltration-Excess) or Dunne (Saturation-Excess) type runoff.

APPENDIX A

COMPARISON OF OVERLAND FLOW PLANE SLOPES
SLOPES = 16.22%, 9.12%, AND 4.05%
DIMENSIONLESS HYDROGRAPHS
SYNTHETIC RECTANGULAR BASINS

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
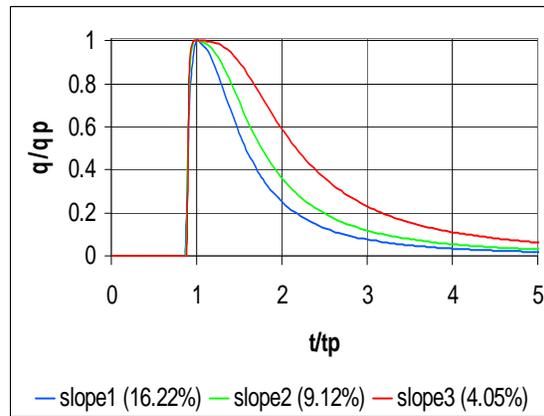
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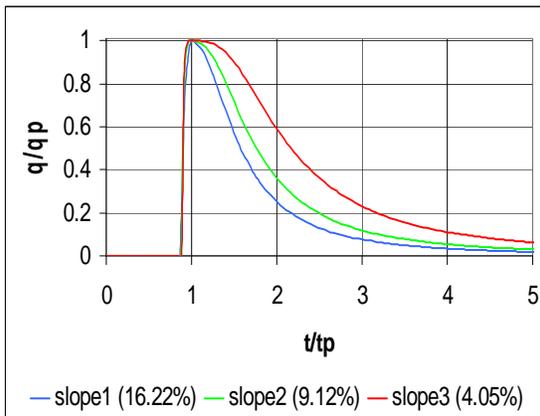
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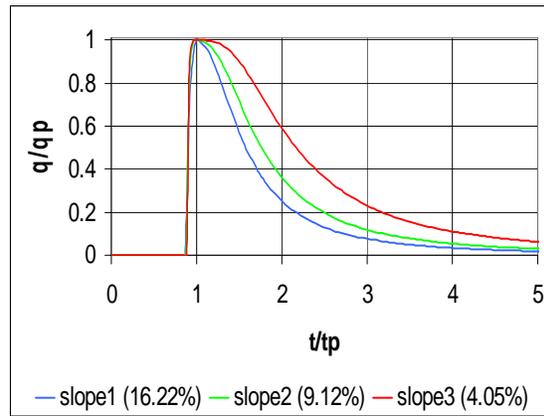
Constant Length (cl)

Appendix 1a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Shape Factor = 1

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
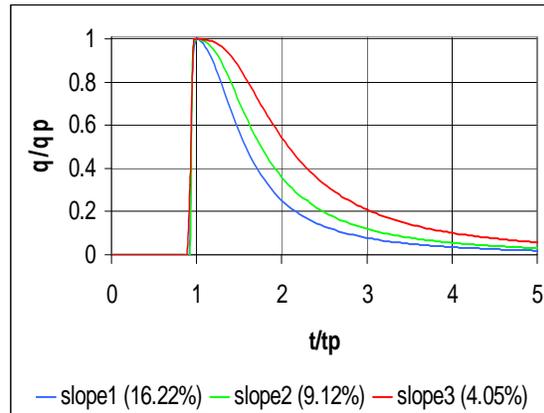
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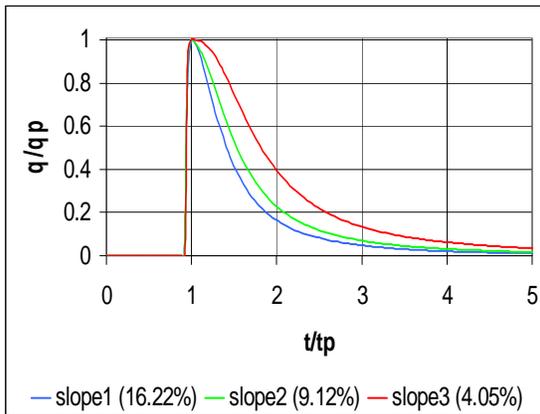
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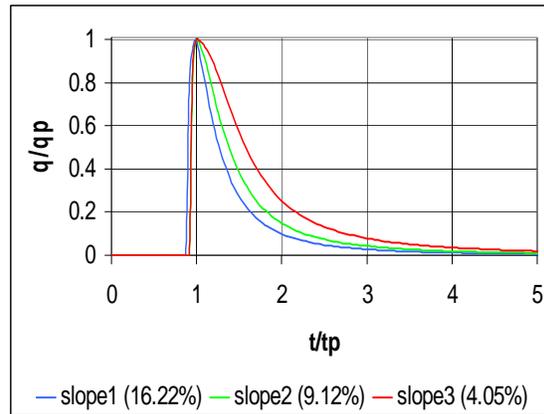

Constant Length (cl)

Appendix 2a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
                   Dimensionless Hydrographs – Synthetic Rectangular Basins
                   Stationary Storm – Upper 20% – Distributed Rainfall
                   Shape Factor = 2

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
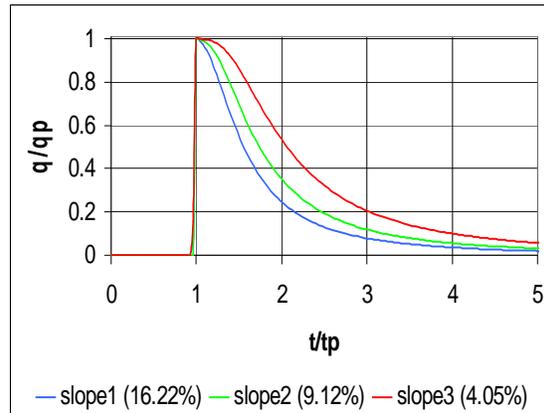
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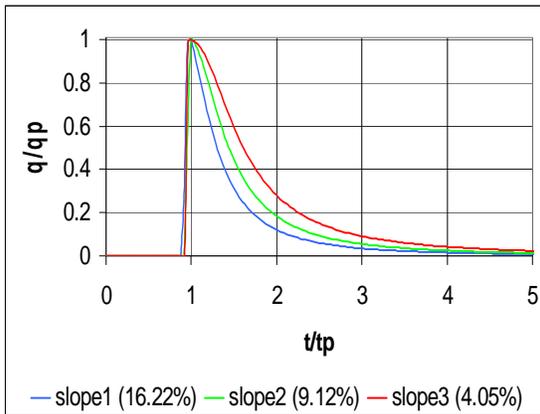
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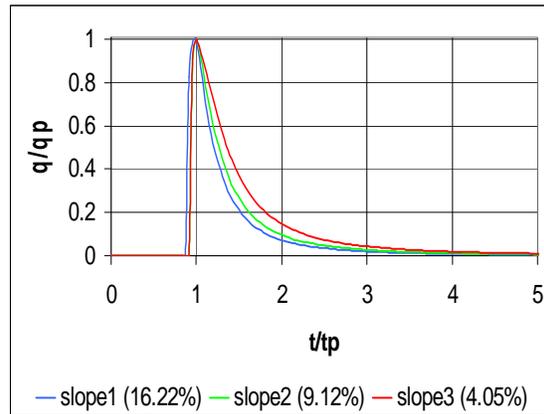

Constant Length (cl)

Appendix 3a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Shape Factor = 3

252

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
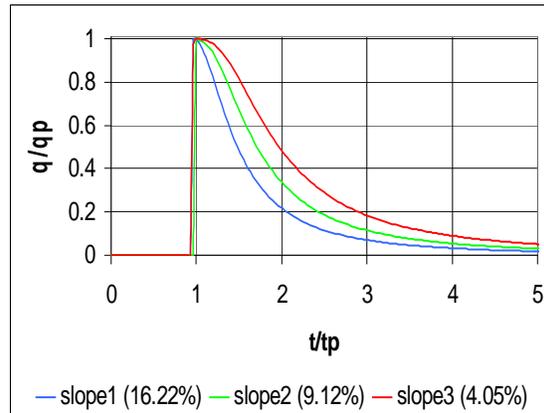
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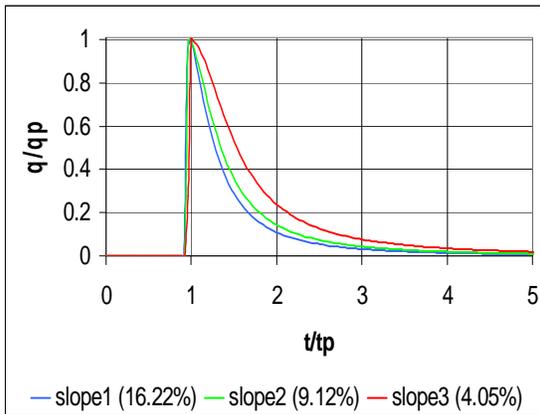
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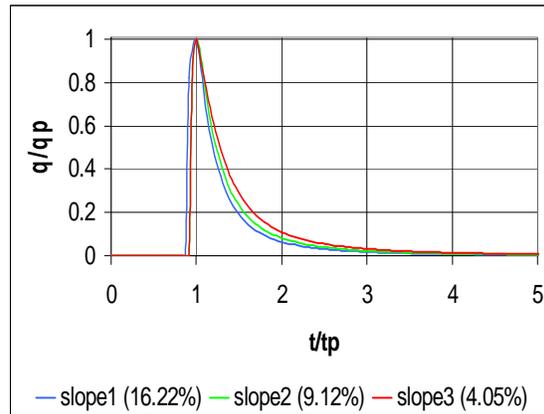

Constant Length (cl)

Appendix 4a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Shape Factor = 4

253

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
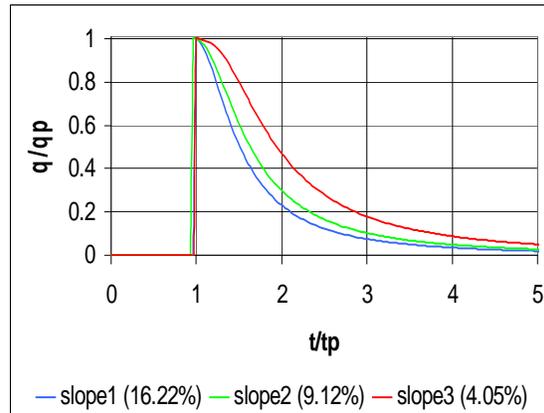
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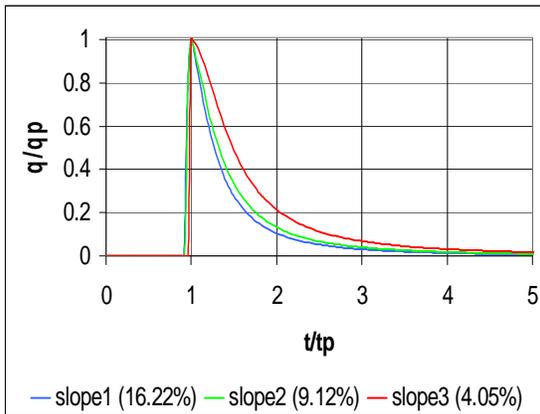
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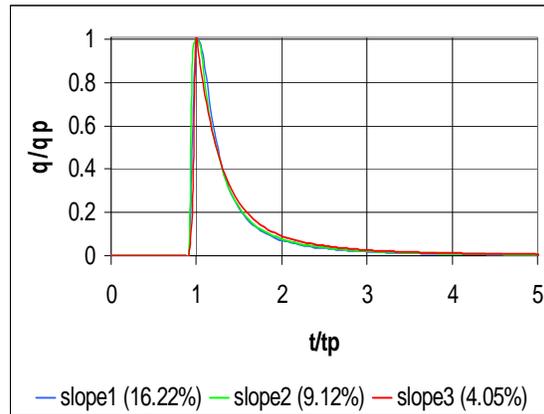
Constant Length (cl)

Appendix 5a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Shape Factor = 5

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
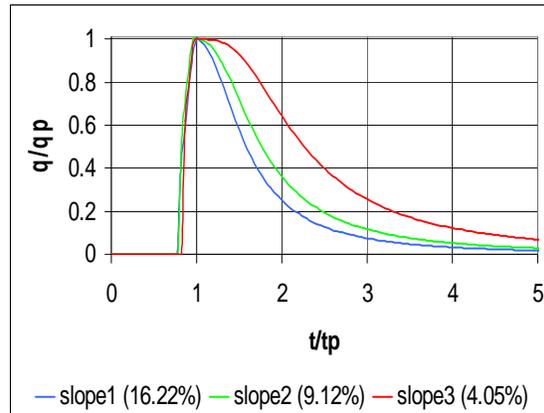
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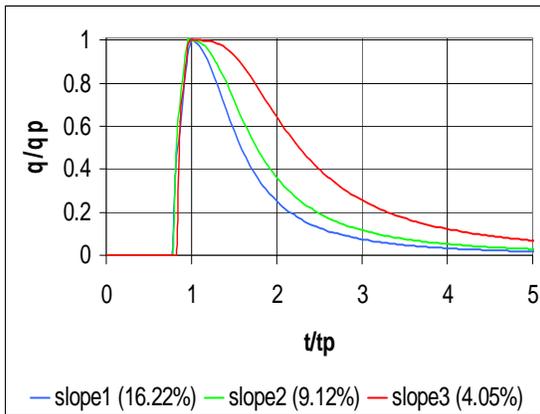
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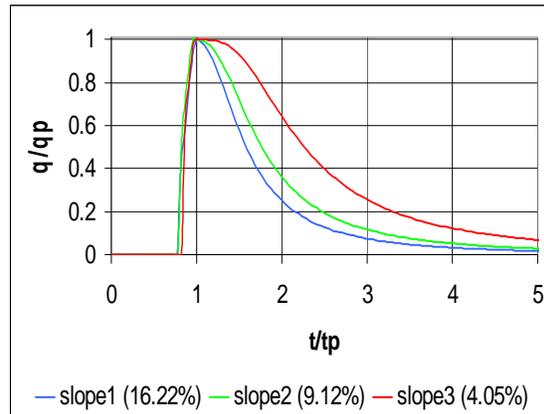
Constant Length (cl)

Appendix 6a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Shape Factor = 1

255

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
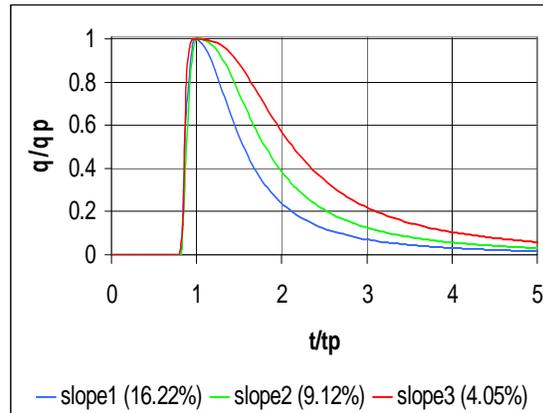
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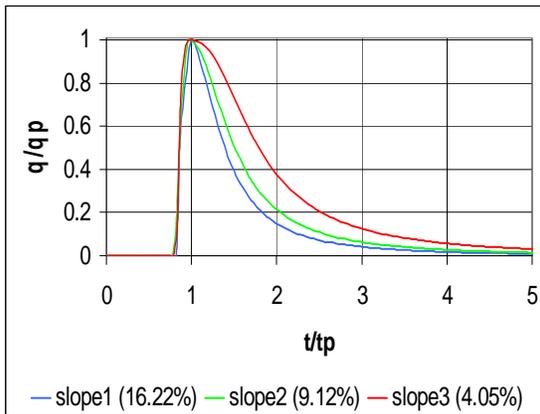
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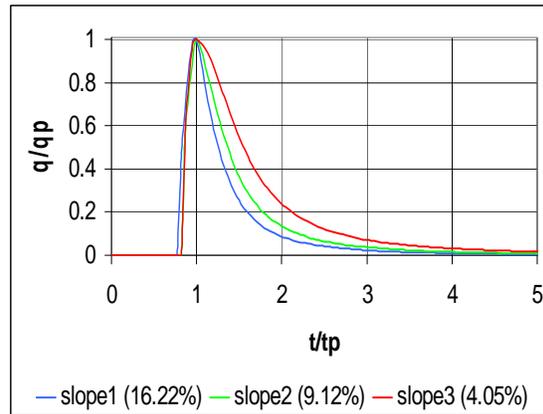
Constant Length (cl)

Appendix 7a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Shape Factor = 2

256

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
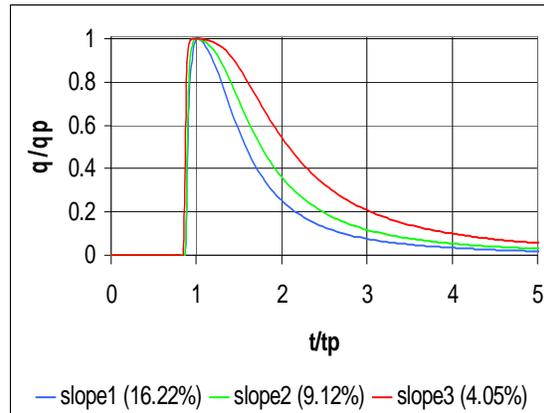
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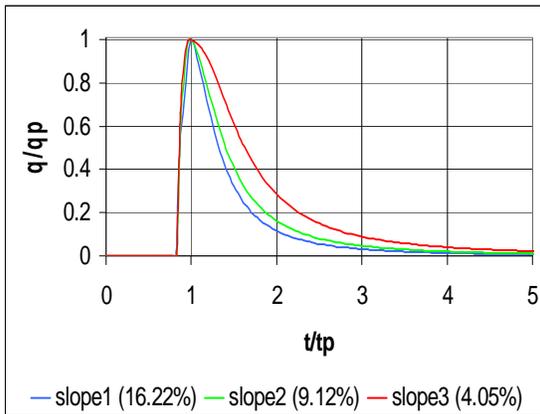
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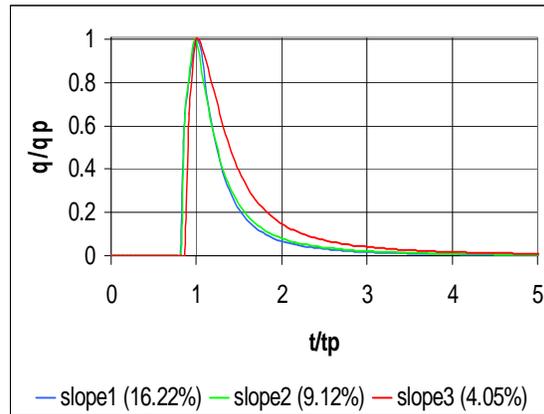
Constant Length (cl)

**Appendix 8a.** Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Shape Factor = 3

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
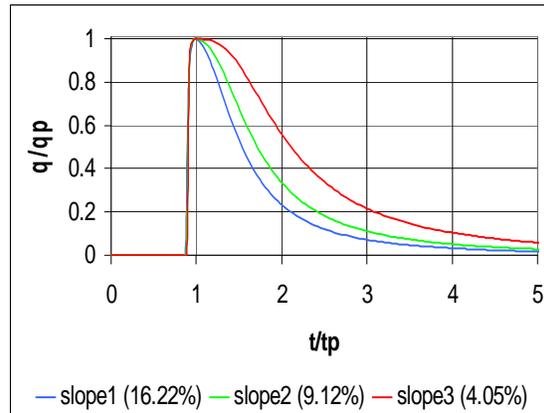
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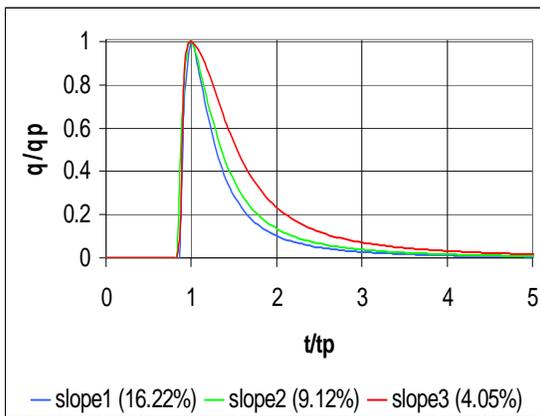
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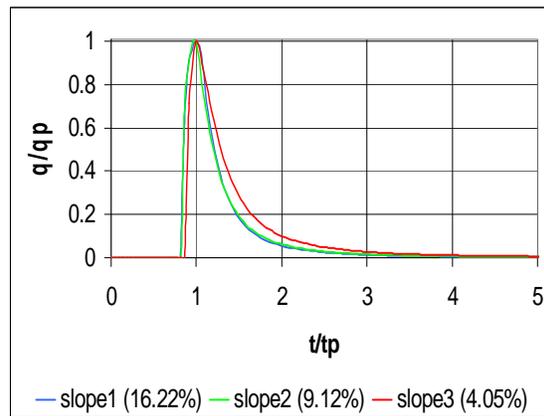
Constant Length (cl)

**Appendix 9a.**   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Shape Factor = 4

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
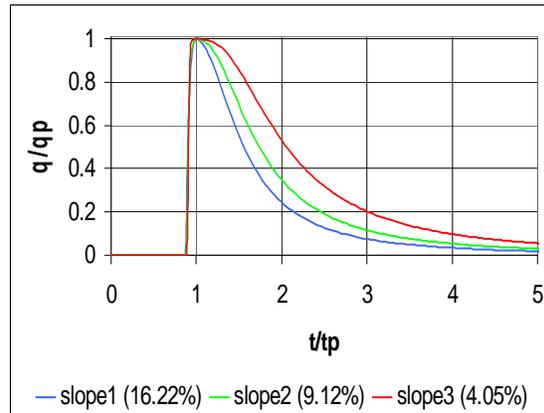
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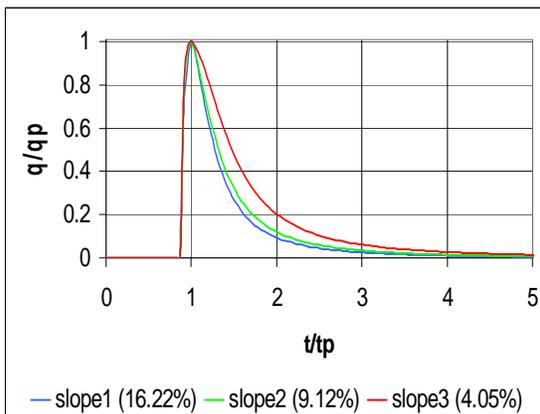
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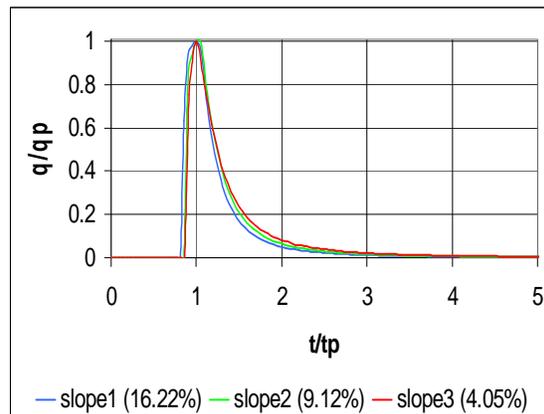
Constant Length (cl)

**Appendix 10a.** Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Shape Factor = 5

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
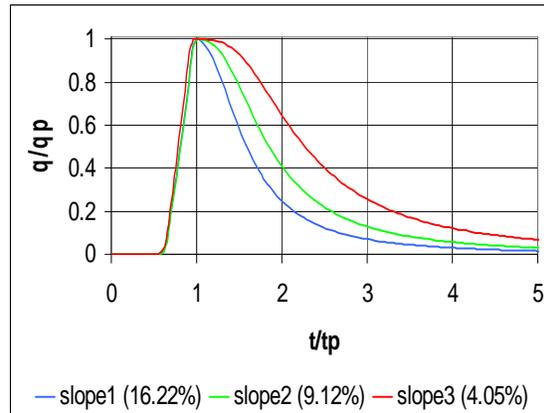
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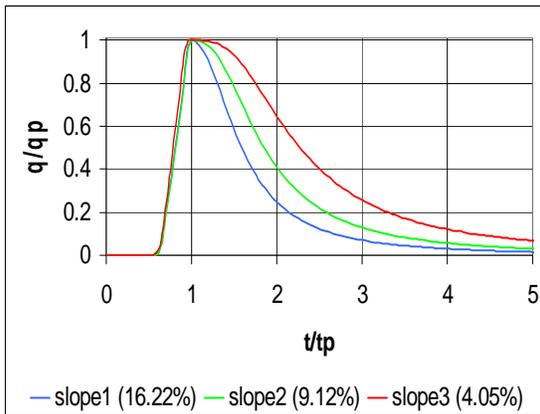
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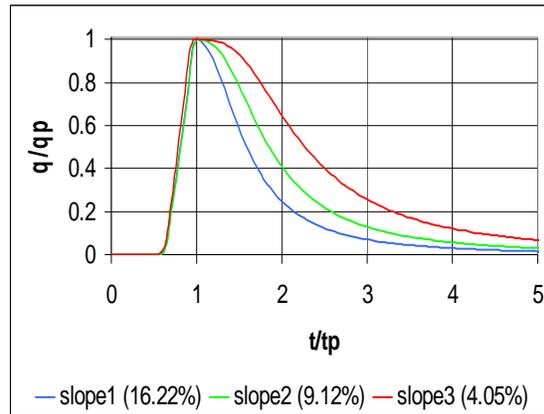

Constant Length (cl)

Appendix 11a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Shape Factor = 1

260

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
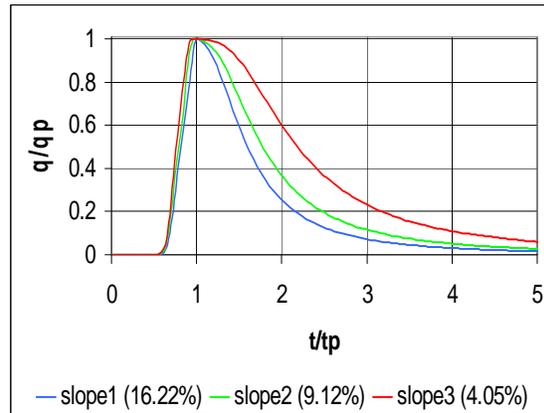
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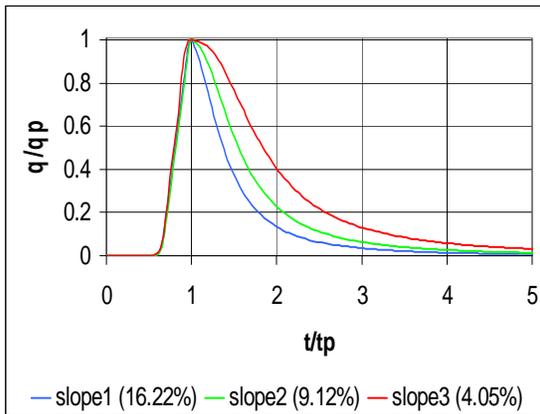
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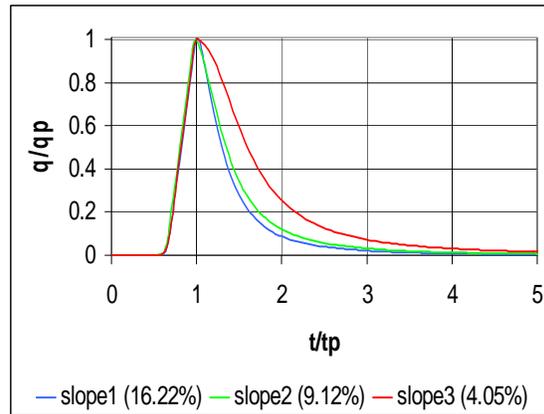
Constant Length (cl)

Appendix 12a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Shape Factor = 2

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
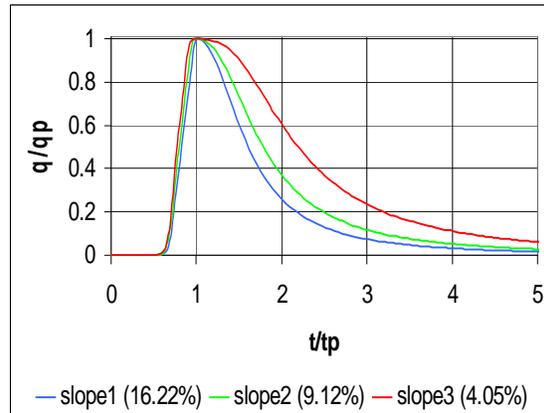
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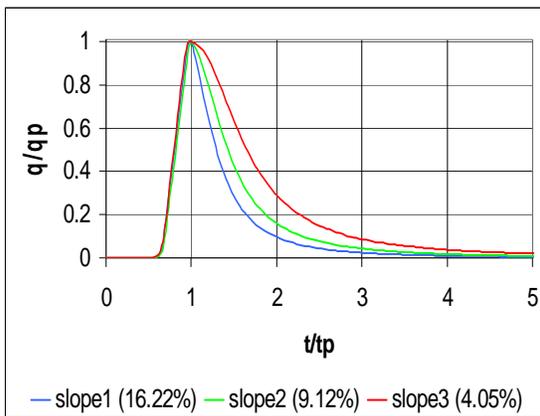
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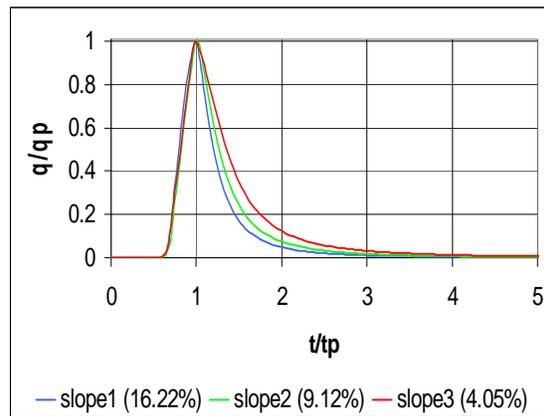

Constant Length (cl)

Appendix 13a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Shape Factor = 3

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
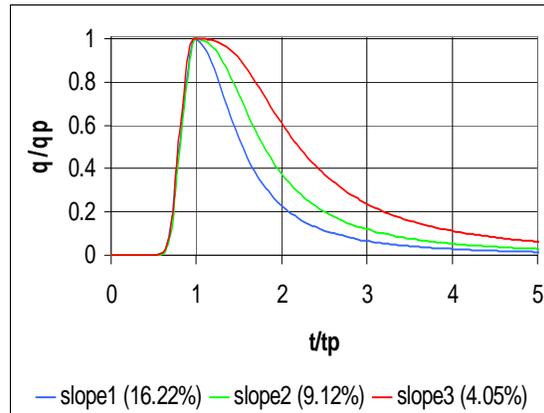
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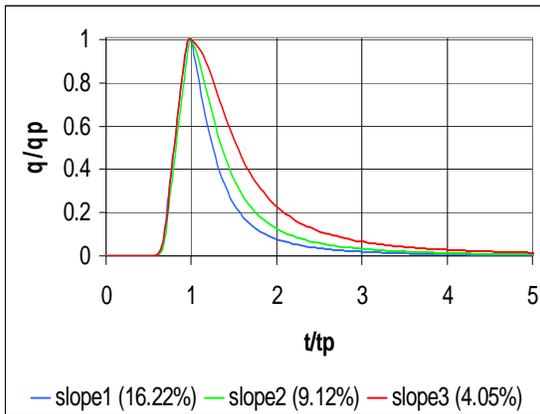
Constant Area (ca)
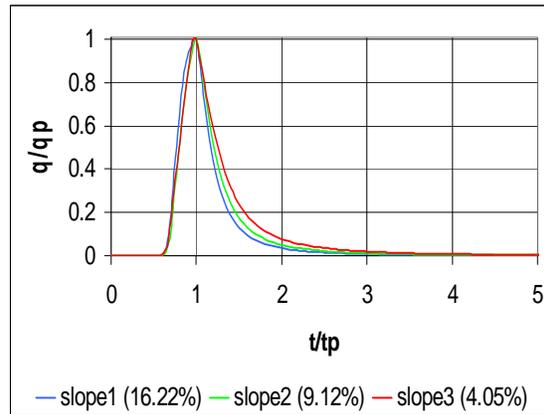

Constant Length (cl)

Appendix 14a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Shape Factor = 4

263

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
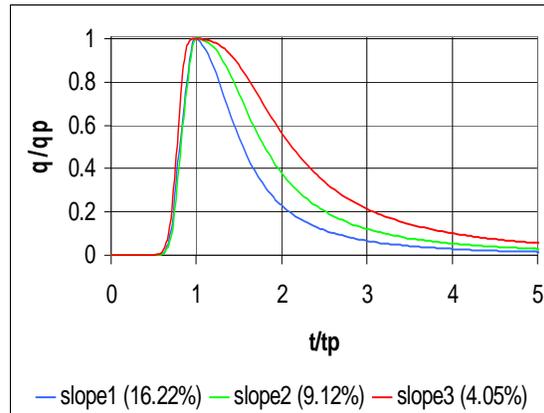
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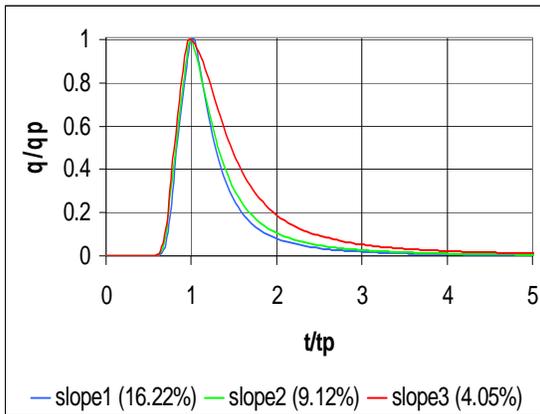
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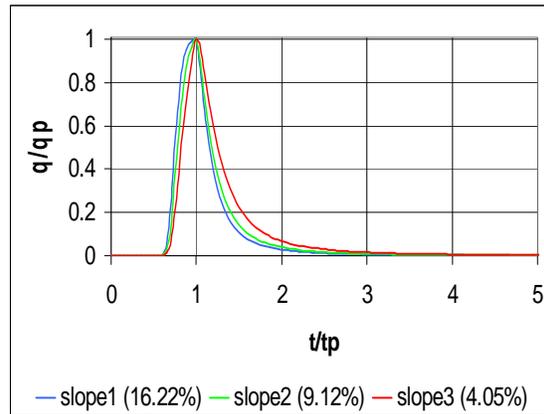

Constant Length (cl)

Appendix 15a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Shape Factor = 5

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
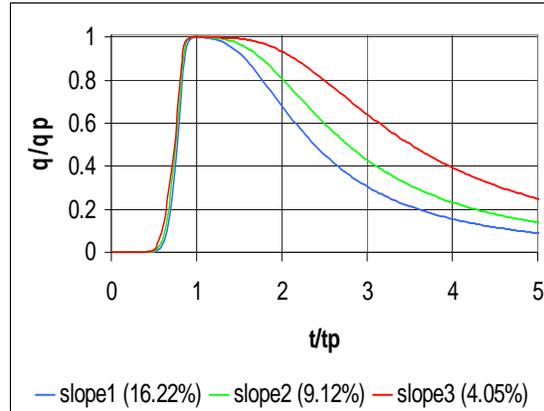
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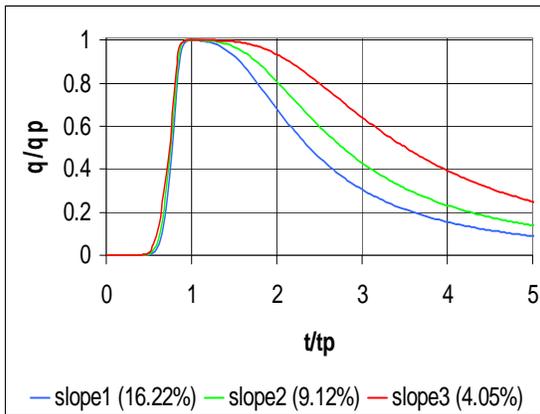
Constant Area (ca)
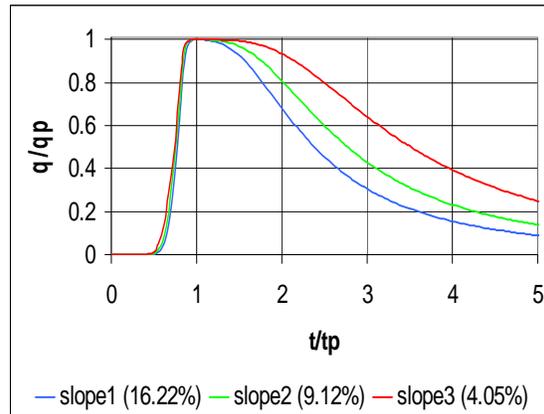
Constant Length (cl)

Appendix 16a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Shape Factor = 1

265

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
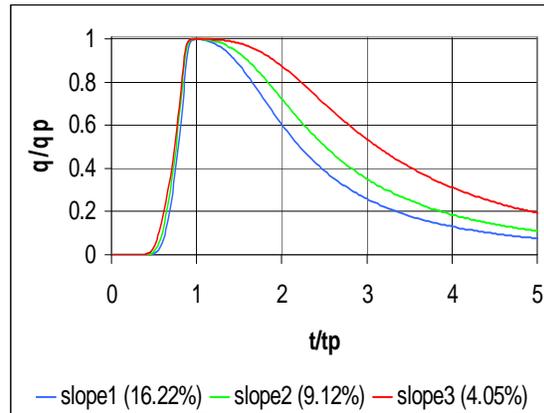
Constant Width (cw)
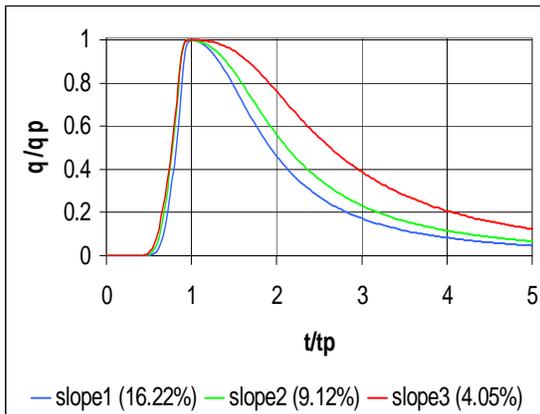
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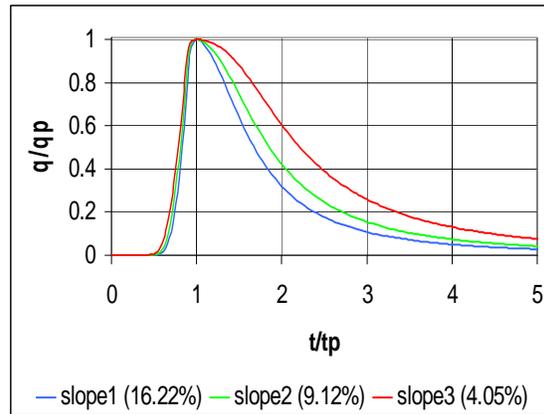
Constant Length (cl)

Appendix 17a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Shape Factor = 2

266

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
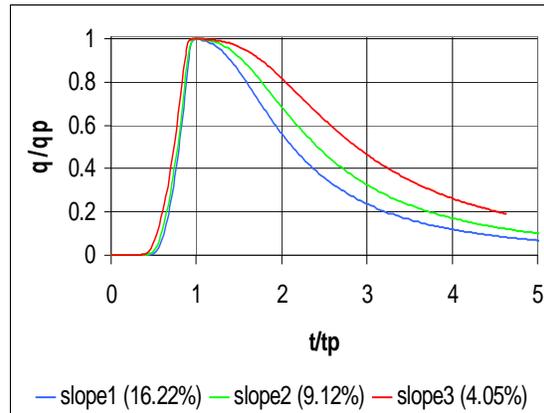
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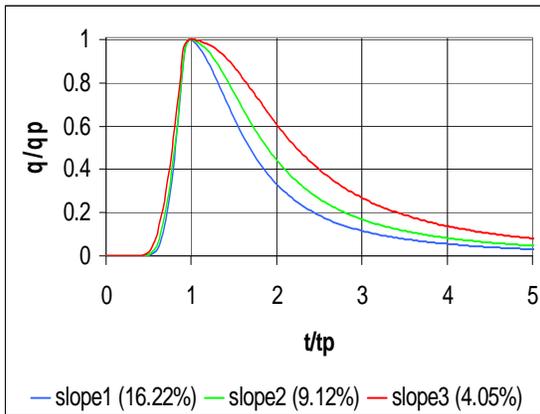
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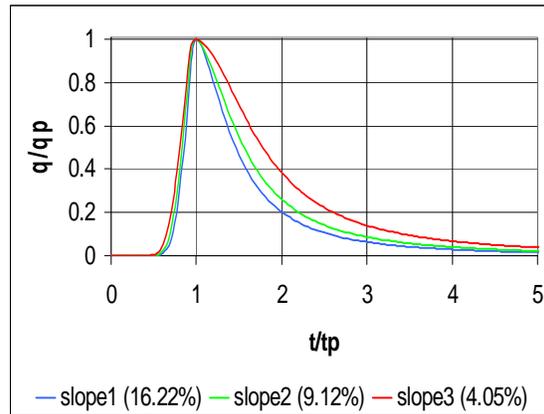
Constant Length (cl)

Appendix 18a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Shape Factor = 3

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
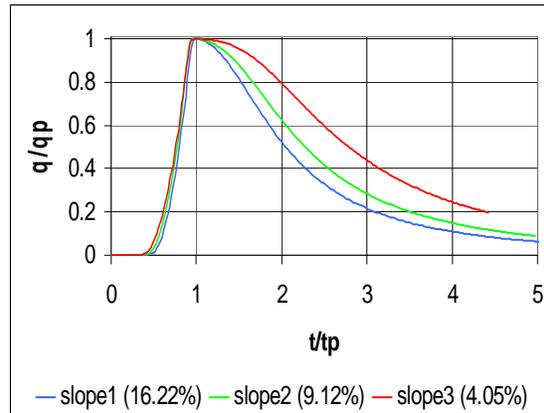
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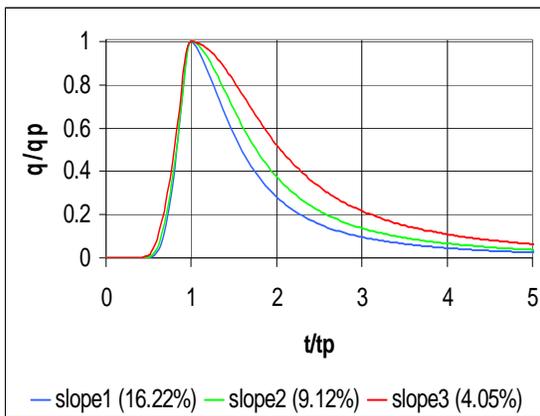
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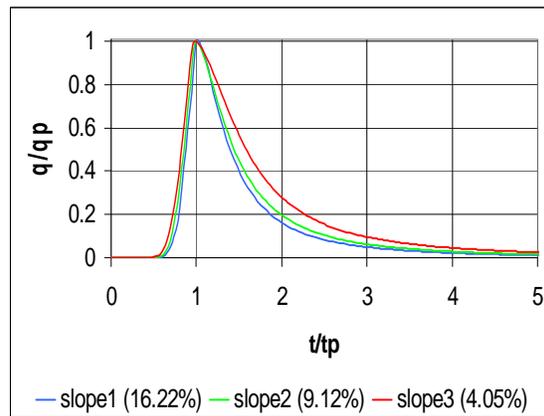
Constant Length (cl)

Appendix 19a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Shape Factor = 4

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
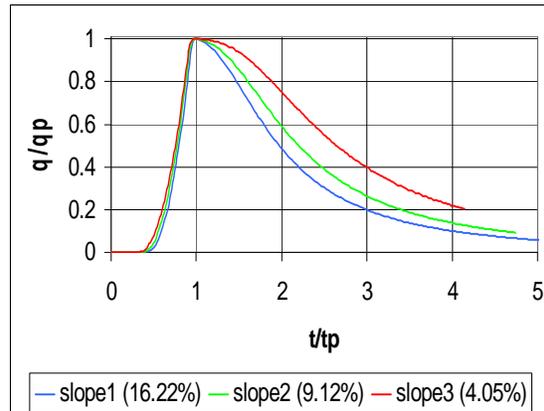
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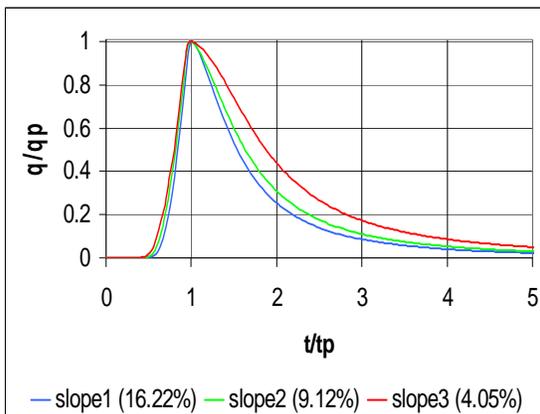
Constant Area (ca)
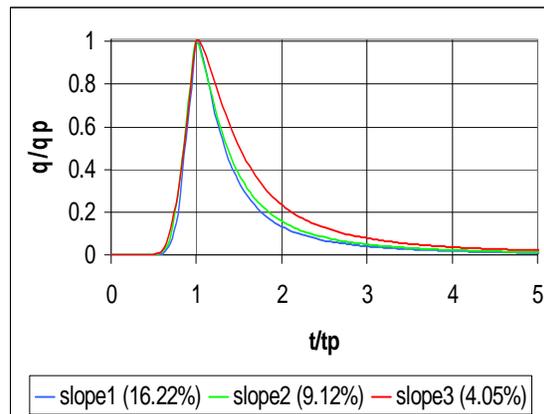
Constant Length (cl)

Appendix 20a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Shape Factor = 5

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
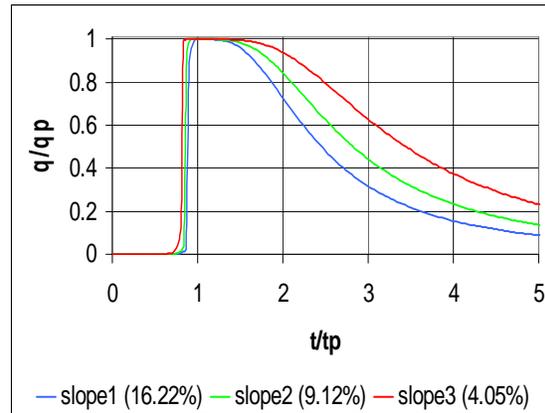
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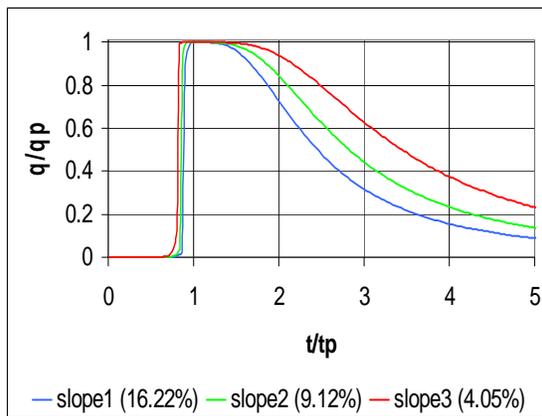
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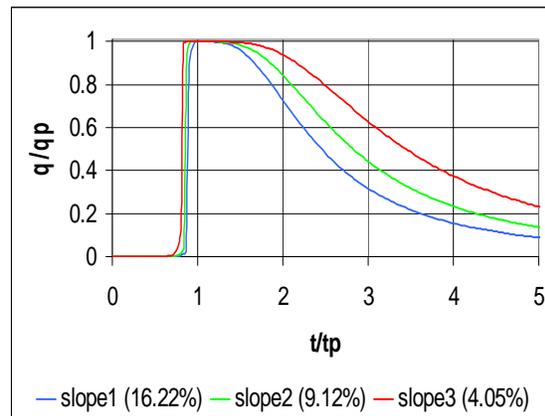
Constant Length (cl)

Appendix 21a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Shape Factor = 1

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
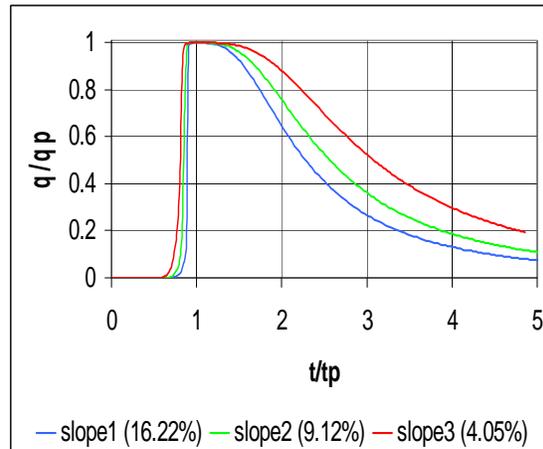
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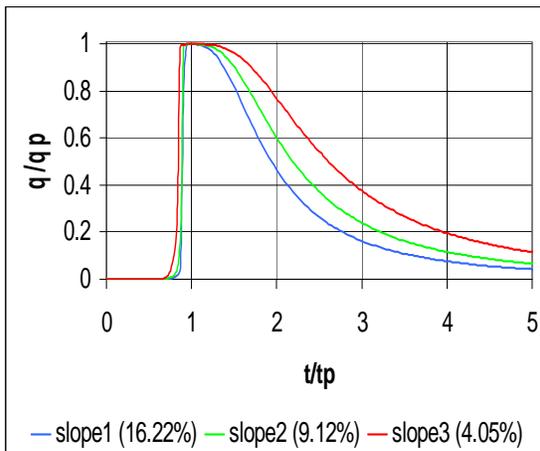
Constant Area (ca)
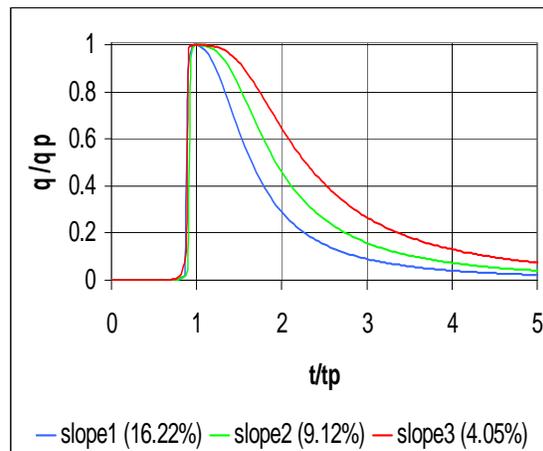
Constant Length (cl)

Appendix 22a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Shape Factor = 2

271

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
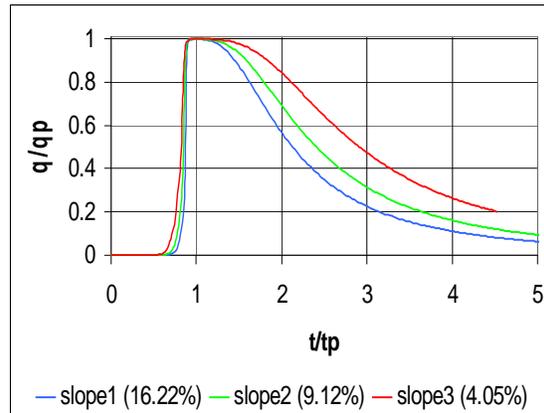
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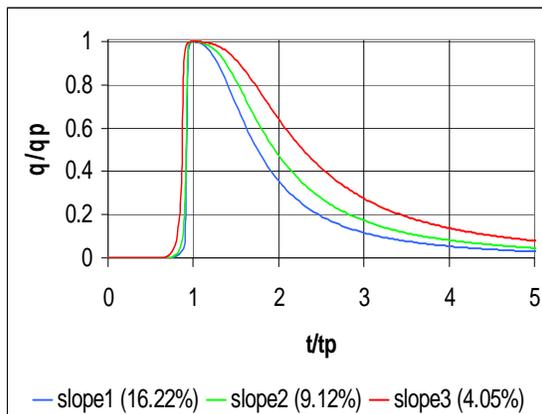
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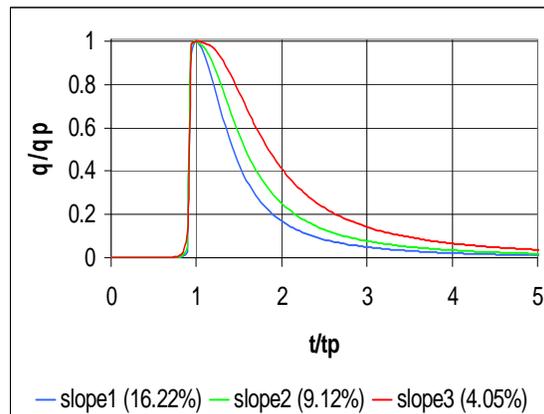
Constant Length (cl)

Appendix 23a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Shape Factor = 3

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
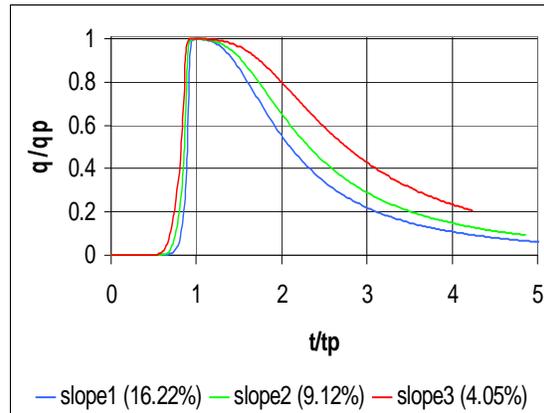
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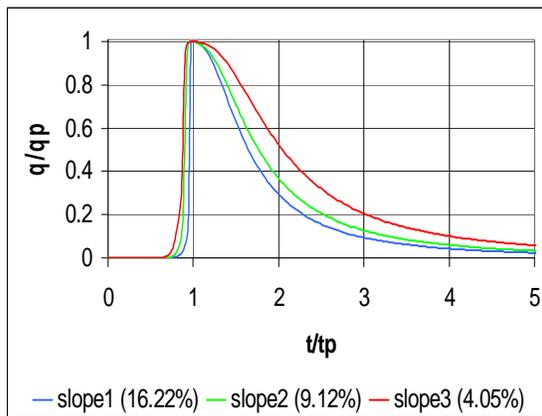
Constant Area (ca)
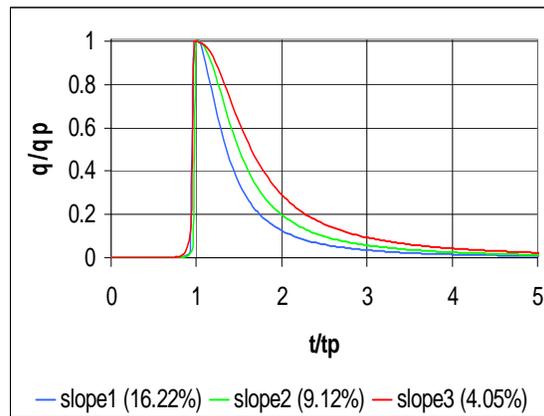
Constant Length (cl)

Appendix 24a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Shape Factor = 4

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
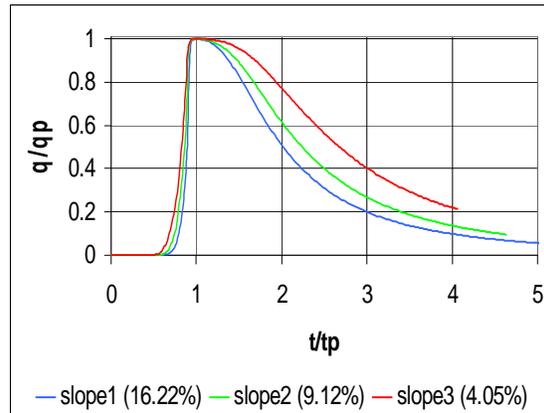
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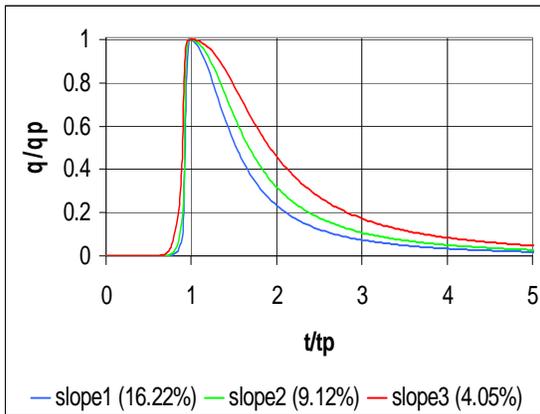
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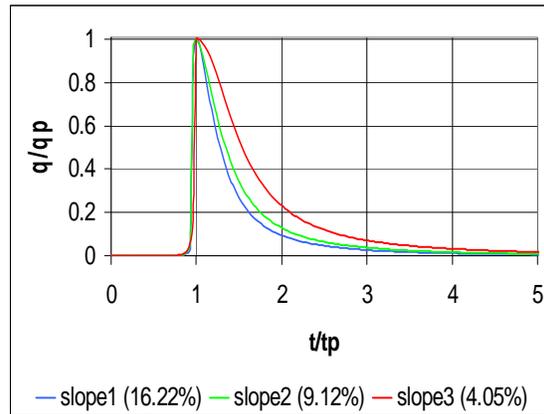
Constant Length (cl)

Appendix 25a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Shape Factor = 5

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
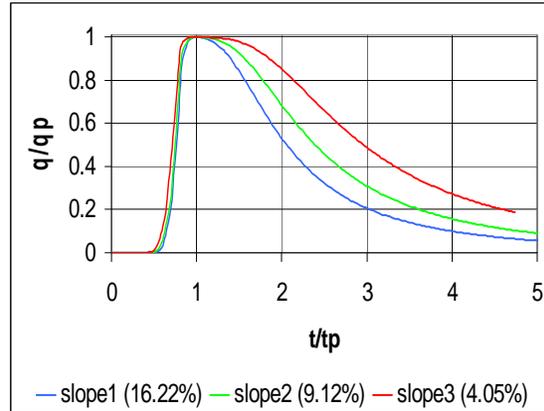
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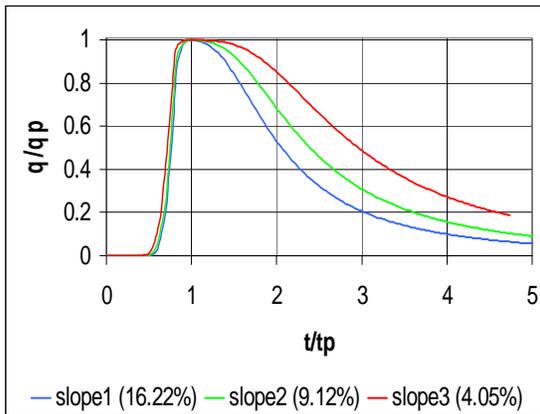
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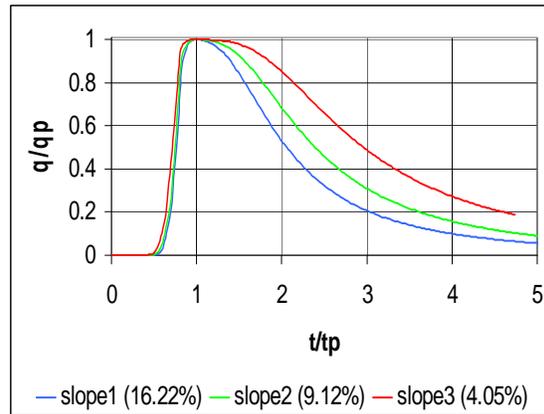
Constant Length (cl)

Appendix 26a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Shape Factor = 1

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
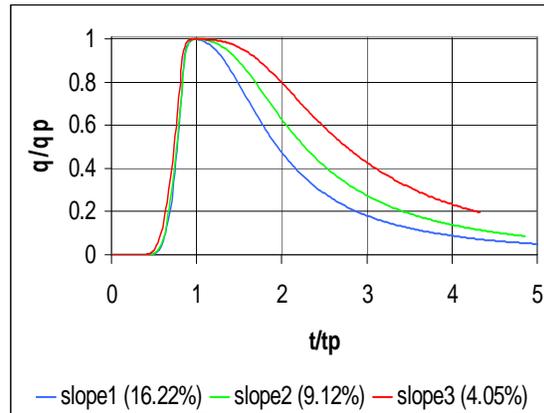
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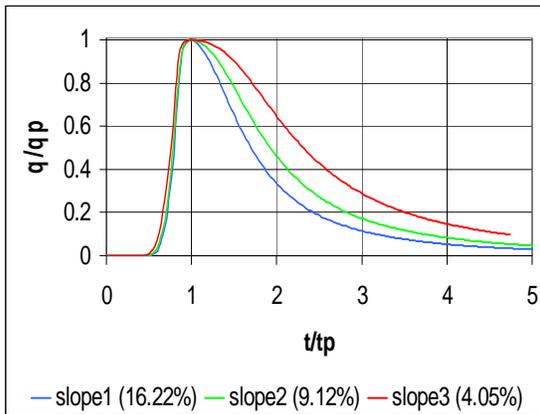
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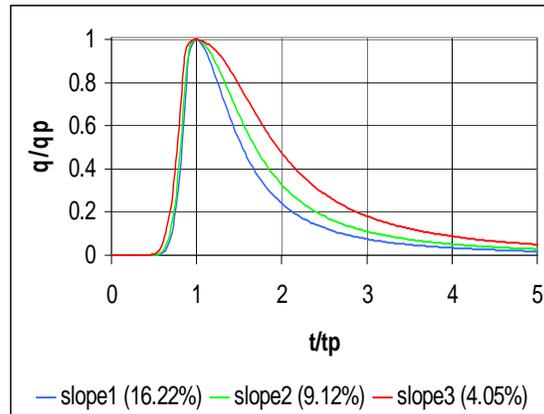
Constant Length (cl)

Appendix 27a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Shape Factor = 2

276

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
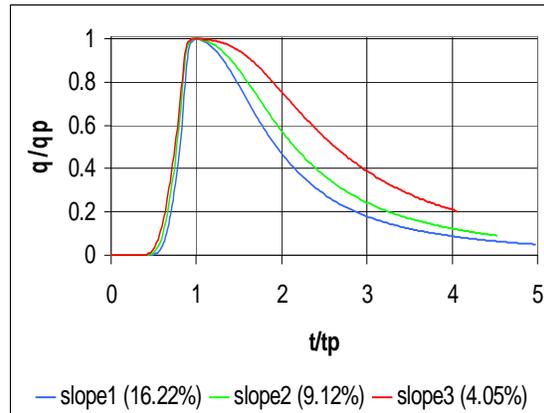
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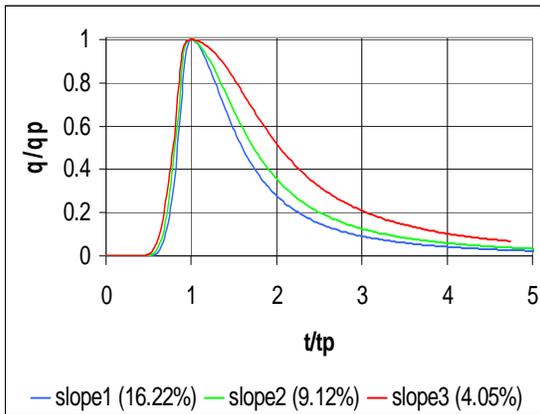
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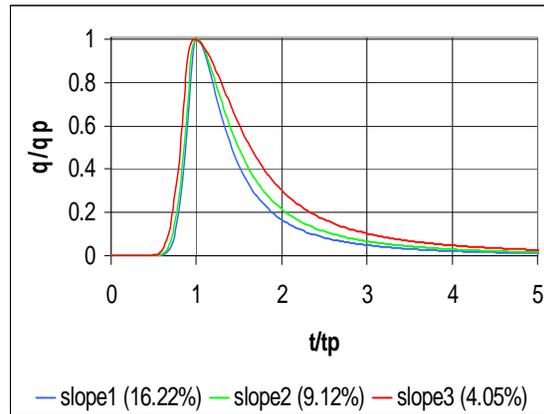
Constant Length (cl)

Appendix 28a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Shape Factor = 3

277

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
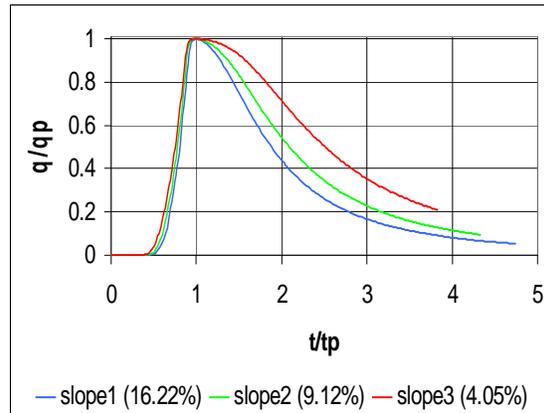
Constant Width (cw)
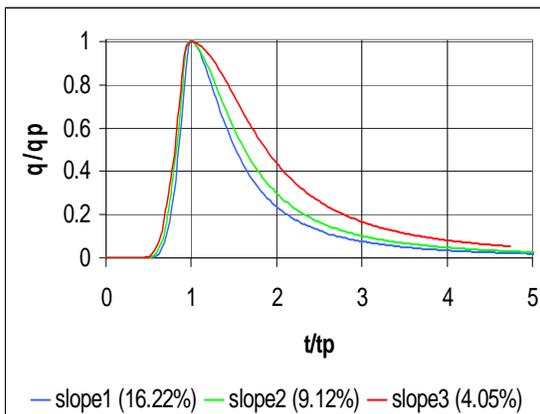
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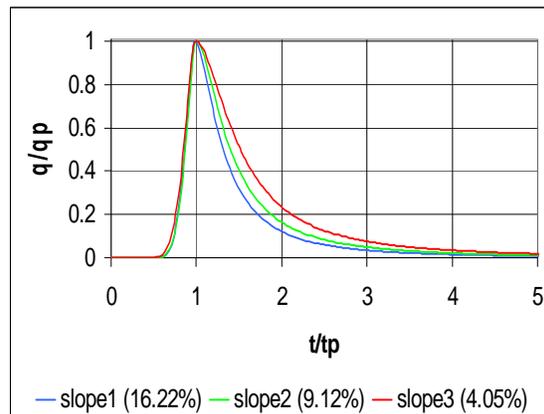
Constant Length (cl)

Appendix 29a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Shape Factor = 4

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
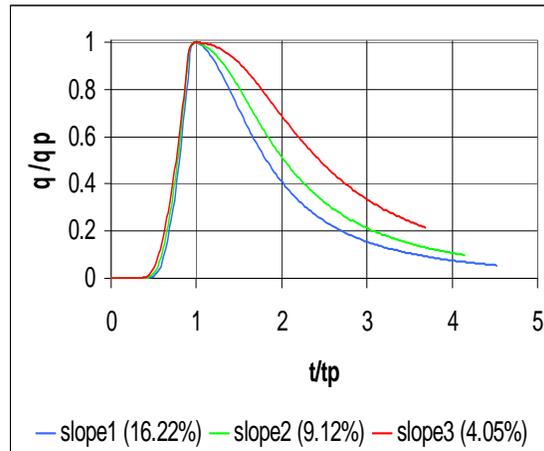
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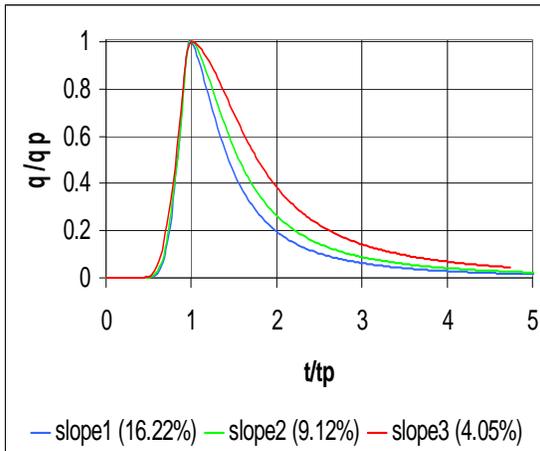
Constant Area (ca)
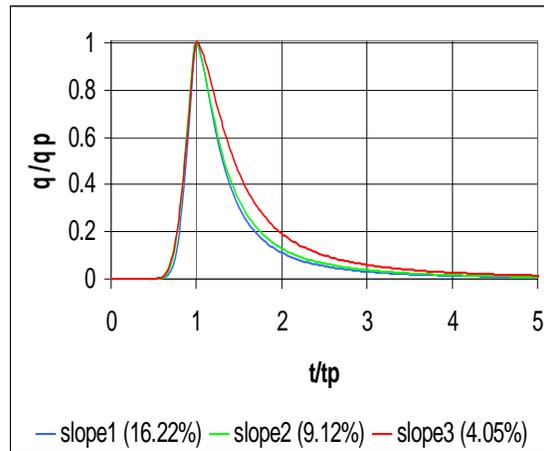
Constant Length (cl)

Appendix 30a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Shape Factor = 5

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
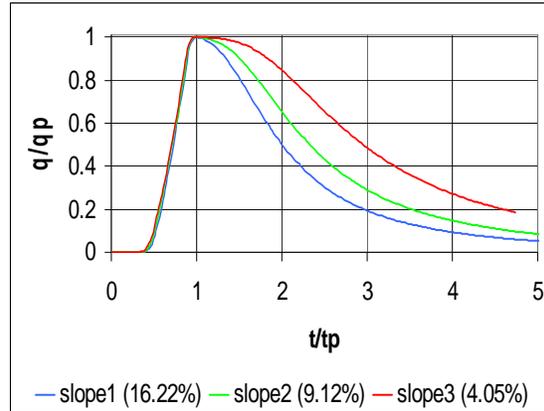
Constant Width (cw)
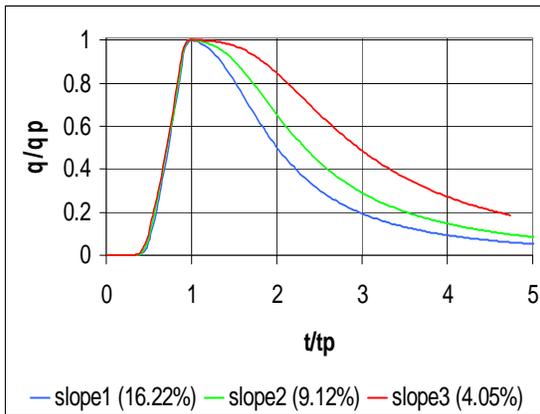
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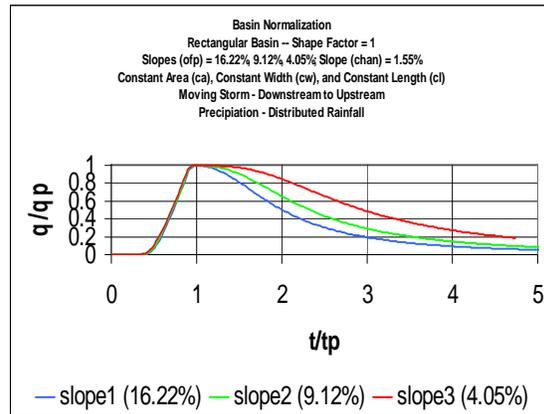
Constant Length (cl)

Appendix 31a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Shape Factor = 1

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
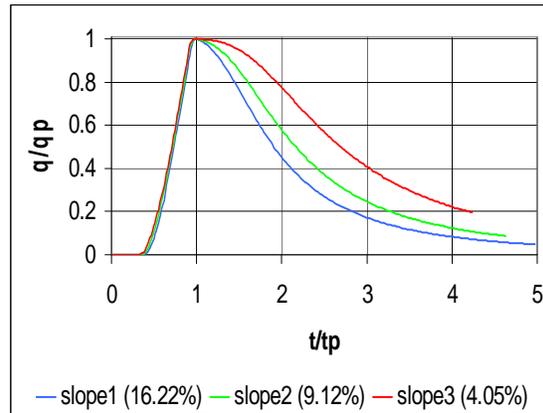
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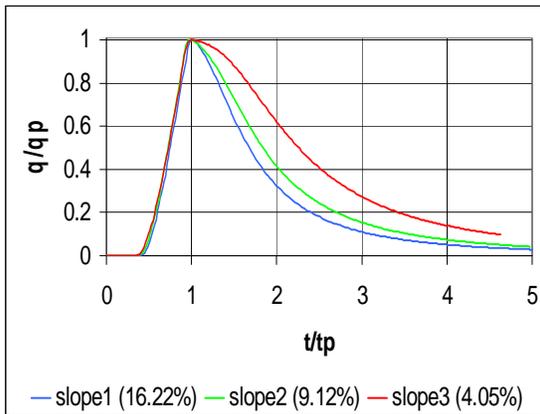
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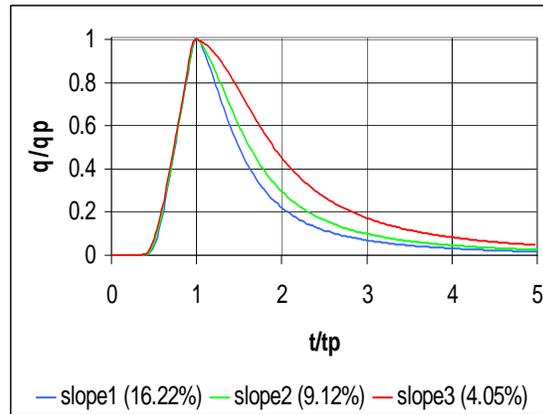
Constant Length (cl)

Appendix 32a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Shape Factor = 2

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
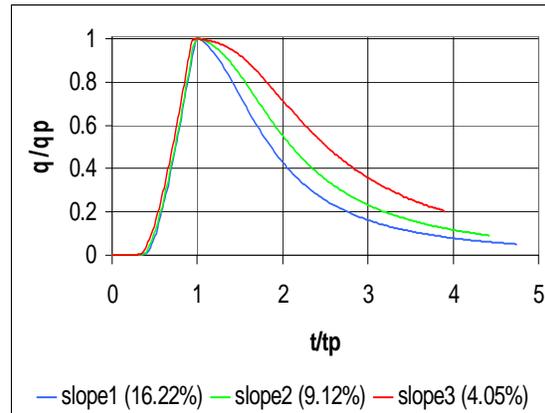
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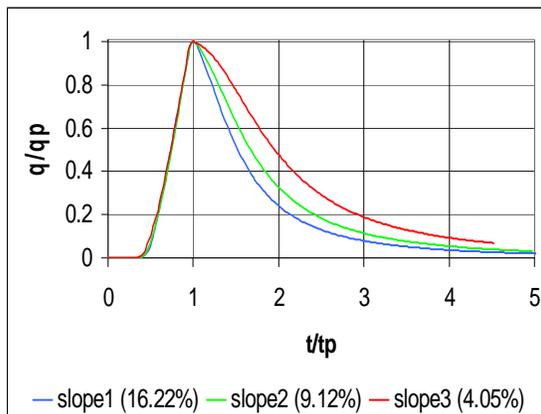
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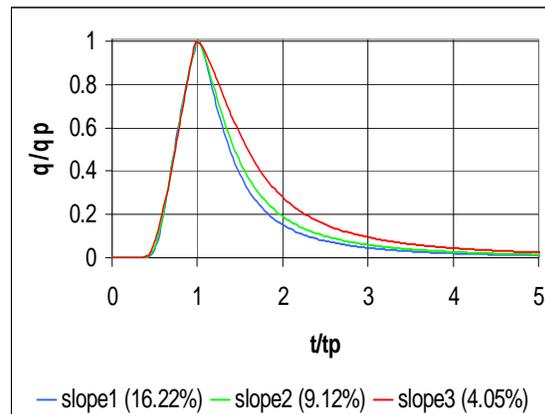
Constant Length (cl)

Appendix 33a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Shape Factor = 3

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
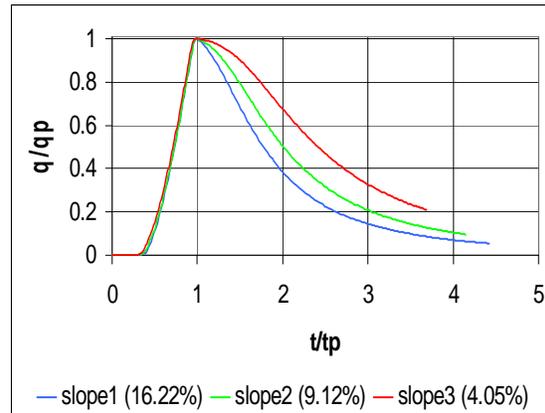
Constant Width (cw)
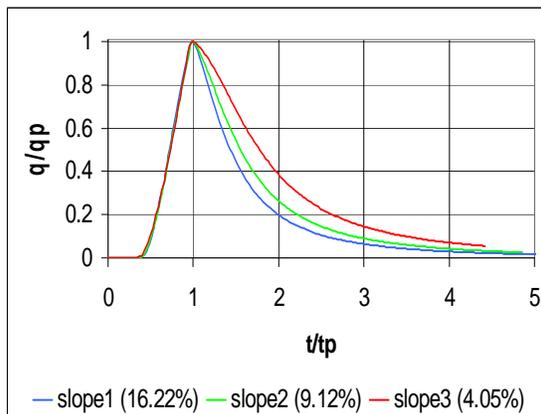
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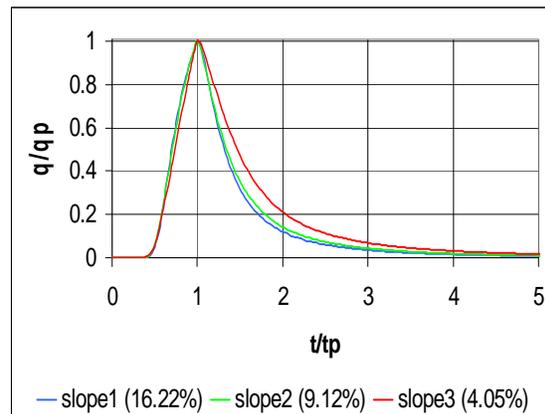
Constant Length (cl)

Appendix 34a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Shape Factor = 4

283

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
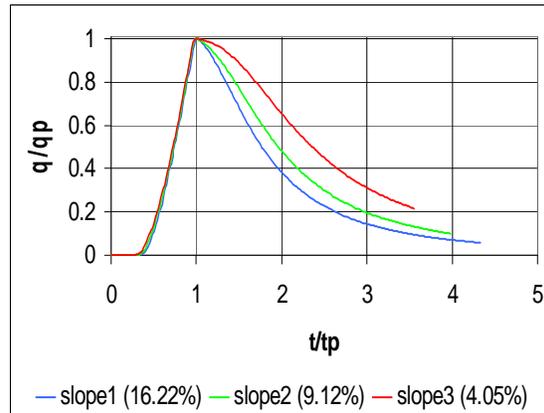
Constant Width (cw)
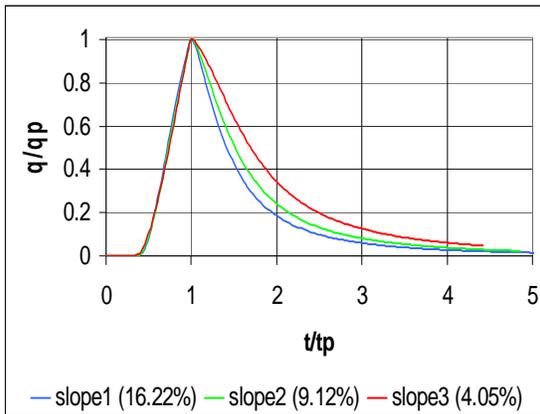
Constant Area (ca)
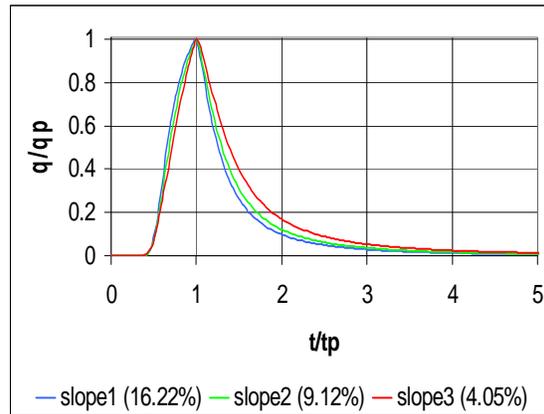
Constant Length (cl)

Appendix 35a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Shape Factor = 5

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
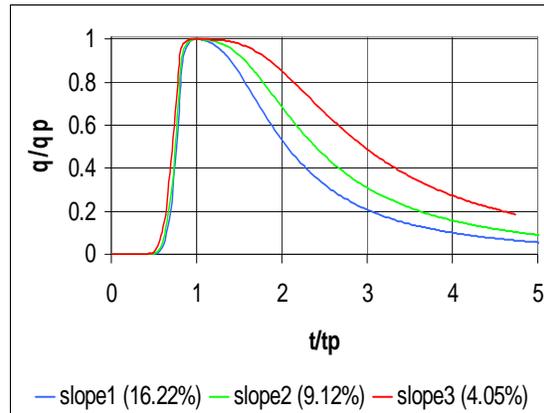
Constant Width (cw)
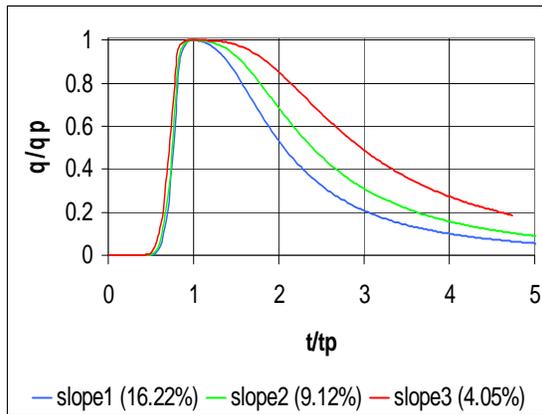
Constant Area (ca)
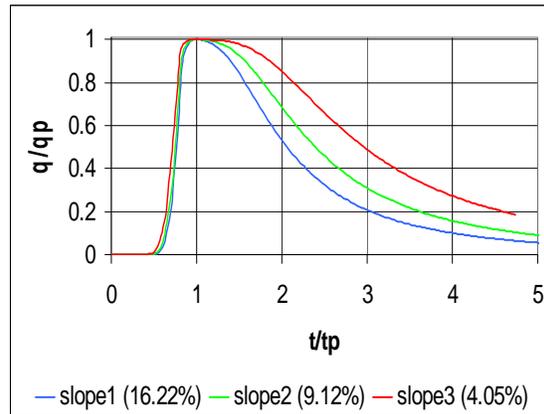
Constant Length (cl)

Appendix 36a.   Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Shape Factor = 1

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Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
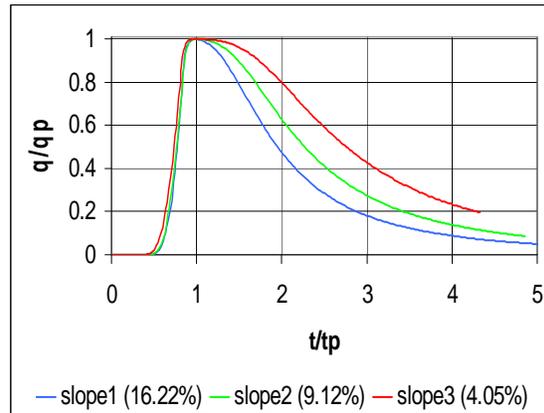
Constant Width (cw)
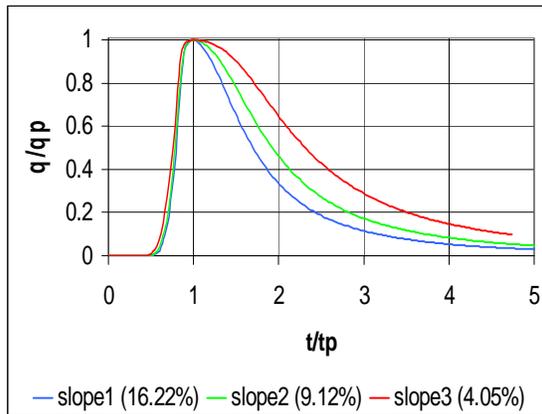
Constant Area (ca)
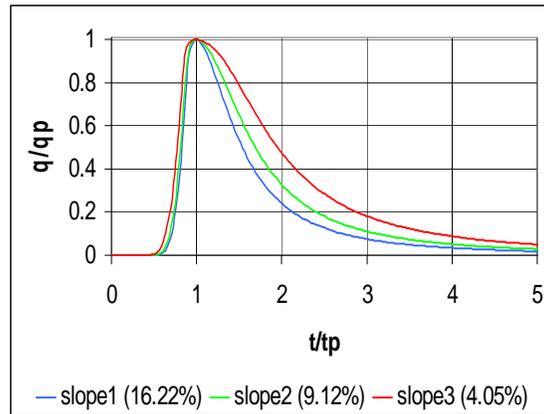
Constant Length (cl)

Appendix 37a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Shape Factor = 2

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
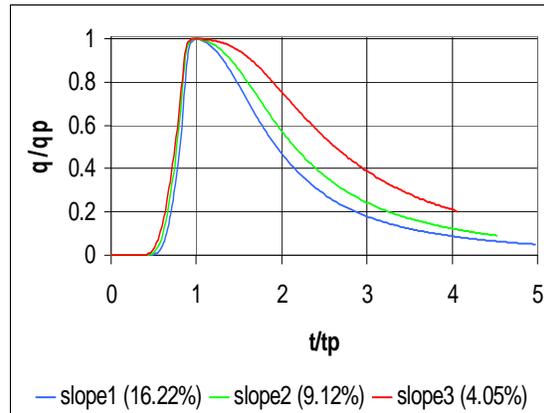
Constant Width (cw)
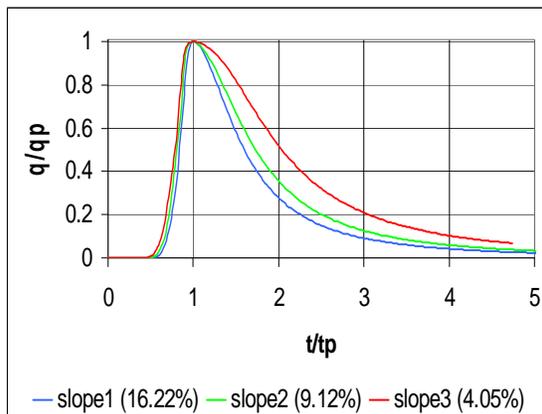
Constant Area (ca)
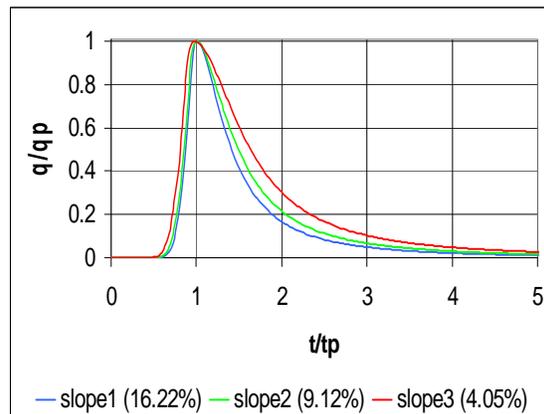
Constant Length (cl)

Appendix 38a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Shape Factor = 3

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
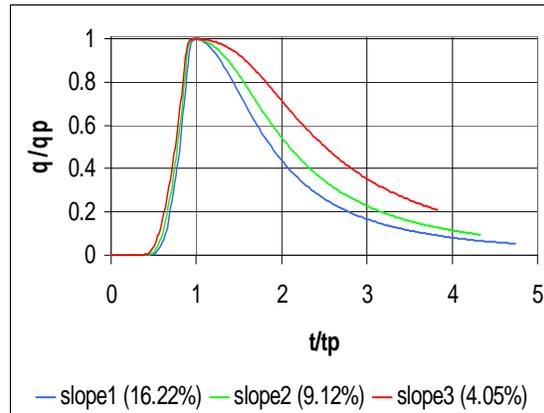
Constant Width (cw)
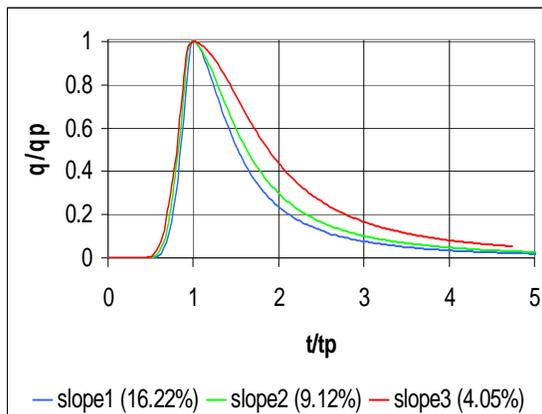
Constant Area (ca)
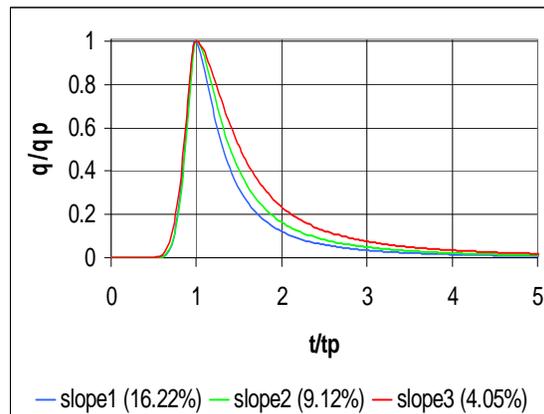
Constant Length (cl)

Appendix 39a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Shape Factor = 4

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Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
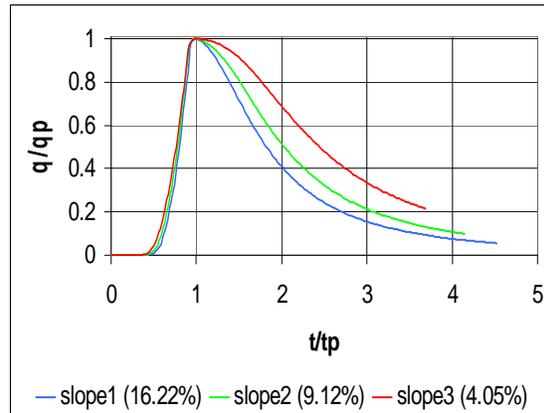
Constant Width (cw)
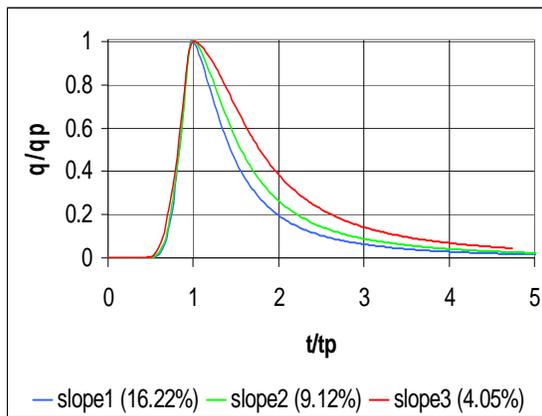
Constant Area (ca)
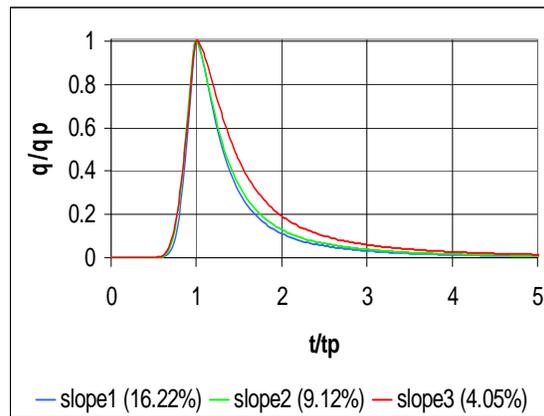
Constant Length (cl)

Appendix 40a. Overland Flow Plane Slope Comparisons (16.22%, 9.12%, 4.05%)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Shape Factor = 5

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APPENDIX B

COMPARISON OF SHAPE FACTORS
SHAPE FACTORS = 1, 2, 3, 4, AND 5
DIMENSIONLESS HYDROGRAPHS
SYNTHETIC RECTANGULAR BASINS

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
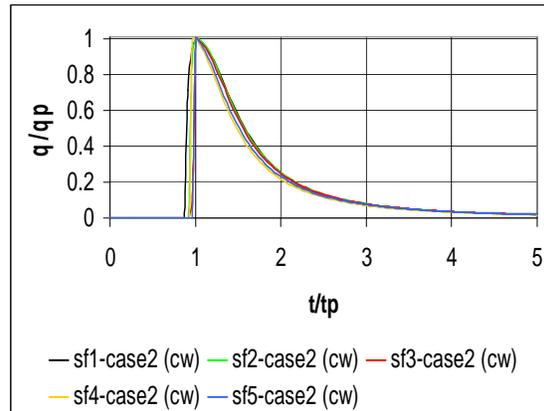
Constant Width (cw)
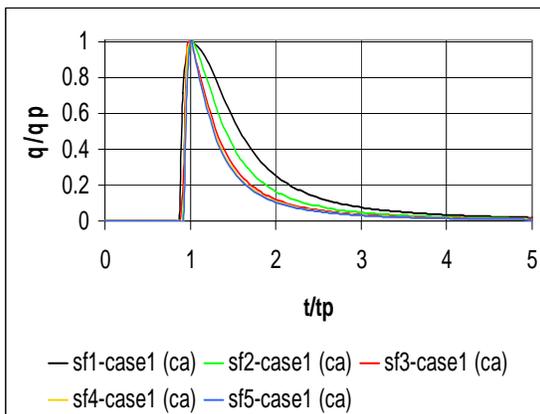
Constant Area (ca)
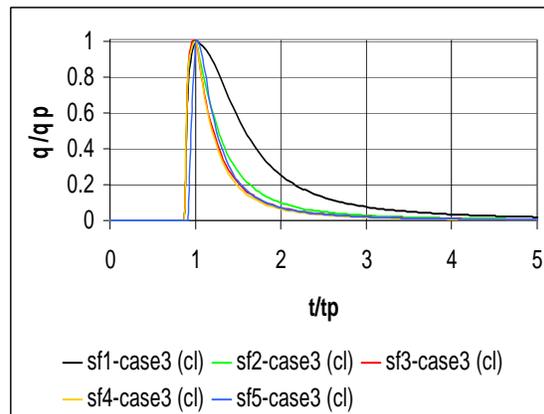
Constant Length (cl)

Appendix 1b.   Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
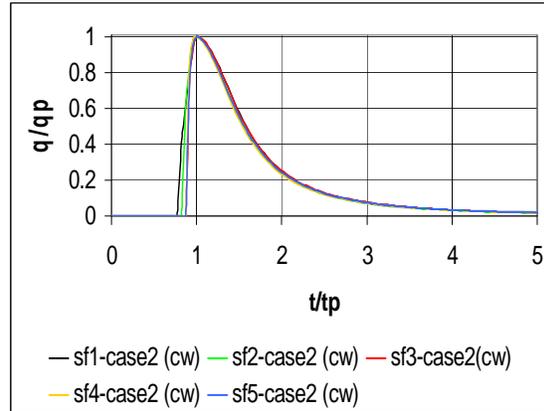
Constant Width (cw)
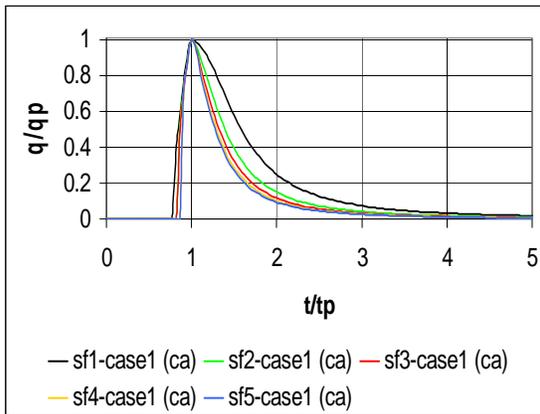
Constant Area (ca)
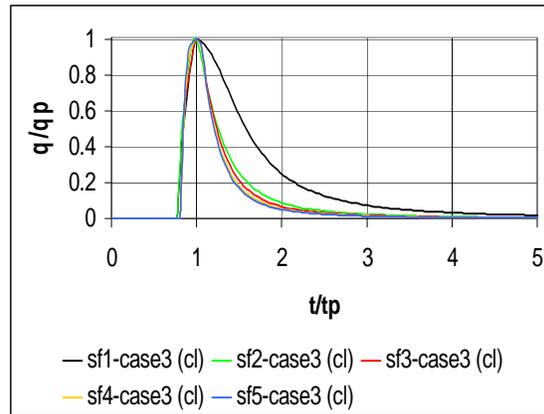
Constant Length (cl)

Appendix 2b.   Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
               Dimensionless Hydrographs – Synthetic Rectangular Basins
               Stationary Storm – Middle 20% – Distributed Rainfall
               Overland Flow Plane Slope = 16.22%

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
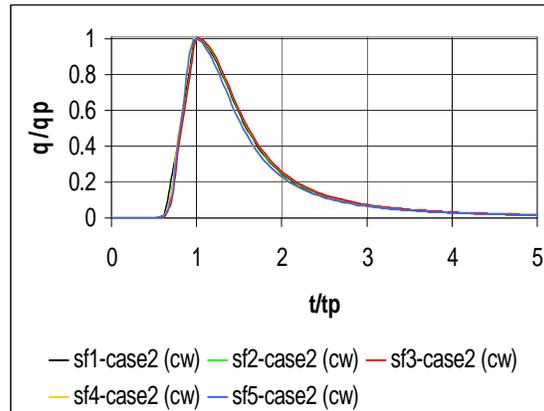
Constant Width (cw)
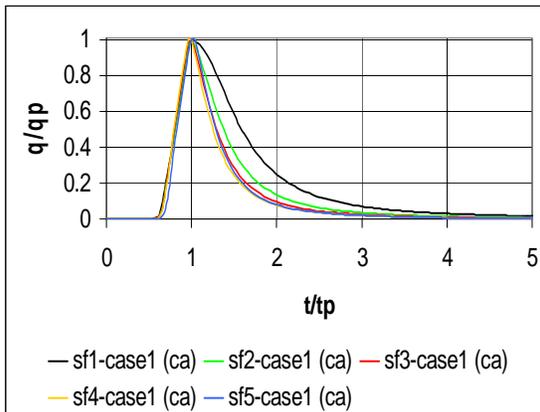
Constant Area (ca)
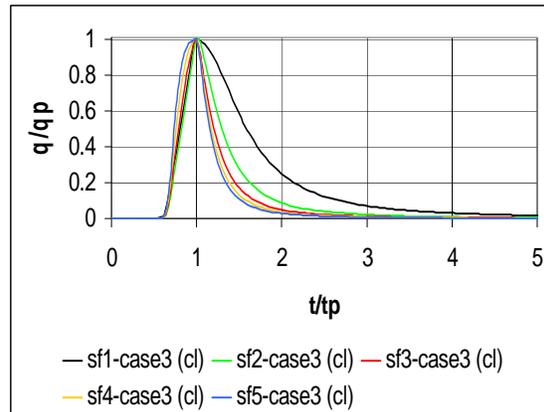
Constant Length (cl)

Appendix 3b.   Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
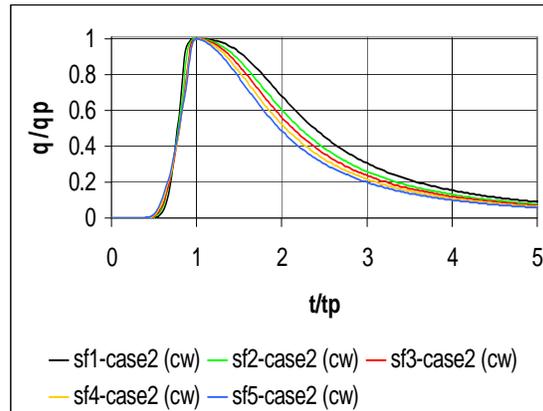
Constant Width (cw)
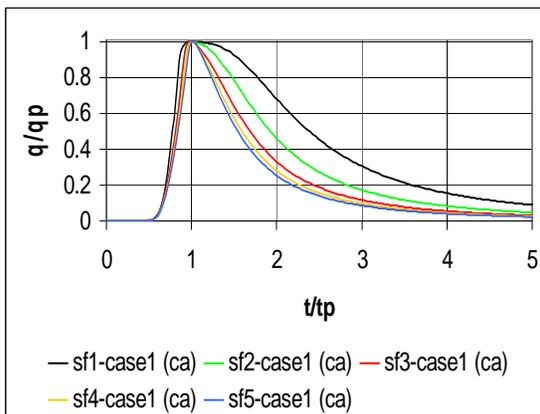
Constant Area (ca)
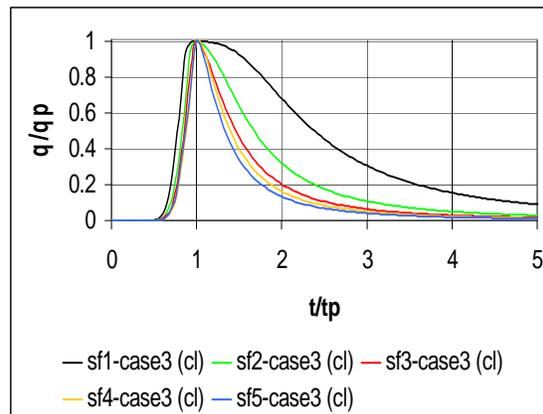
Constant Length (cl)

Appendix 4b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
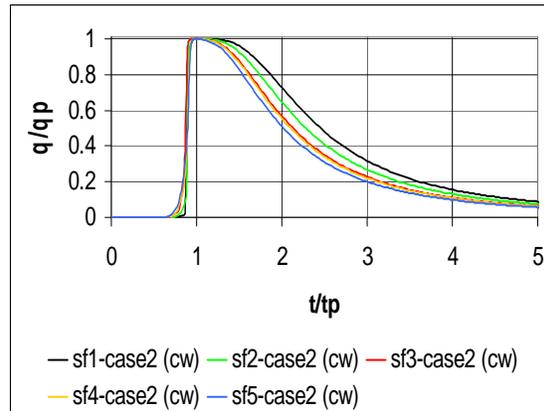
Constant Width (cw)
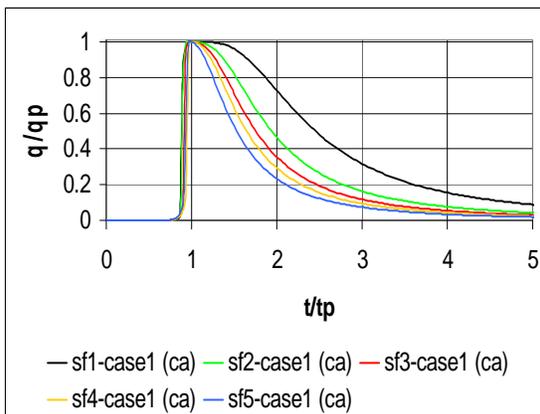
Constant Area (ca)
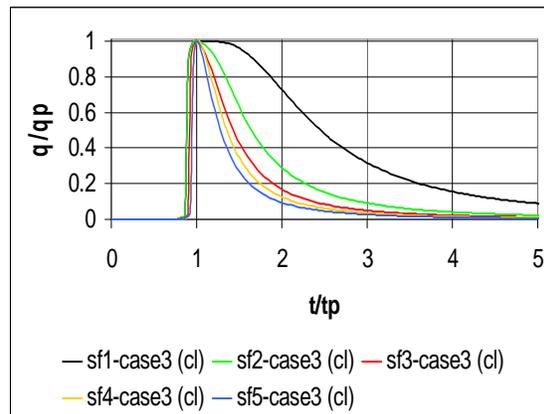
Constant Length (cl)

Appendix 5b.   Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
             Dimensionless Hydrographs – Synthetic Rectangular Basins
             Moving Storm – Upstream to Downstream – Distributed Rainfall
             Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
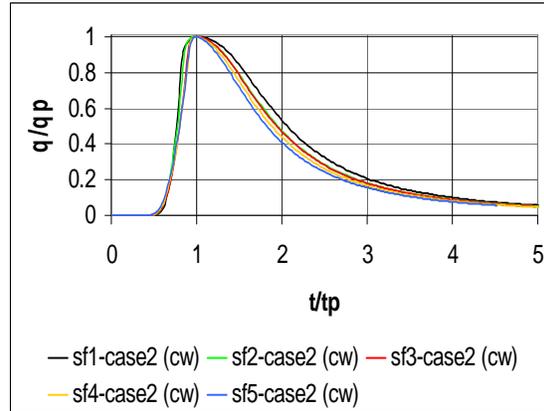
Constant Width (cw)
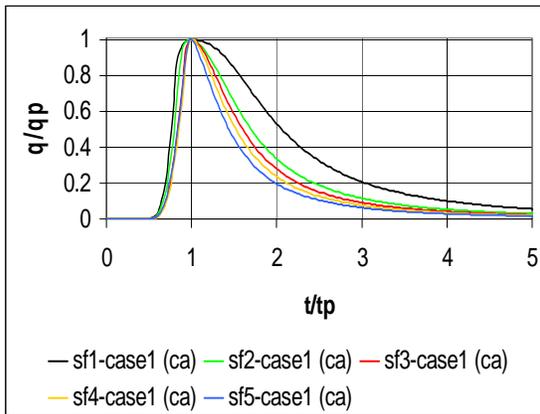
Constant Area (ca)
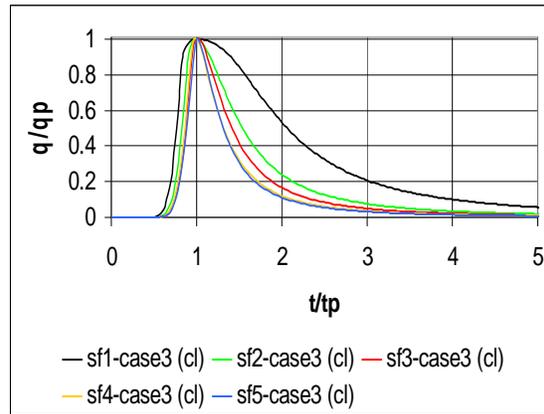
Constant Length (cl)

Appendix 6b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
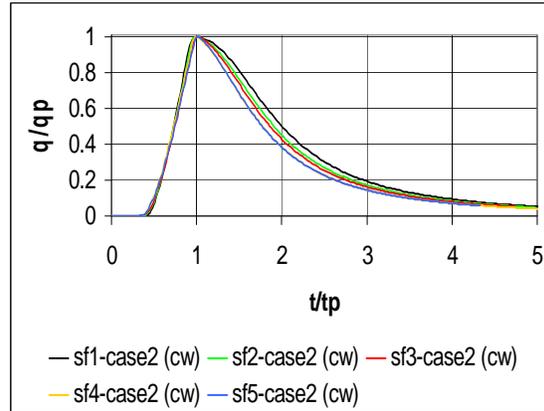
Constant Width (cw)
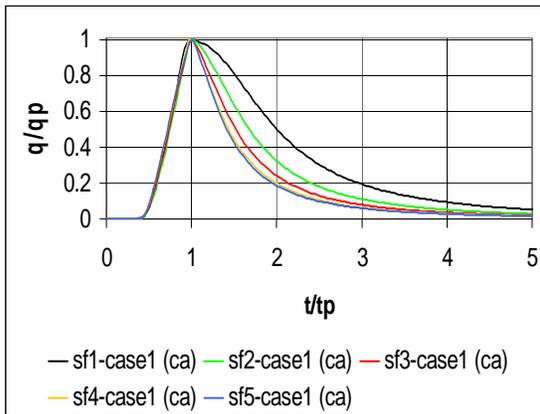
Constant Area (ca)
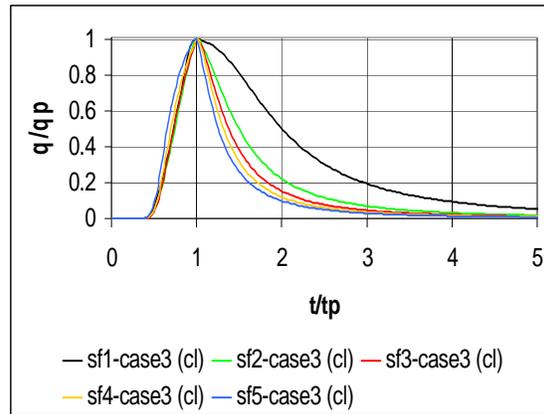
Constant Length (cl)

Appendix 7b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
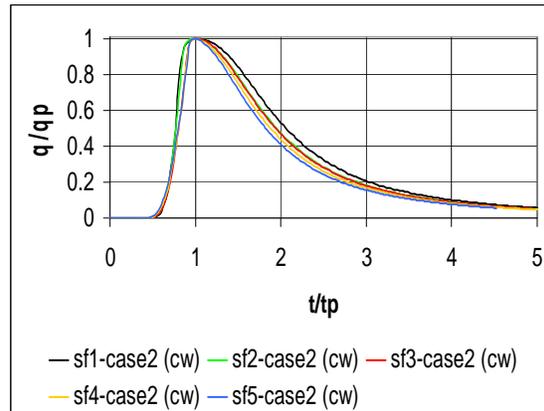
Constant Width (cw)
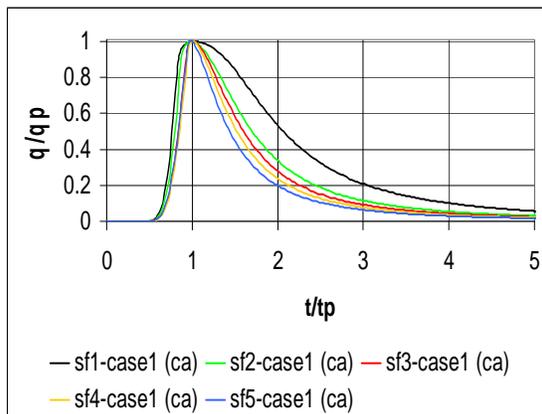
Constant Area (ca)
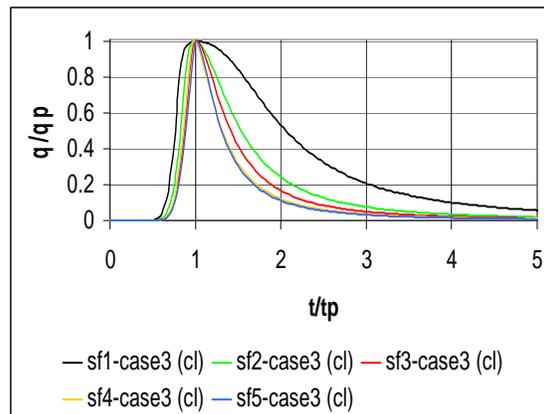
Constant Length (cl)

Appendix 8b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
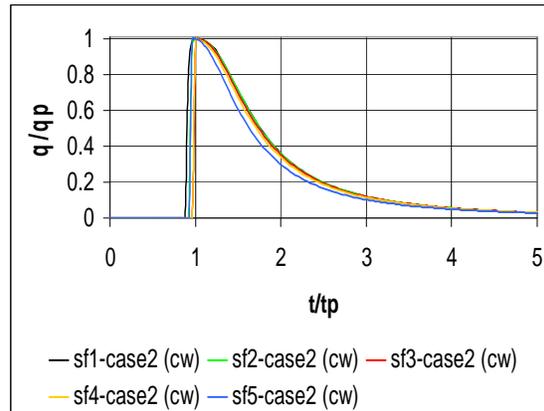
Constant Width (cw)
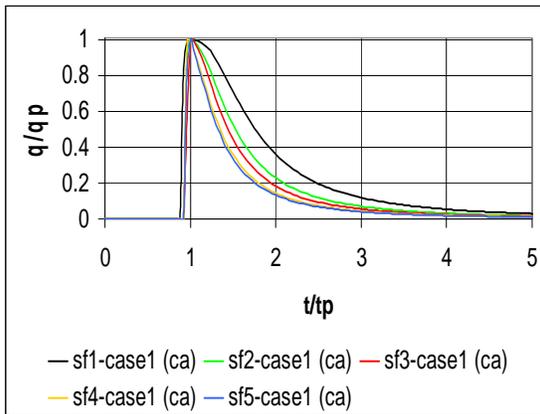
Constant Area (ca)
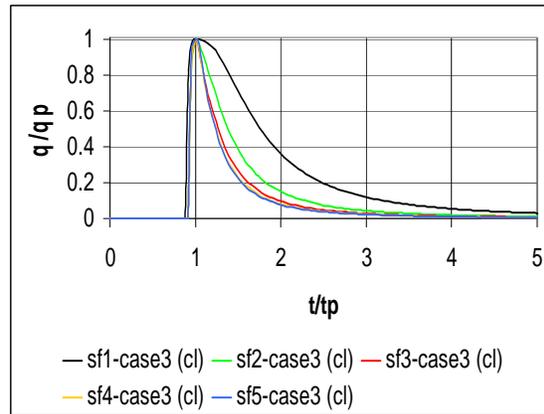
Constant Length (cl)

Appendix 9b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
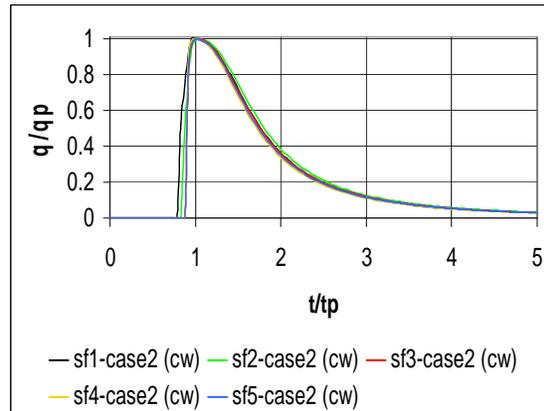
Constant Width (cw)
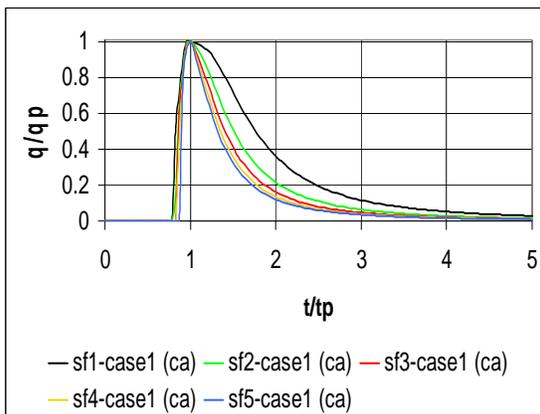
Constant Area (ca)
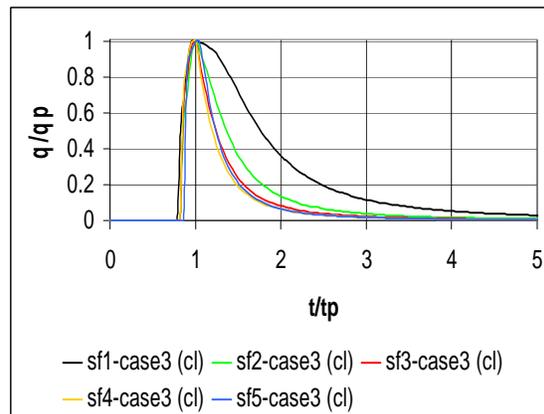
Constant Length (cl)

Appendix 10b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
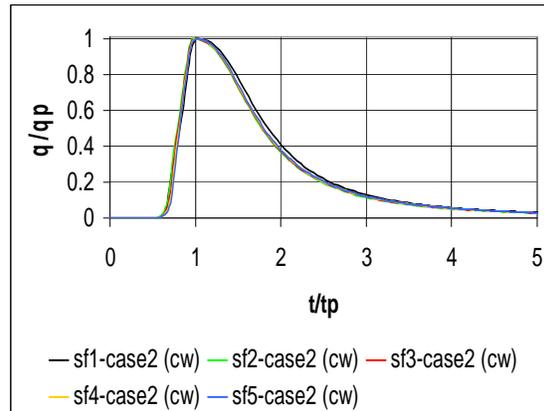
Constant Width (cw)
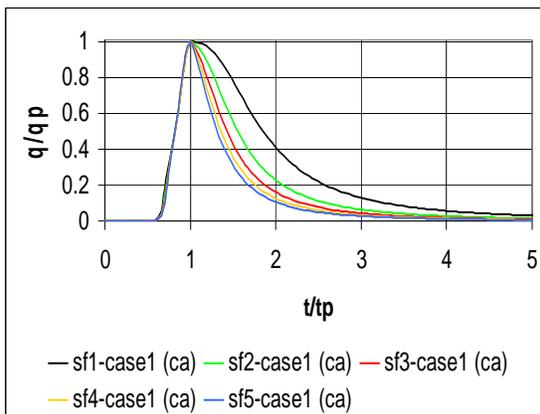
Constant Area (ca)
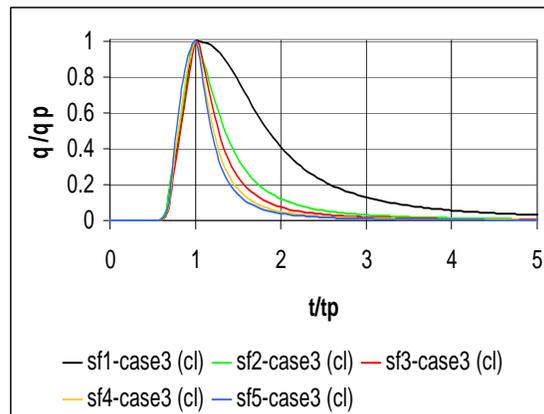
Constant Length (cl)

Appendix 11b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
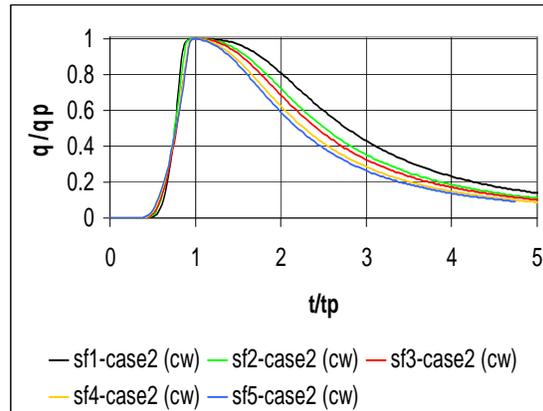
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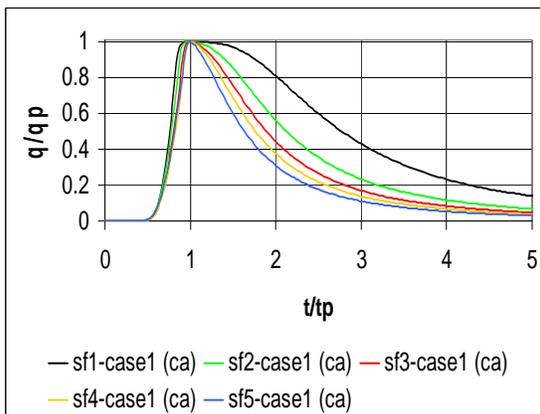
Constant Area (ca)
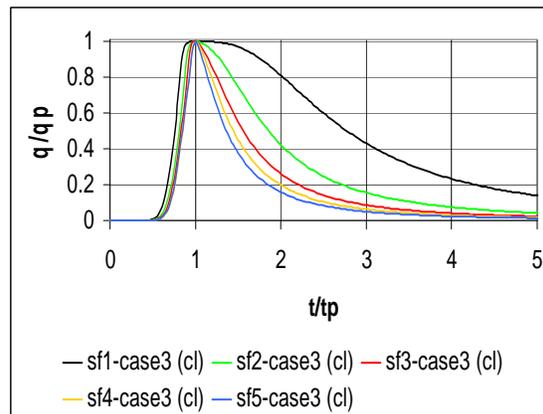
Constant Length (cl)

Appendix 12b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
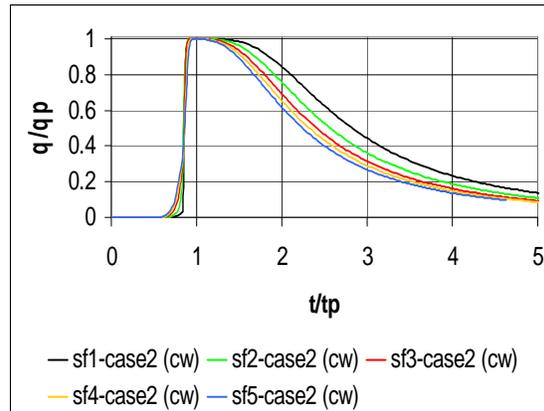
Constant Width (cw)
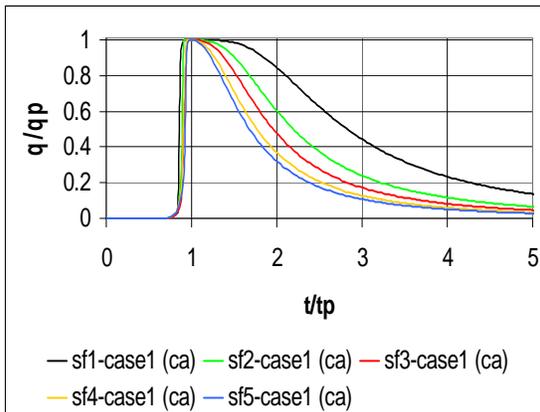
Constant Area (ca)
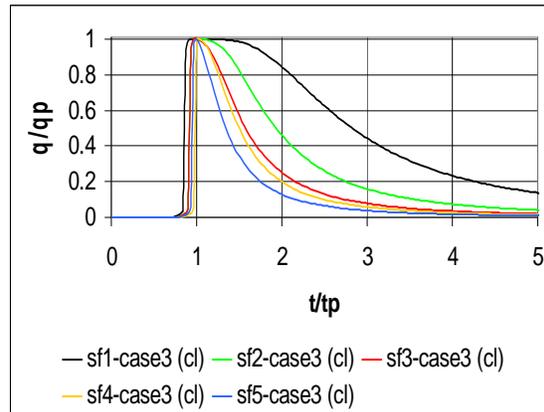
Constant Length (cl)

**Appendix 13b.** Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

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Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
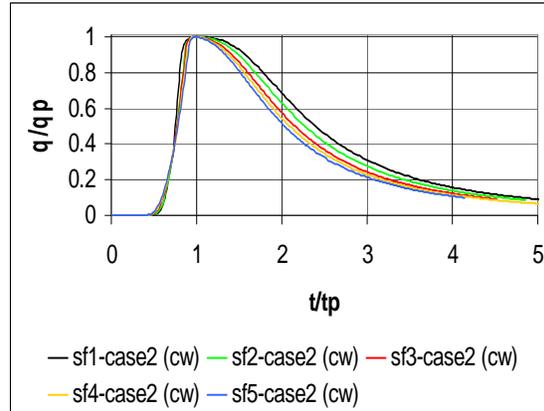
Constant Width (cw)
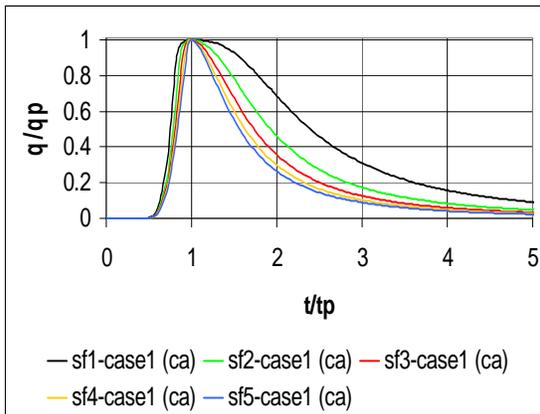
Constant Area (ca)
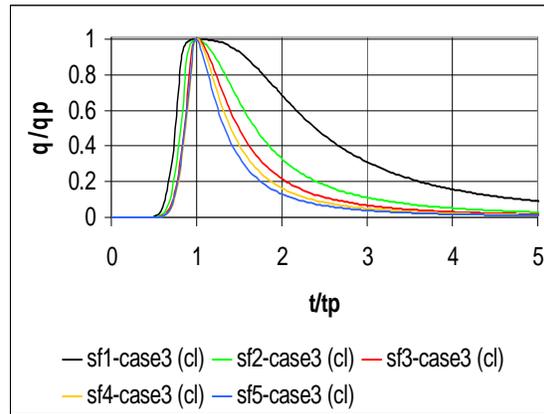
Constant Length (cl)

Appendix 14b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
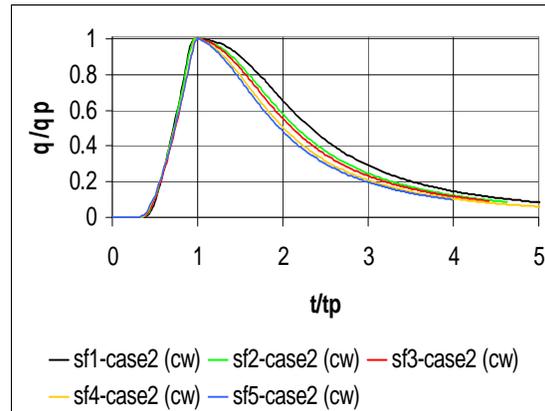
Constant Width (cw)
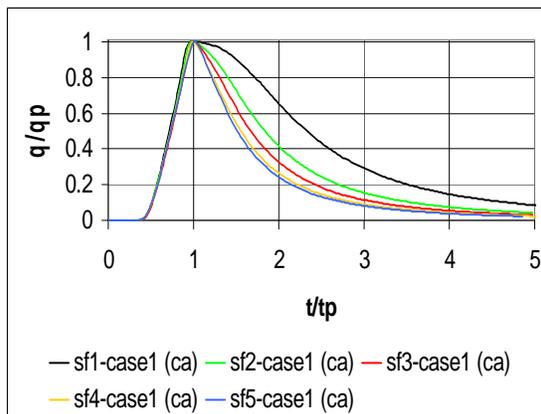
Constant Area (ca)
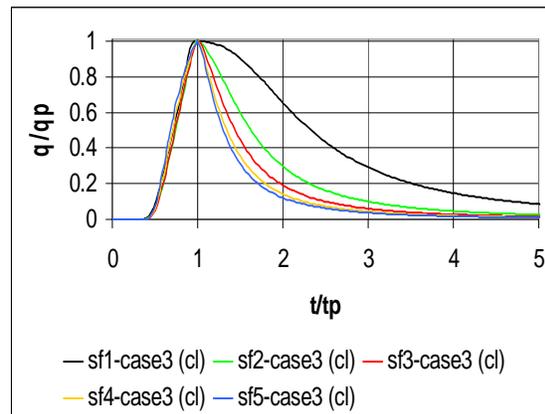
Constant Length (cl)

Appendix 15b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
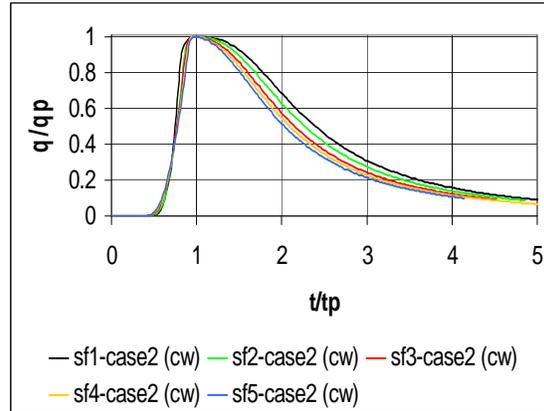
Constant Width (cw)
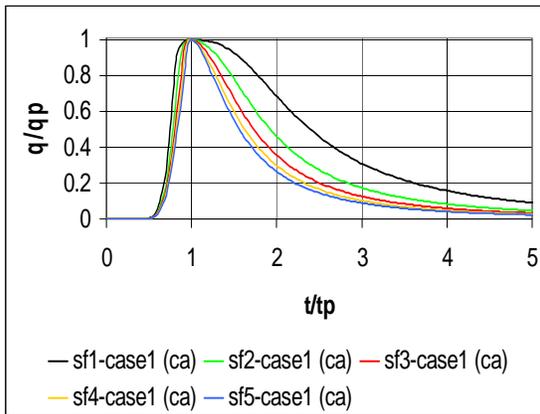
Constant Area (ca)
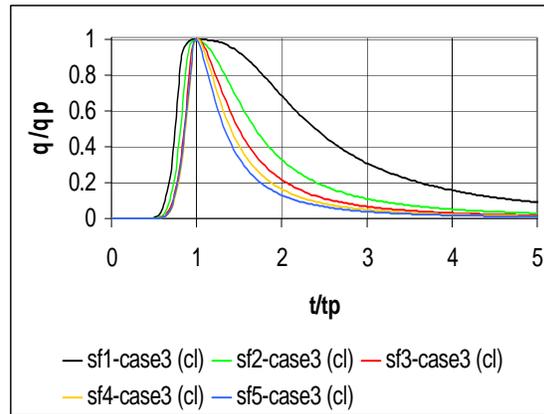

Constant Length (cl)

Appendix 16b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.
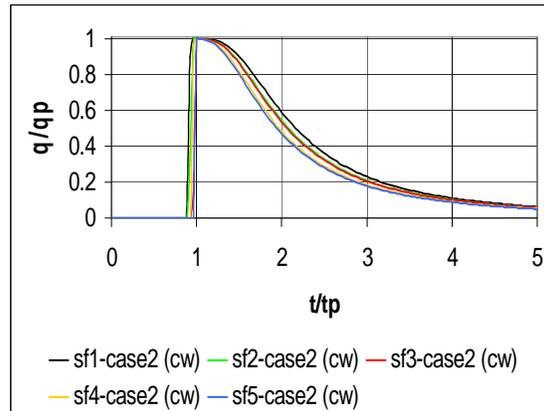
Constant Width (cw)
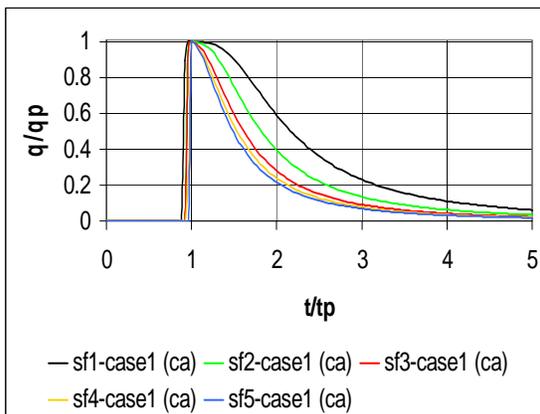
Constant Area (ca)
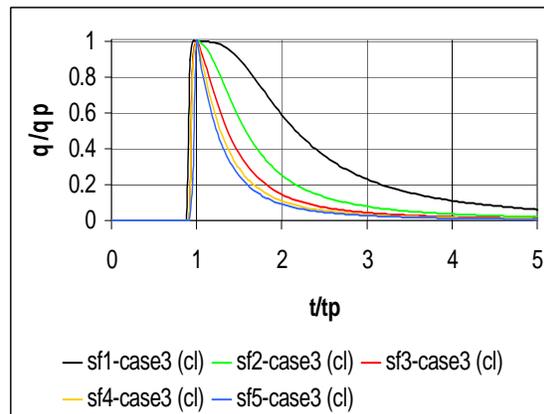
Constant Length (cl)

Appendix 17b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.
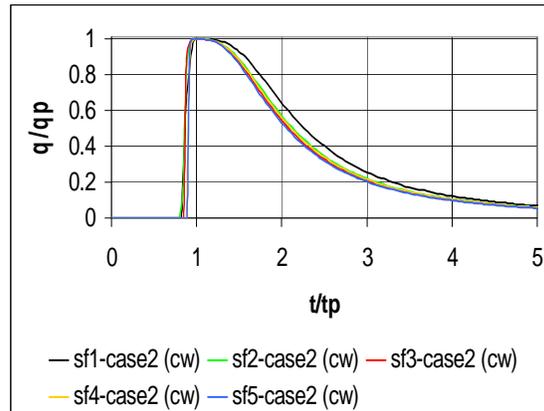
Constant Width (cw)
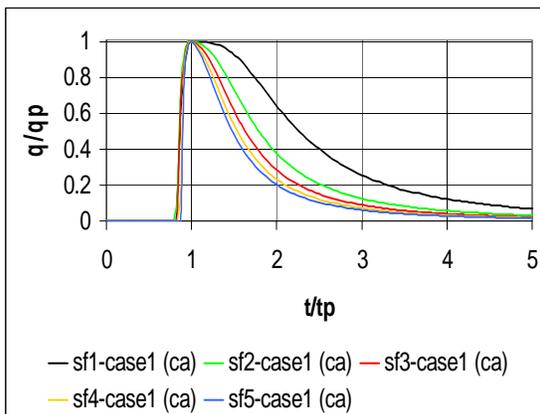
Constant Area (ca)
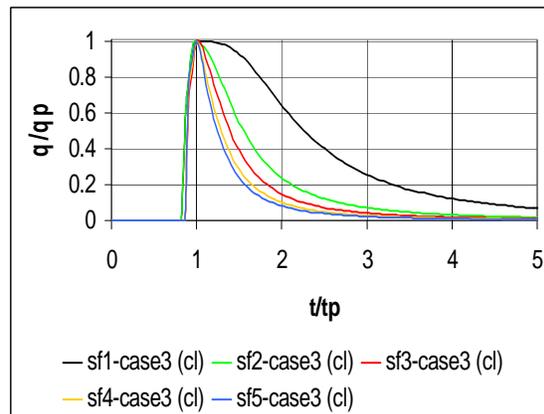
Constant Length (cl)

Appendix 18b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.
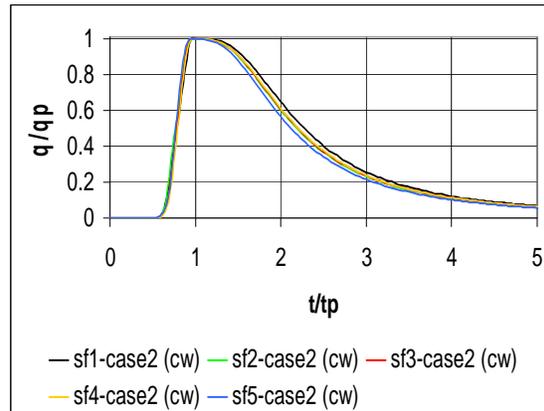
Constant Width (cw)
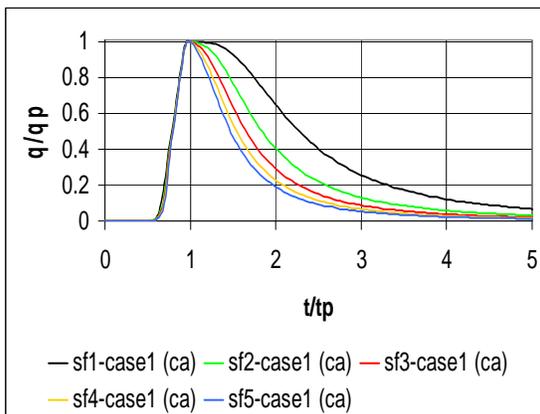
Constant Area (ca)
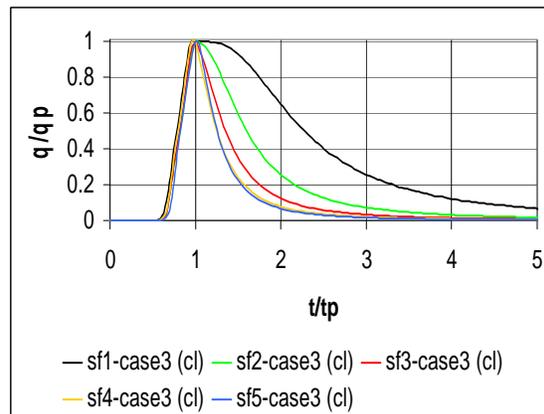
Constant Length (cl)

Appendix 19b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
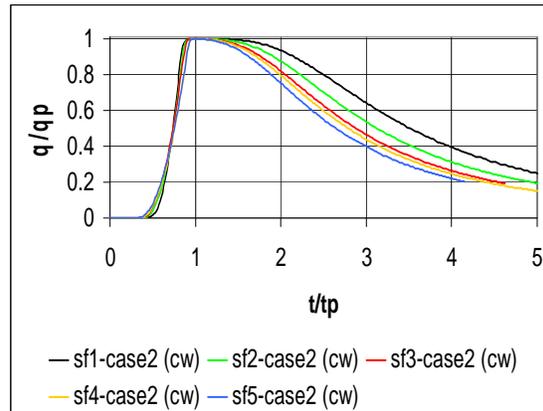
Constant Width (cw)
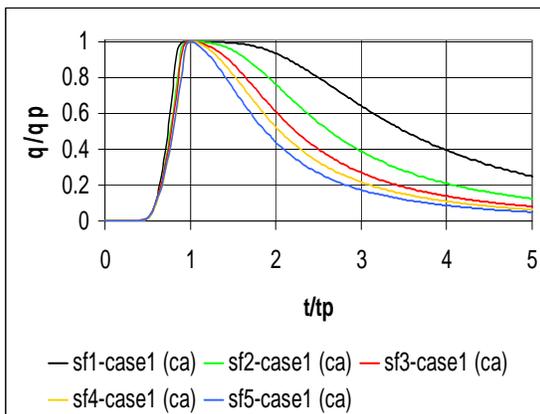
Constant Area (ca)
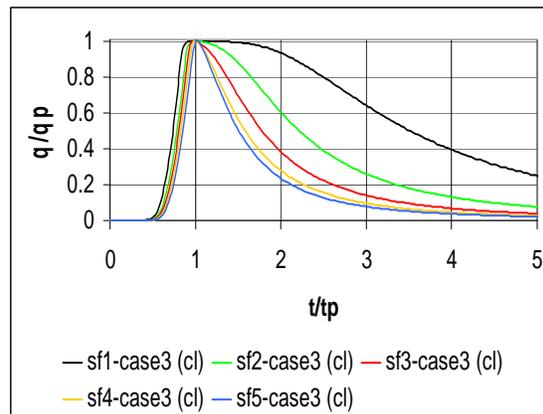
Constant Length (cl)

Appendix 20b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
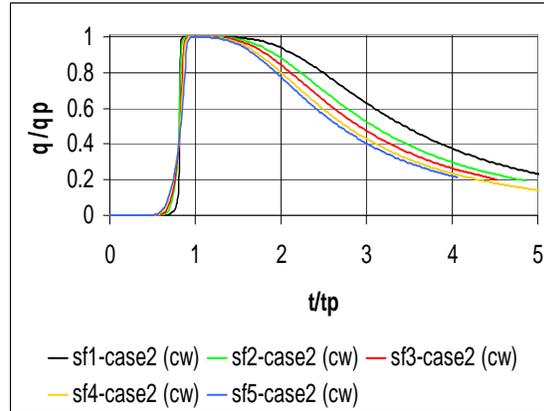
Constant Width (cw)
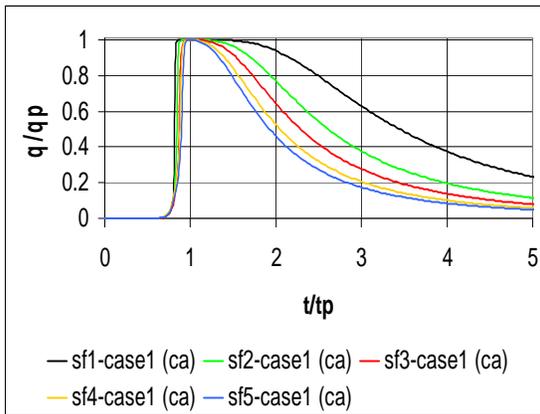
Constant Area (ca)
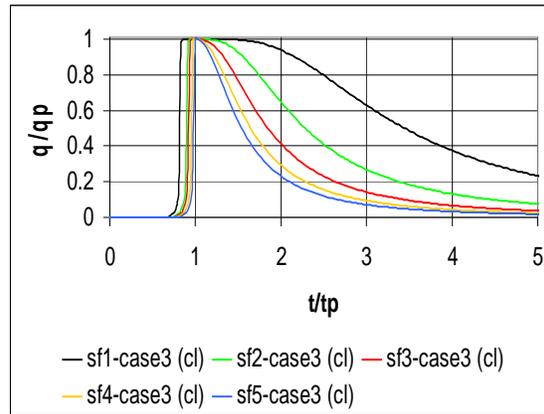
Constant Length (cl)

Appendix 21b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
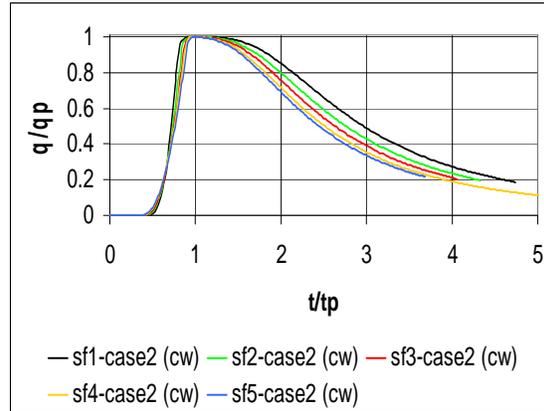
Constant Width (cw)
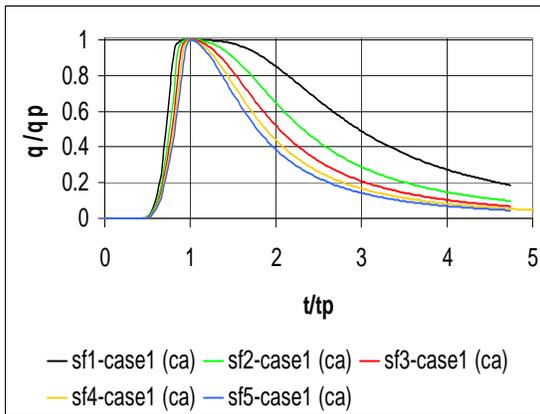
Constant Area (ca)
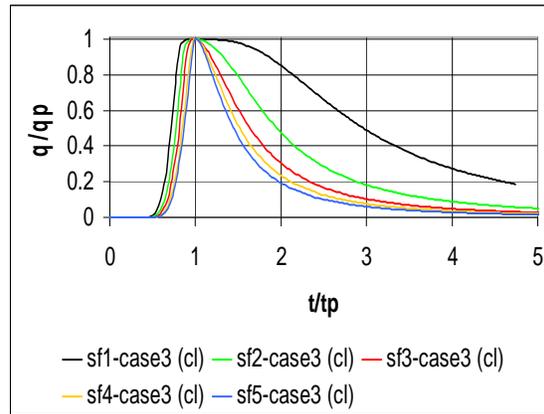
Constant Length (cl)

Appendix 22b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.
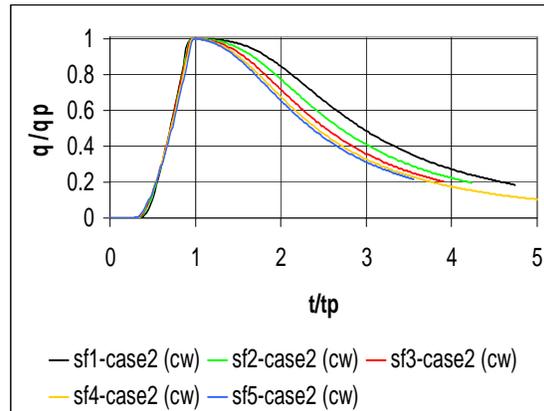
Constant Width (cw)
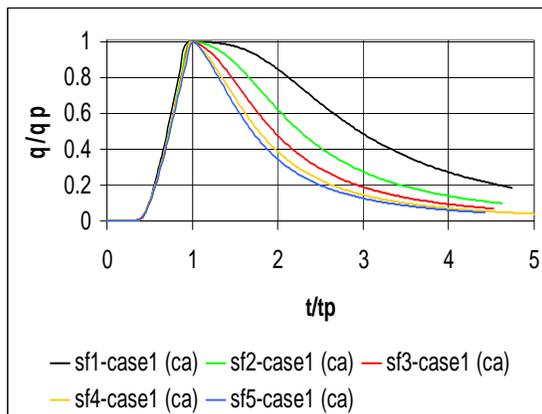
Constant Area (ca)
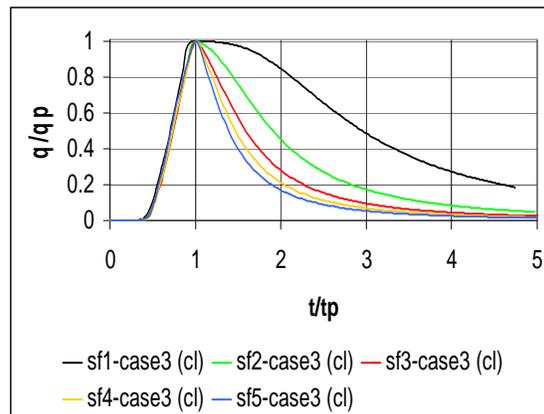
Constant Length (cl)

Appendix 23b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
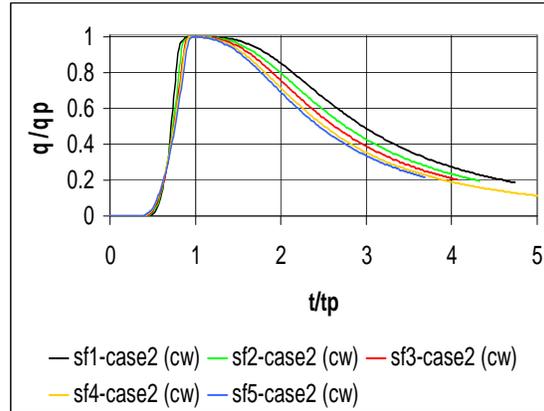
Constant Width (cw)
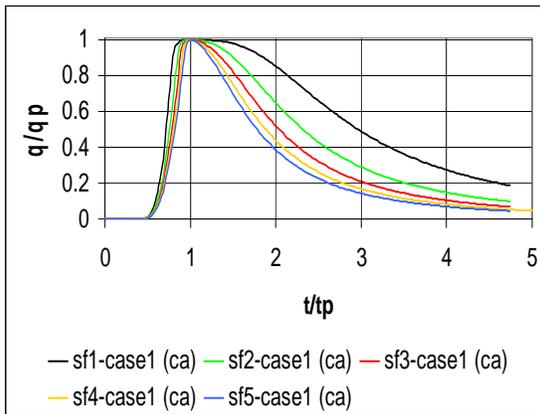
Constant Area (ca)
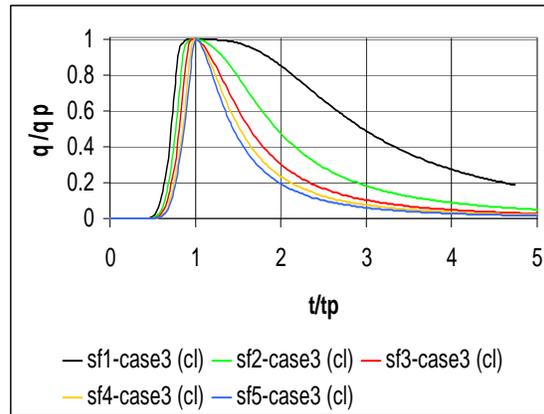
Constant Length (cl)

Appendix 24b. Shape Factor Comparisons (Shape Factors 1, 2, 3, 4, 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 4.05%

APPENDIX C

COMPARISON OF BASIN CONFIGURATIONS
CONSTANT AREA, LENGTH, AND WIDTH
DIMENSIONLESS HYDROGRAPHS
SYNTHETIC RECTANGULAR BASINS

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
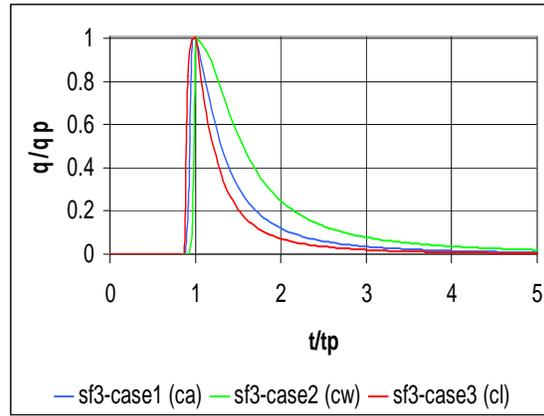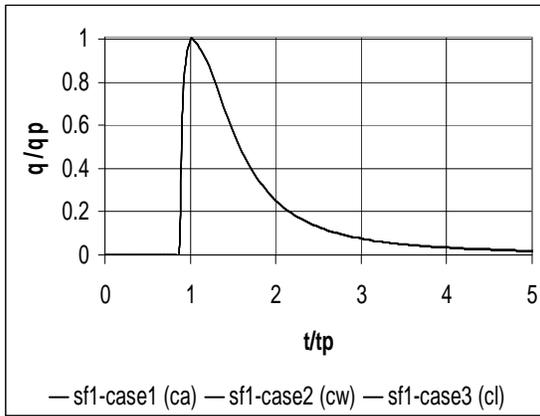
Shape Factor = 3
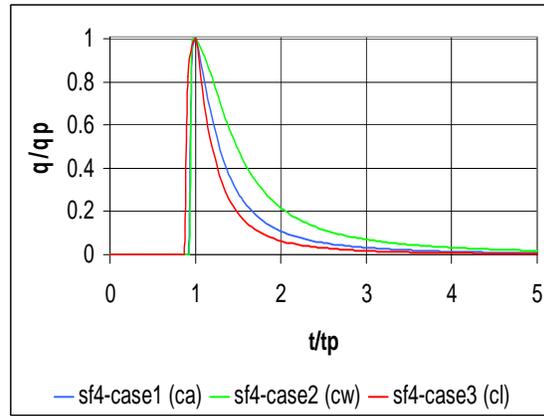
Shape Factor = 1
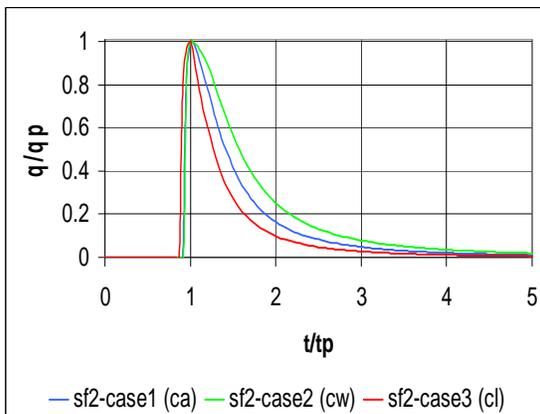

Shape Factor = 4
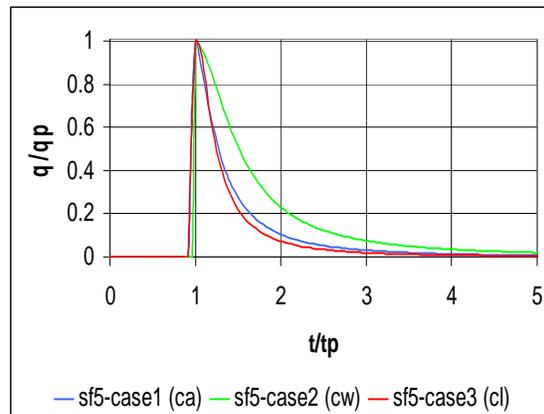
Shape Factor = 2

Shape Factor = 5

Appendix 1c.   Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
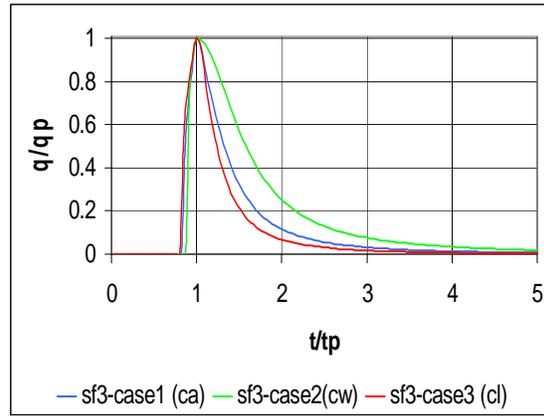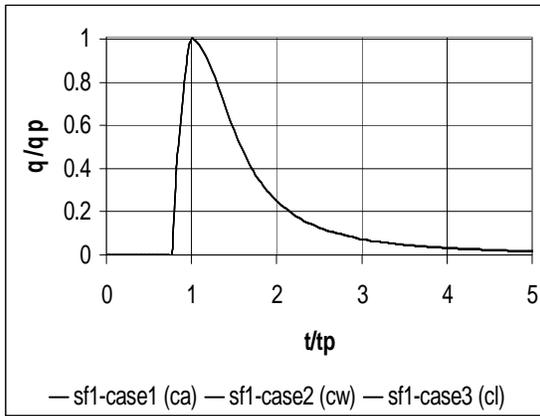
Shape Factor = 3
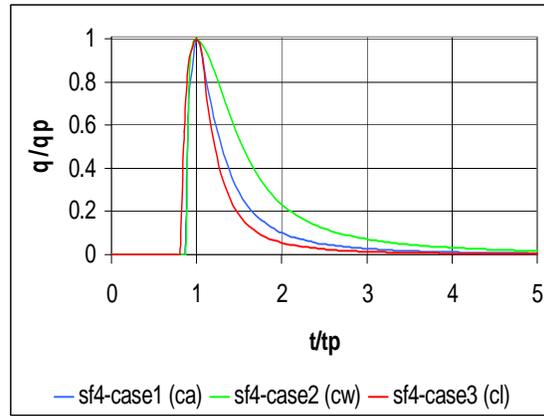
Shape Factor = 1
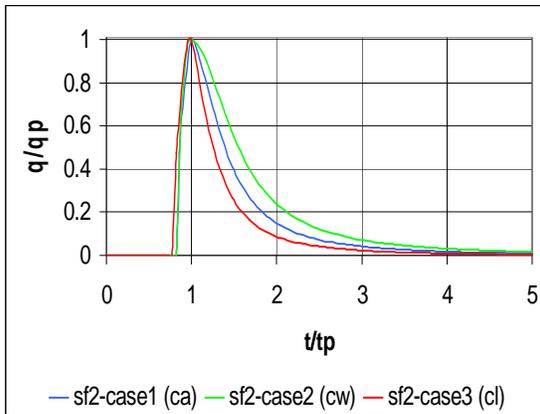
Shape Factor = 4
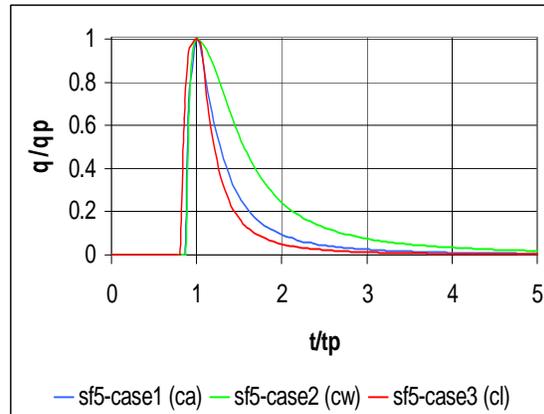
Shape Factor = 2

Shape Factor = 5

Appendix 2c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

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Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
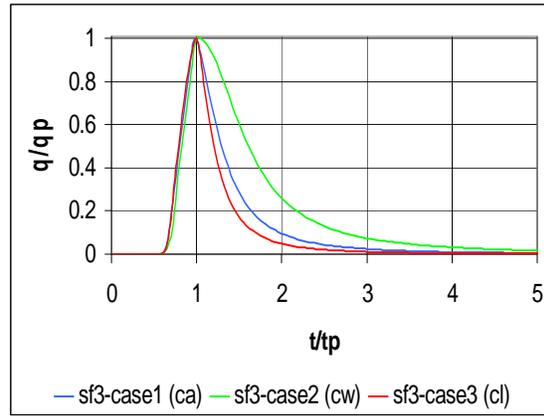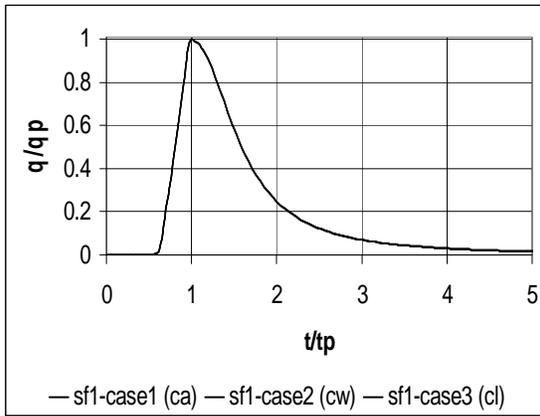
Shape Factor = 3
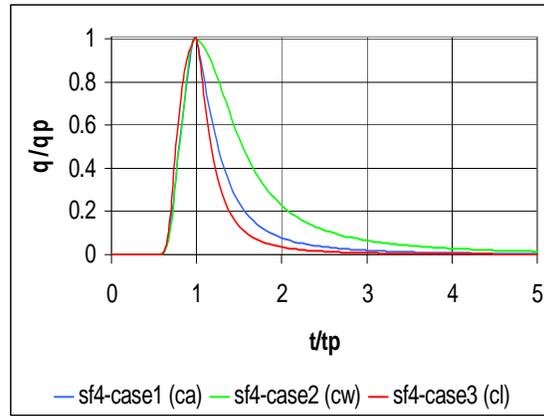
Shape Factor = 1
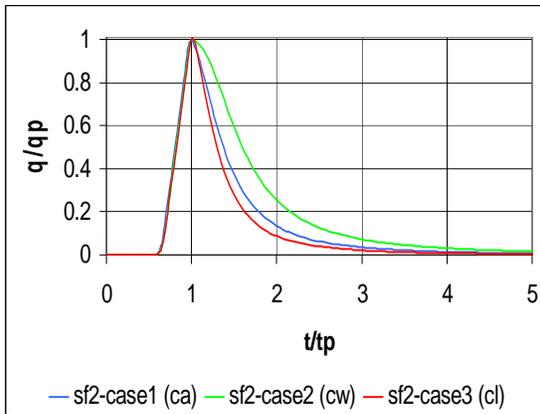
Shape Factor = 4
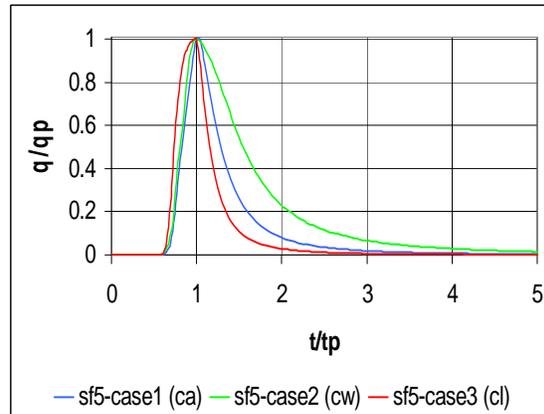
Shape Factor = 2

Shape Factor = 5

Appendix 3c. Basin Configuration Comparisons (Constant Area, Length, Width)
           Dimensionless Hydrographs – Synthetic Rectangular Basins
           Stationary Storm – Lower 20% – Distributed Rainfall
           Overland Flow Plane Slope = 16.22%

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
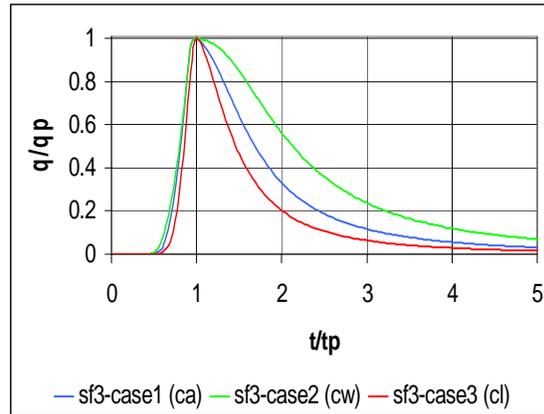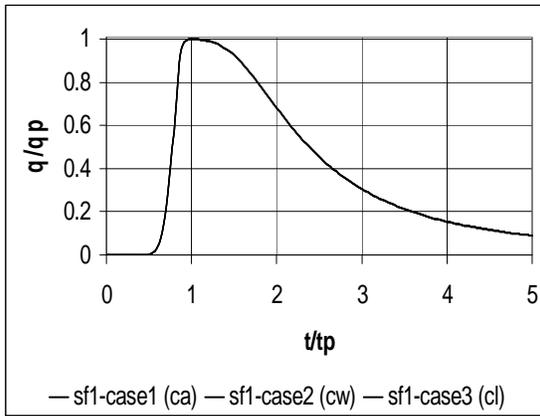
Shape Factor = 3
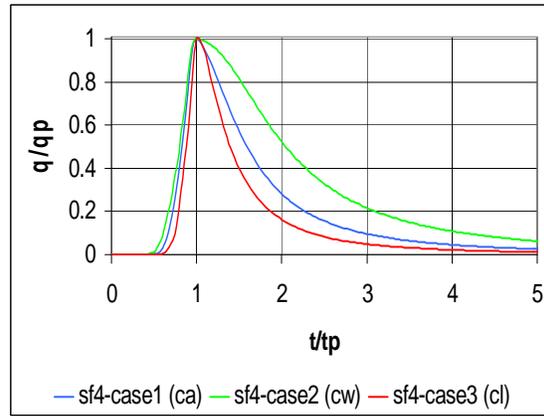
Shape Factor = 1
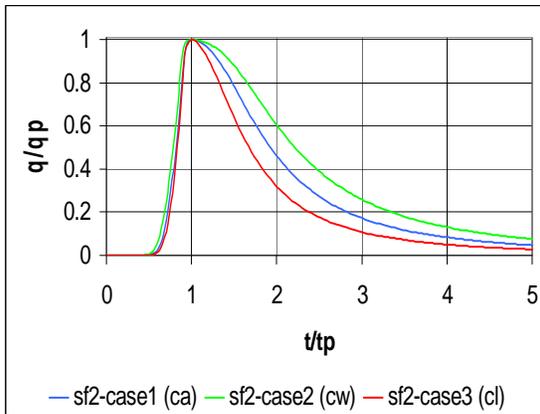
Shape Factor = 4
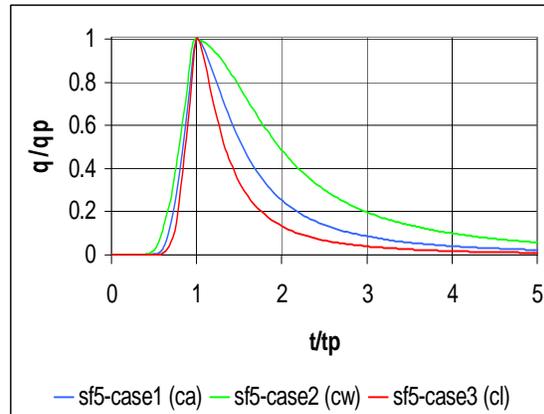
Shape Factor = 2

Shape Factor = 5

Appendix 4c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
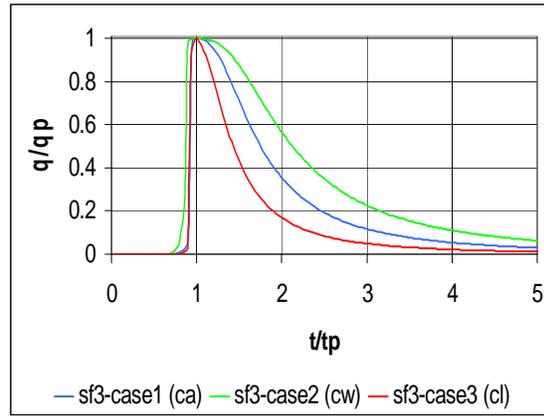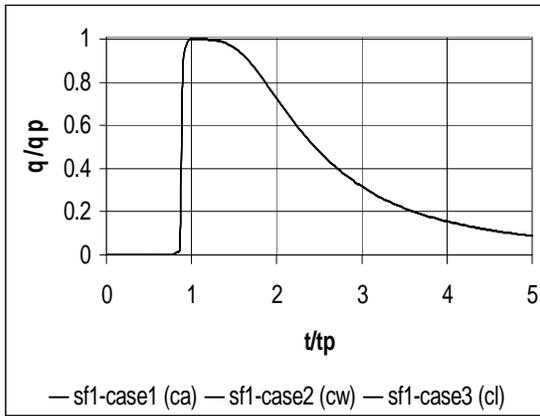
Shape Factor = 3
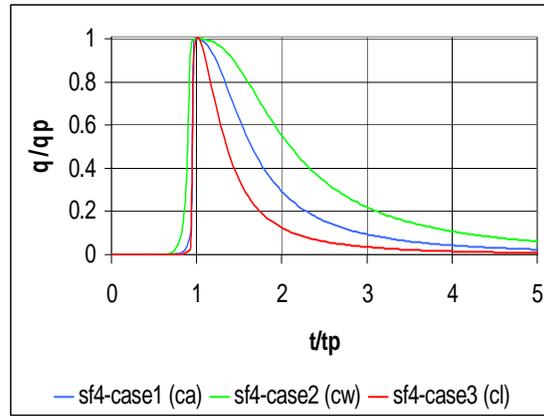
Shape Factor = 1
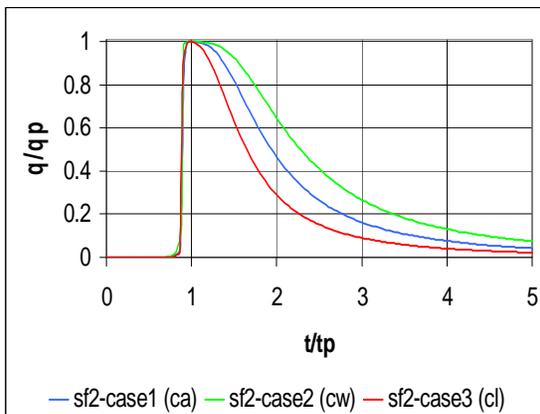
Shape Factor = 4
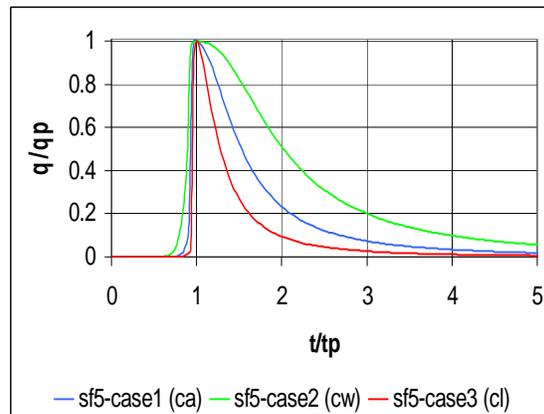
Shape Factor = 2

Shape Factor = 5

Appendix 5c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
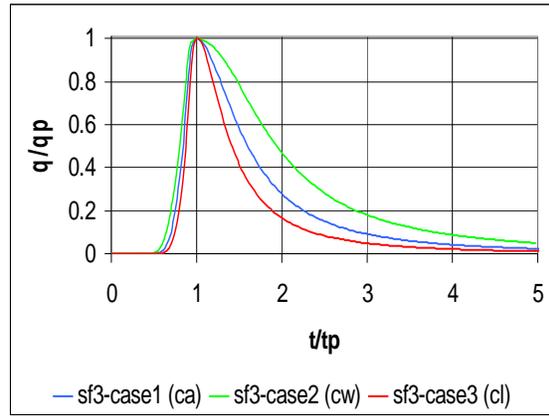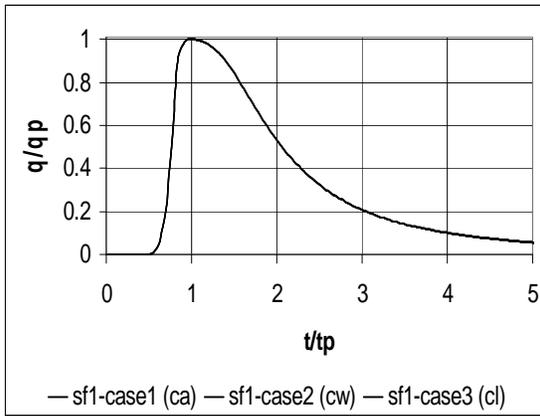
Shape Factor = 3
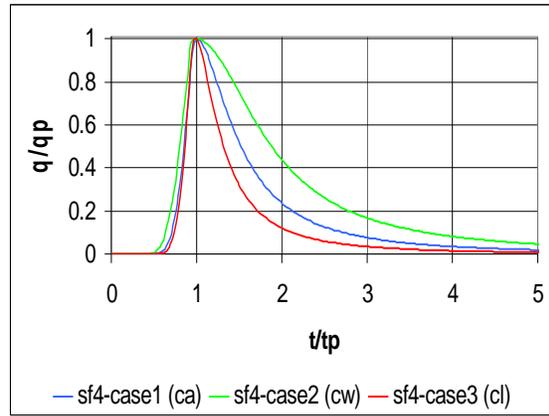
Shape Factor = 1
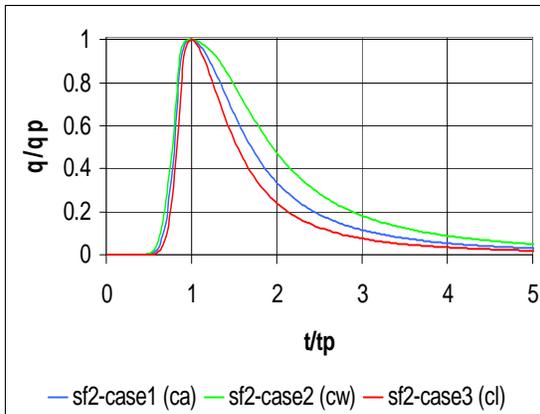


Shape Factor = 4
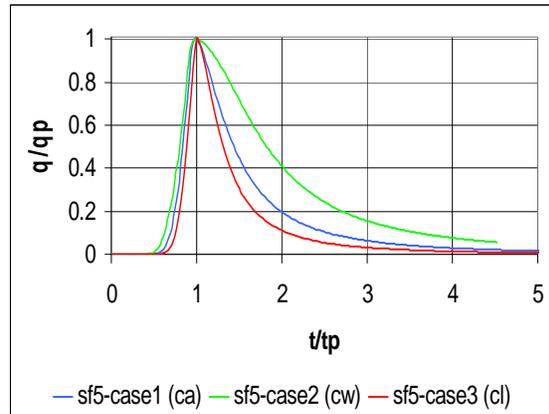
Shape Factor = 2

Shape Factor = 5

Appendix 6c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
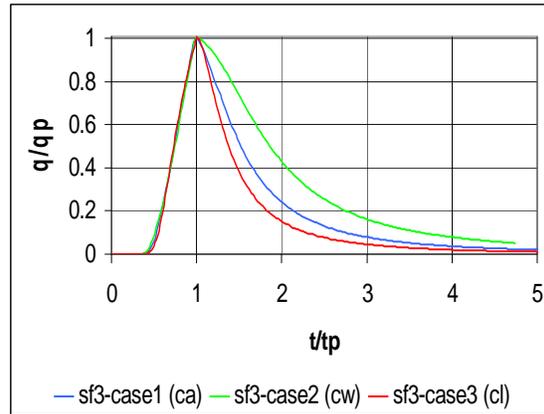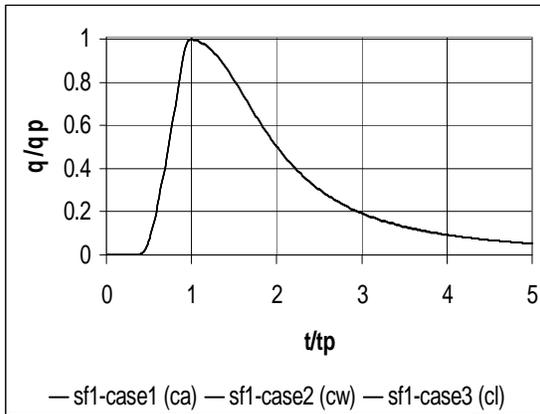
Shape Factor = 3
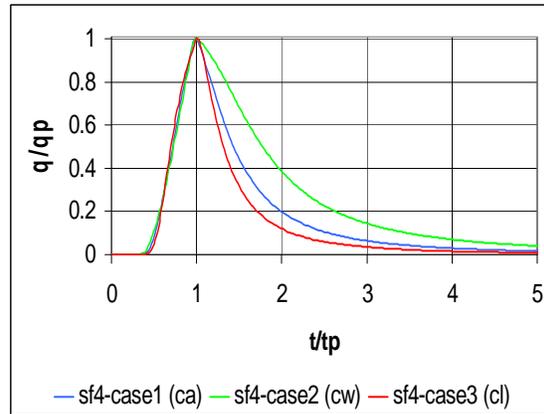
Shape Factor = 1
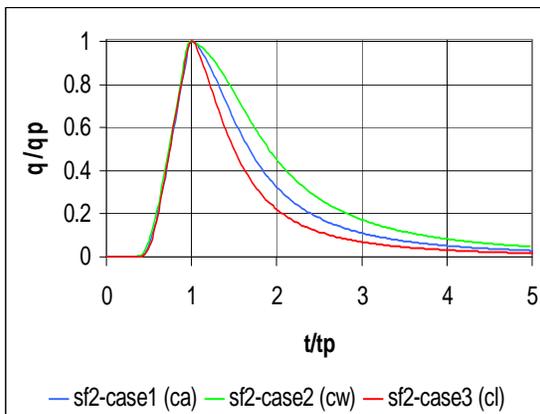


Shape Factor = 4
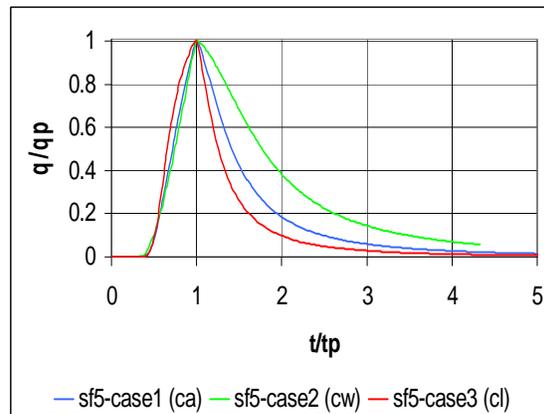
Shape Factor = 2

Shape Factor = 5

Appendix 7c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 16.22%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
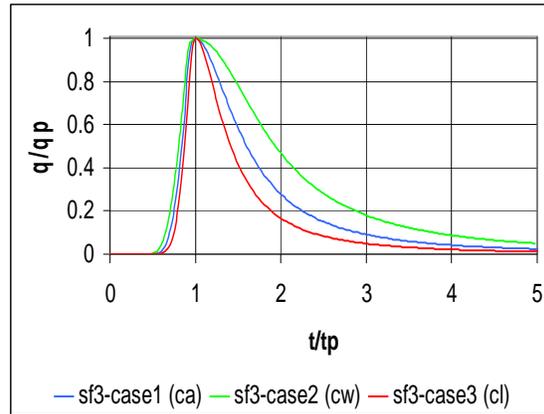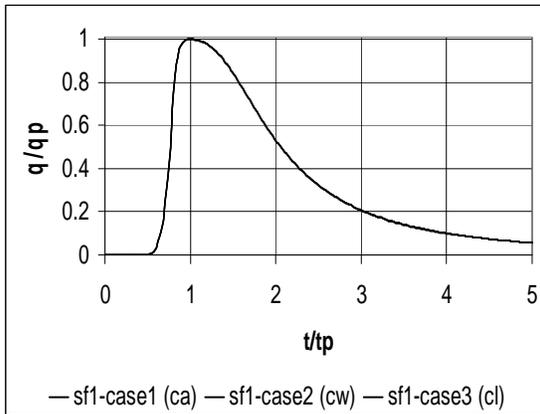
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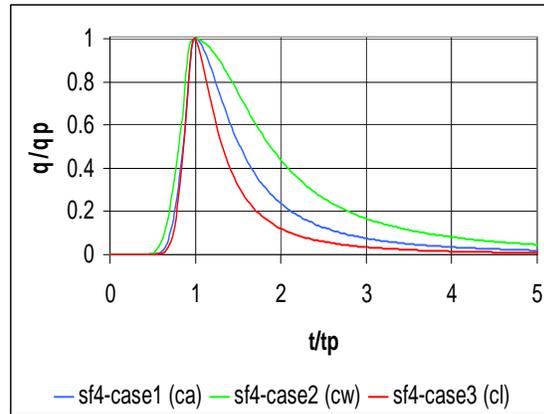
Shape Factor = 1
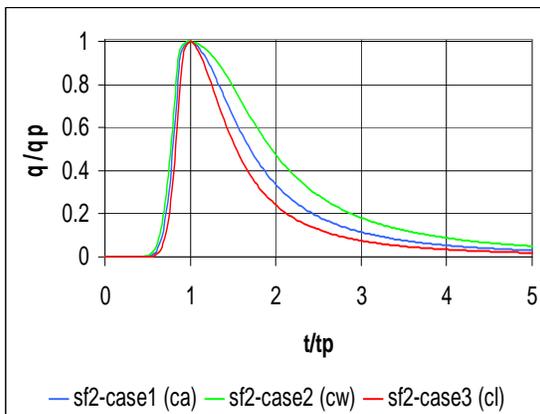
Shape Factor = 4
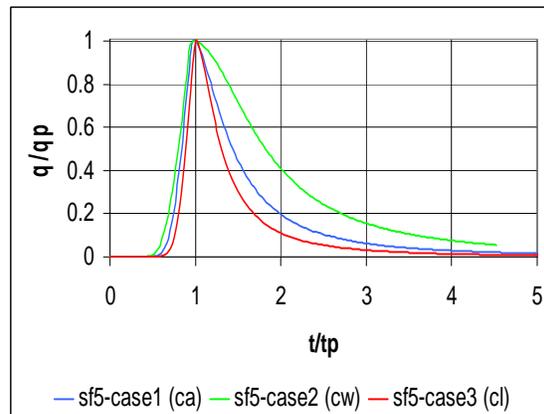
Shape Factor = 2

Shape Factor = 5

Appendix 8c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 16.22%

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
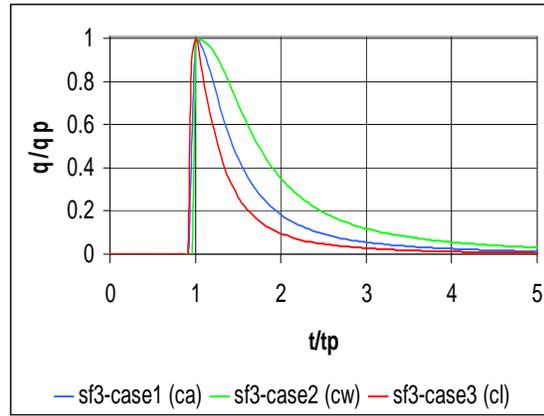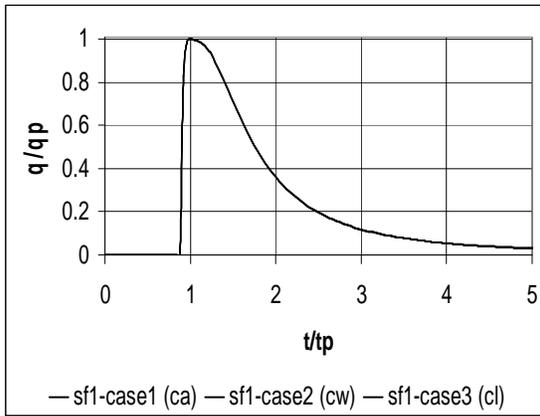
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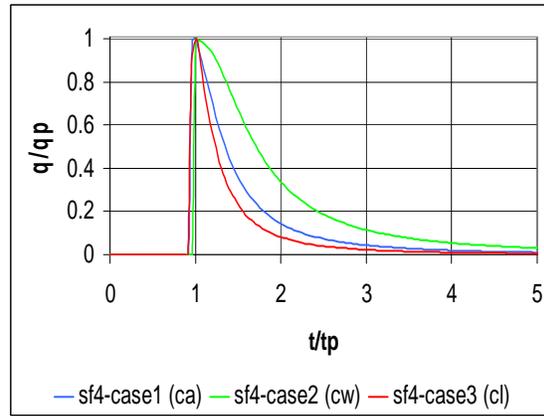
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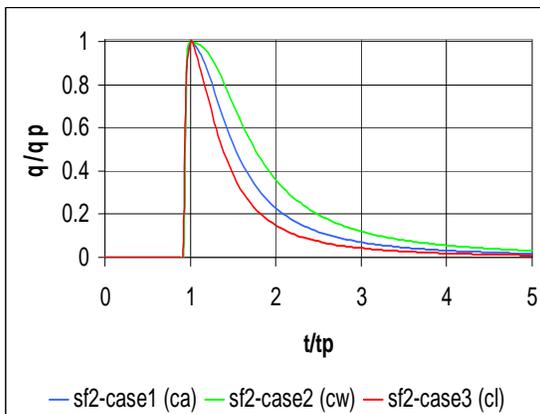
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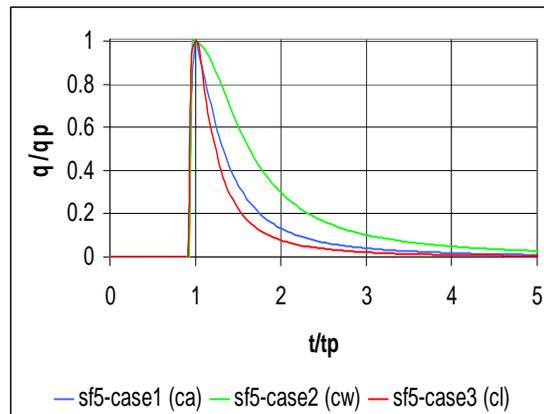
Shape Factor = 2

Shape Factor = 5

Appendix 9c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
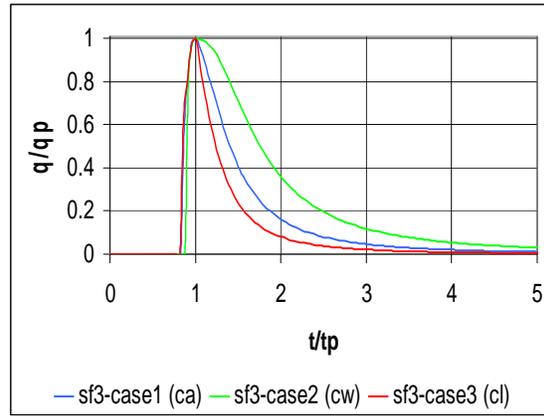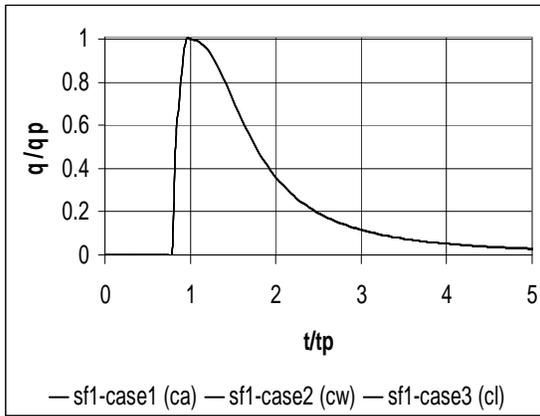
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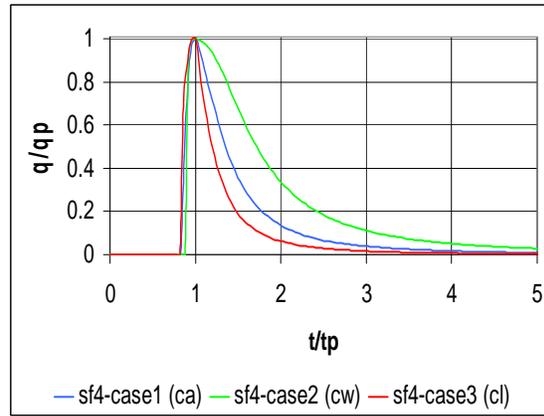
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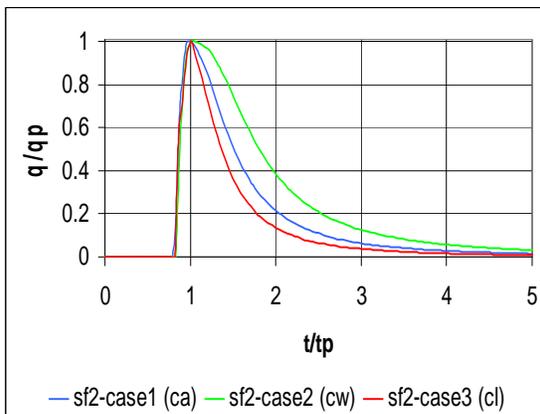

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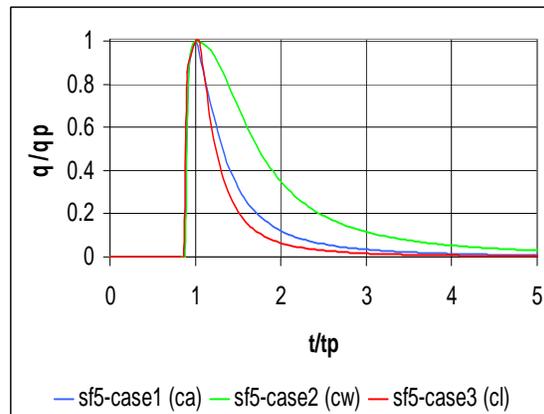
Shape Factor = 2

Shape Factor = 5

Appendix 10c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
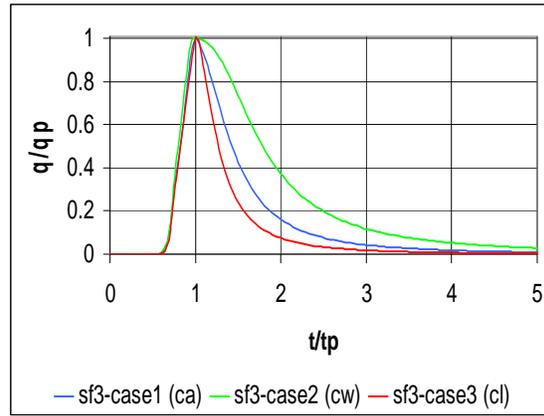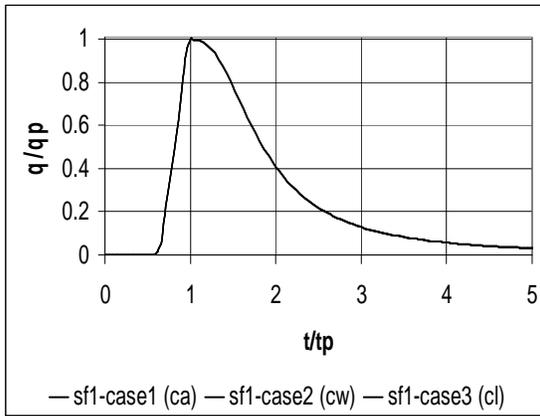
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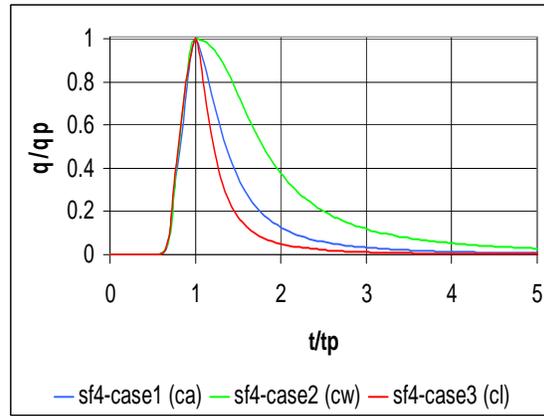
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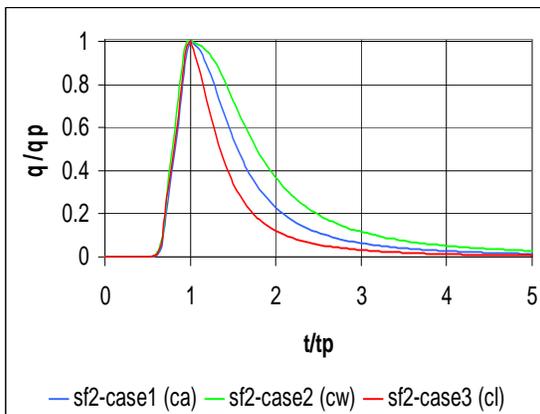

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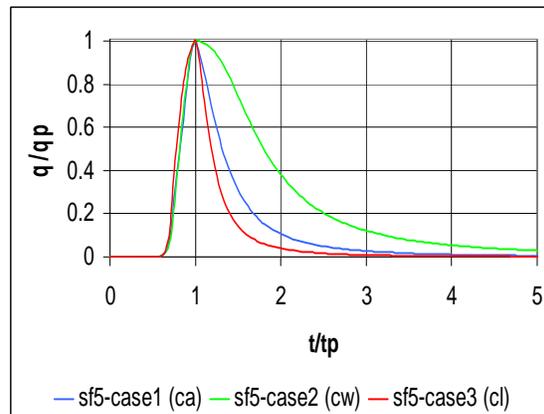
Shape Factor = 2

Shape Factor = 5

Appendix 11c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

326

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
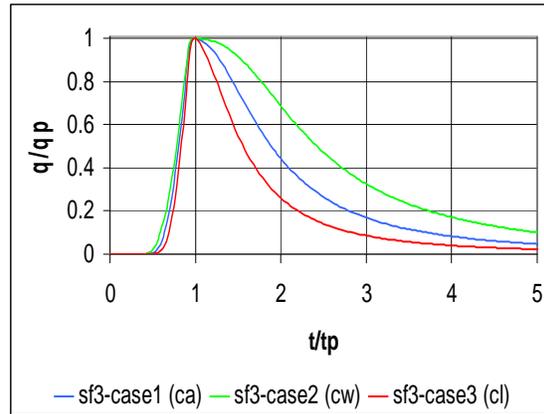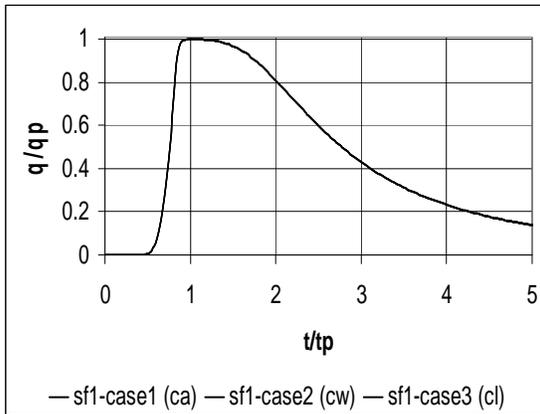
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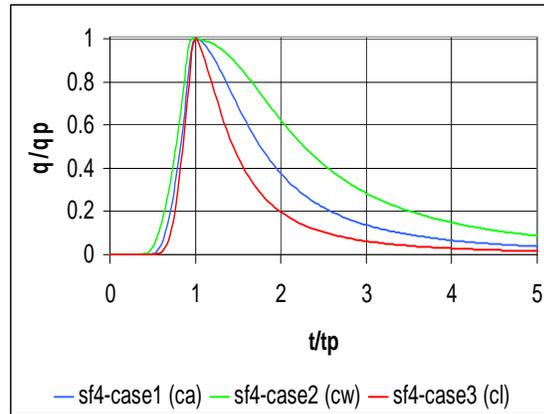
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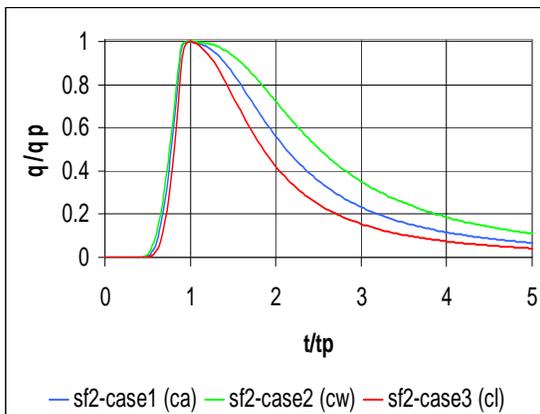
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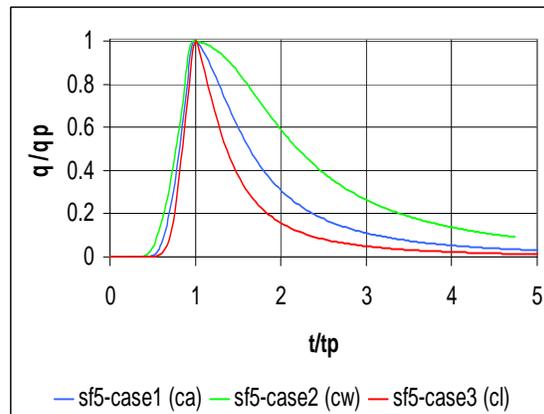
Shape Factor = 2

Shape Factor = 5

Appendix 12c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Entire Basin – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
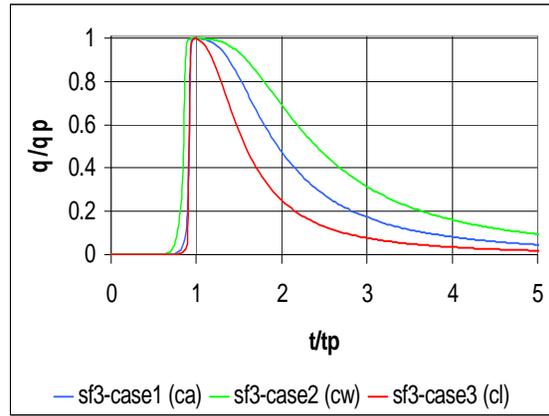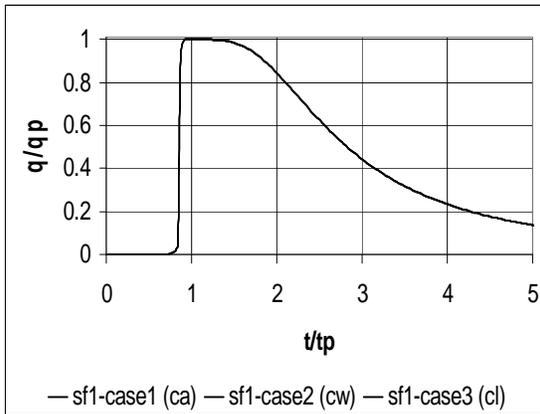
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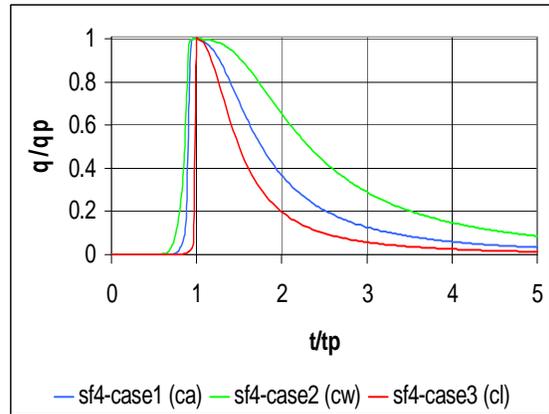
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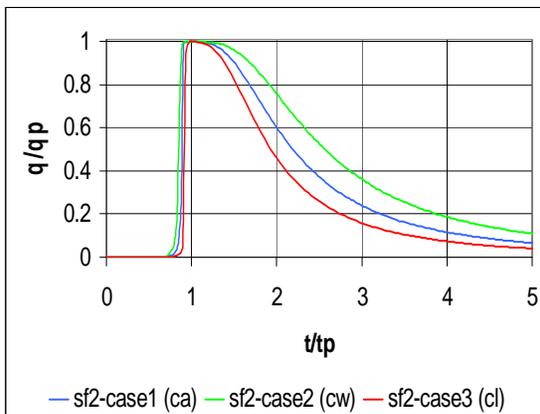
Shape Factor = 4
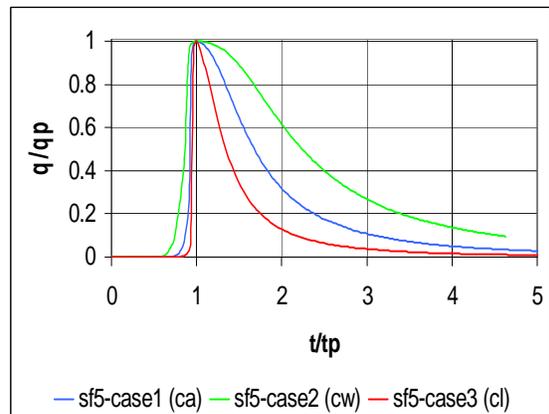
Shape Factor = 2

Shape Factor = 5

Appendix 13c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
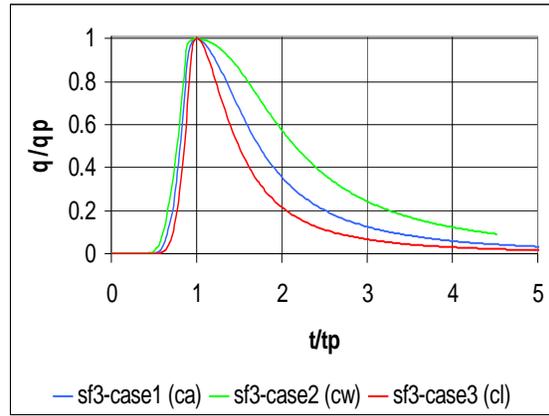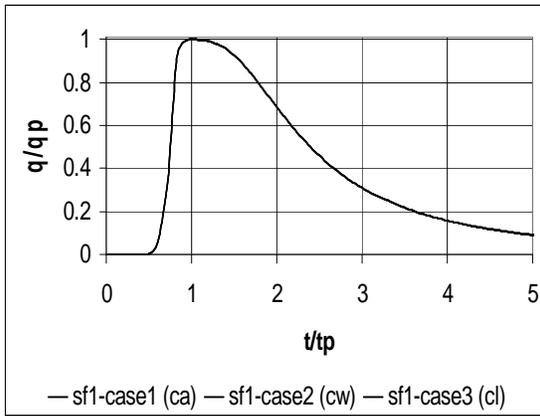
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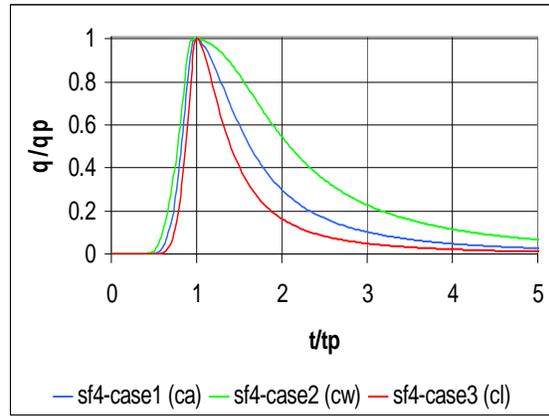
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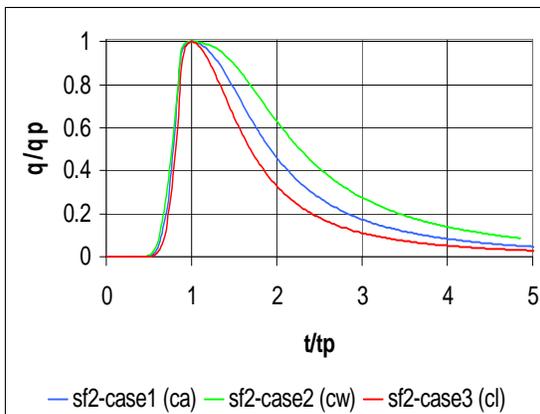
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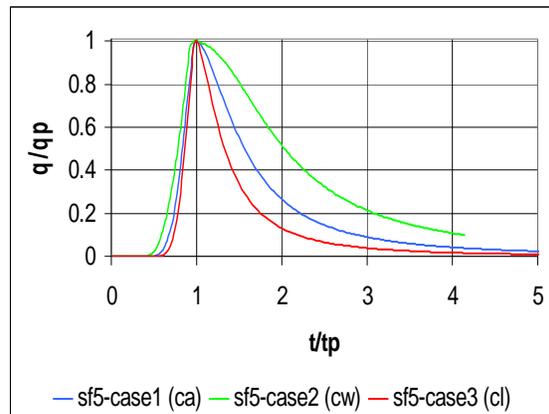
Shape Factor = 2

Shape Factor = 5

Appendix 14c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
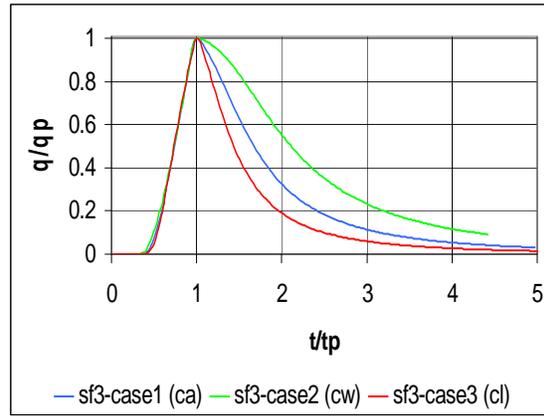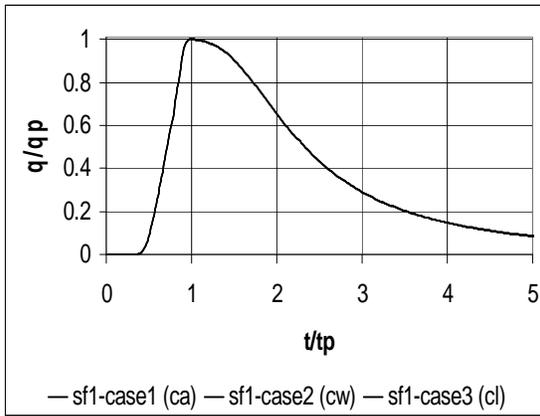
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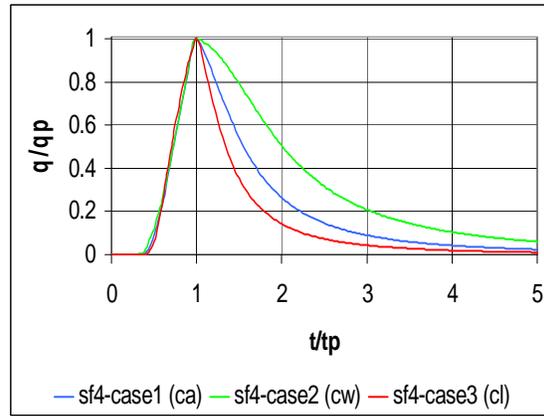
Shape Factor = 1
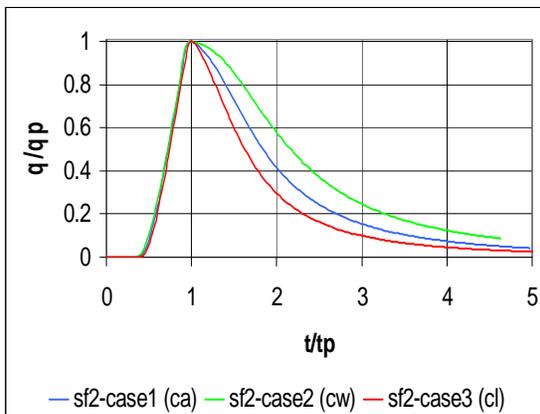
Shape Factor = 4
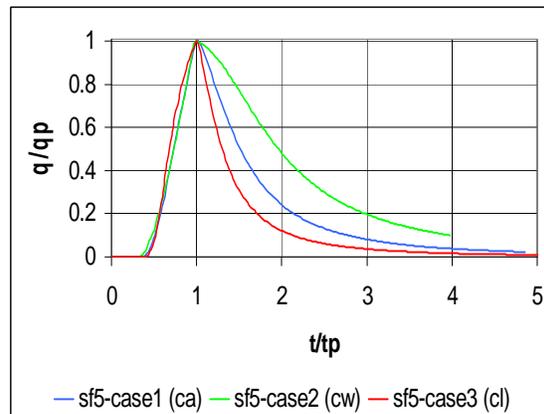
Shape Factor = 2

Shape Factor = 5

Appendix 15c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 9.12%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
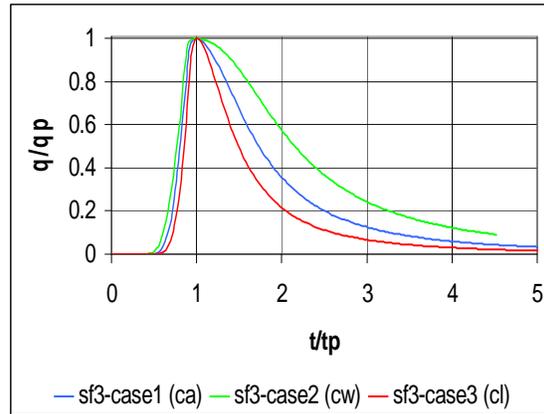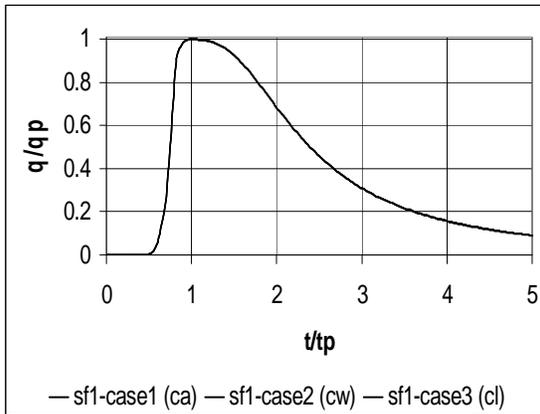
Shape Factor = 3
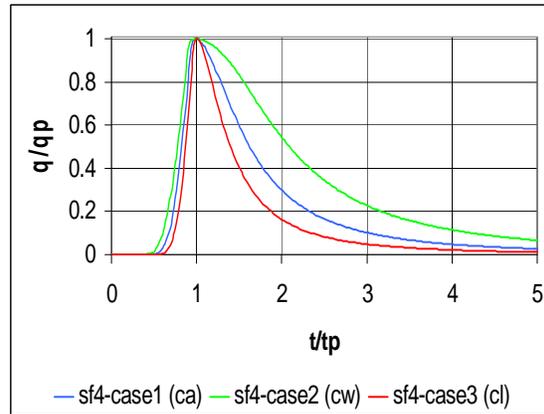
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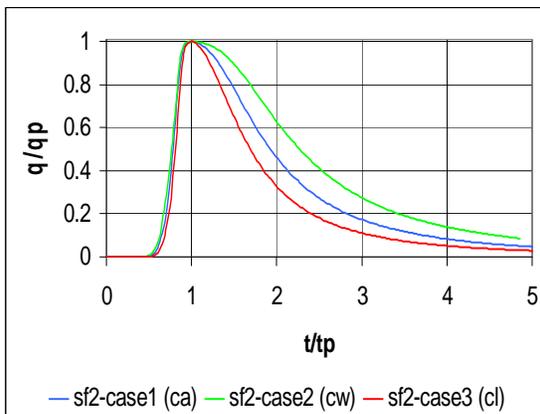
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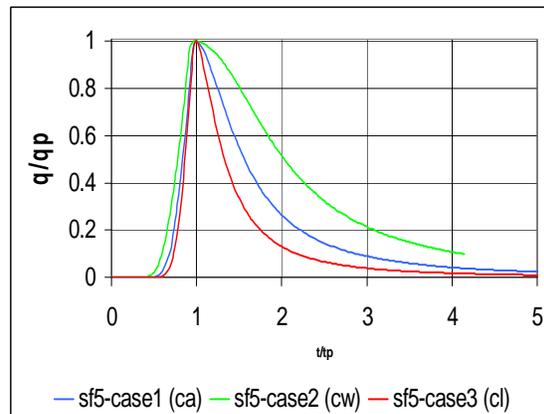
Shape Factor = 2

Shape Factor = 5

Appendix 16c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 9.12%

331

Stationary Storm – Upper 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
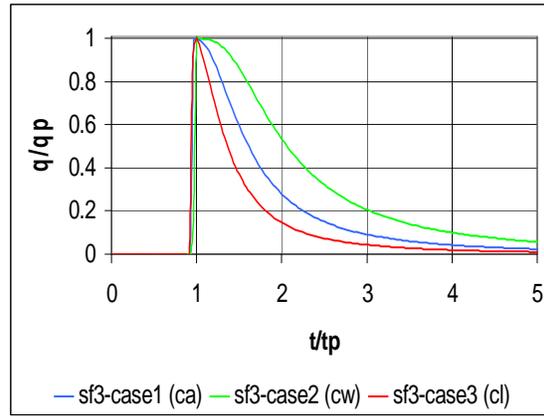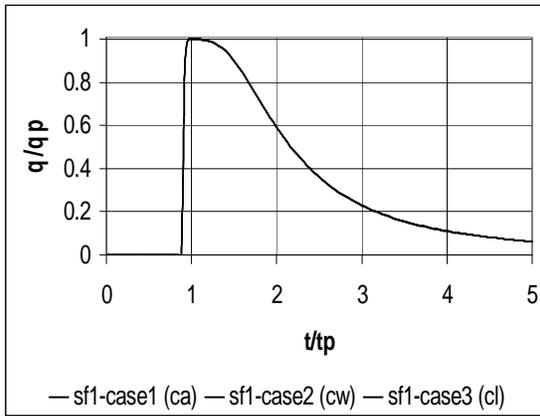
Shape Factor = 3
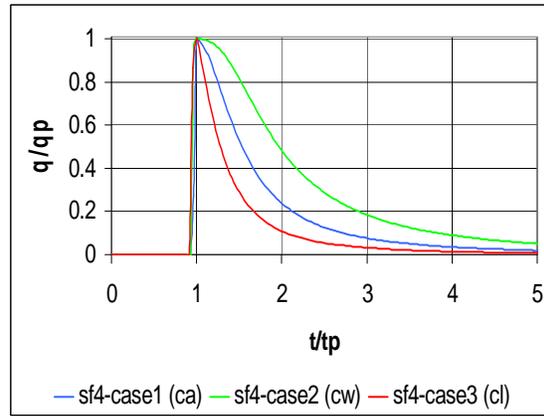
Shape Factor = 1
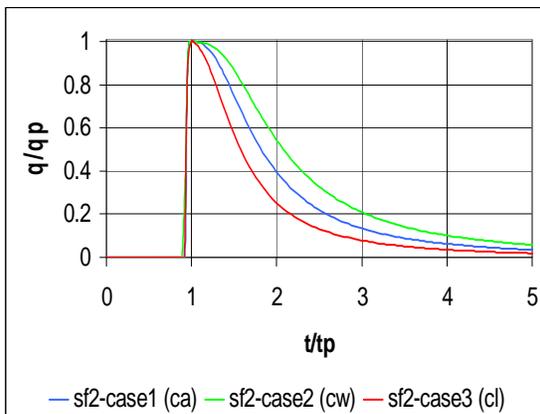
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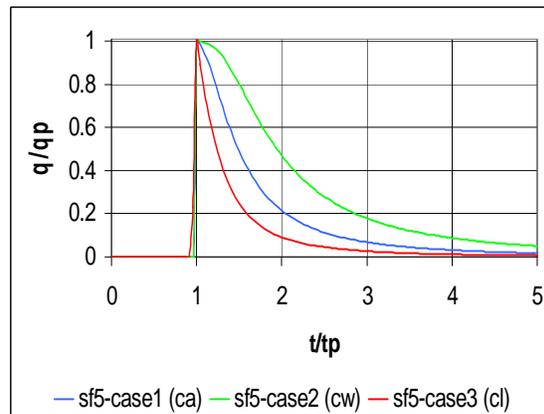
Shape Factor = 2

Shape Factor = 5

Appendix 17c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Upper 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

332

Stationary Storm – Middle 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the middle 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)

Shape Factor = 3

Shape Factor = 1

Shape Factor = 4

Shape Factor = 2

Shape Factor = 5
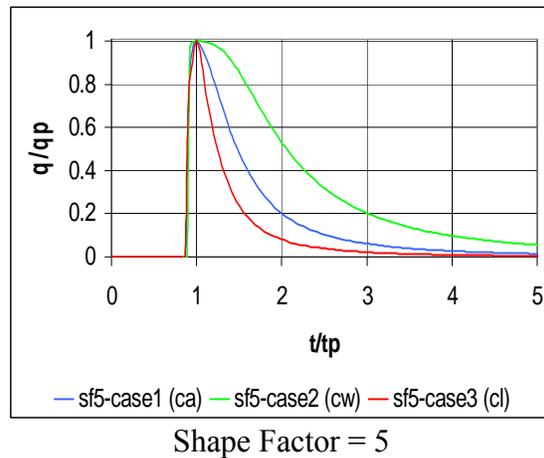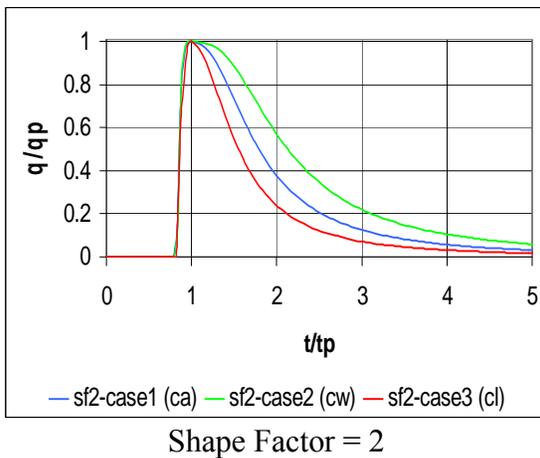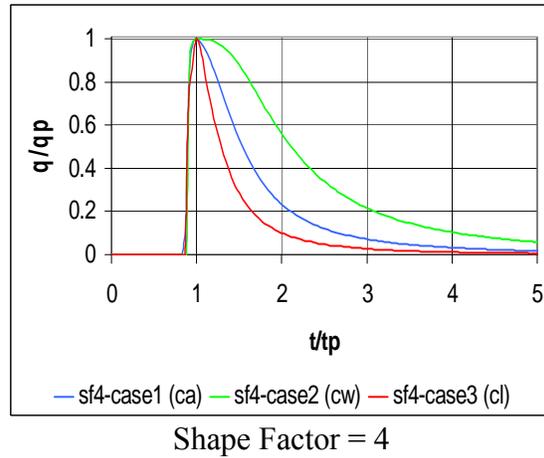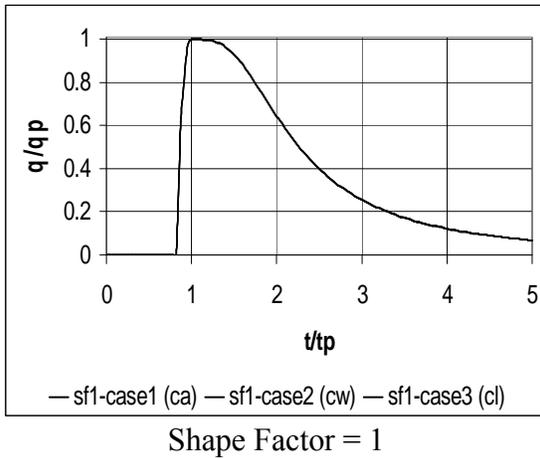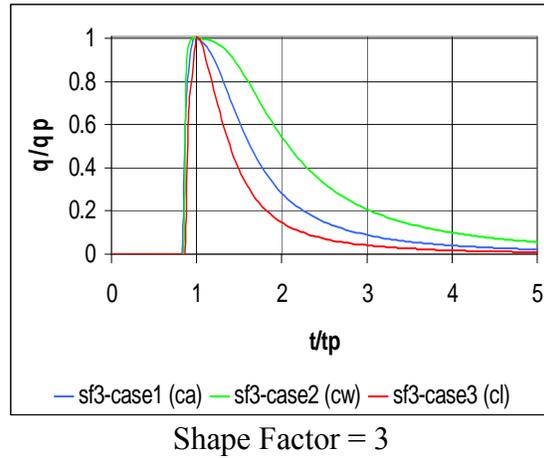
Appendix 18c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Middle 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Stationary Storm – Lower 20% of Basin
Precipitation – Distributed Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the lower 20% of each basin. No
rainfall was applied over the remaining
80%.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
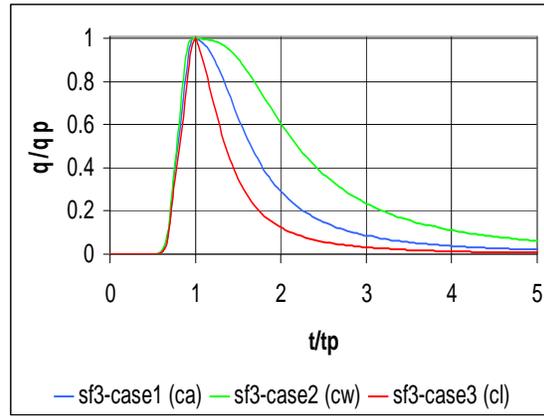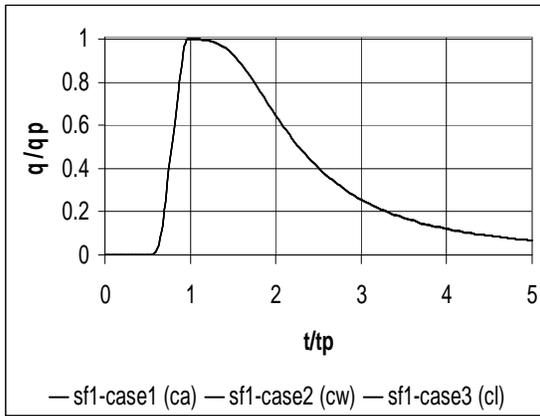
Shape Factor = 3
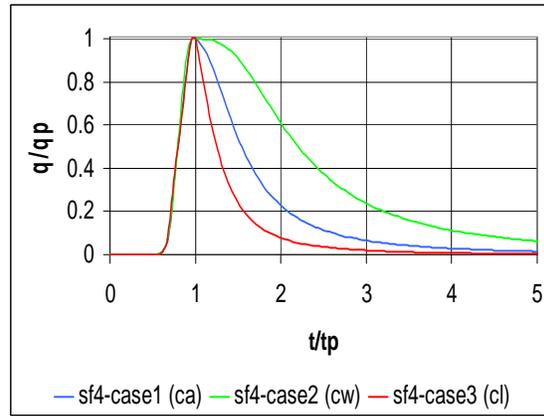
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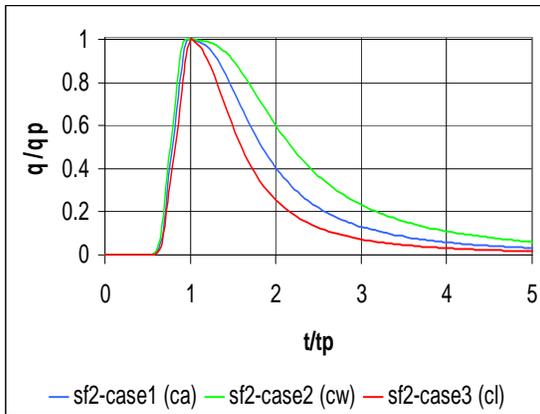
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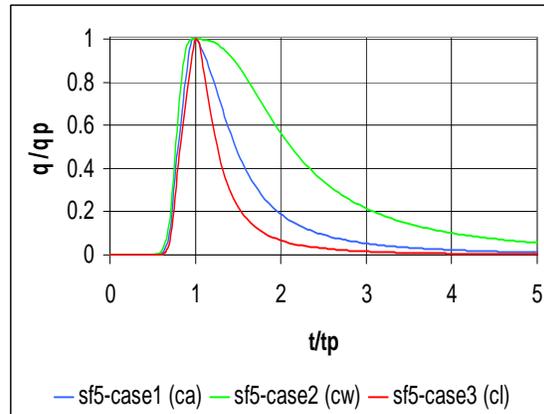
Shape Factor = 2

Shape Factor = 5

Appendix 19c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storm – Lower 20% – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Stationary Storm – Entire Basin
Precipitation – Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
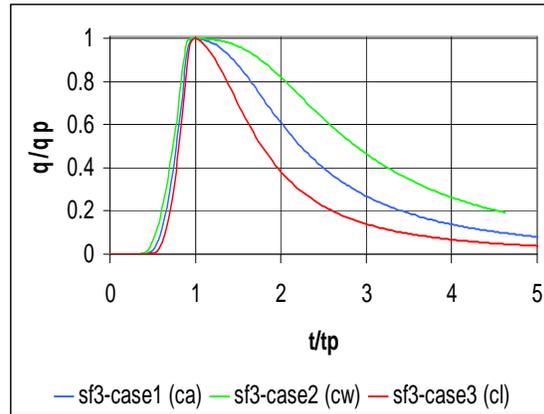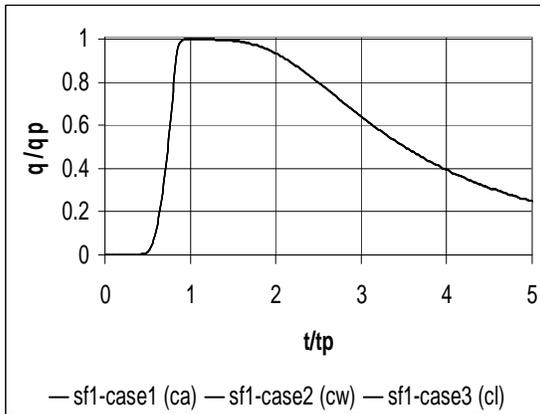
Shape Factor = 3
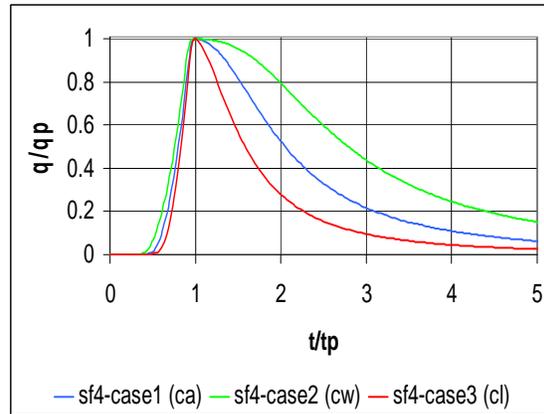
Shape Factor = 1
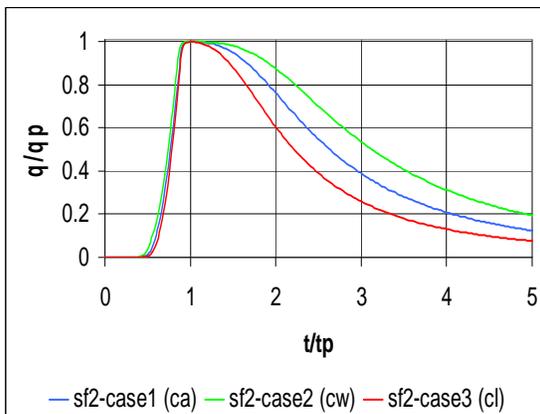
Shape Factor = 4
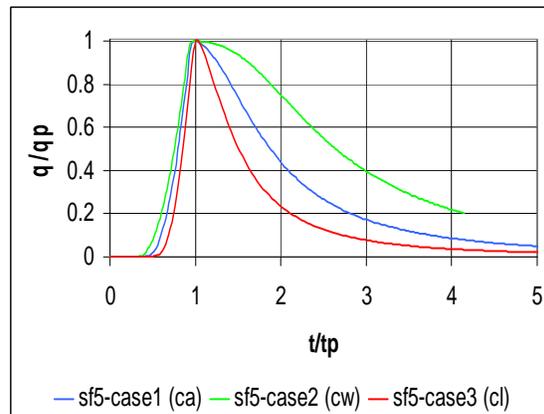
Shape Factor = 2

Shape Factor = 5

Appendix 20c. Basin Configuration Comparisons (Constant Area, Length, Width)
  Dimensionless Hydrographs – Synthetic Rectangular Basins
  Stationary Storm – Entire Basin – Lumped Rainfall
  Overland Flow Plane Slope = 4.05%

335

Moving Storm – Upstream to Downstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
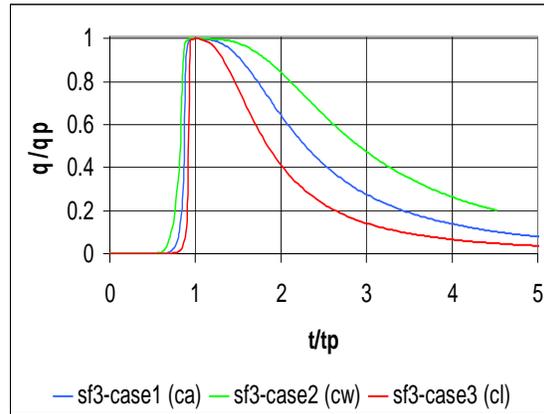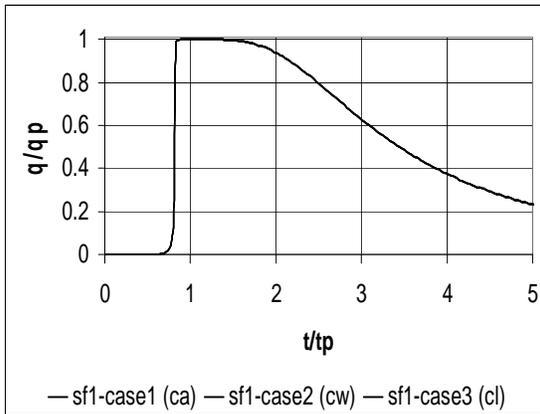
Shape Factor = 3
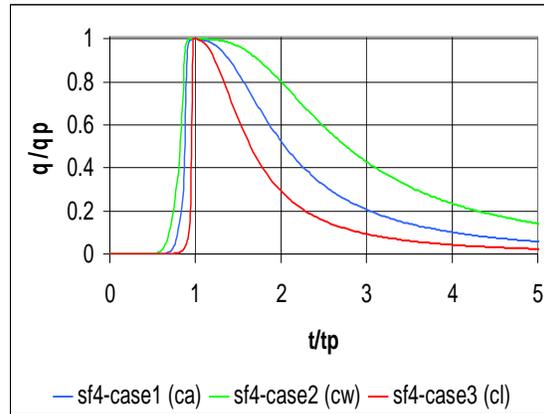
Shape Factor = 1
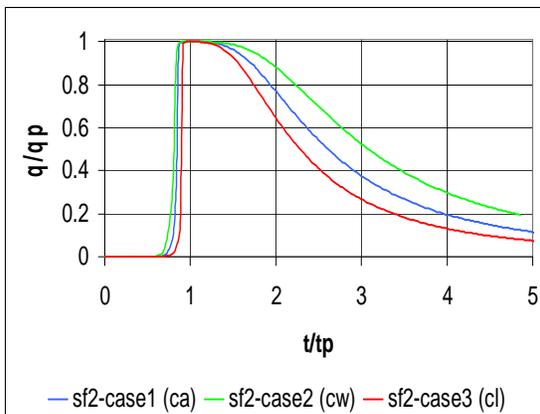
Shape Factor = 4
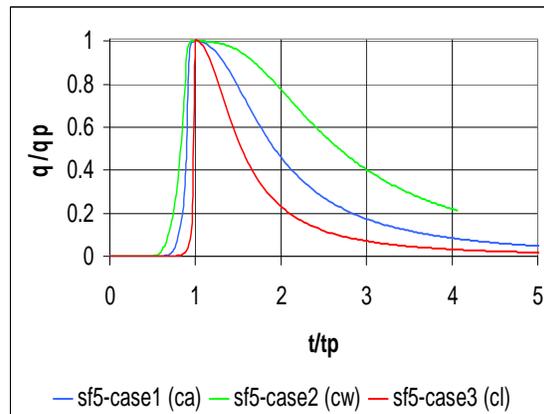
Shape Factor = 2

Shape Factor = 5

Appendix 21c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
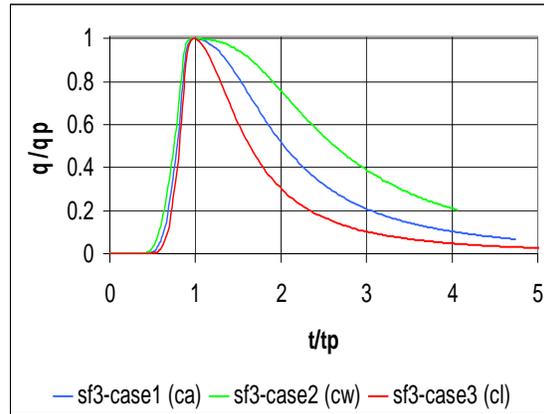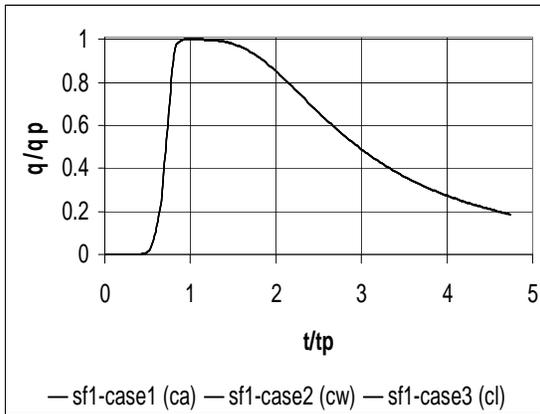
Shape Factor = 3
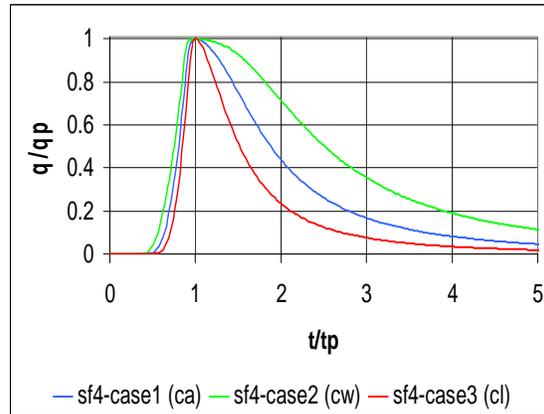
Shape Factor = 1
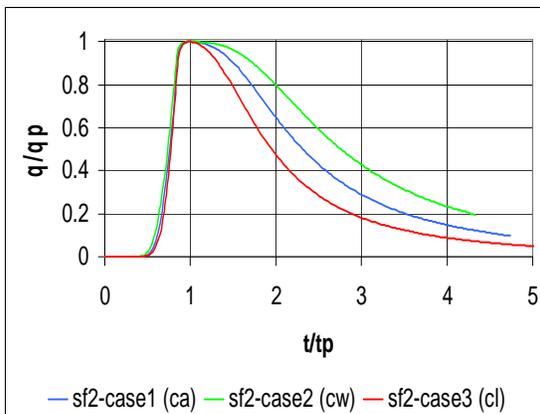
Shape Factor = 4
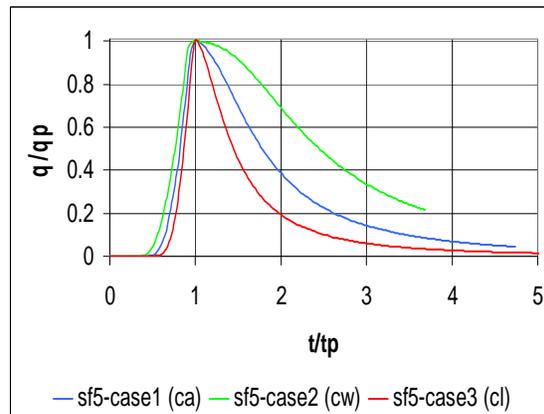
Shape Factor = 2

Shape Factor = 5

Appendix 22c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Upstream to Downstream – Lumped Rainfall
Overland Flow Plane Slope = 4.05%

337

Moving Storm – Downstream to Upstream
Precipitation – Distributed Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
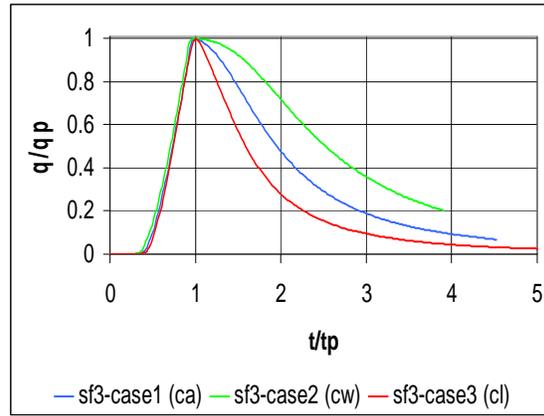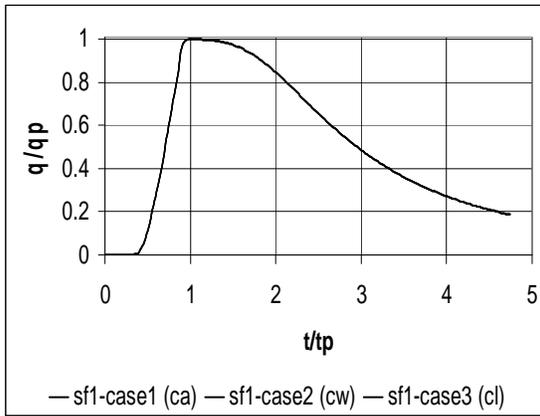
Shape Factor = 3
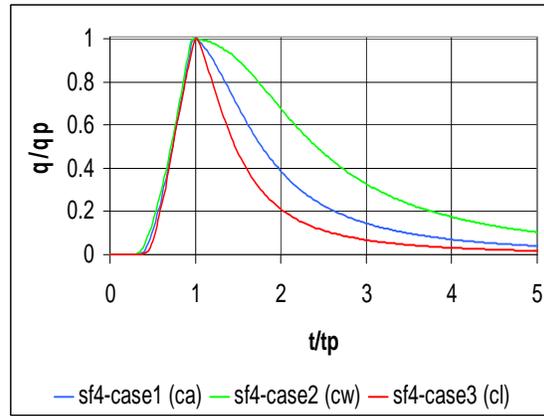
Shape Factor = 1
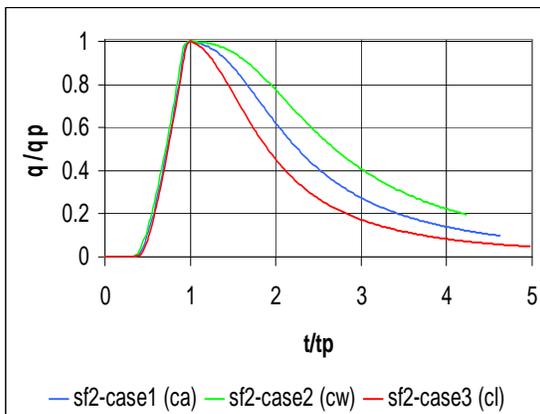
Shape Factor = 4
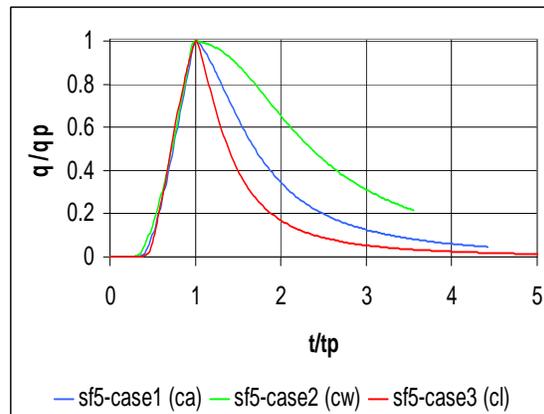
Shape Factor = 2

Shape Factor = 5

Appendix 23c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Distributed Rainfall
Overland Flow Plane Slope = 4.05%

Moving Storm – Downstream to Upstream
Precipitation – Lumped Rainfall
Storm moves at constant velocity
Total rainfall equals 0.2 inch
Total storm period equals 20 minutes

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.

Constant Area (ca)
Constant Length (cl)
Constant Width (cw)
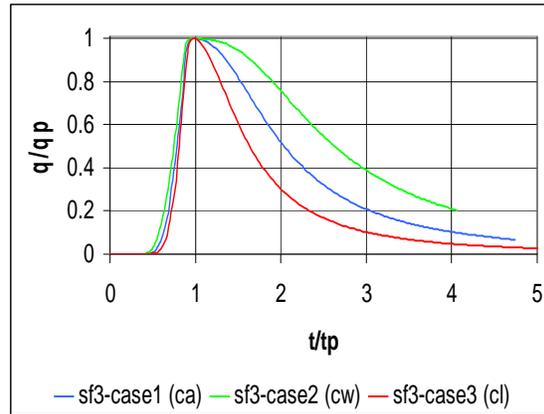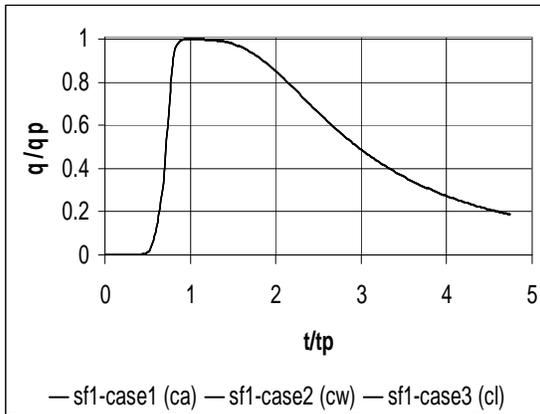
Shape Factor = 3
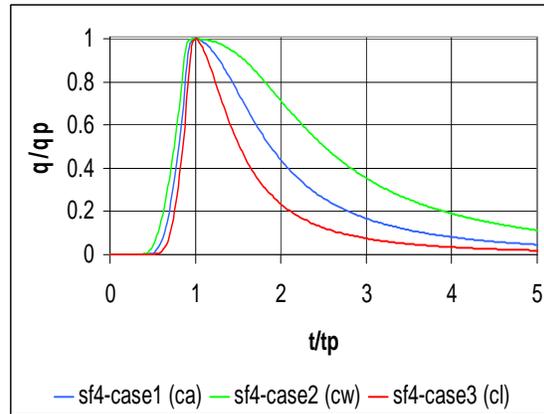
Shape Factor = 1
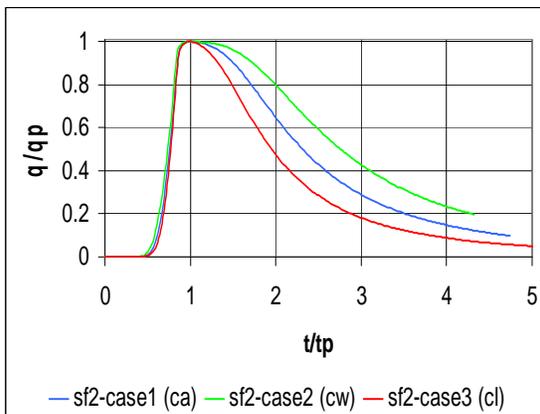
Shape Factor = 4
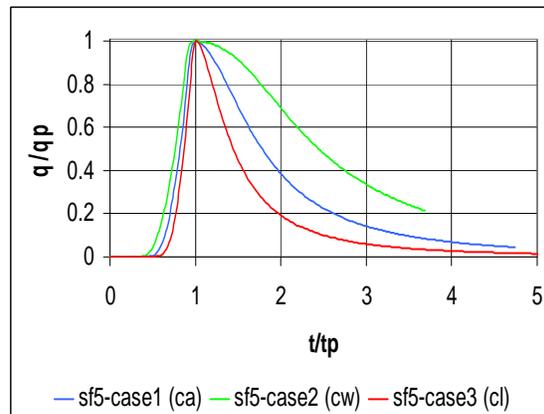
Shape Factor = 2

Shape Factor = 5

Appendix 24c. Basin Configuration Comparisons (Constant Area, Length, Width)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storm – Downstream to Upstream – Lumped Rainfall
Overland Flow Plane Slope = 4.05%

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APPENDIX D

COMPARISON OF DISTRIBUTED AND LUMPED RAINFALL
DIMENSIONLESS HYDROGRAPHS
SYNTHETIC RECTANGULAR BASINS

Stationary Storms – Upper 20%,
                          Middle 20%,
                          Lower 20%,
                          Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.
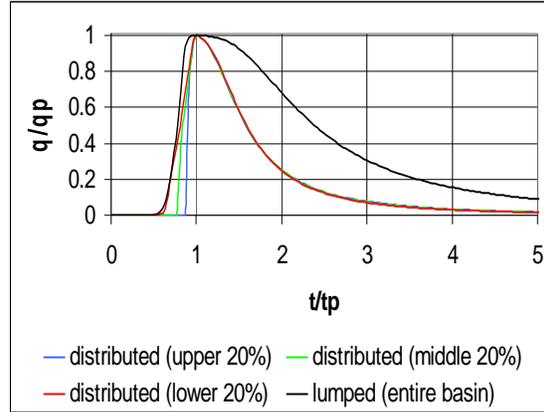
Constant Width (cw)
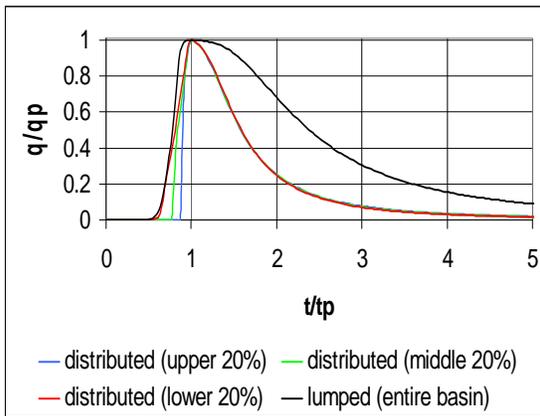
Constant Area (ca)
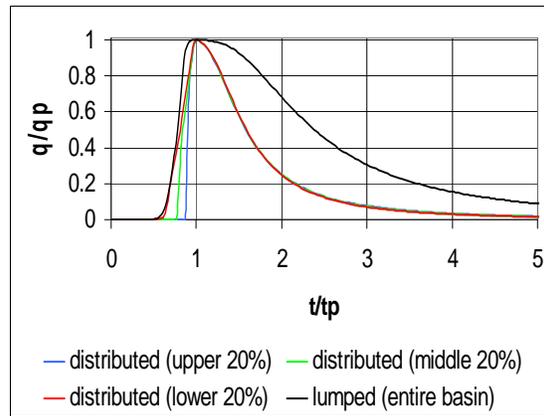
Constant Length (cl)

Appendix 1d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 16.22%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 2d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 16.22%

Stationary Storms – Upper 20%,
 Middle 20%,
 Lower 20%,
 Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 3d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
 Dimensionless Hydrographs – Synthetic Rectangular Basins
 Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
 Overland Flow Plane Slope = 16.22%

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Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 4d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 16.22%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 5d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
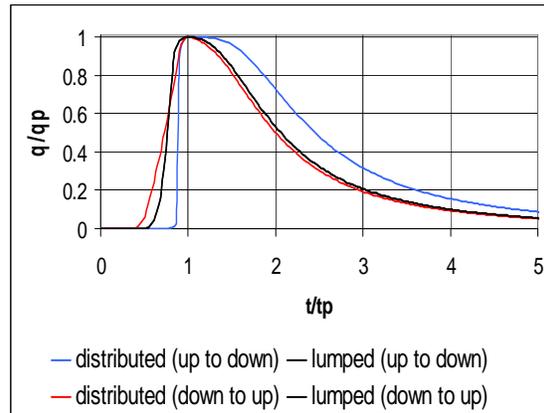
Constant Width (cw)
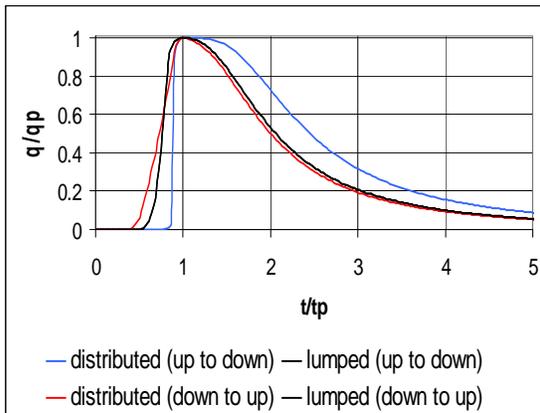
Constant Area (ca)
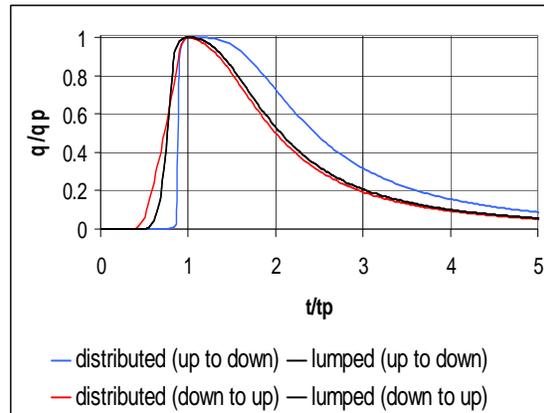
Constant Length (cl)

Appendix 6d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
                Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
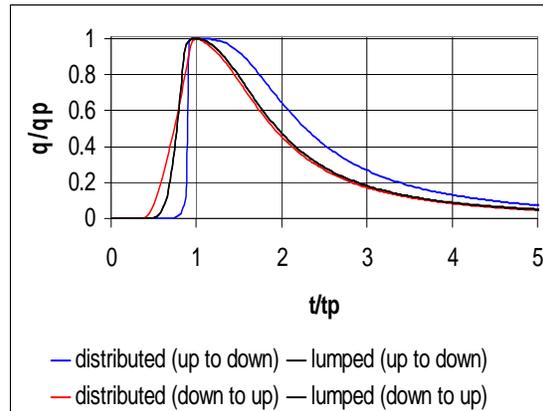
Constant Width (cw)
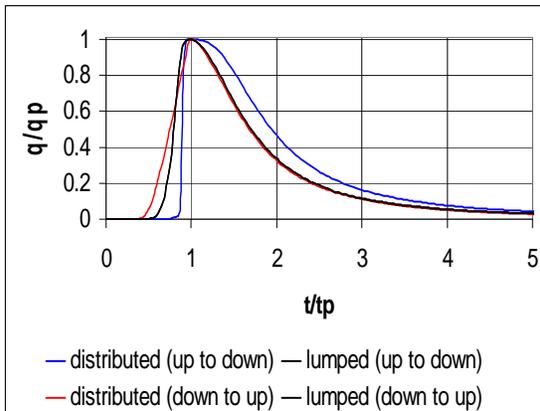
Constant Area (ca)
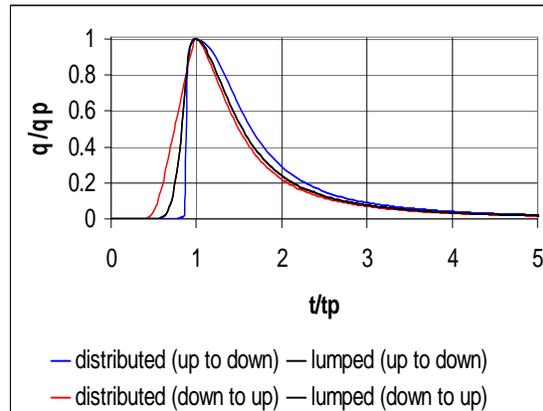
Constant Length (cl)

Appendix 7d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
                Dimensionless Hydrographs – Synthetic Rectangular Basins
                Moving Storms – Upstream to Downstream, Downstream to Upstream
                Overland Flow Plane Slope = 16.22%

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Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
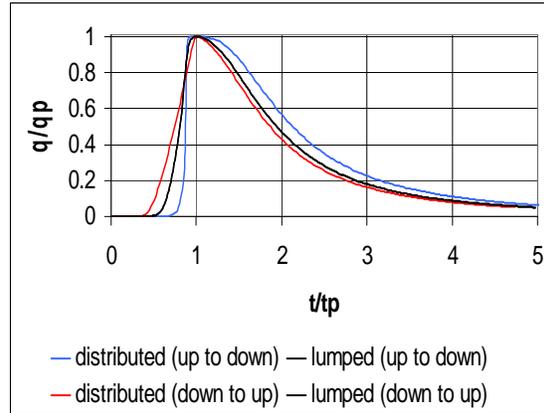
Constant Width (cw)
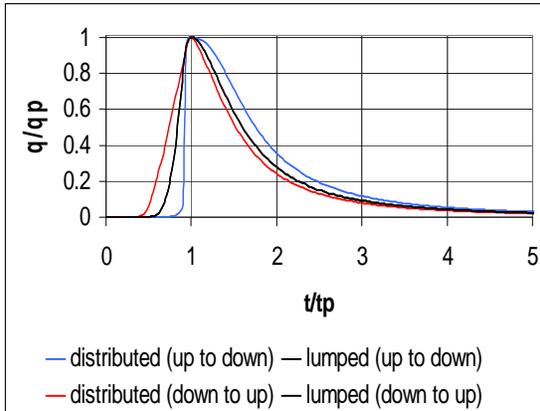
Constant Area (ca)
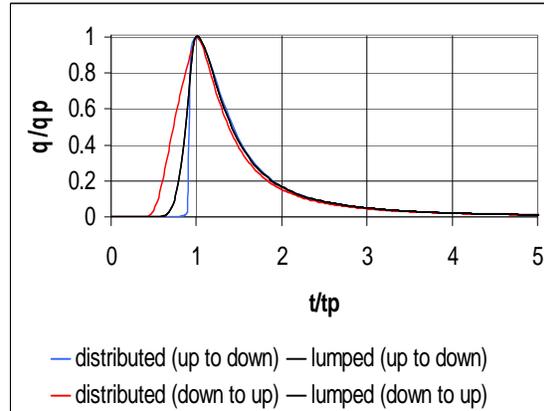
Constant Length (cl)

Appendix 8d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
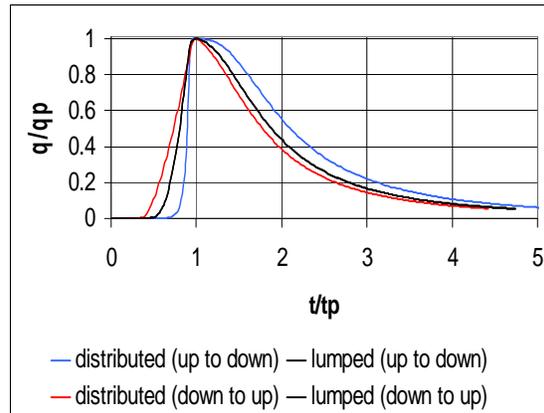

Constant Width (cw)
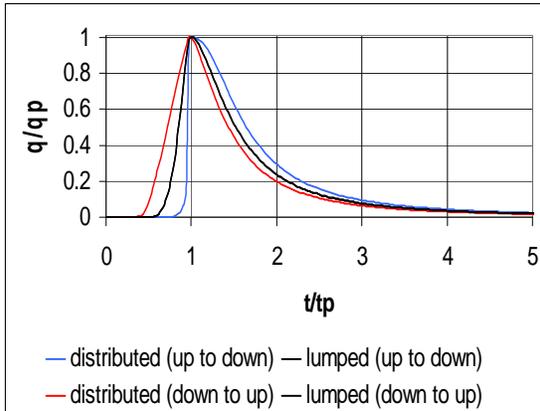
Constant Area (ca)
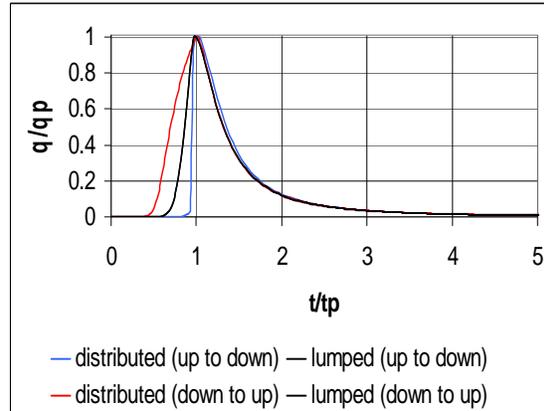
Constant Length (cl)

Appendix 9d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
Dimensionless Hydrographs - Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 16.22%

Moving Storm – Upstream to Downstream
             Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
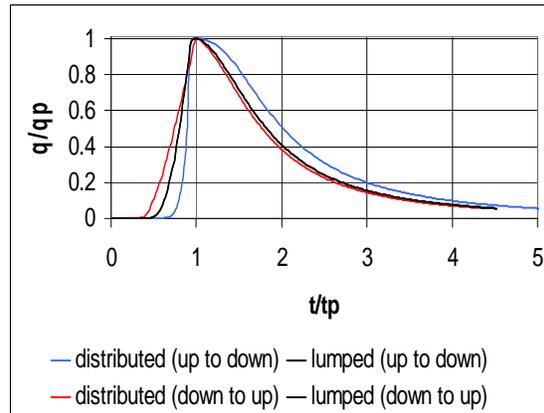

Constant Width (cw)
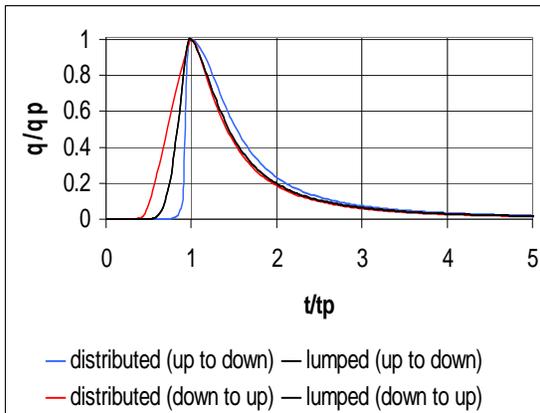
Constant Area (ca)
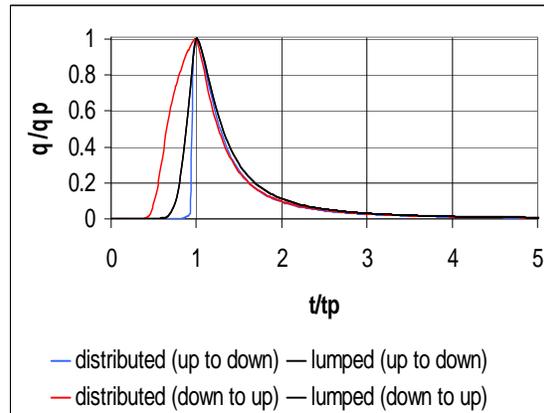
Constant Length (cl)

Appendix 10d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
             Dimensionless Hydrographs – Synthetic Rectangular Basins
             Moving Storms – Upstream to Downstream, Downstream to Upstream
             Overland Flow Plane Slope = 16.22%

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Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 11d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basin
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 9.12%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 12d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 9.12%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.


Constant Width (cw)


Constant Area (ca)

Constant Length (cl)

Appendix 13d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 9.12%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 14d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 9.12%

354

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 15d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
                        Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
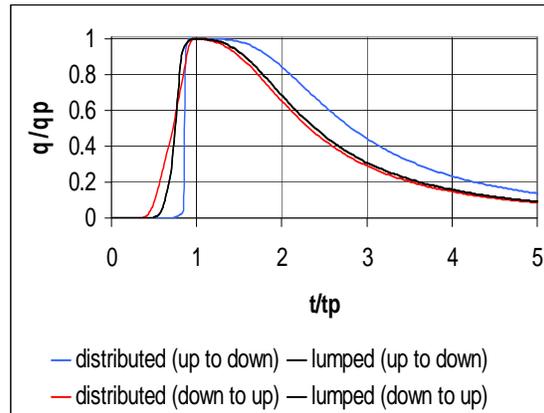
Constant Width (cw)
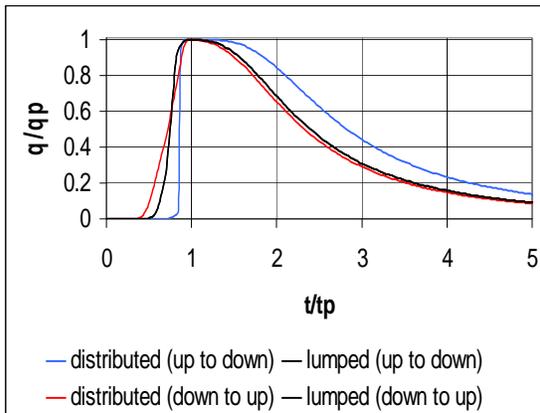
Constant Area (ca)
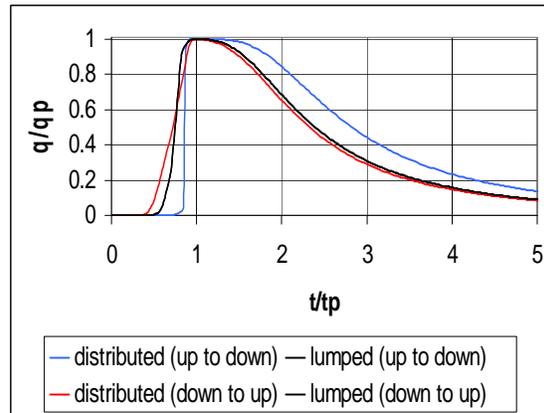
Constant Length (cl)

Appendix 16d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 9.12%

356

Moving Storm – Upstream to Downstream
                Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
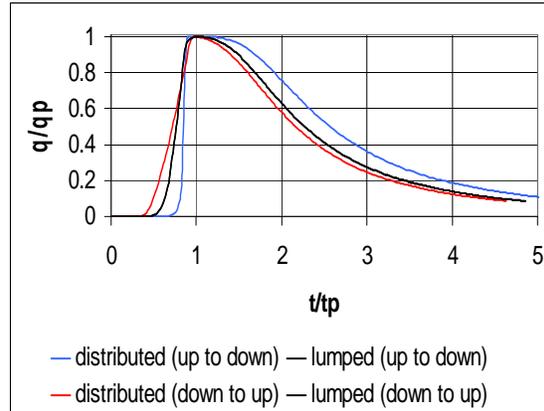

Constant Width (cw)
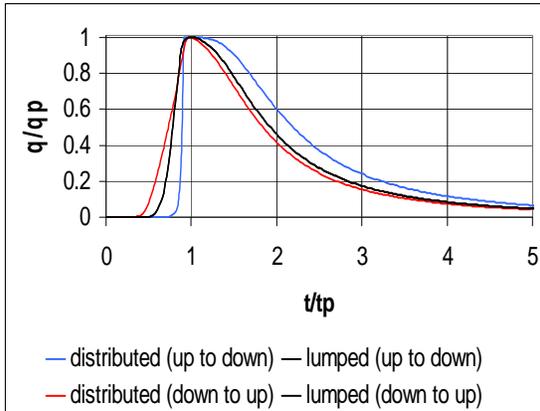
Constant Area (ca)
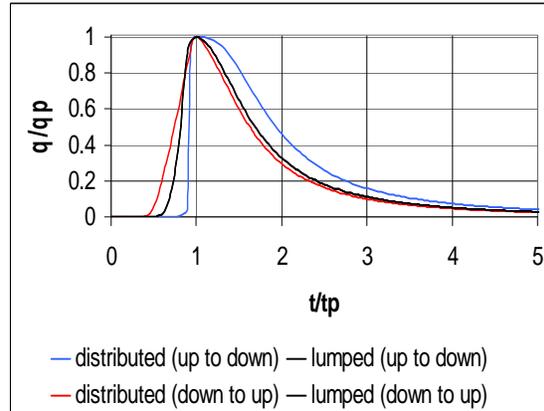
Constant Length (cl)

Appendix 17d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
                Dimensionless Hydrographs – Synthetic Rectangular Basins
                Moving Storms – Upstream to Downstream, Downstream to Upstream
                Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
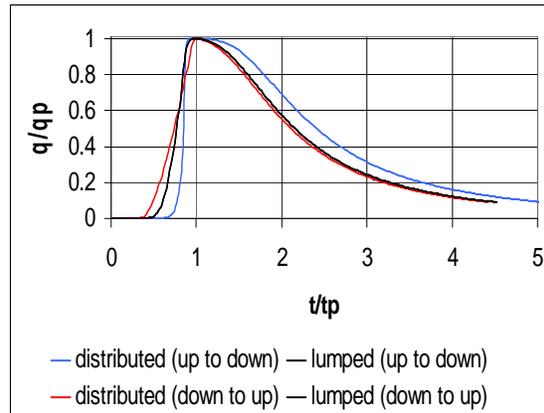

Constant Width (cw)
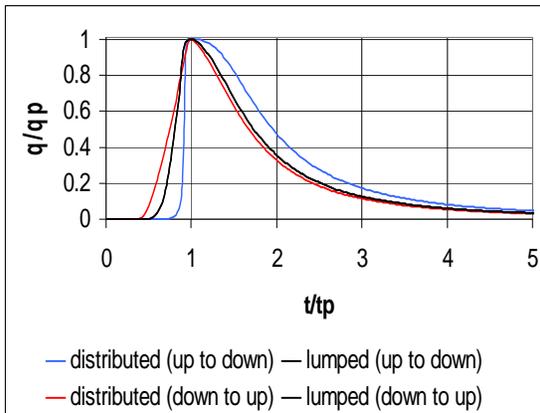
Constant Area (ca)
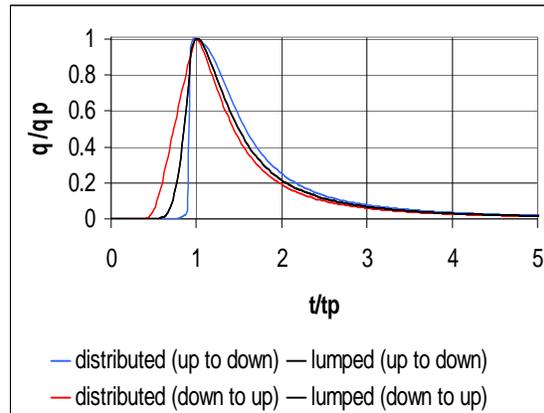
Constant Length (cl)

Appendix 18d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
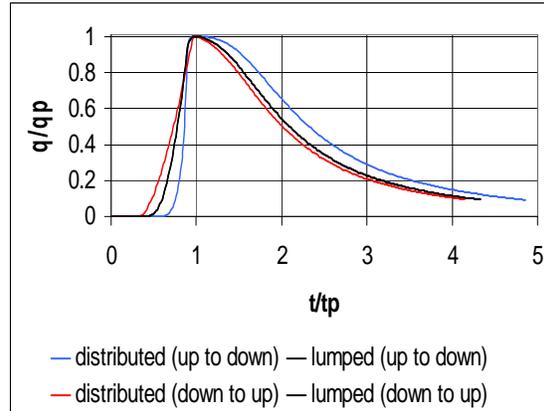

Constant Width (cw)
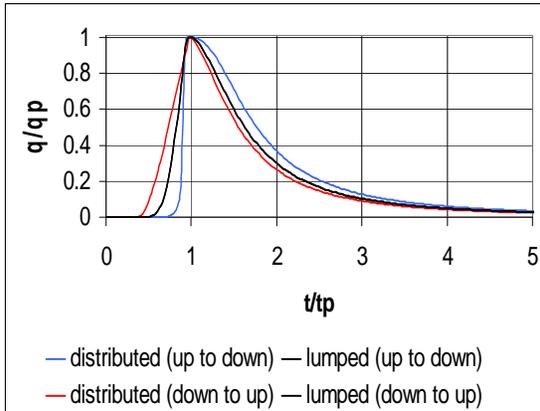
Constant Area (ca)
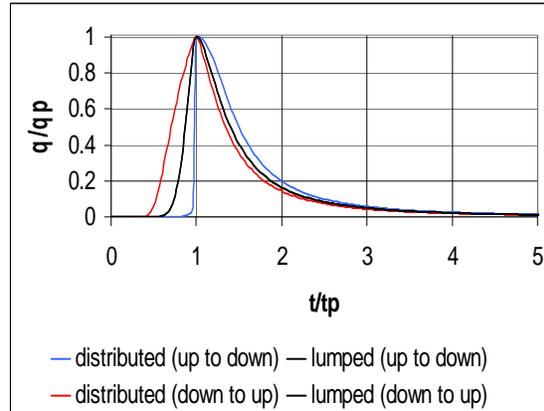
Constant Length (cl)

Appendix 19d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 9.12%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
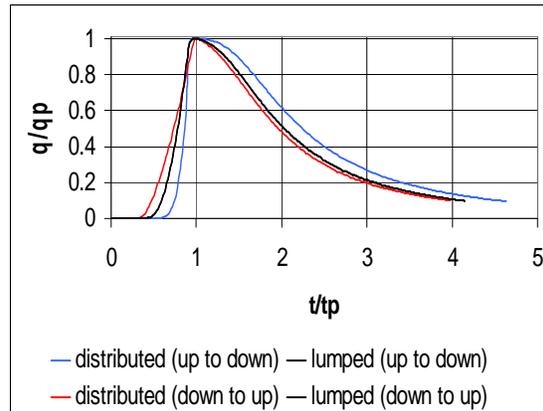
Constant Width (cw)
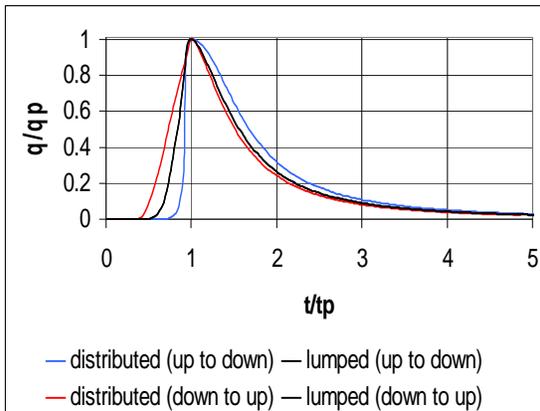
Constant Area (ca)
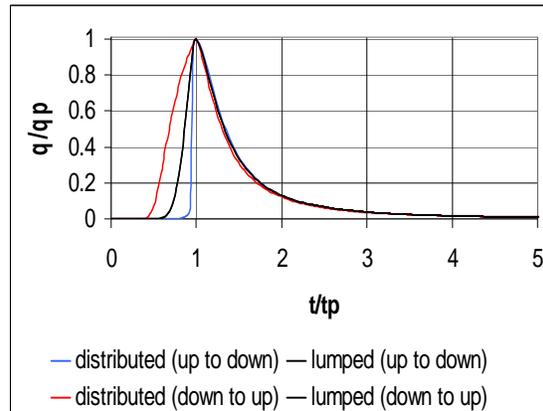
Constant Length (cl)

Appendix 20d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 9.12%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 21d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basin
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 4.05%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.


Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 22d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 4.05%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with
a 10 minute time duration was applied
over the upper 20%, middle 20%, or lower
20% of each basin. No rainfall was
applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of
0.2 inch with a 10 minute time duration
was applied uniformly over the entire
basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 23d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 4.05%

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Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 24d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 4.05%

Stationary Storms – Upper 20%,
Middle 20%,
Lower 20%,
Entire Basin
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch

Distributed rainfall amounts of 1 inch with a 10 minute time duration was applied over the upper 20%, middle 20%, or lower 20% of each basin. No rainfall was applied over the remaining 80%.

Lumped (mean areal) rainfall amounts of 0.2 inch with a 10 minute time duration was applied uniformly over the entire basin.

Constant Width (cw)

Constant Area (ca)

Constant Length (cl)

Appendix 25d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Stationary Storms – Upper 20%, Middle 20%, Lower 20%, Entire Basin
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
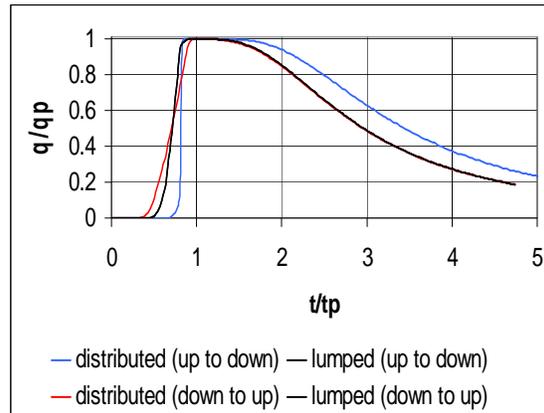
Constant Width (cw)
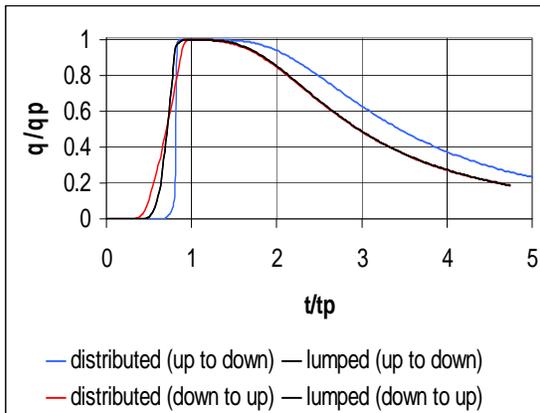
Constant Area (ca)
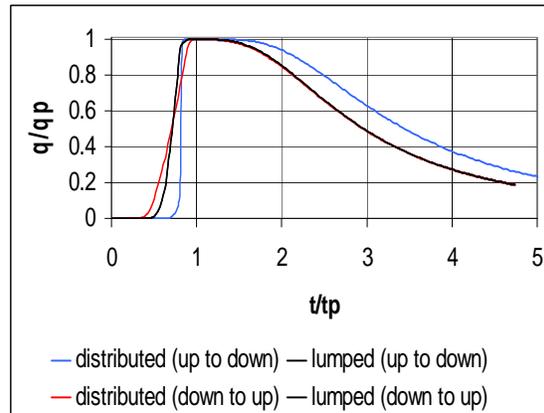
Constant Length (cl)

Appendix 26d. Distributed and Lumped Rainfall Comparison (Shape Factor = 1)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
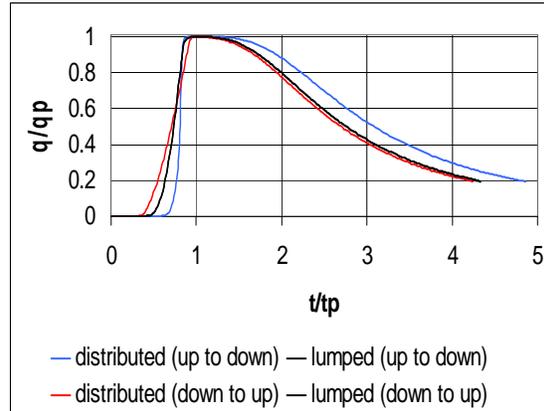
Constant Width (cw)
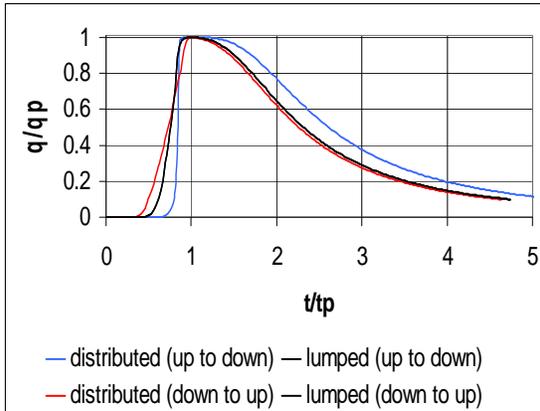
Constant Area (ca)
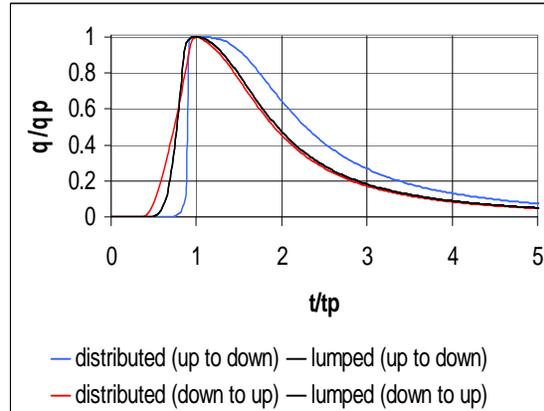
Constant Length (cl)

Appendix 27d. Distributed and Lumped Rainfall Comparison (Shape Factor = 2)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
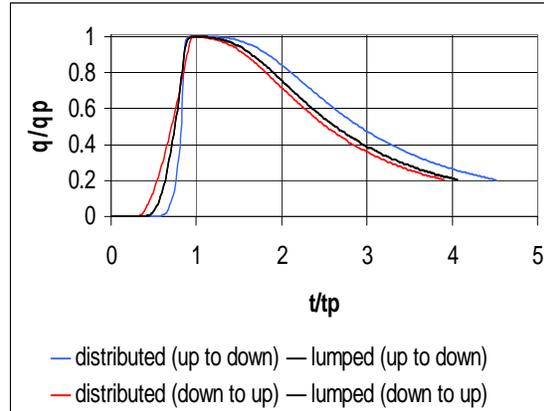
Constant Width (cw)
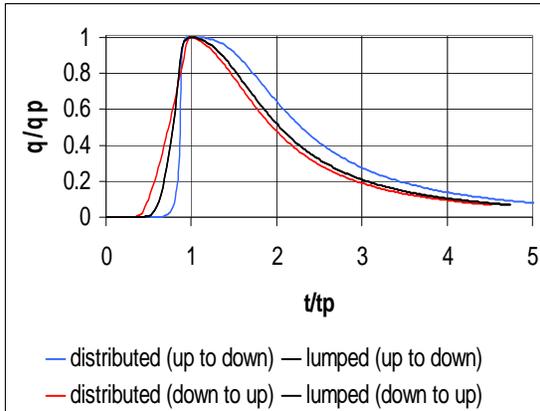
Constant Area (ca)
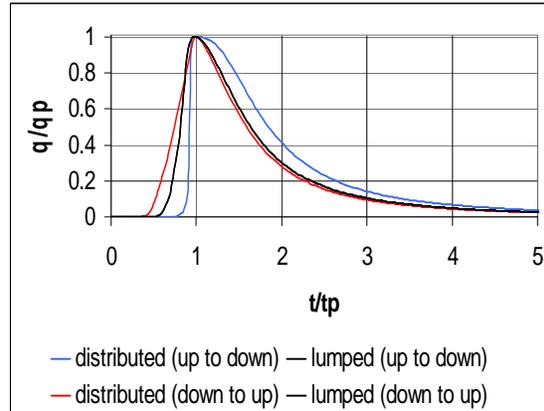
Constant Length (cl)

Appendix 28d. Distributed and Lumped Rainfall Comparison (Shape Factor = 3)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 4.05%

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Moving Storm – Upstream to Downstream
               Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1
minute time intervals as the storm system
moved across each basin.

Lumped (mean areal) rainfall was applied
at 1 minute time intervals as the storm
system moved across each basin.
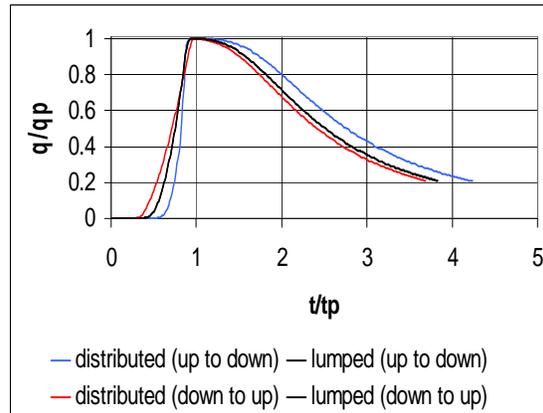
Constant Width (cw)
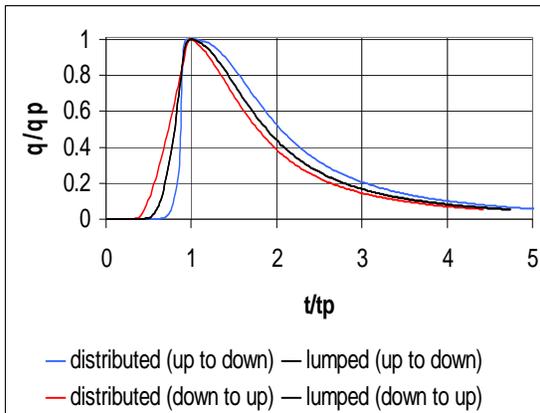
Constant Area (ca)
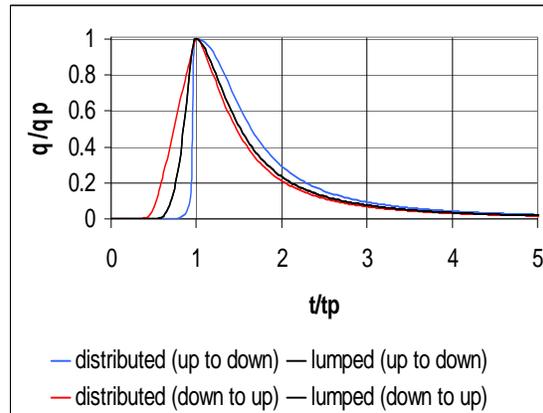
Constant Length (cl)

Appendix 29d. Distributed and Lumped Rainfall Comparison (Shape Factor = 4)
                Dimensionless Hydrographs – Synthetic Rectangular Basins
                Moving Storms – Upstream to Downstream, Downstream to Upstream
                Overland Flow Plane Slope = 4.05%

Moving Storm – Upstream to Downstream
Downstream to Upstream
Distributed & Lumped Rainfall
Mean areal basin rainfall equals 0.2 inch
Total storm period equals 20 minutes

Distributed rainfall was applied at 1 minute time intervals as the storm system moved across each basin.

Lumped (mean areal) rainfall was applied at 1 minute time intervals as the storm system moved across each basin.
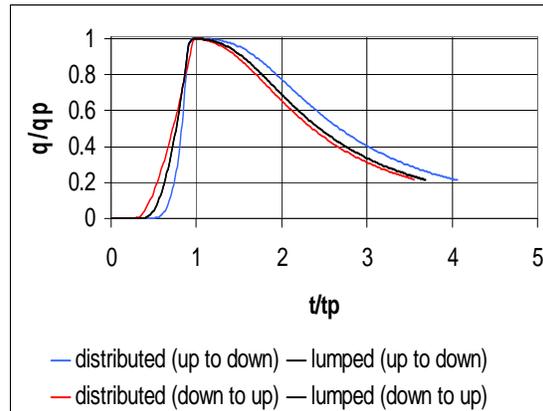
Constant Width (cw)
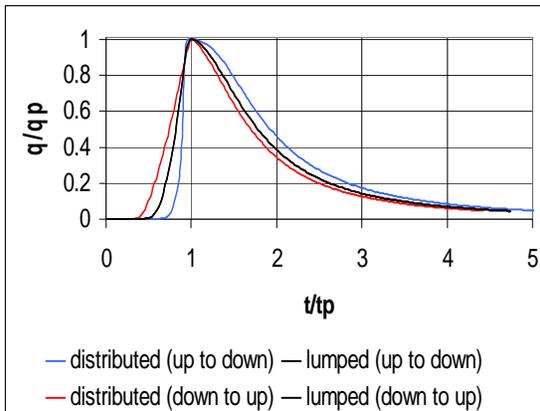
Constant Area (ca)
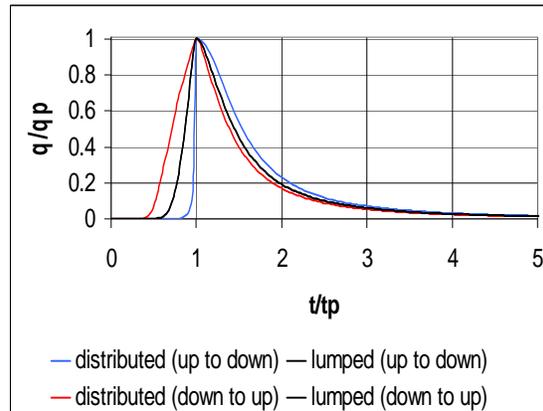
Constant Length (cl)

Appendix 30d. Distributed and Lumped Rainfall Comparison (Shape Factor = 5)
Dimensionless Hydrographs – Synthetic Rectangular Basins
Moving Storms – Upstream to Downstream, Downstream to Upstream
Overland Flow Plane Slope = 4.05%

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APPENDIX E

COMPARISON OF DISTRIBUTED AND LUMPED RAINFALL
DIMENSIONLESS HYDROGRAPHS
COWLEECH FORK SABINE RIVER NEAR GREENVILLE, TEXAS

Distributed & Lumped Rainfall Comparison
Cowleech Fork Sabine River near Greenville, Texas

Rainfall Intensity = 1 inch in 5 hours
Mean Areal Basin Rainfall = 0.22 inch

Distributed rainfall amounts of 1 inch with a 5 hour time duration was applied over the upper 22%, middle 22%, and lower 22% of each basin. No rainfall was applied over the remaining 78%.

Lumped (mean areal) rainfall amounts of 0.22 inch with a 5 hour time duration was applied uniformly over the entire basin.
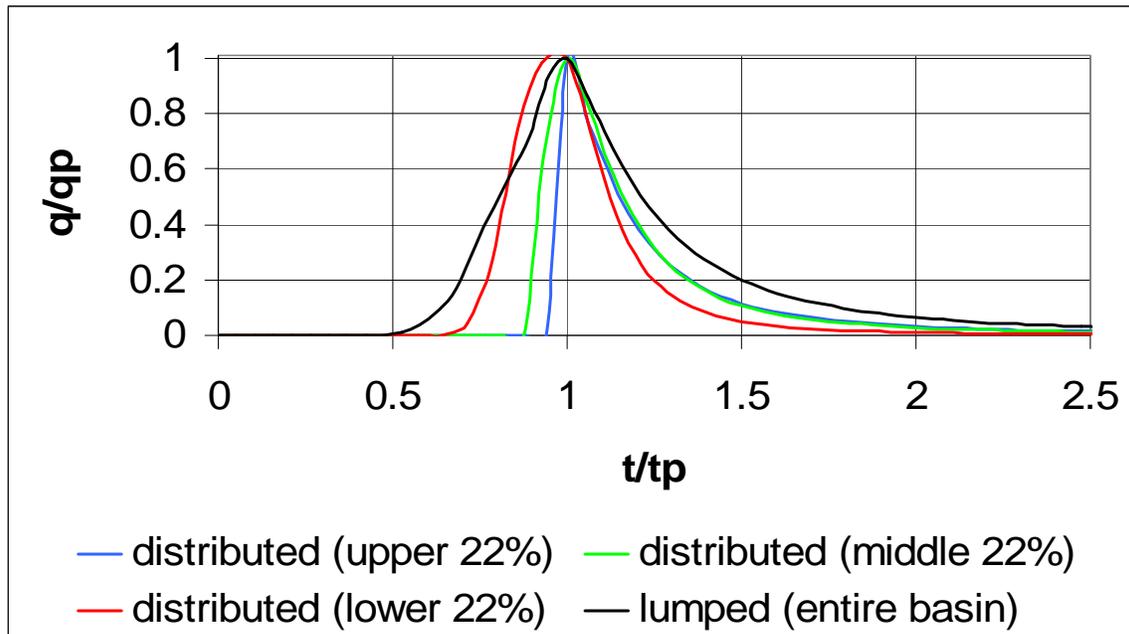
Appendix 1e. Distributed and Lumped Rainfall Comparison
Dimensionless Hydrograph
Cowleech Fork Sabine River near Greenville, Texas
Stationary Storms – Upper 22%, Middle 22%, Lower 22%, Entire Basin
Rainfall Intensity = 1 inch in 5 hours

Distributed & Lumped Rainfall Comparison
Cowleech Fork Sabine River near Greenville, Texas

Rainfall Intensity = 1 inch in 5 hours
Mean Areal Basin Rainfall = 0.22 inch

Distributed rainfall was applied at 1 hour time intervals as the storm system moved across the basin.

Lumped (mean areal) rainfall was applied at 1 hour time intervals as the storm system moved across the basin.
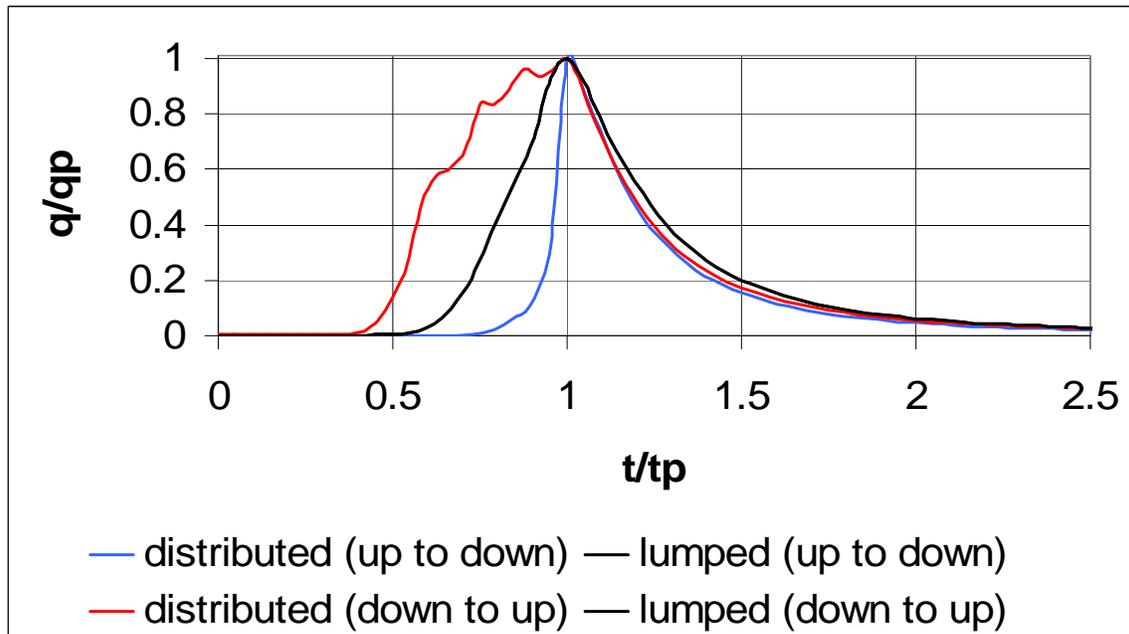
Appendix 2e. Distributed and Lumped Rainfall Comparison
Dimensionless Hydrograph
Cowleech Fork Sabine River near Greenville, Texas
Moving Storms – Upstream to Downstream, Downstream to Upstream
Rainfall Intensity = 1 inch in 5 hours

Distributed & Lumped Rainfall Comparison
Cowleech Fork Sabine River near Greenville, Texas

Rainfall Intensity = 1 inch in 10 hours
Mean Areal Basin Rainfall = 0.22 inch

Distributed rainfall amounts of 1 inch with a 10 hour time duration was applied over the upper 22%, middle 22%, and lower 22% of each basin. No rainfall was applied over the remaining 78%.

Lumped (mean areal) rainfall amounts of 0.22 inch with a 10 hour time duration was applied uniformly over the entire basin.
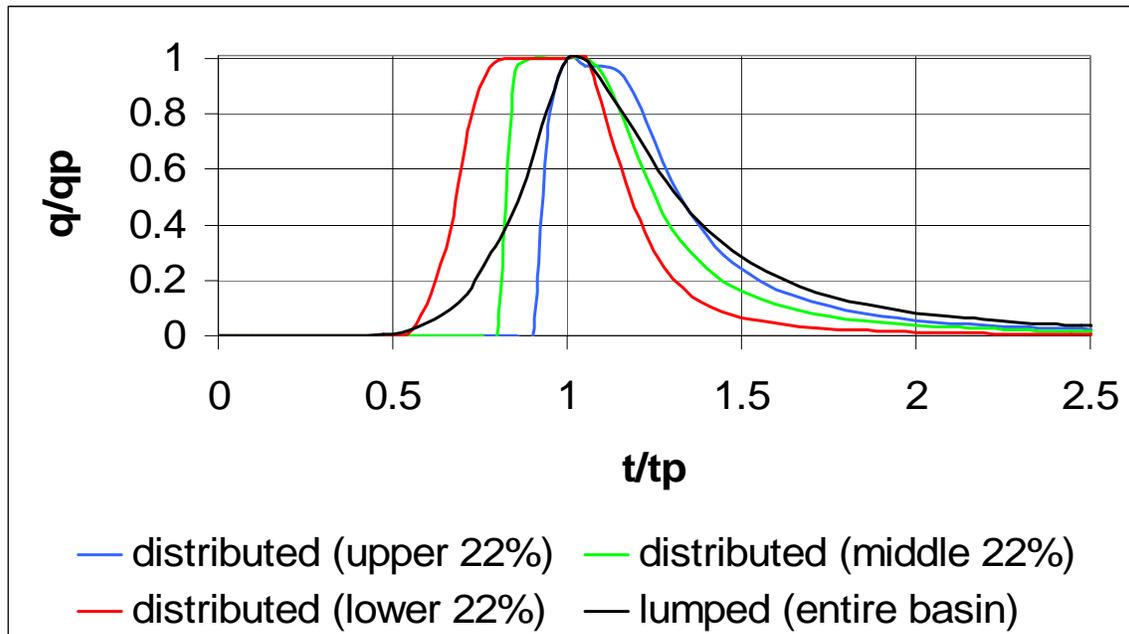
Appendix 3e. Distributed and Lumped Rainfall Comparison
Dimensionless Hydrograph
Cowleech Fork Sabine River near Greenville, Texas
Stationary Storms – Upper 22%, Middle 22%, Lower 22%, Entire Basin
Rainfall Intensity = 1 inch in 10 hours

Distributed & Lumped Rainfall Comparison
Cowleech Fork Sabine River near Greenville, Texas

Rainfall Intensity = 1 inch in 10 hours
Mean Areal Basin Rainfall = 0.22 inch

Distributed rainfall was applied at 1 hour time intervals as the storm system moved across the basin.

Lumped (mean areal) rainfall was applied at 1 hour time intervals as the storm system moved across the basin.
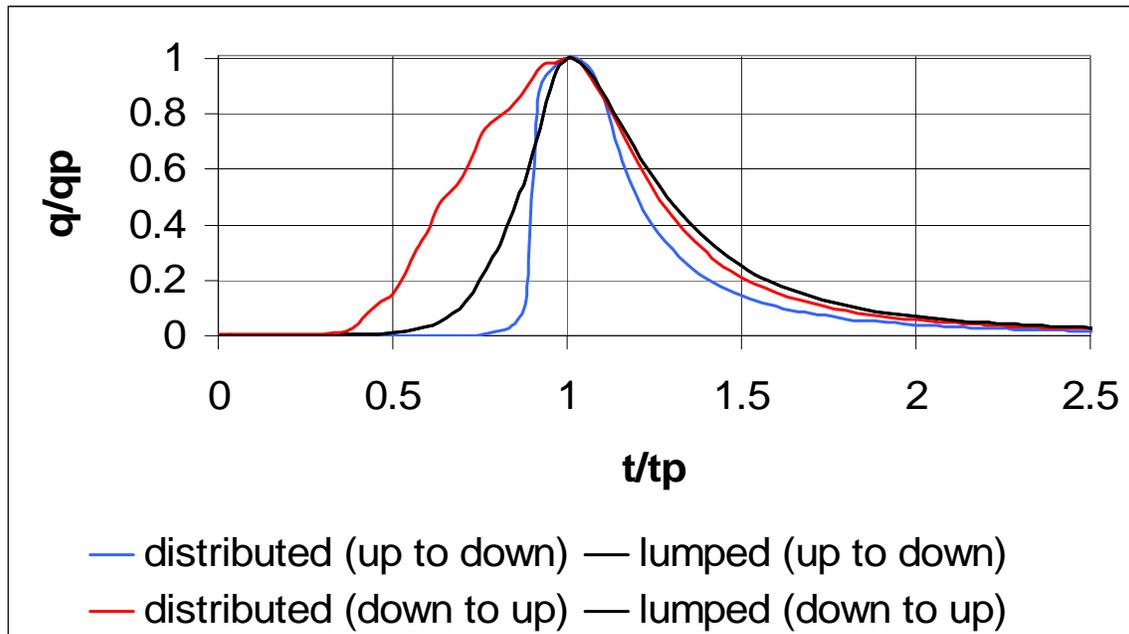
Appendix 4e. Distributed and Lumped Rainfall Comparison
Dimensionless Hydrograph
Cowleech Fork Sabine River near Greenville, Texas
Moving Storms – Upstream to Downstream, Downstream to Upstream
Rainfall Intensity = 1 inch in 10 hours

APPENDIX F

DRAINAGE BASIN CONFIGURATION
DETAILED INFORMATION FOR EACH SUBBASIN
COWLEECH FORK SABINE RIVER NEAR GREENVILLE, TEXAS

Table F.1. Drainage Basin Configuration (Detailed Information)
Cowleech Fork Sabine River near Greenville, Texas

Overland Flow Planes										Channel Segments			
Rain Area	OFP Basin	Length	Width	Area	Slope	Mannings n	Soil Type	Cover Type		Channel Segment	Length	Slope	Manning's n
		(feet)	(feet)	(acres)							(feet)		
1	1	1809.2	22210	922.3	0.02	0.6	Clay	Trees		23	22210	0.004	0.05
1	2	2072.6	22210	1056.6	0.018	0.6	Clay	Trees		23	22210	0.004	0.05
1	3	2092.5	17377	834.6	0.018	0.6	Clay	Trees		18	17377	0.004	0.05
1	4	1443.5	17377	575.7	0.016	0.6	Clay	Trees		18	17377	0.004	0.05
1	5	1843.2	19601	829.2	0.019	0.6	Clay	Trees		20	19601	0.004	0.05
1	6	1447	19601	664.5	0.017	0.6	Clay	Trees		20	19601	0.004	0.05
2	7	843.2	8694	168.2	0.028	0.4	Clay	Shrubs		27	8694	0.008	0.05
2	8	1449.8	8694	289.2	0.022	0.4	Clay	Shrubs		27	8694	0.008	0.05
2	11	1401.2	20366	655	0.017	0.4	Clay	Shrubs		28	20366	0.005	0.05
2	12	836.8	11460	220	0.015	0.6	Clay	Trees		30	11460	0.006	0.05
2	13	2066.5	11460	543.4	0.021	0.6	Clay	Trees		30	11460	0.006	0.05
2	14	1361.5	20366	636.4	0.027	0.4	Clay	Shrubs		28	20366	0.005	0.05
2	18	966.1	12545	278.1	0.022	0.6	Clay	Trees		32	12545	0.002	0.05
2	20	243.8	12545	701.9	0.019	0.6	Clay	Trees		32	12545	0.002	0.05
2	21	915.8	3986	83.7	0.009	0.6	Clay	Trees		34	3986	0.002	0.05
2	22	3063.3	12067	848.3	0.024	0.6	Clay	Trees		38	12067	0.002	0.05
2	30	2106.6	16355	790.7	0.02	0.6	Clay	Trees		25	16355	0.006	0.05
2	31	1411.2	16355	529.7	0.036	0.13	Clay	Bare Soil		25	16355	0.006	0.05
2	32	795.6	3986	72.7	0.036	0.6	Clay	Trees		34	3986	0.002	0.05
2	34	2897.5	12067	802.4	0.023	0.6	Clay	Trees		38	12067	0.002	0.05
3	15	1036.4	19964	474.9	0.024	0.13	Clay	Bare Soil		24	19964	0.006	0.05
3	16	1310.8	19964	600.6	0.026	0.13	Clay	Bare Soil		24	19964	0.006	0.05
3	37	2524.2	25972	1504.7	0.024	0.6	Clay	Trees		8	25972	0.005	0.05
3	45	1523	25972	907.8	0.04	0.6	Clay	Trees		8	25972	0.005	0.05
4	9	1561.1	12426	445.2	0.024	0.6	Clay	Trees		26	12426	0.007	0.05
4	10	1498.9	12426	427.5	0.017	0.6	Clay	Trees		26	12426	0.007	0.05

Table F.1 – continued

4	17	665.9	10119	154.6	0.026	0.6	Clay	Trees		22	10119	0.008	0.05
4	19	3443.3	10338	816.8	0.02	0.6	Clay	Trees		33	10338	0.003	0.05
4	23	1256.3	10119	291.8	0.026	0.13	Clay	Bare Soil		22	10119	0.008	0.05
4	26	824.5	13381	253.2	0.02	0.6	Clay	Trees		19	13381	0.007	0.05
4	27	1472.3	10338	349.2	0.02	0.6	Clay	Trees		33	10338	0.003	0.05
4	28	1353.6	18512	575.1	0.021	0.13	Clay	Bare Soil		29	18512	0.007	0.05
4	29	1768.2	18512	751.3	0.024	0.6	Clay	Trees		29	18512	0.007	0.05
4	33	992.2	13381	304.7	0.024	0.6	Clay	Trees		19	13381	0.007	0.05
4	38	1244.9	15849	452.8	0.032	0.6	Clay	Trees		39	15849	0.002	0.05
4	39	944.9	15849	343.7	0.017	0.6	Clay	Trees		39	15849	0.002	0.05
4	44	2629.3	3844	231.8	0.019	0.6	Clay	Trees		41	3844	0.003	0.05
4	48	2261.5	5257	272.8	0.023	0.6	Clay	Trees		42	5257	0.003	0.05
4	50	962.1	14578	321.9	0.025	0.6	Clay	Trees		1	14578	0.008	0.05
4	53	778.6	14578	260.5	0.039	0.6	Clay	Trees		1	14578	0.008	0.05
4	54	498.6	3844	43.9	0.019	0.6	Clay	Trees		41	3844	0.003	0.05
4	55	593.6	15303	208.5	0.023	0.6	Clay	Trees		4	15303	0.009	0.05
4	56	585.2	5257	70.6	0.018	0.6	Clay	Trees		42	5257	0.003	0.05
4	57	1199.5	15303	421.3	0.04	0.6	Clay	Trees		4	15303	0.009	0.05
4	62	1080.1	17366	430.4	0.03	0.6	Clay	Trees		9	17366	0.007	0.05
5	42	917.9	12024	253.2	0.026	0.6	Clay	Trees		5	12024	0.009	0.05
5	43	750.8	12024	207.1	0.018	0.6	Clay	Trees		5	12024	0.009	0.05
5	46	880.5	16679	337	0.024	0.6	Clay	Trees		7	16679	0.007	0.05
5	47	784.8	16679	300.4	0.018	0.6	Clay	Trees		7	16679	0.007	0.05
5	52	1868.8	8928	385	0.023	0.6	Clay	Trees		40	8928	0.001	0.05
5	58	896.6	11559	237.9	0.023	0.6	Clay	Trees		3	11559	0.009	0.05
5	59	1118.3	12106	308.4	0.023	0.6	Clay	Trees		43	12106	0.001	0.05
5	60	1180.7	8928	243.3	0.021	0.6	Clay	Trees		40	8928	0.001	0.05
5	61	1047.6	11559	277.9	0.03	0.6	Clay	Trees		3	11559	0.009	0.05
5	63	1397.1	17366	556.8	0.036	0.6	Clay	Trees		9	17366	0.007	0.05
5	64	2038.1	12106	562.1	0.043	0.6	Clay	Trees		43	12106	0.001	0.05
5	65	1016.4	3895	90.8	0.019	0.6	Clay	Trees		44	3895	0.002	0.05
5	70	2719.4	3895	243.1	0.023	0.4	Clay	Shrubs		44	3895	0.002	0.05

Table F.1 – continued

5	71	731.6	2495	41.8	0.015	0.4	Clay	Shrubs		45	2495	0.001	0.05
5	72	75.7	2495	32.4	0.019	0.4	Clay	Shrubs		45	2495	0.001	0.05
6	24	1623.2	27079	1008.9	0.017	0.6	Clay	Trees		21	27079	0.004	0.05
6	25	3025.9	27079	1880.8	0.017	0.6	Clay	Trees		21	27079	0.004	0.05
6	36	1239.8	34482	981.2	0.018	0.6	Clay	Trees		6	34482	0.004	0.05
6	40	1658.8	30745	1170.6	0.025	0.13	Clay	Bare Soil		36	30745	0.002	0.05
6	41	2642.3	30745	1864.6	0.024	0.6	Clay	Trees		36	30745	0.002	0.05
6	69	1248.4	18652	534.4	0.022	0.4	Clay	Shrubs		15	18652	0.008	0.05
6	74	2048.5	18652	876.9	0.021	0.6	Clay	Trees		15	18652	0.008	0.05
7	35	1540.2	34482	1219	0.02	0.6	Clay	Trees		6	34482	0.004	0.05
7	49	1749	11770	472.4	0.019	0.6	Clay	Trees		2	11770	0.005	0.05
7	51	2106	11770	568.9	0.019	0.6	Clay	Trees		2	11770	0.005	0.05
7	66	1681.9	14363	554.4	0.015	0.6	Clay	Trees		35	14363	0.002	0.05
7	67	1829.2	14698	617	0.032	0.4	Clay	Shrubs		46	14698	0.001	0.05
7	68	2680.5	14363	883.6	0.023	0.6	Clay	Trees		35	14363	0.002	0.05
7	73	2433.1	14698	820.7	0.012	0.6	Clay	Trees		46	14698	0.001	0.05
7	75	577.5	10179	134.9	0.022	0.6	Clay	Trees		14	10179	0.007	0.05
7	76	1441.4	10179	336.7	0.023	0.6	Clay	Trees		14	10179	0.007	0.05
8	77	1670.7	21042	806.9	0.014	0.4	Clay	Shrubs		16	21042	0.005	0.05
8	78	2092	4253	204.1	0.02	0.13	Clay	Bare Soil		47	4253	0.004	0.05
8	79	1582.5	10338	375.4	0.02	0.6	Clay	Trees		17	10338	0.006	0.05
8	80	592.2	10338	140.5	0.014	0.6	Clay	Trees		17	10338	0.006	0.05
8	81	1148.2	21042	554.5	0.014	0.6	Clay	Trees		16	21042	0.005	0.05
8	84	1265.6	8876	257.8	0.025	0.6	Clay	Trees		31	8876	0.003	0.05
8	85	966.9	13284	294.7	0.017	0.6	Clay	Trees		11	13284	0.007	0.05
8	86	272.8	4253	26.6	0.047	0.6	Clay	Trees		47	4253	0.004	0.05
8	87	2735.6	3739	234.6	0.013	0.6	Clay	Trees		48	3739	0.001	0.05
8	88	1941.1	13284	591.7	0.02	0.6	Clay	Trees		11	13284	0.007	0.05
8	89	223.6	3739	19.1	0.039	0.6	Clay	Trees		48	3739	0.001	0.05
8	90	1369.1	5933	186.4	0.013	0.6	Clay	Trees		49	5933	0.001	0.05
8	92	552.3	8876	112.5	0.022	0.6	Clay	Trees		31	8876	0.003	0.05
8	93	1734.1	19829	789.2	0.014	0.6	Clay	Trees		10	19829	0.005	0.05

Table F.1 - continued

9	82	2511.6	23076	1330.3	0.019	0.6	Clay	Trees		37	23076	0.001	0.05
9	83	1997.7	23076	1058.1	0.018	0.6	Clay	Trees		37	23076	0.001	0.05
9	91	2310.9	7905	419.2	0.019	0.6	Clay	Trees		13	7905	0.004	0.05
9	94	3378.8	19829	1537.7	0.022	0.6	Clay	Trees		10	19829	0.005	0.05
9	95	200.2	5933	27.2	0.043	0.6	Clay	Trees		49	5933	0.001	0.05
9	96	893.5	7905	162.1	0.008	0.6	Clay	Trees		13	7905	0.004	0.05
10	97	1726.6	10153	402.3	0.012	0.6	Clay	Trees		50	10153	0.001	0.05
10	98	3147.9	10153	733.5	0.016	0.6	Clay	Trees		50	10153	0.001	0.05
10	99	1008.6	13956	323	0.021	0.6	Clay	Trees		12	13956	0.006	0.05
10	100	1529.9	13956	490	0.021	0.4	Clay	Shrubs		12	13956	0.006	0.05
10	101	806.4	4840	89.5	0.017	0.13	Clay	Bare Soil		51	4840	0.002	0.05
10	102	2380	4840	264.3	0.016	0.13	Clay	Bare Soil		51	4840	0.002	0.05

REFERENCES

Alley, William M. and Peter E. Smith (1982). "Distributed Routing Rainfall-Runoff Model—Version II. Computer Program Documentation User's Manual." U.S. Geological Survey, Water Resources Division, Open-File Report 82-344.

Bandaragoda, Christina, David G. Tarboton, and Ross Woods (2004). "Application of TOPNET in the Distributed Model Intercomparison Project." Journal of Hydrology, 298, pp. 178-201.

Bedient, Philip B. and Wayne C. Huber (1992). Hydrology and Floodplain Analysis (Second Edition). Addison – Wesley Publishing Company, New York.

Bedient, Philip B., Brian C. Hoblit, Dawn C. Gladwell, and Baxter E. Vieux (2000). "NEXRAD Radar for Flood Prediction in Houston." Journal of Hydrologic Engineering, July 2000, pp. 269-277.

Bergstrom, Sten, and L. Phil Graham (1998). "On the Scale Problem in Hydrological Modelling". Journal of Hydrology, 211, pp. 253-265.

Beven, Keith J. and George M. Hornberger (1982). "Assessing the Effect of Spatial Pattern of Precipitation in Modeling Stream Flow Hydrographs." Water Resources Bulletin, Volume 18, Number 5, pp. 823-829.

Black, Peter E. (1970a). "The Watershed in Principle." Water Resources Bulletin, Volume 6, Number 2, pp. 153-162.

Black, Peter E. (1970b). "Runoff from Watershed Models." Water Resources Research, Volume 6, No. 2, pp. 465-477.

Black, Peter E. and James W. Cronn, Jr. (1975). "Hydrograph Responses to Watershed Model Size and Similitude Relations." Journal of Hydrology, 26, pp. 255-266.

Black, Peter E. (1996). Watershed Hydrology (Second Edition). Lewis Publishers, New York.

Boyle, Douglas P., Hoshin V. Gupta, Soroosh Sorooshian, Victor Koren, Ziya Zhang, and Michael Smith (2001). "Toward Improved Streamflow Forecasts: Value of Semidistributed Modeling." Water Resources Research, Volume 37, No. 11, pp. 2749-2759.

Butts, Michael B., Jeffrey T. Payne, Michael Kristensen, and Henrik Madsen (2004). "An Evaluation of the Impact of Model Structure on Hydrological Modelling Uncertainty for Streamflow Simulation." Journal of Hydrology, 298, pp. 242-266.

Carpenter, Theresa M., Konstantine P. Georgakakos, and Jason A. Sperfslagea (2001). "On the Parametric and NEXRAD-Radar Sensitivities of a Distributed Hydrologic Model Suitable for Operational Use." Journal of Hydrology, 253, pp. 169-193.

Carpenter, Theresa M. and Konstantine P. Georgakakos (2004). "Continuous Streamflow Simulation with the HRCDHM Distributed Hydrologic Model". Journal of Hydrology, 298, pp. 61-79.

Choi, G. W. and Kang, K. W. (1990). "Application of the Generalized Channel Routing Model." Hydraulic Engineering, Volume 1. Proceedings of the 1990 National Conference sponsored by the Hydraulics Division of the American Society of Civil Engineers, San Diego, California.

Chow, Ven Te (1959). Open-Channel Hydraulics. McGraw-Hill Book Company, New York.

Chow, Ven Te, David R. Maidment, and Larry W. Mays (1988). Applied Hydrology. McGraw-Hill Book Company, New York.

Corps of Engineers (COE) (1991). "Unsteady Flow." Chapter 5 of EM 1110-2-9020 (Draft), U.S. Army, June, 1991.

Dawdy, David R., John C. Schaake, Jr., and William M. Alley (1978). "Distributed Routing Rainfall-Runoff Model." U.S. Geological Survey, Water-Resources Investigations Report 78-90.

Dingman, S. Lawrence (1994). Physical Hydrology. Prentice Hall, Englewood Cliffs, New Jersey.

Downer, Charles W., Fred L. Ogden, William D. Martin, and Russell S. Harmon (2002). "Theory, Development, and Applicability of the Surface Water Hydrologic Model CASC2D." Hydrological Processes, 16, pp 255-275.

Downer, Charles W. and Fred L. Ogden (2003). "Prediction of Runoff and Soil Moistures at the Watershed Scale: Effects of Model Complexity and Parameter Assignment." Water Resources Research, Vol. 39, No. 3, SWC (Surface Water and Climate), pp. 1-1 to 1-13.

Downer, Charles W. and Fred L. Ogden (2004). "GSSHA: Model to Simulate Diverse Stream Flow Producing Processes." Journal of Hydrologic Engineering, pp 161-174.

Duncan, M.R., B. Austin, F. Fabry, and G.L. Austin (1993). "The Effect of Gauge Sampling Density on the Accuracy of Streamflow Prediction for rural Catchments." Journal of Hydrology, 142, pp. 445-476.

Dunne, Thomas and Richard D. Black (1970). "An Experimental Investigation of Runoff Production in Permeable Soils." Water Resources Research, Vol. 6, No. 2, pp. 478-490.

Dunne, Thomas and Luna B. Leopold (1978). Water in Environmental Planning. W. H. Freeman and Company, San Francisco.

Federal Highway Administration (FHA) (2001). "Urban Drainage Design Manual." U.S. Department of Transportation Federal Highway Administration. Hydraulic Engineering Circular No. 22, Second Edition.

Finnerty, Bryce D., Michael B. Smith, Dong-Jun Seo, Victor Koren, and Glenn E. Moglen (1997). "Space-Time Scale Sensitivity of the Sacramento Model to Radar-Gage Precipitation Inputs." Journal of Hydrology, 203, pp. 21-38.

Fread, D. L. (1974). "Numerical Properties of Implicit Four-Point Finite Difference Equations of Unsteady Flow." NOAA Technical Memorandum NWS HYDRO-18, Office of Hydrology, Washington, D.C., March 1974.

Fread, D. L. (1988). "The NWS DAMBRK Model – Theoretical Background/User Documentation." Hydrologic Research Laboratory, Office of Hydrology, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, Maryland.

Garbrecht, J. and G. Brunner (1991). "Hydrologic Channel-Flow Routing for Compound Sections." Journal of Hydraulic Engineering, ASCE, 117(5), pp. 629-642.

Gray, Don M. (1961). "Interrelationships of Watershed Characteristics." Journal of Geophysical Research, Volume 66, Number 4, pp. 1215-1223.

Gray, Donald M. (1970). <u>Handbook on the Principles of Hydrology</u>. National Research Council of Canada.

Guo, Jianzhong, Xu Liang, and L. Ruby Leung (2004). "Impacts of Different Precipitation Data Sources on Water Budgets." Journal of Hydrology, 298, pp. 311-334.

Gupta, Ram S. (1989). <u>Hydrology & Hydraulic Systems</u>. Waveland Press, Inc., Prospect Heights, Illinois.

Hayakawa, Kiroshi, Kunihide Uchijima, and Mutsuhiro Fujita (1995). "A Study on Subcatchment Scale for a Distributed Runoff Model." Environment Internation, Vol. 21, No. 3., pp. 491-496.

Henderson, F.M. (1966). <u>Open Channel Flow</u>. Prentice Hall, Upper Saddle River, New Jersey.

Horton, Robert E. (1932). "Drainage-Basin Characteristics." Transactions of the American Geophysical Union, 13, pp. 350-361.

Horton, Robert E. (1933). "The Role of Infiltration in the Hydrologic Cycle." Transactions of the American Geophysical Union, 14, pp. 446-460.

Horton, Robert E. (1945). "Erosional Development of Streams and Their Drainage Basins; Hydrophysical Approach to Quantitative Morphology." Bulletin of the Geological Society of America, 56, pp. 275-370.

Hydrologic Engineering Center (HEC) (1979). "Introduction and Application of Kinematic Wave Routing Techniques Using HEC-1." Training Document No. 10. Prepared by Johannes J. DeVries and Robert C. MacArthur for the U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (HEC) (1980). "Comparative Analysis of Flood Routing Methods." Research Document No. 24. Prepared by Theodor Strelkoff for the U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (HEC) (1990). <u>River Routing With HEC-1 and HEC-2</u>. Training Document No. 30. U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (HEC) (2000). <u>Hydrologic Modeling System HEC-HMS</u>. Technical Reference Manual (March 2000). U.S. Army Corps of Engineers, Davis, California.

Hydrologic Engineering Center (HEC) (2002). <u>River Analysis System HEC-RAS</u>. Hydraulic Reference Manual (November 2002). U.S. Army Corps of Engineers, Davis, California.

Ivanov, Valeriy Y., Enrique R. Vivoni, Rafael L. Bras, and Dara Entekhabi (2004). "Preserving High-Resolution Surface and Rainfall Data in Operational-Scale Basin Hydrology: a Fully-Distributed Physically-Based Approach." Journal of Hydrology, 298, pp. 80-111.

Johnson, Dennis L. and Arthur C. Miller (1997). "A Spatially Distributed Hydrologic Model Utilizing Raster Data Structures." Computers and Geosciences, Vol. 23, No. 3, pp. 267-272.

Koren, V.I., B.D. Finnerty, J.C. Schaake, M.B. Smith, D.-J. Seo, and Q.-Y. Duan (1999). "Scale Dependencies of Hydrologic Models to Spatial Variability of Precipitation." Journal of Hydrology, 217, pp. 285-302.

Koren, Victor, Seann Reed, Michael Smith, Ziya Zhang, and Dong-Jun Seo (2004). "Hydrology Laboratory Research Modeling System (HL-RMS) of the US National Weather Service." Journal of Hydrology, 291, pp. 297-318.

Krajewski, Witold F., Venkataraman Lakshmi, Konstantine P. Georgakakos, and Subhash C. Jain (1991). "A Monte Carlo Study of Rainfall Sampling Effect on a Distributed Catchment Model." Water Resources Research, Volume 27, No. 1, pp. 119-128.

Langbein, Walter B. (1947). "Topographic Characteristics of Drainage Basins." U.S. Geological Survey Water-Supply Paper 968-C. Washington, D.C.

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and L.G. Saindon (1983). "Precipitation-Runoff Modeling System: User's Manual." U.S. Geological Survey, Water-Resources Investigations Report 83-4238.

Leavesley, G.H., P.J. Restrepo, S.L. Markstrom, M. Dixon, and L.G. Stannard (2004). "The Modular Modeling System (MMS)—A Modeling Framework for Multidisciplinary Research and Operational Applications (User's Manual)." This is on the USGS MMS Homepage internet site.

Leavesley, G.H. (2006). Personal Communication. U.S. Geological Survey. National Research Program. Precipitation / Runoff Modeling Project. Lakewood, Colorado.

Leopold, Luna B., and John P. Miller (1956). "Ephemeral Streams – Hydraulic Factors and Their Relation to the Drainage Net." U.S. Geological Survey Professional Paper 282-A.

Leopold, Luna B., M. Gordon Wolman, and John P. Miller (1964). <u>Fluvial Processes in Geomorphology</u>. Dover Publications, Inc., New York.

Leopold, Luna B. (1994). <u>A View of the River</u>. Harvard University Press, Cambridge, Massachusetts.

Linsley, Ray K., Max A. Kohler, and Joseph L. H. Paulhus (1949). <u>Applied Hydrology</u>. McGraw-Hill Book Company, Inc., New York.

Loague, Keith M. and R. Allan Freeze (1985). "A Comparison of Rainfall-Runoff Modeling Techniques on Small Upland Catchments." Water Resources Research, Volume 21, No. 2, pp. 229-248.

Loague, Keith (1990). "R-5 Revisited – Reevaluation of a Quasi-Physically Based Rainfall-Runoff Model With Supplemental Information." Water Resources Research, Volume 26, No. 5, pp. 973-987.

Luzio, Mauro Di, and Jeffrey G. Arnold (2004). "Formulation of a Hybrid Calibration Approach for a Physically Based Distributed Model with NEXRAD Data Input." Journal of Hydrology, 298, pp. 136-154.

Maidment, David R. (1993). <u>Handbook of Hydrology</u>. McGraw-Hill, Inc., New York.

Mays, Larry W. (1996). <u>Water Resources Handbook</u>. McGraw-Hill, Inc., New York.

McCuen, Richard H. (1989). <u>Hydrologic Analysis and Design</u>. Prentice Hall, Englewood Cliffs, New Jersey.

Michaud, Jene Diane and Sorooshian (1994a). "Comparison of Simple Versus Complex Distributed Runoff Models on a Midsized Semiarid Watershed." Water Resources Research, Volume 30, No. 3, pp. 593-605.

Michaud, Jene Diane and Sorooshian (1994b). "Effect of Rainfall-Sampling Errors on Simulations of Desert Flash Floods." Water Resources Research, Volume 30, No. 10, pp. 2765-2775.

Miller, Jeffrey E. (1984). "Basic Concepts of Kinematic-Wave Models." U.S. Geological Survey Professional Paper, 1302.

Morisawa, Marie (1958). "Measurement of Drainage-Basin Outline Form." Journal of Geology, Volume 66, pp. 587-591.

National Oceanic and Atmospheric Administration (NOAA) (1961). "Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 years." U.S. Weather Bureau Technical Paper No. 40.

National Oceanic and Atmospheric Administration (NOAA) (1977). "Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States." NOAA Technical Memorandum NWS Hydro-35.

National Weather Service (NWS) (2001). Service Assessment – Tropical Storm Allison, Heavy Rains and Floods, Texas and Louisiana, June, 2001.

Obled, Ch., J. Wendling, and K. Beven (1994). "The Sensitivity of Hydrological Models to Spatial Rainfall Patterns: An Evaluation Using Observed Data". Journal of Hydrology, 159, pp. 305-333.

Ogden, Fred L. and Pierre Y. Julien (1993). "Runoff Sensitivity to Temporal and Spatial Rainfall Variability at Runoff Plane and Small Basin Scales." Water Resources Research, Vol. 29, No. 8, pp. 2589 – 2597.

Ogden, Fred L. and Pierre Y. Julien (1994). "Runoff Model Sensitivity to Radar Rainfall Resolution." Journal of Hydrology, 158, pp. 1-18.

Ogden, F. L., H. O. Sharif, S. U. S. Senarath, J. A. Smith, M. L. Baeck, and J. R. Richardson (2000). "Hydrologic Analysis of the Fort Collins, Colorado, Flash Flood of 1997." Journal of Hydrology, 228, pp. 82-100.

Overton, Donald E. and Michael E. Meadows (1976). Stormwater Modeling. Academic Press, New York.

Ponce, Victor Miguel, Ruh-Ming Li, and Daryl B. Simons (1978a). "Applicability of Kinematic and Diffusion Models." Journal of Hydraulic Engineering, ASCE, 104(3), pp. 353-360.

Ponce, Victor Miguel and Vujica Yevjevich (1978b). "Muskingum-Cunge Method with Variable Parameters." Journal of Hydraulic Engineering, ASCE, 104(12), pp. 1663-1667.

Ponce, Victor M. (1991). "The Kinematic Wave Controversy." Journal of Hydraulic Engineering, ASCE, 117(4), pp. 511-525.

Reed, Seann, Victor Koren, Michael Smith, Ziya Zhang, Fekadu Moreda, Dong-Jun Seo, and DMIP Participants (2004). "Overall Distributed Model Intercomparison Project Results." Journal of Hydrology, 298, pp. 27-60.

Refsgaard, Jens Christian and Jesper Knudsen (1996). "Operational Validation and Intercomparison of Different Types of Hydrological Models." Water Resources Research, Volume 32, No. 7, pp. 2189-2202.

Refsgaard, Jens Christian (1997). "Parameterization, Calibration, and Validation of Distributed Hydrological Models. Journal of Hydrology, 198, pp. 69-97.

Roberson, John A., John J. Cassidy, and M. Hanif Chaudhry (1998). Hydraulic Engineering. John Wiley & Sons, Inc., New York.

Schumm, Stanley A. (1956). "Evolution of Drainage Systems and Slopes in Badlands at Perth Amboy, New Jersey." Bulletin of the Geological Society of America, Volume 67, pp. 597-646.

Senarath, Sharika U. S., Fred L. Ogden, Charles W. Downer, and Hatim O. Sharif (2000). "On the Calibration and Verification of Two-Dimensional, Distributed, Hortonian, Continuous Watershed Models." Water Resources Research, Vol. 36, No. 6, pp. 1495-1510.

Shah, S.M.S., P.E. O'Connell, J.R.M. Hosking (1996a). "Modelling the Effects of Spatial Variability in Rainfall on Catchment Response. 1. Formulation and Calibration of a Stochastic Rainfall Field Model." Journal of Hydrology, 175, pp. 67-88.

Shah, S.M.S., P.E. O'Connell, J.R.M. Hosking (1996b). "Modelling the Effects of Spatial Variability in Rainfall on Catchment Response. 2. Experiments with Distributed and Lumped Models." Journal of Hydrology, 175, pp. 89-111.

Sharif, Hatim O., Fred L. Ogden, Witold F. Krajewski, and Ming Xue (2002). "Numerical Simulations of Radar Rainfall Error Propagation." Water Resources Research, Vol. 38, No.8, pp. 15-1 to 15-14.

Sharif, Hatim O., Fred L. Ogden, Witold F. Krajewski, and Ming Xue (2004). "Statistical Analysis of Radar Rainfall Error Propagation." Journal of Hydrometeorology, Vol. 5., pp. 199-212.

Sherman, LeRoy K. (1932). "The Relation of Hydrographs of Runoff to Size and Character of Drainage-Basins." Transactions of the American Geophysical Union, Volume 13, pp. 332-339.

Shultz, Michael J. (1992). "Comparison of Flood Routing Methods for a Rapidly Rising Hydrograph Routed Through a Very Wide Channel." Master of Science Thesis, Department of Civil Engineering, College of Engineering, The University of Texas at Arlington.

Shultz, Michael J. and Robert J. Corby (2006a). "Development, Calibration, and Implementation of a Distributed Model for use in Real-Time River Forecasting." Proceedings of the 3rd Federal Interagency Hydrologic Modeling Conference, April 2-6, 2006, Reno, Nevada.

Shultz, Michael J. and Robert J. Corby (2006b). "Development, Calibration, and Implementation of a Distributed Hydrologic Model for Drainage Basins Located Along the Texas Gulf Coast for use in Real-Time River Flood Forecast Operations." Coastal Hydrology and Processes. Edited by Vijay P. Singh and Y. Jun Xu. Proceedings of the American Institute of Hydrology 25th Anniversary Meeting & International Conference "Challenges in Coastal Hydrology and Water Quality", May, 2006, Baton Rouge, Louisiana.

Singh, Vijay P. (1988). Hydrologic Systems – Rainfall-Runoff Modeling (Volume 1). Prentice Hall, Englewood Cliffs, New Jersey.

Singh, Vijay P. (1989). Hydrologic Systems – Rainfall-Runoff Modeling (Volume 2). Prentice Hall, Englewood Cliffs, New Jersey.

Singh, Vijay P. (1992). Elementary Hydrology. Prentice Hall, Englewood Cliffs, New Jersey.

Singh, Vijay P. (1996). Kinematic Wave Modeling in Water Resources. John Wiley & Sons, Inc., New York.

Smart, J. S. and A. J. Surkan (1967). "The Relation Between Mainstream Length and Area in Drainage Basins." Water Resources Research, Volume 3, Number 4, pp. 963-974.

Smith, Michael B. (1993). "A GIS-Based Distributed Parameter Hydrologic Model for Urban Areas." Hydrologic Processes, Volume 7, pp. 45-61.

Smith, Michael, Victor Koren, Bryce Finnerty, and Dennis Johnson (1999). "Distributed Modeling: Phase 1 Results." NOAA Technical Report NWS 44.

Smith, Michael B. and Konstantine P. Georgakakos (2004a). "The Distributed Model Intercomparison Project (DMIP) – preface". Journal of Hydrology, 298, pp. 1-3.

Smith, Michael B., Dong-Jun Seo, Victor I. Koren, Seann M. Reed, Ziya Zhang, Qingyun Duan, Fekadu Moreda, Shuzheng Cong (2004b). "The Distributed Model Intercomparison Project (DMIP): Motivation and Experiment Design". Journal of Hydrology, 298, pp. 4-26).

Stephenson, David and Michael E. Meadows (1986). Kinematic Hydrology and
    Modeling. Elsevier, New York.

Strahler, Arthur N. (1957). "Quantitative Analysis of Watershed Geomorphology."
    Transactions, American Geophysical Union, Volume 38, Number 6, pp. 913-920.

Streeter, Victor L. and E. Benjamin Wylie (1979). Fluid Mechanics (Seventh Edition).
    McGraw-Hill Book Company, New York.

Troutman, Brent M. (1983). "Runoff Prediction Errors and Bias in Parameter Estimation
    Induced by Spatial Variability of Precipitation." Water Resources Research,
    Volume 19, No. 3, pp. 791-810.

United Stages Geological Survey National Training Center (USGSNTC) (2004).
    Watershed Modeling Training Notes, USGS National Training Center, 2004.

Vazquez, R. F., L. Feyen, J. Feyen, and J.C. Refsgaard (2002). "Effect of Grid Size on
    Effective Parameters and Model Performance of the MIKE-SHE Code."
    Hydrological Processes, Volume 16, pp. 355-372.

Viessman, Warren, Jr., John W. Knapp, Gary L. Lewis, and Terence E. Harbaugh.
    (1977). Introduction to Hydrology (second edition). Harper & Row, Publishers,
    Inc., New York.

Viessman, Warren, Jr. and Gary L. Lewis. (1996). Introduction to Hydrology (fourth
    edition). HarperCollins College Publishers, New York.

Vieux, Baxter E., Jean E. Vieux, Chiarong Chen, and Kenneth W. Howard (2003a).
    "Operational Deployment of a Physics-Based Distributed Rainfall-Runoff Model for
    Flood Forecasting in Taiwan." International Symposium on Information from
    Weather Radar and Distributed Hydrological Modeling, Sapporo, Japan, July 7-8,
    2003.

Vieux, Baxter and Fekadu G. Moreda (2003b). "Ordered Physics-Based Parameter
    Adjustment of a Distributed Model." Calibration of Watershed Models, Volume 6,
    pp. 267-281.

Vieux, Baxter E., Zhengtao Cui, and Anubhav Gaur (2004). "Evaluation of a Physics-
    Based Distributed Hydrologic Model for Flood Forecasting." Journal of Hydrology,
    298, pp. 155-177).

Wilson, Charles B., Juan B. Valdes, and Ignacio Rodriguez-Iturbe (1979). "On the
    Influence of the Spatial Distribution of Rainfall on Storm Runoff." Water Resources
    Research, Volume 15, No. 2, pp. 321-328.

Winchell, Michael, Hoshin Vijai Gupta, and Soroosh Sorooshian (1998). "On the Simulation of Infiltration- and Saturation-Excess Runoff Using Radar-Based Rainfall Estimates: Effects of Algorithm Uncertainty and Pixel Aggregation." Water Resources Research, Volume 34, No. 10, pp. 2655-2670.

Wisler, C. O., and E. F. Brater. (1959). Hydrology (Second Edition). John Wiley & Sons, Inc., New York.

Woolhiser, David A. (1996). "Search for Physically Based Runoff Model—A Hydrologic El Dorado?" Journal of Hydraulic Engineering, Volume 122, Number 3, pp. 122-129.

Wurbs, Ralph A. (1985). "Military Hydrology—State-of-the-Art Review and Annotated Bibliography of Dam-Breach Flood Forecasting." Miscellaneous Paper EL-79-6. Prepared for the Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi.

Wurbs, Ralph A. (1986). "Comparative Evaluation of Dam-Breach Flood Wave Models." Texas Civil Engineer, May, 1986.

BIOGRAPHICAL INFORMATION

Michael Jay Shultz was born in Grand Junction, Colorado on September 11, 1960.

Michael graduated from Grand Junction High School in May, 1978.

In the fall of 1978, Michael enrolled at Colorado State University, College of

Forestry and Natural Resources, Department of Earth Resources and received Bachelor of

Science degree in Watershed Sciences in May, 1983. In the fall of 1987, Michael

enrolled at the University of Texas at Arlington, College of Engineering, Department of

Civil Engineering and received a Master of Science degree in Civil Engineering in

August, 1992. In the winter of 1998, Michael once again, enrolled at the University of

Texas at Arlington and received a Doctor of Philosophy degree in Civil Engineering in

December, 2007.

Between 1981 and 1983, Michael was employed as an engineering technician

(summer hire) with the U.S. Bureau of Land Management in Grand Junction, Colorado.

His assignments included mapping BLM roads, performing road inventory assessments,

and assisting with a survey crew. In the summer of 1984, he was employed as an

engineering technician for the U.S. Army Corps of Engineers, Sacramento District,

Regulatory Unit, in Grand Junction, Colorado. His assignments included evaluating

Section 404 Dredge and Fill Permits for projects located in Western Colorado.

In early 1985, Michael was hired on as a permanent employee as an engineering

technician with the U.S. Army Corps of Engineers, New England Division, Regulatory

Unit in Waltham, Massachusetts. His assignments included evaluating Section 404

Dredge and Fill Permits and Section 10 River and Harbor Permits for projects located in

Western Connecticut.

Between late 1985 and late 1993, Michael was employed as a hydrologist with the

U.S. Army Corps of Engineers, Fort Worth District, Lake Control Unit, in Fort Worth,

Texas. His assignments included operating flood control reservoirs and hydrologic

modeling.   During this time, he worked several significant floods events which occurred

over large areas across the State of Texas. Of special note is the Spring, 1989 flood

across North Texas, the Spring, 1990 flood also across North Texas, and the Christmas

1991 flood over North, Central, and Southeast Texas.

Since, late 1993, Michael has been employed as a hydrologist with the National

Weather Service, West Gulf River Forecast Center in Fort Worth, Texas. His

assignments include forecasting river and flood stages during flood events and hydrologic

and hydraulic modeling. He is currently a member of a national team evaluating

hydraulic models for inclusion into the river forecast mission of the National Weather

Service. Since 1993, he has worked many catastrophic flood events which occurred over large areas across the State of Texas. Of special note is the October, 1994 flood across Southeast Texas, the October, 1998 flood on the Guadalupe River, and Tropical Storm Allison which occurred over Houston, Texas in June, 2001.

Michael is also an Eagle Scout (1976). He is currently active with the Boy Scouts of America serving as a merit badge counselor in Soil and Water Conservation, Engineering, Weather, Environmental Science, Chemistry, Geology, and Forestry. He also serves on rank advancement board of reviews, including those for Eagle Scout. He recently served as a national staff member for the merit badge midway exhibit at the 2005 National Boy Scout Jamboree, located at Fort A.P. Hill, Virginia.

Michael is registered as a Professional Engineer in the States of Texas and Colorado. He is also certified as a Professional Hydrologist through the American Institute of Hydrology.