Hypothetical Watershed Modeling – Block B

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by:

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1 Introduction

This report presents the post ground-work phase hypothetical watershed modeling component of the Block B study. In this report example conceptualizations are presented with some results and comments. The ground-work phase of the Block B study was to develop the necessary skills to model "spill" between parcels, approximate on-watershed storage, and examine documentable conceptualization approaches to simulate progressive watershed development at the indicated scale using EPA SWMM 5.0 (Rossman, 2008).

Two kinds of models are examined in this report: generic models and semi-realistic models. The generic models were constructed to allow the modeling team refined control over hydraulic elements, basin development factor (BDF), and to a lesser extent slopes, and runoff generation. The semi-realistic models simulate behavior on three watersheds varying in size either within or proximal to Harris County. The purpose of the semi-realistic models were to be sure the modeling effort produces results (hydrographs) that were similar to observed hydrographs without an involved calibration exercise.

1.1 The Basin Development Factor, BDF

The Basin Development Factor, BDF is a measure of runoff transport efficiency of the drainage systems in a watershed (Sauer et al., 1983). It is a categorical variable, which is assigned a value based on the prevalence of certain drainage conditions that predict the urbanization of a watershed. The BDF takes the numerical value based on the significant presence of certain properties which are briefly explained below[3]:

1. Channel Improvements: Refers to engineered improvements in the drainage channel and its principal tributaries (creating, widening, deepening, straightening, etc.). If any of these activities are present in at least 50% of the main channel and its tributaries, then, a value of one is given to the third of the watershed under consideration; otherwise the third of the watershed is assigned a value of zero.

2. Channel linings: If more than 50% of the main channel length is lined with concrete or other friction reducing material, then a value of one is given to the third of the watershed under study, otherwise a value of zero is assigned. Usually, if the drainage channel is lined it will also reflect some level of channel improvement. Hence this aspect is an added factor to portray a highly developed drainage system.

3. Storm drains or Storm sewers: Enclosed drainage structures that are used on the secondary tributaries, that collect the drainage from parking lots, streets etc., and

[3] This discussion of BDF predates the changes ultimately recommended by the Block B team, however it reflects the thinking used in the hypothetical and semi-realistic models.

drain into open channels or into channels enclosed as pipe or box culverts. When over 50% of the secondary tributaries have storm drains, then a value of one is assigned, otherwise a value of zero is assigned.

4. Curbs and Gutters: this element reflects the actual urbanization of the watershed area. If more than 50% of the area is developed or contains residential or commercial buildings and if streets and freeways are constructed, then a value of one is assigned. Else the value zero is given. Curbs and gutters take drainage to storm drains. In this part of the study, the placement of streets in the hypothetical models is reflected by this scoring component – thus the additon of a street, that could serve intentionally or unintentionally as a conduit elevates this score.

As an illustrative example, consider Figure 1, an aerial image of a watershed in Dallas, Texas.

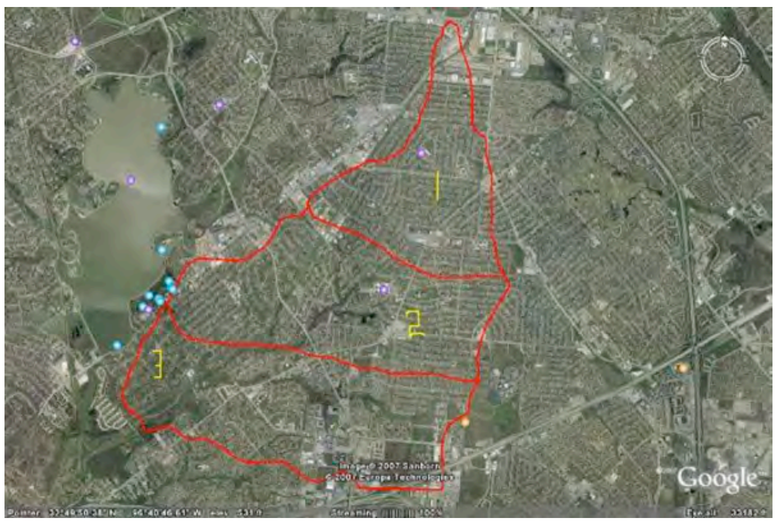

Figure 1: Example of BDF determination from aerial imagery for Station 0807320 Ashcreek, Dallas, Texas.

An approximate delineation is shown on the figure and the watershed is divided into thirds[4] Table 1 lists the values for each component in each thrid of the watershed.

Then this is divided into 3 equal parts. The 3 parts are examined for channel improvements, channel linings, storm drains and curbs and gutters. The scores obtained by the three parts are as follows.

[4]The division lines in this particular example are not necessarily unique, and different analysis would divide the thirds differently – however they are sufficient for this example.

Table 1: Ash Creek BDF computation example

Component	Channel Improvements	Channel linings	Storm drains	Curbs and gutters
Top (1)	0	0	0	1
Middle (2)	1	1	0	1
Bottom (3)	1	1	0	1

The top portion of the watershed (Area # 1) has no channel and thus channel improvements,channel lining, and storm sewers are assigned a value 0, however the image shows it has some residential or commercial set up. So curbs and gutters are assigned a value of 1. In the middle and the bottom portion of the watershed, the channel improvements and linings are assigned the value 1 as the enlarging of the channel is observed and concrete walls can be seen when observed closely. Also, the curbs and gutters are assigned a value 1 because of the obvious transportation infrastructure. The BDF value for the Ashcreek watershed is $1 + 3 + 3 = 7$.

1.2 Summary of Findings

Through a series of hypothetical simulation models and a series of semi-realistic models the researchers arrived at the following set of findings. These findings are discussed in more detail along with the interpretation of the modeling results that support these findings.

The research findings are:

1. The initial act of development as simulated by a change in impervious cover (or a reduction in Green-Ampt saturated conductivity) causes at least a two-fold increase in runoff, if not more. Mitigation of this runoff, which is an actual increase and not a result of reduced travel times will have to be accomplished by either some kind of on-watershed storage or by some kind of compensating loss strategy.

2. Internal drainage improvements (drainage using streets, ditches, and or sewers as conveyance tools) results in a reduced watershed response time and an increased peak discharge rate. These improvements produce another doubling of peak discharge, but do not change the volume that must be accommodated.

3. The watershed response to larger magnitude events in this study appear to be topographically explained while response to smaller magnitude events is explained by the behavior of engineered systems (i.e. the engineered drainage system).

4. Basin Development Factor used as a surrogate for development appears to be a meaningful small watershed approach in lieu of SWMM models or similar tools.

5. Based upon exploratory data analysis and a power law model fit of the modeled results the relative change in peak discharge as basin development factor is increased is on the order of one-half a log cycle (log10) for an increase from 0 to 12.

The remainder of the report described how the models were built and operated as well as how the results were interpreted to arrive at these these findings.

2 Methods

The modeling approach used is a hybrid interpretation of the link node models usually constructed in the Storm Water Management Model (SWMM) (Rossman, 2008) and a quasi-2 dimensional flow direction approach reminiscent of a groundwater flow model. In the approach the nodes are modeled as storage elements and all on-watershed storage properties are assigned to and computed at the nodes. A handful of conventional junction nodes are used in parts of each model to increase the graphical resolution in water surface profile plots, but otherwise are not important.

Nodes are connected by hydraulic elements that represent various averaged geometric and development conditions. Storm sewers are included as separate elements, thus a hypothetical watershed with a storm sewer could potentially have two entirely independent drainage networks (the surface or overland, and the subsurface system), interconnected only at the storage elements, with flow within each network governed by the water depth in each storage element.

2.1 Generic Hypothetical Models

The generic hypothetical models are comprised of three panels of 18 sub-basins that all drain into a common channel element. The size of the sub-basins range from $\frac{1}{4}$-acre to 4-acres. The linear distances are adjusted such that all the sub-basins are rectangles of constant aspect ratio[5]. The elevations of each sub-basin establish the overall watershed slopes and these elevations are held constant as the linear distances are changed.

Figure 2 depicts the generic hypothetical layout. In the upper left corner of the figure, a watershed cell is highlighted. All such cells contain a runoff element (a sub-basin in SWMM), a storage node (used in this effort to manage volumes in storage in the watershed), and at least two, as many as four surface-flow elements. The cells also may contain a sewer element and a sewer node for cases when the watershed is developed with sewers. These nodes and sewer elements are set with elevations below the storage node elevation so that the sewers would preferentially drain a node before surface flow could occur[6].

The runoff elements in the figure are sub-basins in the SWMM model environment. These sub-basin sizes are set equal to that of the cells. SWMM defaults are used except for overland flow length which is one-half the linear dimension of the cell and percent impervious cover which is varied in these simulations to represent undeveloped (0%) to developed (30%).

[5] All the sub-basins are square.

[6] In practice, the modeling team built these fully developed models and adjusted the sewer node elevations to be well above the storage node elevations, thereby removing the sewers ability to carry flow.

Rainfall time series were supplied to the model through a single raingage element (not identified; the small "weeping cloud" in the upper right of figure 2 is the raingage element). All the runoff elements (sub-basins) receive their rainfall from this single source. Spatially variable rainfall thus was not considered.

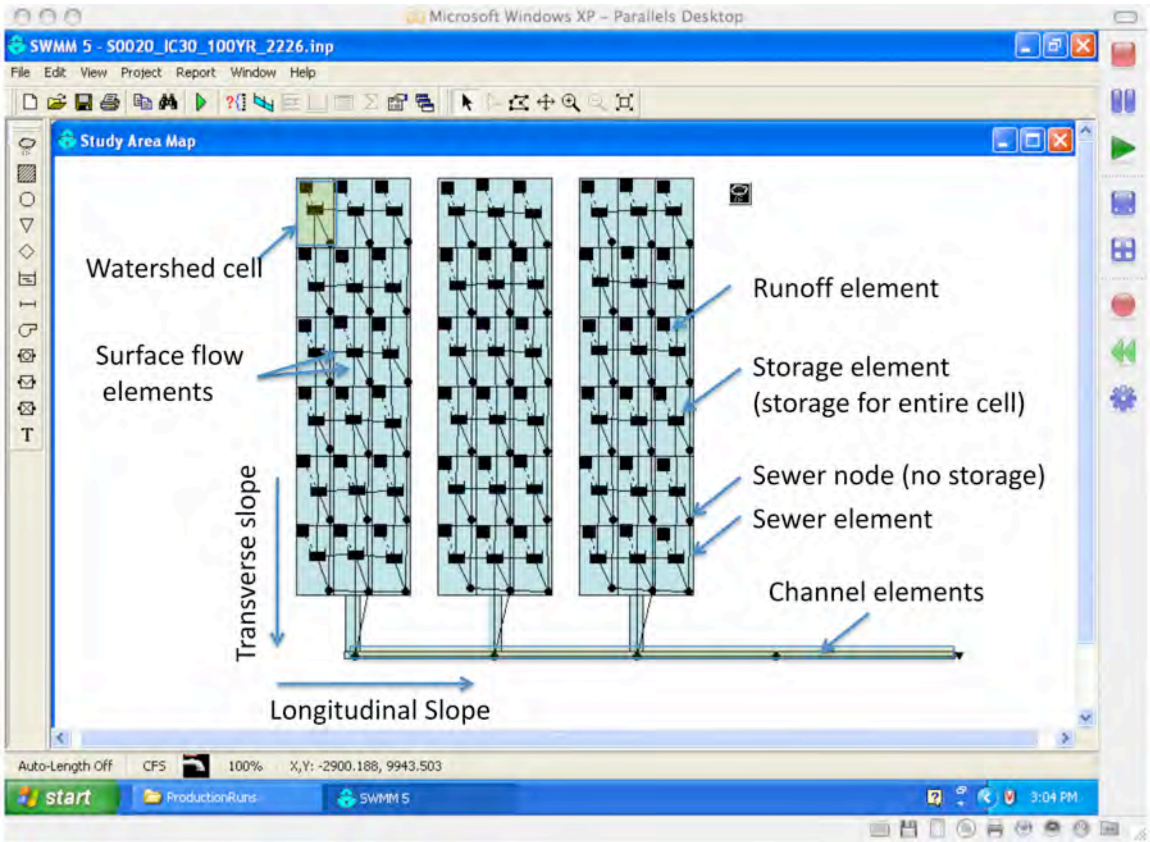

Figure 2: Generic hypothetical model layout. This figure depicts a model with all elements in place; surface elements, sewer elements, storage elements, and channel elements. Less developed conditions are modeled by removing or changing such elements.

The three vertical elements that join the panels to the channel elements are the only components of this model that do not change. These connections are trapezoidal channels with very small friction terms. These connections are intended to have limited impact on the hydraulic behavior to the system. All the panels drain from the top of the figure towards the channel, and from their edges to their centerline. Models constructed as such do not have any isolated "low spots."

The resulting range of overall basin size (drainage area) and transverse slopes are listed in

Table 2.

Table 2: Total drainage area, slopes, and cell area sizes used in hypothetical studies.

Cell Size (acres)	Slope (dimensionless)	Drainage Area (acres)
$\frac{1}{4}$	0.01	13.5
$\frac{1}{4}$	0.002	13.5
1	0.001	54.0
1	0.005	54.0
4	0.0005	216.0
4	0.003	216.0

2.1.1 Generating the Excess Rainfall

Excess rainfall (runoff) is generated by the sub-basin module(s) in SWMM. The three principal components used in this study to impact excess generation are the drainage area and its corresponding width[7], the percent impervious cover, and the loss model.

SWMM defaults are used in this module except for the area, basin width, and percent impervious cover. The loss rates (volumes) were computed using the Green-Ampt (Green and Ampt, 1911) model. In the hypothetical studies Green-Ampt values consistent with a Sandy-Loam soil texture (Rawls et al., 1983) were used with some minor variation in the initial part of the study to produce runoff signals similar to some observed signals in the area. Specifically the values used in the Green-Ampt computations in this part of the hypothetical study are:

$$\begin{aligned} K_{sat} &= 0.5 \quad \text{inches per hour} \\ \Psi &= 3.0 \quad \text{inches} \\ \Delta\phi &= 0.4 \end{aligned}$$

Figure 3.1 is a plot of the hypothetical, 6-hour duration rainfall used throughout this report. The curves represent incremental rainfall (depth that falls during the increment) for a 50%-chance event, 10%-chance event, and 1%-chance event (2, 10, and 100-year return interval events).

Table 3 lists the values for impervious cover and the cell dimensions used in the hypothetical studies. The effect of changing percent impervious cover can be argued as having an effect

[7] The ratio of area to width produces a length dimension that establishes a travel time for runoff from the sub-basin. In this study the individual sub-areas are kept small so this time is correspondingly small, and the routing time of significance is modeled in the hydraulic elements.

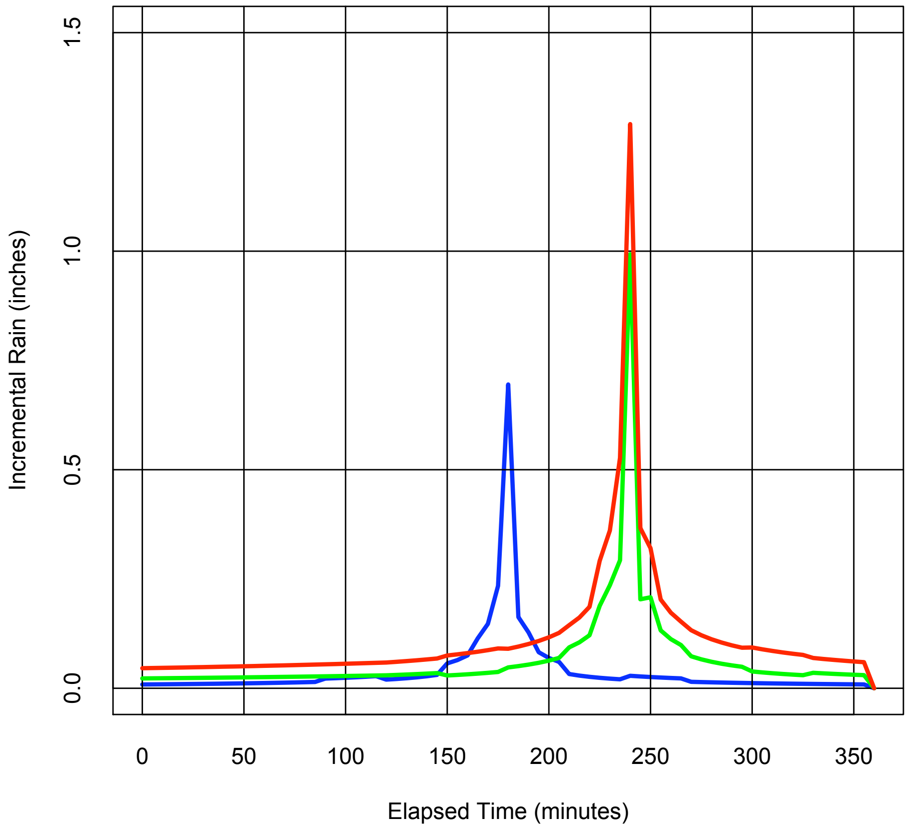

Figure 3: Rainfall used in all models in this report. Blue curve is 50% event (2-year), Green curve is 10% event (10-year), and Red curve is the 1% event (100-year). Duration is fixed in all cases to 6-hours.

equivalent to adjusting the hydraulic conductivity and to a lesser extent the initial moisture deficit in a Green-Ampt model of infiltration.

The percent impervious cover listed in table 3 is at the computational cell level. The hypothetical watershed is comprised of three panels which are developed independently; hence next impervious cover values of 0, 10, 20, and 30 were constructed. A handful of simulations using even higher values of impervious cover were considered, but these results are not presented here.

Table 3: Impervious cover and cell dimensions used in hypothetical studies.

Cell Size (acres)	Impervious Cover (%)	Width (feet)	Remarks
$\frac{1}{4}$	0	104	undeveloped
$\frac{1}{4}$	30	104	developed
1	0	208	undeveloped
1	30	208	developed
4	0	416	undeveloped
4	30	416	developed

2.1.2 Surface Hydraulic Elements – Streets, Ditches, and Backyards

The surface system hydraulic links are represented as irregular cross sections in the SWMM program. The effects of different surface conditions (houses, streets, etc.) are modeled using different friction terms in different portions of the cross sections as well as different geometric configurations. Each section is "glass-walled" to restrict the total possible flow width to a computational cell dimension. This geometric structure requires that flow to adjacent elements must pass through a node element — these node elements are treated as storage nodes for storage accounting.

Backyard Sections

The predevelopment conditions are represented a nearly planar section with a small V-channel in the middle — the V-channel is 1-foot wide and 1-foot deep in all sections of this type. This section type is referred to as a "Backyard Section" for the purposes of this report. Figure 4 depicts the geometry of this type of section. Table 4 lists the friction coefficients used in these hypothetical watersheds. The values are intentionally large and are at the larger end of values shown in the literature (e.g. Figure 6.3 in Simon and Korom (1997)).

Table 4: Friction values for used in Backyard Section hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Pre-development	0.6	0.4	0.6
Post-development	0.6	0.4	0.6

Street Sections

The development conditions are represented a Street Section with the curb edges located

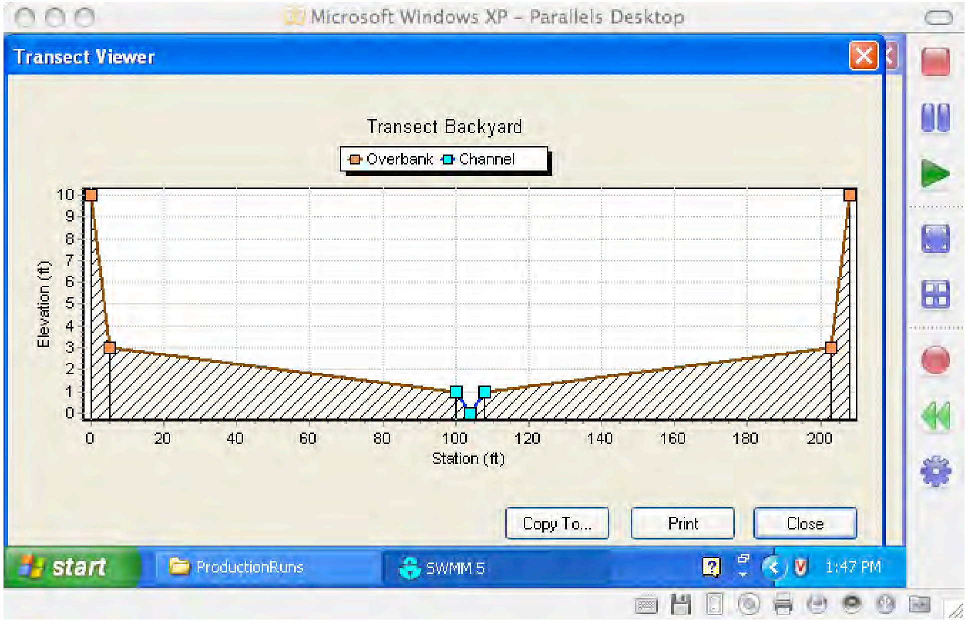

Figure 4: Backyard Section. Used as pre-development hydraulic element with various friction terms. Used in post-development models to distinguish from street, street and ditch, and ditch/channel sections.

at the reference (node) elevation. This section type is referred to as a "Street Section" for the purposes of this report. Figure 5 depicts the geometry of this type of section. Table 5 lists the friction coefficients used in these hypothetical watersheds. The values are varied slightly (not reported) in some simulations to reduce or mitigate numerical oscillations. in computed discharge and water depth values. Observe that these friction-term values are one order of magnitude smaller than the pre-developed situation.

Table 5: Friction values for used in Street Section hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Pre-development	N/A	N/A	N/A
Post-development	0.06	0.02	0.06

The development conditions also are representable with a street section with the curb edges located at the reference (node) elevation and roadside ditches adjacent to the streets but below the reference elevation. This section type is referred to as a "Street with Ditch Sec-

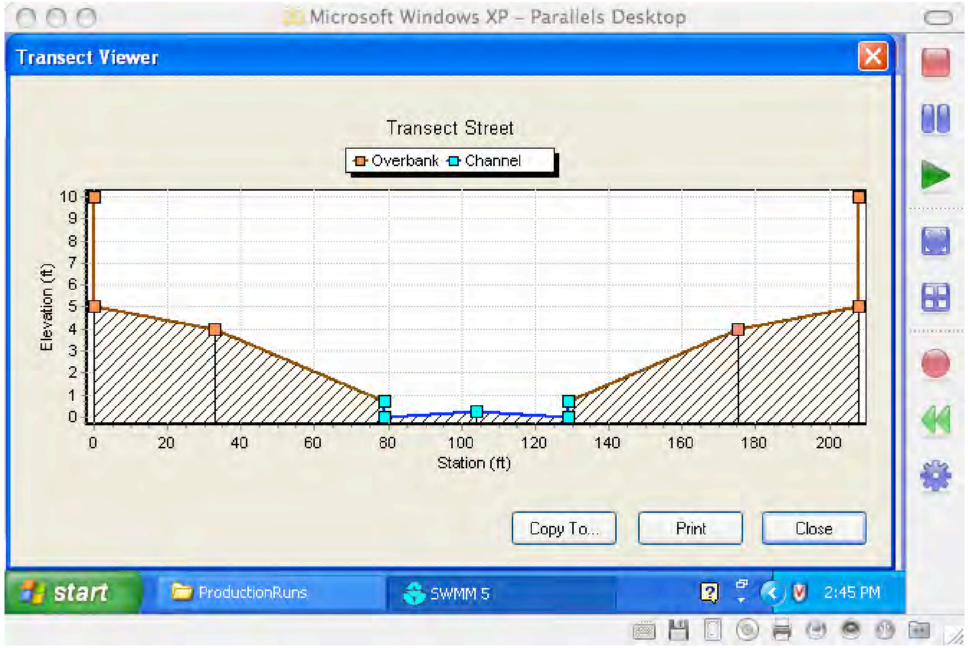

Figure 5: Street Section. Used as a post-development hydraulic element with various friction terms. Minor variations in friction terms were used in simulations to preserve model stability (with regards to numerical oscilliations).

tion" for the purposes of this report. Figure 6 depicts the geometry of this type of section. Table 6 lists the friction coefficients used in these hypothetical watersheds. Observe that these friction-term values are also one order of magnitude smaller than the pre-developed situation.

Table 6: Friction values for used in Street with Ditch Section hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Pre-development	N/A	N/A	N/A
Post-development	0.06	0.02	0.06

Channel Elements

The final type of section is the drainage channel depicted at the bottom of the model in Figure 2. The channel elements are a trapezoidal ditch with a small rectangular "pilot-channel" section. The friction terms are adjusted to reflect the presence or absence of

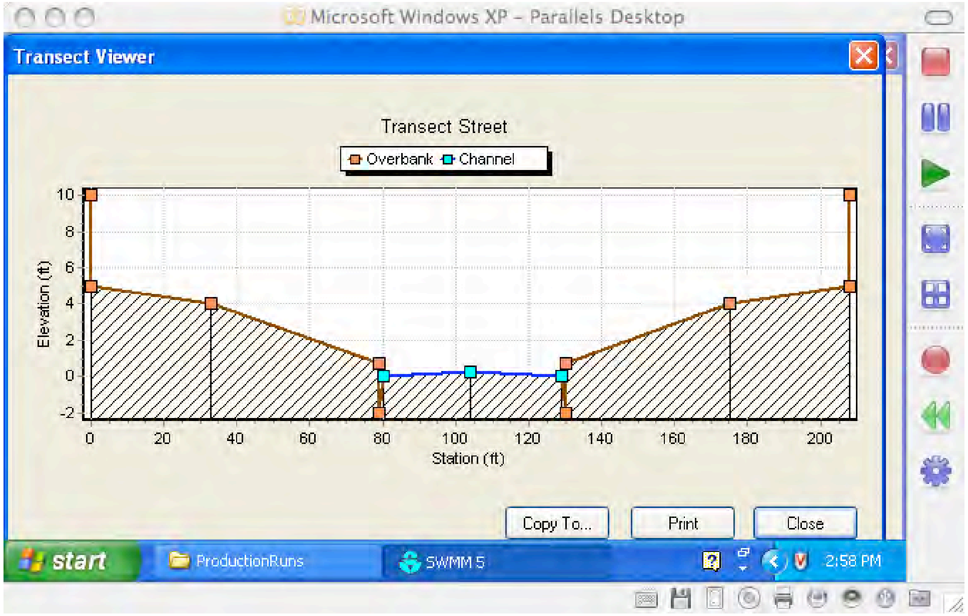

Figure 6: Street with Ditch Section. Used as a post-development hydraulic element with various friction terms. Ditch portion adjacent to streets is below reference elevations — water must fill these ditches before the streets to preserve continuity.

channel improvement. Consideration was given to changing the geometry (the geometry of the section is representative of developed drainage infrastructure), but eventually abandoned so that the research team was adjusting only one component at a time as the hypothetical watershed is developed.

Figure 7 depicts the channel geometry used in the study. Table 7 lists the values of friction terms used at different categories of development.

Table 7: Friction values for used in Street with Ditch Section hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Unimproved	0.6	0.4	0.6
Improved	0.035	0.035	0.035
Lined	0.035	0.01	0.035

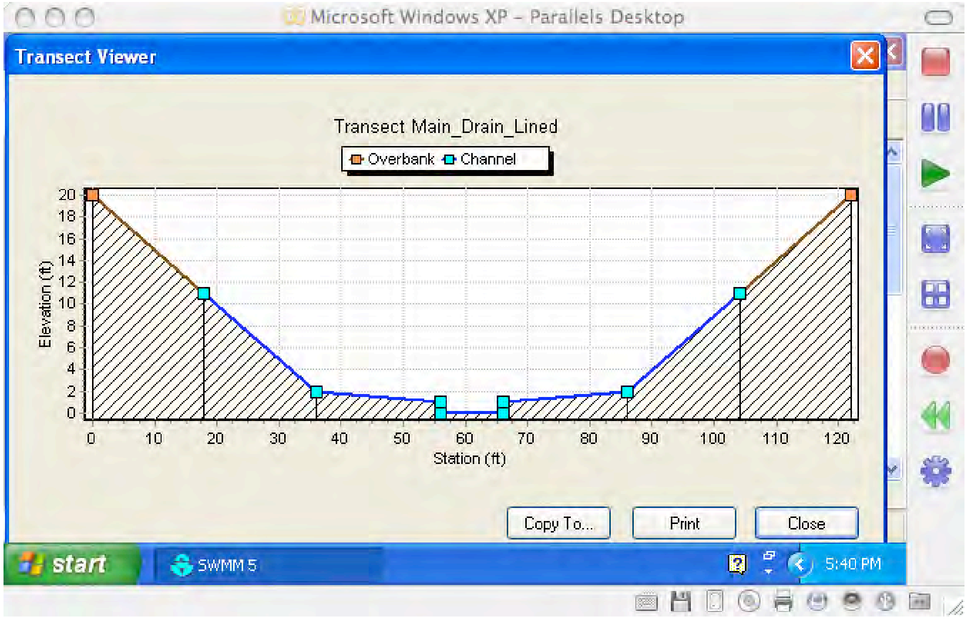

Figure 7: Channel section. Geometry is maintained, friction terms adjusted for undeveloped, improved, and concrete lined.

2.1.3 Subsurface Hydraulic Elements — Storm Sewers

Storm sewers when incorporated in the hypothetical models were modeled as circular conduits connected to one another by junction nodes. The junction node elevations were generally below the elevation of the surface system[8]. Sewers are connected to the surface system at watershed cell centers (storage nodes) by short circular sections. With the exception of these connections, the entire system formed a network independent of the surface hydraulic elements (i.e. backyard, street, and ditch).

2.1.4 Surface Storage — Storage Nodes within the System

Each watershed cell served as a storage node in the model. In the hypothetical component of the study, the functional form of the depth-storage relationship was used. Figure 8 depicts the relationship.

At the time of this study, the researchers overlooked that the depth-storage relationship

[8]In fact this was always true, however on some occasions the authors found it useful to leave a sewer system in-place and simply elevate all the nodes above grade to effectively remove the sewer system from the model.

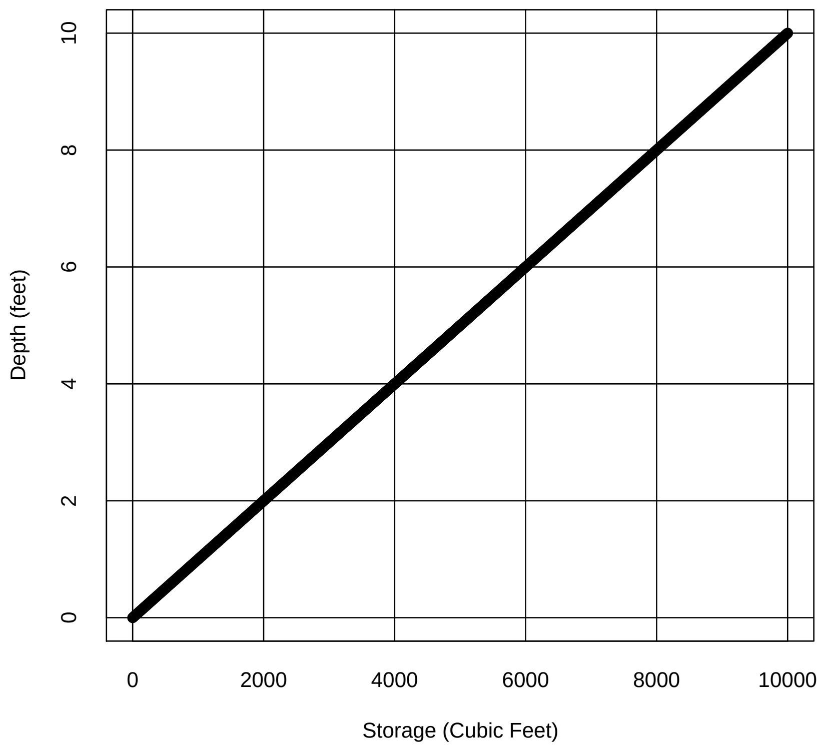

Figure 8: Depth-storage relationship for hypothetical study.

was held constant regardless of cell size, hence the small area watersheds had more storage per unit area than the larger cell models. In the semi-realistic models, storage behavior was adjusted for different sized watershed cells.

2.2 Semi-Realistic Hypothetical Models

A second set of hypothetical watersheds are referred to as semi-realistic, or analog watersheds. The use of analogs was explored so that the researchers could have some confidence that simulations are realistic and reflect responses typical to Harris County. In this section three analog watersheds are described. Similar to the generic hypothetical watersheds, is the computational grid structure (containing all the storage information within the model) and hydraulic element structure (4-cell pour point type linkages). Each analog watershed differs in shape, size, basin slope, and some other physical features, as well as in their ultimate build-out conditions. Whereas the analog watersheds resemble real watersheds, the models are not intended to be faithful representations of real conditions.

Watershed Analogs

A watershed analog in this study is a model (computer program and supporting input files) which is similar in structure to an authentic watershed,but not necessarily a congruent replica. A watershed analog is expected to function similarly enough to the real watershed that conclusions made by adding or removing components (changing development state, drainage features, etc.) would apply to the real watershed (if such changes could be made on the real watershed).

The use of the analog concept allows the researchers to validate that the model (analog) responds similarly to observed behavior when configured closely to the observed conditions, further building confidence in the effects of changes. The analogs correspond to watersheds for which the team has access to some observed rainfall and runoff data, and this data constitutes the test bed for the models.

The analogs are constructed, then tested against the observed behavior to be sure the analog responses are similar to the observed responses. Minor adjustments of hydraulic elements may be made during this phase, but these models are in no way calibrations and should not be interpreted as such. A better concept is that the models mimic observed responses and thus represent valid approximations of Harris County watersheds.

2.2.1 Generating Excess Rainfall

Excess rainfall (runoff) is generated in a fashion identical to that of the generic hypothetical models. The Green-Ampt parameters are selected to reflect soil conditions representative of the analog watersheds locations.

$$
\begin{aligned}
K_{sat} &= 0.45 \quad \text{inches per hour} \\
\Psi &= 4.5 \quad \text{inches} \\
\Delta\phi &= 0.45
\end{aligned}
$$

As before, program defaults are used except for the above Green-Ampt values, the area, the basin width, and the percent impervious cover.

2.2.2 Surface Hydraulic Elements — Streets, Ditches, and Backyards

The predevelopment and natural conditions are represented by four different section types. All types have similar geometry (nearly planar with a small V-channel in the middle — the V-channel is 1-foot wide and 1-foot deep in all sections of this type). The friction values are adjusted (as in the generic models) to reflect different degrees of development.

Total relief depicted in these sketches is 1foot. Widths vary for different hypothetical watersheds, but the smallest is 200 feet. The V-channel is used as a way to maintain a water continuum in the SWMM program that greatly increases computational stability.

Figure 9: Natural (Pre-development), Wooded Section

Figure 9 is a sketch of how a natural section is conceptualized. This section type is identical in SWMM as the "Backyard" section in the generic hypothetical model (Figure 4). The entire section is assigned a friction term (Manning's n) to represent flow resistance in the section. If woods are not present (e.g. long grass, mowed grass, bare earth) the geometry is unchanged, but the frictional effects are different. While the section will have lengths and depths associated water flowing in the section, these volumes are considered to be in-transit and are not part of the on-watershed storage.

Figure 10 is an image of the University of Houston Coastal center, Harris County, Texas. In the image both tall grass and wooded type land coverages are represented. The right background is a wooded portion, whereas the foreground is the tall grass type of coverage. The image in Figure 11 is an example of a mowed grass situation. Whereas this particular image is of a golf course, the friction impact is intuitively different than in the tall grass

Table 8: Friction values for used in Realistic Watershed Pre-Development hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Wooded	0.10	0.10	0.10
Tall Grass	0.065	0.065	0.065
Mowed Grass	0.04	0.04	0.04

coverage. This particular conceptualization is used in the hypothetical model to simulate conditions just before development (i.e. placement of structures).

Figure 10: Image of Coastal Prarie. Foreground is analysts concept of a tall grass hydraulic section, background is a wooded portion.

The post-development conditions are represented by combinations of the predevelopment section types with various development changes reflected by addition of a street, ditch, and sub-surface storm sewer. The predominant (used in the hypothetical models) section types used are depicted in the series of following sketches.

Figure 12 is a sketch representing conditions where land is cleared before construction and a street (road) has been added. The sketch differs from Figure 9 only by the addition of the street (and commesurate change in geometry) and well as change in friction terms for only the street portion. The pre-development geometry is indicated in the sketch by the light grey, dashed line. This conceptualization is identical to the Street Section (Figure 5) in the generic model, with some variations of width, crown and total relief.

Figure 13 is a sketch representing conditions where land is cleared and developed, but

Figure 11: Image of a golf course in the Woodlands area. The fairway and greens are representative of a short grass section (although hardly a natural configuration in this image); the trees to the left of the image are a wooded section.

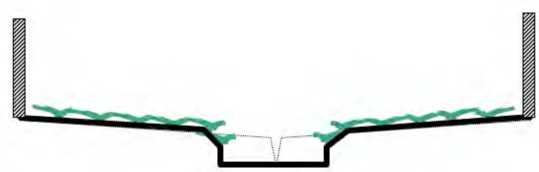

Figure 12: Developed, Street and Grass Section (before structural elements).

without any specific drainage elements (i.e. the street is the principal drainage conveyence). It differs from Figure 12 only by the addition of the structural elements (the houses in the sketch).

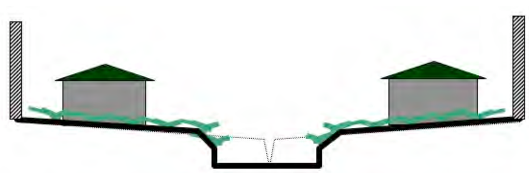

Figure 13: Developed, Street with Structural Elements (Homes or Businesses).

Table 9 lists the frictional terms used to reflect the presence or absence of various structural components and vegetative coverages. The street and ditch sections used the same values (the geometry is different because of the roadside ditch.).

Figure 14 is a sketch representing conditions where land is cleared and developed and

Table 9: Friction values for used in Realistic Watershed Street Section hydraulic element configurations. Last three columns list n values for different applications (development conditions).

Application	Left Bank	Central Channel	Right Bank
Street, No Structures, Wooded	0.11	–	0.11
Street, No Structures, Brushy	0.075	0.015	0.075
Street, No Structures, Mowed	0.055	0.015	0.055
Street, Structures, Wooded	0.10	0.015	0.10
Street, Structures, Brushy	0.065	0.015	0.065
Street, Structures, Mowed	0.045	0.015	0.045

the principal drainage element (other than the street) is a roadside ditch. It differs from Figure 13 only by the addition of the drainage element (the ditch in the sketch).

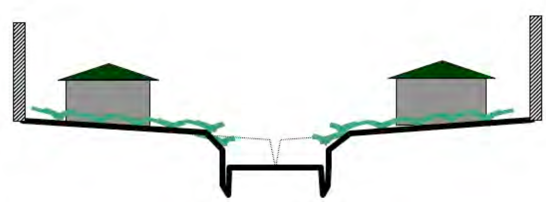

Figure 14: Developed, Street with Ditch and Grass Section.

Figure 15 is a sketch representing conditions where land is cleared and developed, but with storm sewers as the principal drainage elements (other than the street). The storm sewers are separate hydraulic elements (circular conduits) and communicate with the surface components only at the storage nodes. The friction terms in the sewer portions were kept small at SWMM defaults ($n \approx 0.01$) All surface resistances are treated as in the above sections.

2.2.3 Surface System Storage Representation

As in the 3-panel hypothetical study, each watershed cell served as a storage node in the model. In the realistic hypothetical component of this study, each watershed had a depth-storage relationship directly related to the watershed cell dimension — in essence, storage per unit area is identical for each watershed.

The depth-storage tables and plots similar to Figure 8 are shown for each watershed in

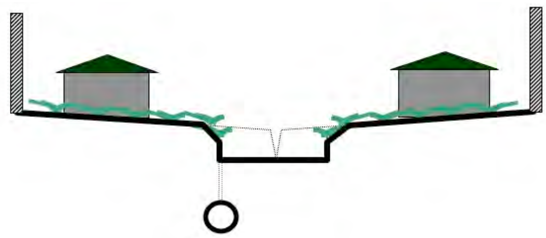

Figure 15: Developed, Street with Sewer and Grass Section.

later sections. Of importance here is that the relationship is no longer linear as in the hypothetical study, and the depth-volume relationship also is cell size dependent.

2.2.4 Subsurface Hydraulic Elements — Storm Sewers

Storm sewers, when incorporated in the semi-realistic models, were modeled as circular conduits connected to one another by junction nodes. Sewers are connected to the surface system at watershed cell centers (storage nodes) by short circular sections. With the exception of these cell-center connections, the entire system formed a network independent of the surface hydraulic elements (i.e. backyard, street, and ditch).

In the semi-realistic models, reasonable "guesses" were used as to the alignment and size of the storm sewers simulated (except for the Lazybrook analog, for which some details of actual systems are available). In the Woodlands analogs, some details became available during the study, but the models were already constructed, so the details were used to validate the general layout modeled. Some connections were moved, but the general models were unchanged.

In this component of the study, sewers were connected and disconnected specifically by changing junction node heights — to remove a sewer, the network was left untouched but the sewer nodes were simply elevated 10 or more feet *above* grade, effectively removing the sewer from the system.

2.2.5 Lazybrook Analog (LZB)

Figure 16 depicts the model structure of the Lazybrook analog watershed. This watershed was selected because it represents a high level of residential development and, more importantly, is well studied by other members of the Block B team. Thus, responses can be compared to their collective knowledge.

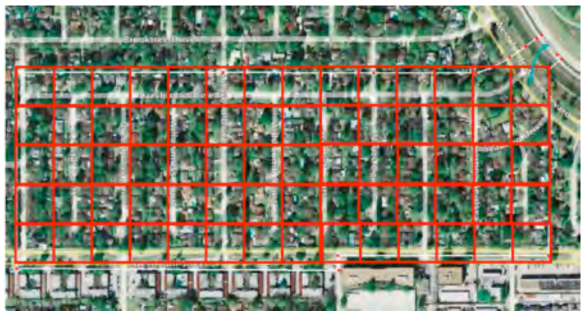

Figure 16: Lazybrook Analog Watershed. Flow links are omitted for clarity. This figure displays cells that were later omitted.

Table 10 lists relavant perteniant physical characteristics of the analog watershed as well as some model characteristics.

Table 10: Physical Characteristics of the Lazybrook Analog Hypothetical Watershed.

Property	Value	Remarks
Area	0.1016 mi^2	-
Slope	0.0047	-
MCL	0.6061mi	-
BDF	12	Value at validation check
Storage Elements	65	Extra cells omitted
Element Area	1 $acre$	-
Overland Links	136	-
Link Length	208 $ft.$	-
Sewer Links	20	-
Link Diameter	1– 6 $ft.$	-

Table 11 lists the depth, flooded area, storage table used in the semi-realistic model for this particular watershed.

A plot of such a depth storage relationship is provided in Figure 17

Table 11: Depth-Area Table for Storage Nodes.

Depth(feet)	Flooded Area(feet^2)	Storage Volume(feet^3)
0.0	0	0
0.5	4,160	2,080
1.0	8,320	8,320
1.5	12,480	18,720
2.0	14,520	29,040
3.0	21,780	65,340
4.0	43,560	174,240
5.0	43,560	217,800
10.0	43,560	435,600
20.0	43,560	871,200

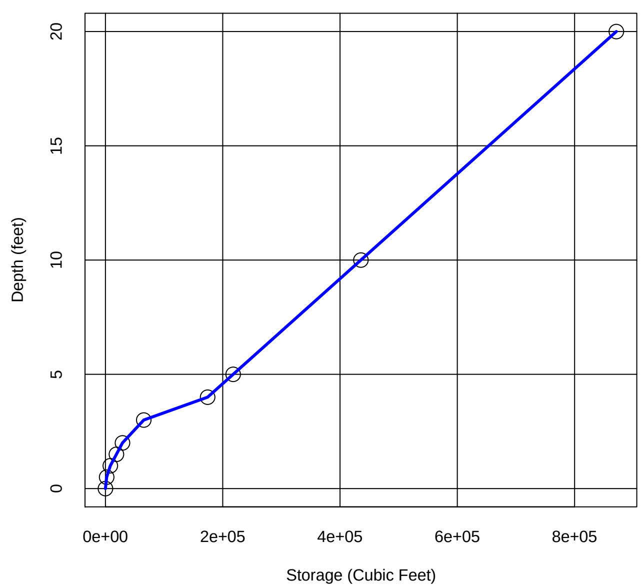

Figure 17: Depth-storage relationship for Lazybrook analog watershed.

2.2.6 Woodlands Ditch A Analog (WDA)

Figure 18 depicts the model structure of the Woodlands Ditch A analog watershed.

Figure 18: Woodlands Ditch A analog. Overland flow links are omitted for clarity.

This watershed was selected because data prior to its complete construction was available and a nearby undeveloped watershed with data from a similar time range was available.

This analog is additionally attractive because this watershed contains a topographic low point within the drainage area that (in the model) requires a relief sewer to the ditch to prevent ponding — the presence of this low point allows some exploration of backwater effects within a watershed. This analog is intended to be interpreted with a nearby companion analog that was completely undeveloped (Woodlands Ditch C analog) at the time of data collection.

Table 12 lists relevant physical characteristics of the analog watershed as well as some model characteristics.

Table 13 lists the depth-storage relationship used in this analog watershed, while the shape and numerical values look similar to the Lazybrook analog, storage is nearly double (in terms of storage per unit depth of innundation). These values are ad-hoc and reflect the researchers opinion of a reasonable model of on-watershed storage.

The plot of such a depth storage relationship is provided in Figure 17.

Table 12: Physical characteristics of the Woodlands Ditch A Analog Hypothetical Watershed.

Property	Value	Remarks
Area	0.41 mi^2	-
Slope	0.0030	-
MCL	1.6 mi	-
BDF	7	Value at validation check
Storage Elements	121	-
Element Area	2.16 $acre$	-
Overland Links	221	-
Link Length	300 $ft.$	-
Sewer Links	60	-
Link Diameter	1-2.5 $ft.$	

Table 13: Depth-Area Table for Storage Nodes.

Depth(feet)	Flooded Area(feet^2)	Storage Volume(feet^3)
0.0	0	0
0.25	1,000	250
0.5	9,000	4,500
1.0	9,000	9,000
1.5	13,000	19,500
2.0	16,000	32,000
2.5	40,000	100,000
3.0	43,560	130,680
4.0	86,000	344,000
10.0	86,000	860,000

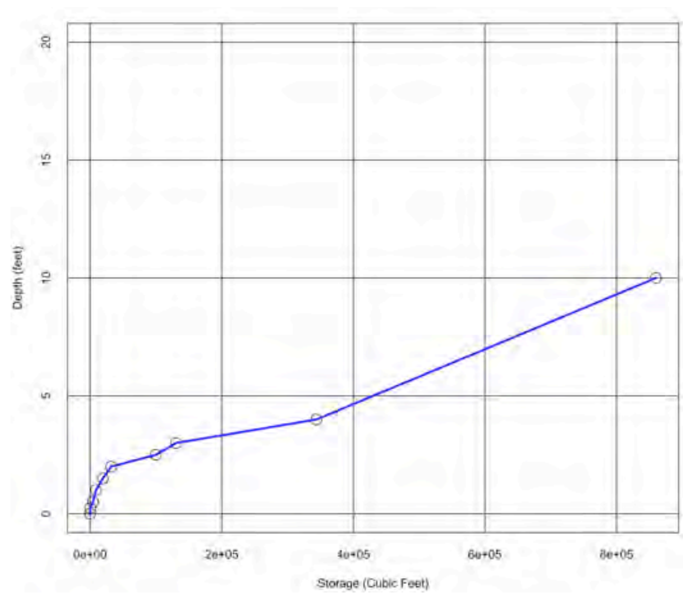

Figure 19: Depth-storage relationship for Woodlands Ditch A analog watershed.

2.2.7 Woodlands Ditch C Analog (WDC)

This watershed was selected because data in its undeveloped state were available and a nearby partially developed watershed with data from a similar time range was available.

This analog is intended to be interpreted with a nearby companion analog that was partially developed(Woodlands Ditch A analog) at the time of data collection.

Table 14 lists relevant physical characteristics of the analog watershed as well as some model characteristics. Table 15 lists the depth-storage relationship used in this analog watershed. The plot of such a depth-storage relationship is provided in Figure 21.

Figure 20: Woodlands Ditch C analog. Overland flow links are omitted for clarity.

Table 14: Physical characteristics of the Woodlands Ditch C Analog Hypothetical Watershed.

Property	Value	Remarks
Area	0.25 mi^2	–
Slope	0.0041	–
MCL	0.93 mi	–
BDF	2	Value at validation check
Storage Elements	90	Extra cells omitted
Element Area	1.77 $acre$	–
Overland Links	162	–
Link Length	278 $ft.$	–
Sewer Links	69	–
Link Diameter	1-2 $ft.$	

Table 15: Depth-Area Table for Storage Nodes.

Depth(feet)	Flooded Area(feet^2)	Storage Volume(feet^3)
0	0	0
0.5	5000	2500
1	6000	6000
1.5	8000	12000
2	12000	24000
2.5	24650	61625
3	38550	115650
5	77101	385505
20	77101	1542020

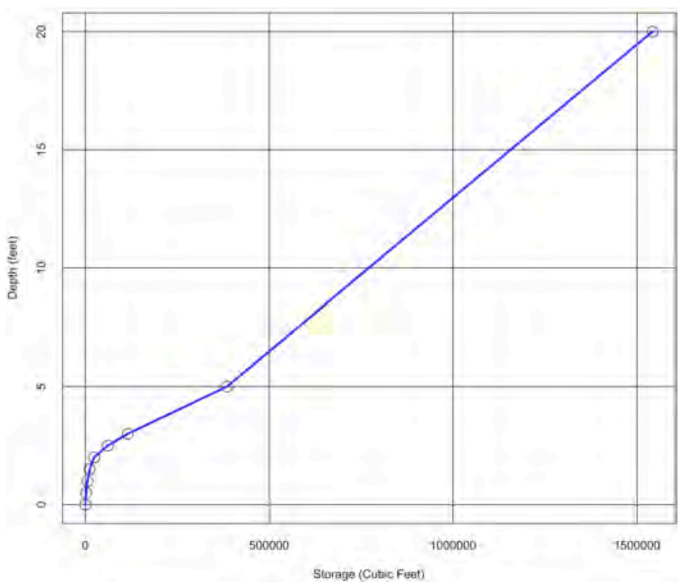

Figure 21: Depth-storage relationship for Woodlands Ditch C analog watershed.

3 Results

The results of the two modeling efforts (Generic and Semi-Realistic) are reported and discussed in this section. A tabulation of all models[9] is presented in Table 16, the contents of which are described later in the report.

3.1 Generic Hypothetical Models

The generic hypothetical models were operated with basin development factor varied from 0 to 12, inclusive; the overland slopes varied from 0.05% to 1%; the collective drainage area varied from 54 to 126 acres; the impervious cover varied from 0% to 30%. The rainfall input hyetograph was a 6-hour, 50%, 10%, and 1% storm; this time series was common to all research teams and is plotted in Figure

None of the variables (area, slope, impervious cover) was continuously varied, but only in a handful of discrete increments. The areas are integer multiples of 13.5 acres (the smallest value) and increment as the square of the length change[10]. The slopes also reflect the discrete nature of the length dimensional change; as invert elevations are held constant the slopes will halve as lengths double. Lastly the impervious cover of a developed sub-area was set at 30% – this value was arrived at by trial-and-error based on semi-realistic modeling of the Berry Bayou watershed (not reported) and the Lazybrook analog watershed. To maintain reasonable Green-Ampt infiltration model values[11] and produce approximately correct runoff volumes the impervious cover numerical value had to be kept low, counter intuitive, but deemed necessary[12].

With these limitations in mind, the generic hypothetical models were used to produce peak discharge values for different basin development factors (and the other different changes just mentioned). The general observations are:

1. As the % impervious is changed from a net of 0% to a net of 30% the excess rainfall approximately doubles. The authors conclude, that whether one believes in imper-

[9] In this context "model" means the combination of input files representing a particular watershed condition and rainfall input time series. All these files are stored on a server for future researchers to use, modify, and critique. The URL is `http://cleveland1.ce.ttu.edu/research/usms_study/`

[10] As each hydraulic element length was doubled the net drainage area increases by a factor of four.

[11] By reasonable the authors mean values that are consistent with published literature values for cohesive clay and silt-clay soils

[12] As an aside, the authors believe that current infiltration models and the current concept of impervious cover do not adequately explain observed behavior in an urban or any setting for that matter and collectively the practice of hydrology is missing something fundamental — it is neither in the scope of this study, nor near-term future studies to address this inadequacy, but the authors note that when the opportunity arises that addressing the true nature of losses would be a worthy engineering-science research activity.

vious cover as currently conceptualized or not, the excess rainfall needs to be about right otherwise the other results are difficult to interpret.

2. As the basin development factor is increased from 0 to 9 without consideration of sewers[13] there is a "mild" increase in peak discharge from the watershed. There is typically a 50% to 100% increase in peak discharge for any development (basin development factor (BDF) from 0 to any larger value). Addition of sewers working from the outlet upstream induces nearly another doubling of discharge.

   The first doubling of discharge (in these models) is caused by the developmental effect on runoff generation (or watershed losses); this doubling not only impacts peak discharge, but is an actual doubling of net runoff volume.

   The second doubling of peak discharge is a consequence of faster travel times for stormwater to accumulate and be conveyed to receiving waters (exactly the purpose of sewer systems — there is no surprise here).

3. The single most important hydraulic element affecting discharge in these hypothetical models after watershed development begins is the presence/absence of sewers. The presence of sewers over an entire hypothetical watershed typically doubles the peak discharge (with consequent reduction in lag time).

As a useful rule of thumb **from these hypothetical watersheds** there is at most a doubling of discharge with basin improvement (streets, ditches, etc.) and a second doubling with addition of a complete sewer system. Thus all other things being equal, one could reasonably expect that peak discharge from a fully developed and sewered watershed would be about four times the undeveloped discharge.

These results are compared to current understanding reflected in the HCFCD Site Runoff Curves for small watersheds. Each of the three different sized generic hypothetical watersheds are plotted on a log-log scale of peak discharge in cubic feet per second versus watershed area in acres. The Site Runoff Curves for the same axes were transferred from the site runoff curves and plotted on the same graph. This exercise was conducted for the 10% and 1% chance rainfall exceedance probabilities.

Figure 22 is such a plot for the 10% chance rainfall. The three hypothetical watersheds under varying levels of development (as reflected by basin development factor) are plotted as circles. The circles plot in the vicinity of the existing knowledge base but do exhibit differences. The authors of this report believe that the hypothetical results exhibit more curvature in log space that the existing Site Runoff Curves convey. The authors additionally think that the undeveloped watershed curve if plotted would approach a much lower slope

[13] In all these models, sewers are added last and all basin development is assumed to use surface features first before subsurface storm sewers are added. The realism of this approach is beyond the author's experience and would need to be adjusted by experienced practitioners as appropriate.

at higher drainage area that is currently depicted, and at the fully developed condition the slope of the runoff curve is slightly lower, but **not parallel** to the undeveloped curve.

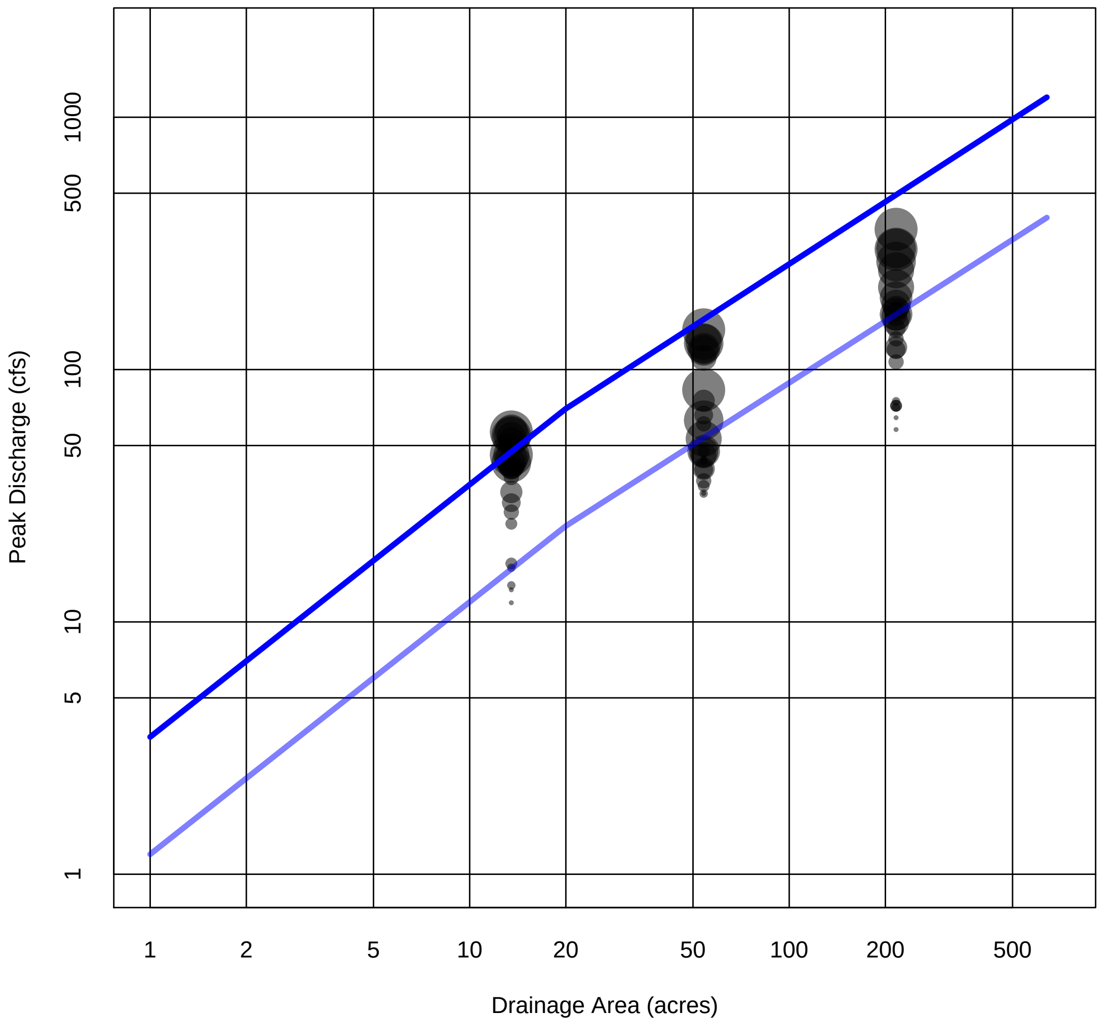

Figure 22: Relation between simulated peak discharges and drainage area for 3 hypothetical watersheds. Symbol size is proportional to model basin development factor (BDF) — smaller symbols are "less developed", larger symbols are "developed"; Lines are 85%(top) and 0%(bottom) impervious cover adapted from HCFCD Site Runoff Curves for 10% rainfall exceedance probability.

Figure 23 is such a plot for the 1% change rainfall. The three hypothetical watersheds under varying levels of development (as reflected by basin development factor) are plotted as circles.

The circles plot in the vicinity of the existing knowledge base but do exhibit differences. The authors of this report believe that the hypothetical results using the higher magnitude, lower probability rainfall also exhibit curvature in log space. The authors of this report think that the undeveloped watershed curve if plotted would approach a lower slope at higher drainage area that is currently depicted, and at the fully developed condition the slope of the runoff curve also is lower. Of note, at these lower probability events, the runoff curves are parallel a distinct and important difference from the higher probability case. The author's interpretation of this difference is that in the 1% chance events, the watersheds are entirely topographically controlled[14], and the difference between developed and undeveloped is the simple doubling effect that occurs because the runoff generation model is reflecting the presence or absence of development (effect of impervious cover and infiltration as previously discussed).

[14] The presence of overwhelmed sewer systems is irrelevant in these cases, the watershed behavior is topographically governed.

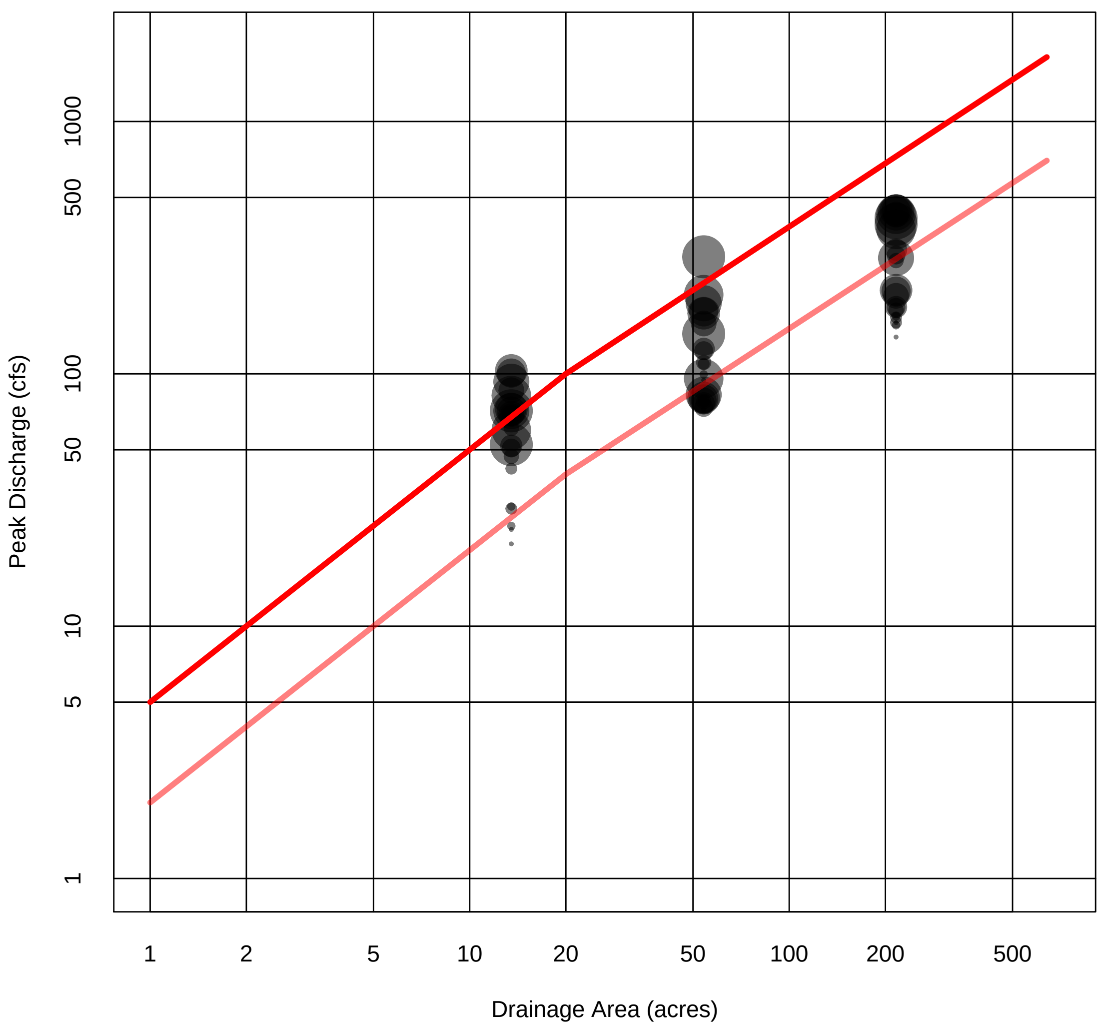

Figure 23: Relation between simulated peak discharges and drainage area for 3 hypothetical watersheds. Symbol size is proportional to model basin development factor (BDF) — smaller symbols are "less developed", larger symbols are "developed"; Lines are 85%(top) and 0%(bottom) impervious cover adapted from HCFCD Site Runoff Curves for 1% rainfall exceedance probability.

3.2 Semi-Realistic Hypothetical Models

3.2.1 Model Validation with Realistic Rainfall

Because the analog watersheds were constructed to resemble real watersheds for which data exist; numerical results could be examined alongside observed values to ensure that the analogs produce realistic results at the level of development known for the data collection period. To simplify data management, multiple storm data were combined into a single input time series with each storm separated by roughly one day of zero padding between storms. The input data thus represent real events, but the inter-storm pattern is fabricated. Similarly, the observed runoff for the real watersheds are combined into a single time series for comparison. Again, the data are real, but the pattern is fabricated. This approach allows the evaluation of all storms in hypothetical cases in a single model run, rather than multiple runs with different files.

Later the various specified design storms were passed into the model for inclusion with the generic hypothetical watersheds. In contrast to the generic hypothetical watershed cases, basin development factor (BDF) was actually decreased by systematically removing development components of the watershed, although the interpretations below are as if the components were added.

Lazybrook Analog

The Lazybrook analog was built to mimic the conditions thought to be in place on the real watershed circa 1980s. Figure 24 is an image of the watershed model at the validation configuration. The right panel is the model network without the background interference. In the network the rectangular nodes are the storage elements, the circular nodes are nodes in the sewer system (if it is present), the line segments are the hydraulic links, and the small squares with dashed links are the sub-areas (runoff generators) in the model.

Figure 24: Lazybrook Analog layout. Left panel is SWMM model overlay on aerial image of watershed. Right panel is link-node array without background. Yellow shading indicates subsurface sewer system(s); Blue shading (none in this model) indicates drainage channels.

Twenty four storms from 1979 to 1987 were available to test the analog model and validate the modeling effort. A subset (13 storms) were combined into a single time series with one to two days zero padding between storms. Both the rainfall time series and observed runoff time series were treated in the same fashion. Figure 25 is a plot of such input and responses for the Lazybrook analog watershed. The upper panel is a cumulative rainfall hyetograph constructed from the 13 storms. The lower panel is the observed response (of the watershed) for the same storms. The authors note that these data are in a sense "real" but such a pattern as depicted here never happened. The purpose of these validation studies was to make minor adjustments to percent impervious cover and Green-Ampt values, but otherwise no adjustments were made.

After the adjustments the validated "model" was used in a fashion similar to the generic hypothetical models — features are added and removed to change basin development factor (BDF) and other elements of the system to observe the effect on watershed discharge that can be attributed to those changes. Figure 26 is a plot of the same output time series with the simulation time series for the same input.

There was no rigorous attempt to calibrate, thus the series were deemed " acceptable" when the peak discharges were close in magnitude and time. Of note in Figure 26 is that there are 6 "storms" where the simulated peak exceeds the observed, and 7 where the opposite

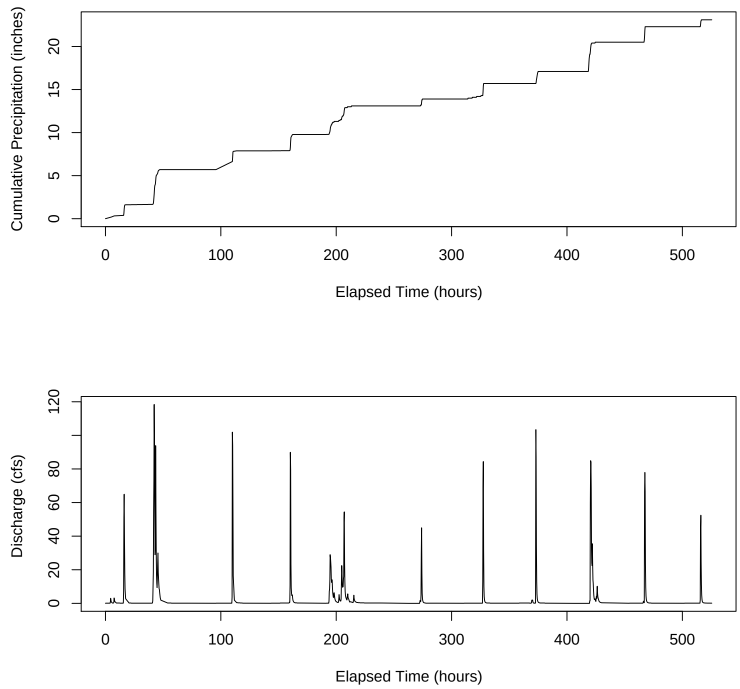

Figure 25: Lazybrook analog, validation time series. Upper panel is rainfall, lower panel is runoff. Data are real, pattern is fabricated.

is depicted. The authors interpret this result as favorable and that the simulations are not displaying a systematic bias. Of further note, these storms are all small magnitude (less than 5-year rainfall events).

Table 16 lists the results of the various Lazybrook analog models. The excess rainfall nearly triples when the impervious cover is raised, the Green-Ampt values are those reported earlier. The peak discharge doubles in the basin development factor (BDF) range of 3 to 60, and triples when BDF is increased to a value of 9. In the Lazybrook analog, sewers were added before the final "improvement"" of a ditch in the street sections[15].

Considering the rule of thumb developed from the generic hypothetical models, this watershed greatly exceeds the rule of fourfold increase in discharge from undeveloped to developed at the high probably, low magnitude rainfall, and falls a bit short at the low

[15] As a semi-realistic model, this "ditch" does not exist in the real watershed, but was used during validation to obtain agreement with observed discharge values and the pre-concieved notion that this watershed should have a high basin development factor (BDF).

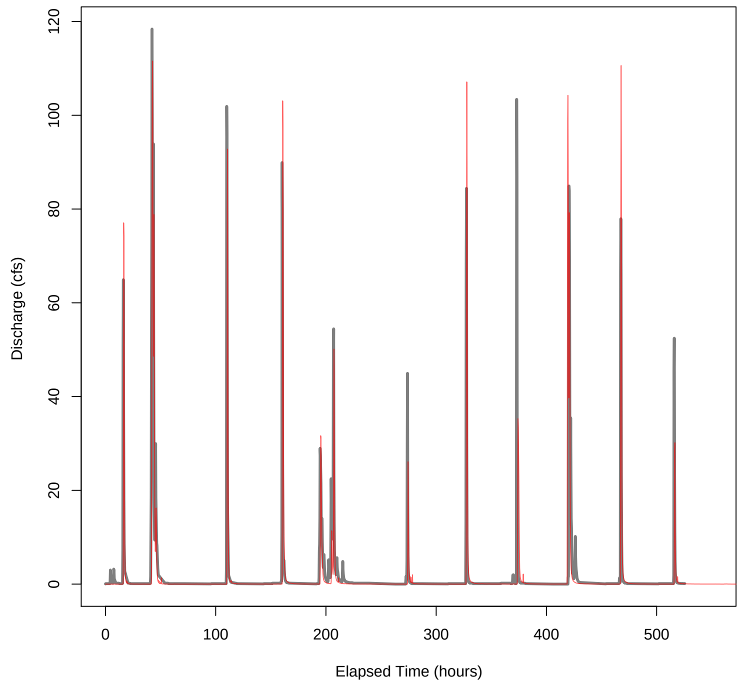

Figure 26: Lazybrook analog validation results. Red curve is the simulation output, grey are observations from multiple storms with one day of zero padding between each storm.

probability, high magnitude rainfall. An explanation offered is that of the generic hypothetical: at higher magnitude rainfall the watershed becomes more topographically controlled and the engineered drainage systems have less impact (as compared to the topographic impact).

Woodlands Ditch A

The Woodlands Ditch A analog was built to mimic the conditions thought to be in place on the real watershed circa 1980s. Figure 27 is an image of the watershed model at the validation configuration. The right panel is the model network without the background interference. In the network the rectangular nodes are the storage elements, the circular nodes are nodes in the sewer system (if it is present), the line segments are the hydraulic links, and the small squares with dashed links are the sub-basins (runoff generators) in the model. The authors note that the sewer system depicted in this analog is not the same as the real system and is simply an approximation based on judgement and verbal descriptions of what was in place circa 1980s.

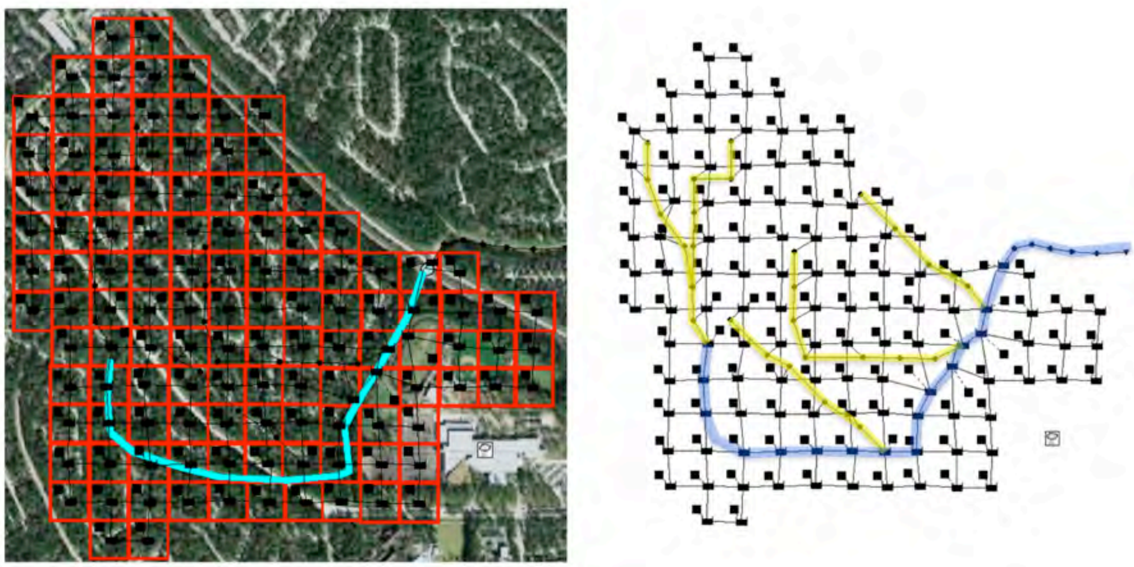

Figure 27: Woodlands Ditch A Analog layout. Left panel is SWMM model overlay on aerial image of watershed. Right panel is link-node array without background. Yellow shading indicates subsurface sewer system(s); Blue shading indicates drainage channels.

Nine storms from 1985 to 1986 were available to test the analog model and validate the modeling effort. These were combined into a single time series with one to two days zero padding between storms. Both the rainfall time series and observed runoff time series were treated in the same fashion. Figure **??** is a plot of such input and responses for the analog watershed. The upper panel is a cumulative rainfall hyetograph constructed from the 9 storms. The lower panel is the observed response (of the watershed) for the same storms[16].

[16]There were 9 separate storms, but several spanned multiple days — where there were distinct breaks the authors broke these into separate storms — hence the 11 "pulses" in the graphs.

These data are in a sense “real” but such a pattern as depicted here never happened. The purpose of these validation studies was to make minor adjustments to percent impervious cover and Green-Ampt values, but otherwise no adjustments were made.

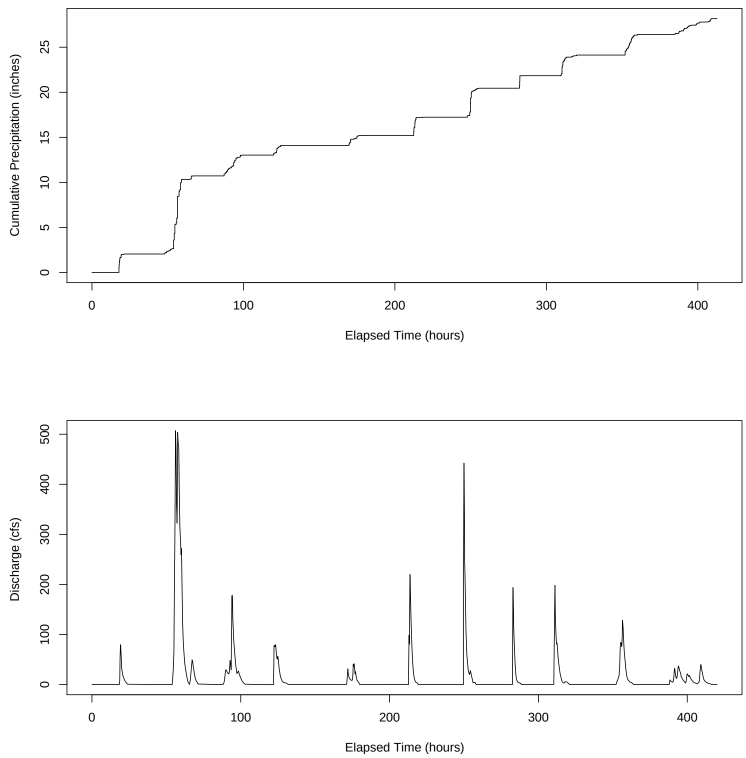

Figure 28: Woodlands Ditch A analog, validation time series. Upper panel is rainfall, lower panel is runoff.

Figure 28 is a plot of such input and responses for the Woodlands Ditch A watershed. The upper panel is a cumulative rainfall hyetograph constructed from 11 storms in the 1980s. The lower panel is the observed response (of the watershed) for the same storms.

After the adjustments the validated “model” was used in a fashion similar to the generic hypothetical models — features are added and removed to change basin development factor (BDF) and other elements of the system to observe the effect on watershed discharge that can be attributed to those changes. Figure 29 is a plot of the same output time series with the simulation time series for the same input.

There was no rigorous attempt to calibrate, thus the series were deemed “ acceptable” when

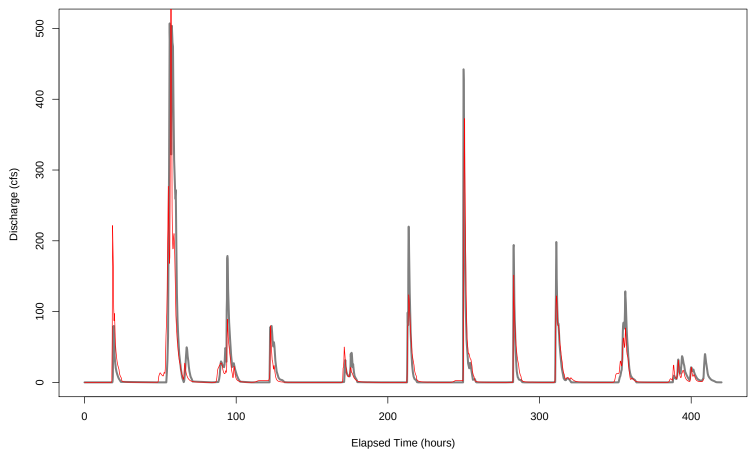

Figure 29: The Woodlands Ditch A analog, validation results. Red curve is the simulation output, grey are observations from multiple storms with one day of zero padding between each storm.

the peak discharges were close in magnitude and time. Of note in Figure 29 is that there are 4 "storms" where the simulated peak exceeds the observed, and 7 where the opposite is depicted. The authors interpret this result as adequate but note that this result suggests some systematic bias — the SWMM model underproduces peak discharges. The arrival times are about right so the authors proceeded with this analog.

Table 16 lists the results of the various Woodlands Ditch A analog models. The excess rainfall increases by a factor of 10 when the watershed is initially developed, the peak discharge at the outlet increasing by a factor of 6. The peak discharge increases by a factor of about 1.5 in the basin development factor (BDF) range of 3 to 9, and doubles (as compared to the BDF=0, %IC=30 condition) when BDF is increased beyond a value of 9. This substantial increase beyond 9 is a direct result of sewers.

Of some interest is that removal of a relief sewer in this model (located at an internal topographic low point) had remarkably little effect on the peak discharge at the outlet although the mass balance was affected (the low point without the relief sewer is completely innundated). The difference in peak discharge in this condition is about that expected if the contributing area of the low point portion of the watershed is removed from the runoff computations.

Considering the rule of thumb developed from the generic hypothetical models, this watershed also greatly exceeds the rule of fourfold increase in discharge from undeveloped to developed at high probability, low magnitude rainfall and is closer to this rule at low probability, high magnitude rainfall — again the author's interpretation is that topography contorls behavior once any engineered drainage systems are overwhelmed.

Woodlands Ditch C

The Woodlands Ditch C analog was built to mimic the conditions thought to be in place on the real watershed circa 1980s. Figure 30 is an image of the watershed model at the validation configuration. The right panel is the model network without the background interference. In the network the rectangular nodes are the storage elements, the circular nodes are nodes in the sewer system (if it is present), the line segments are the hydraulic links, and the small squares with dashed links are the sub-basins (runoff generators) in the model. The authors note that the sewer system depicted in this analog was not present at the time of data collection, nor was the area developed (homes, streets, etc.). The authors assumed the ditch was in-place and otherwise the watershed was undeveloped.

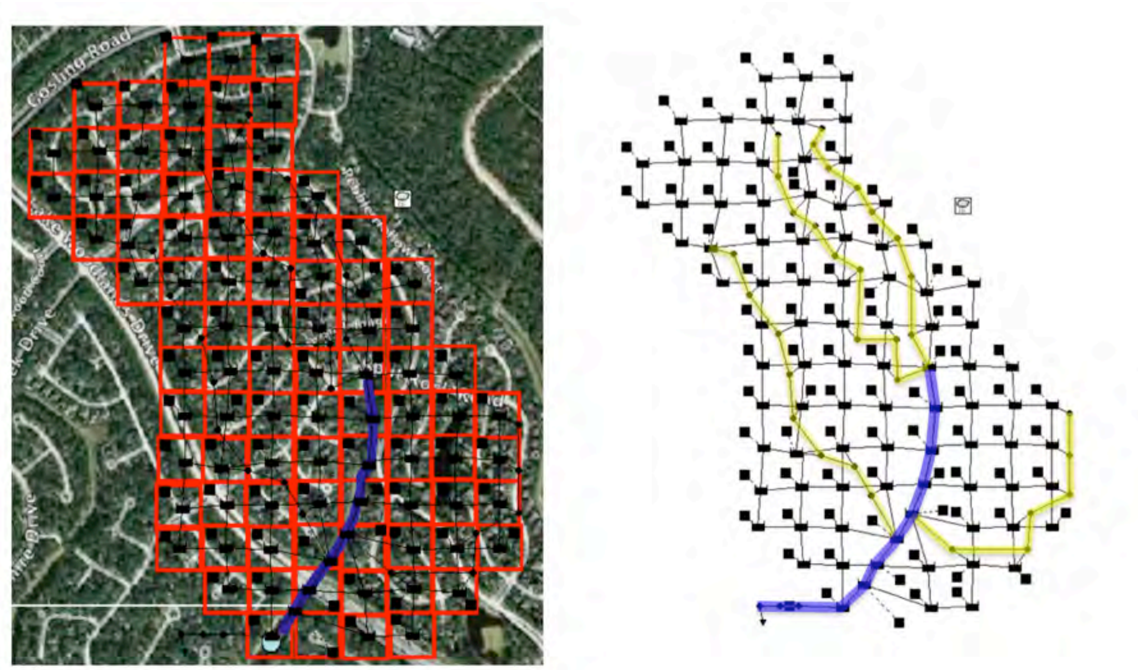

Figure 30: Woodlands Ditch C Analog layout. Left panel is SWMM model overlay on aerial image of watershed. Right panel is link-node array without background. Yellow shading indicates subsurface sewer system(s); Blue shading indicates drainage channels.

Nine storms from 1985 to 1986 were available to test the analog model and validate the modeling effort. These were combined into a single time series with one to two days zero padding between storms. Both the rainfall time series and observed runoff time series were treated in the same fashion. Figure **??** is a plot of such input and responses for the analog watershed. The upper panel is a cumulative rainfall hyetograph constructed from the 9 storms. The lower panel is the observed response (of the watershed) for the same storms. The purpose of these validation studies was to make minor adjustments to percent impervious cover and Green-Ampt values, but otherwise no adjustments were made.

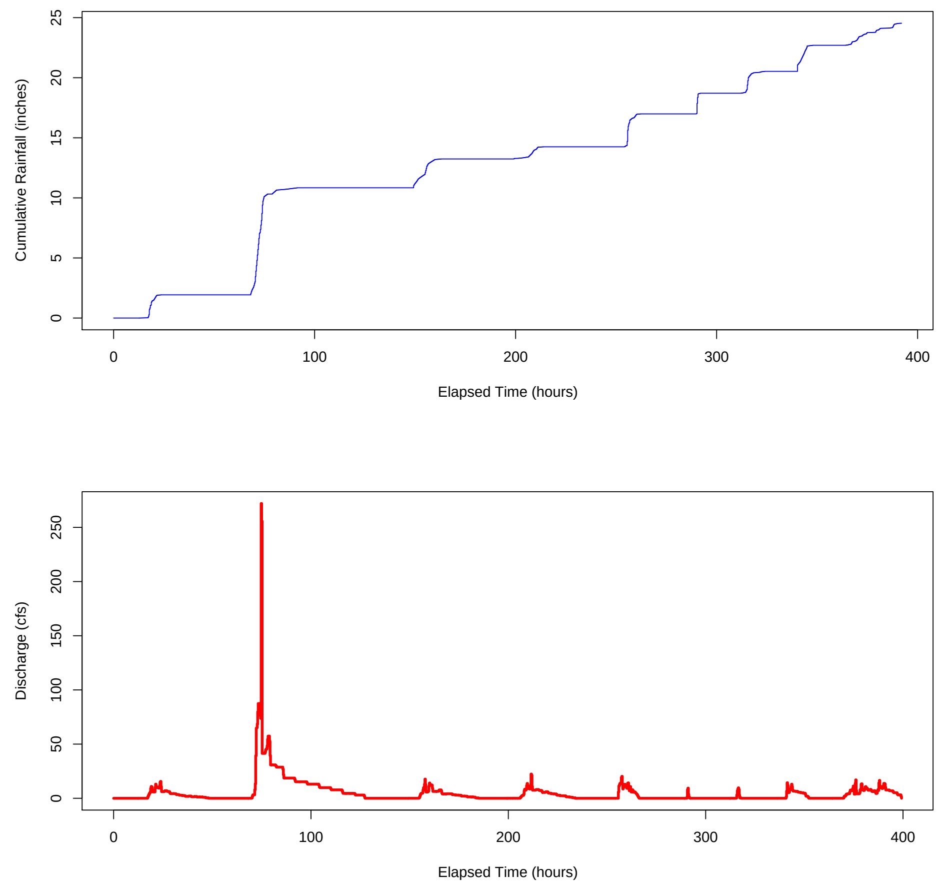

Figure 31: The Woodlands Ditch C analog, validation time series. Upper panel is rainfall, lower panel is runoff.

Figure 31 is a plot of such input and responses for the Woodlands Ditch C watershed. The upper panel is a cumulative rainfall hyetograph constructed from 9 storms in the 1980s. The lower panel is the observed response (of the watershed) for the same storms.

There was no rigorous attempt to calibrate, thus the series were deemed "acceptable" when the peak discharges were close in magnitude and time. Of note in Figure 32 is that there are 7 "storms" where the simulated peak exceeds the observed, and 2 where the opposite is depicted. The authors note that this result suggests some systematic bias — the

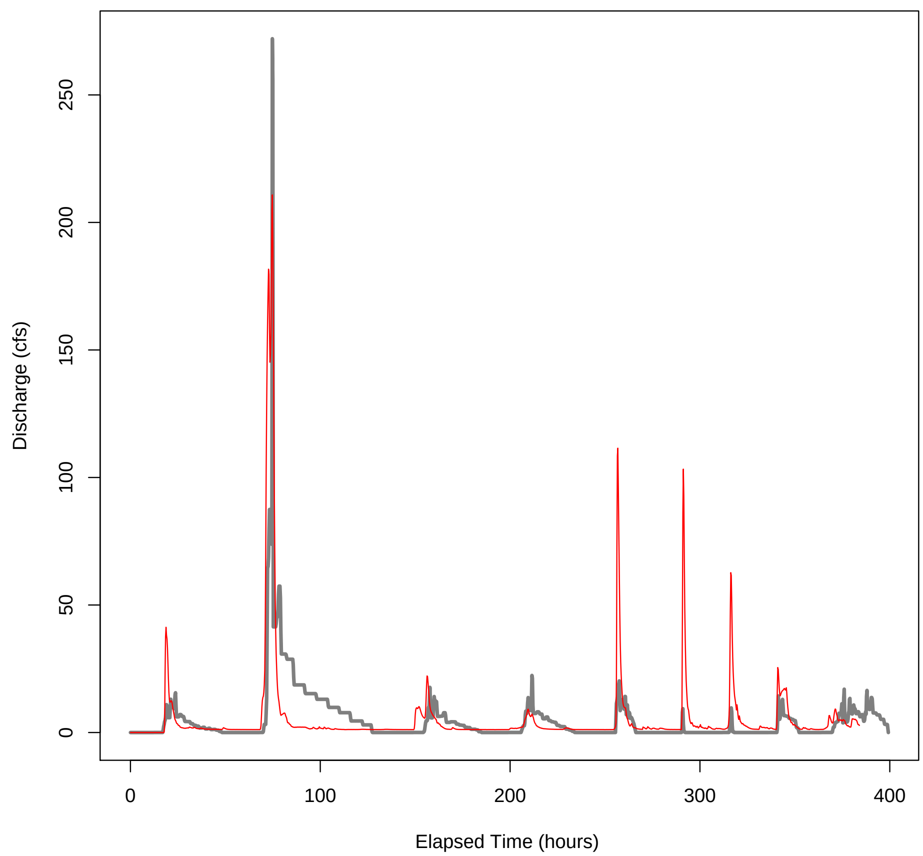

Figure 32: The Woodlands Ditch C analog, validation time series. Red curve is the simulation output, grey are observations from multiple storms with one day of zero padding between each storm.

SWMM model overproduces peak discharges. The suspected cause is the large discharges observed in the second "storm." Assuming the data are correct[17] this storm influences the behavior when validating the system. The second, equally plausible explanation is that this watershed was undeveloped at validation; the generic watershed studies were particularly sensitive to choice of time step size and elevation differences in the undeveloped

[17]The events for the two Woodlands analogs were digitized from hydrograph plots in the Winslow reports (Johnson, 1985), and (Johnson, 1986) using the `g3data` program. There is meaningful analyst influence in digitizing from scanned images and this influential discharge may be an artifact of the analysis and not reflective of actual discharges.

states.

Table 16 lists the results of the various Woodlands Ditch C analog models. The excess rainfall increases by a factor of 1.25 when the watershed is initially developed, the peak discharge at the outlet increasing by a factor of 1.5. The peak discharge increases by a factor of about 2.0 in the basin BDF range of 4 to 12. The addition of sewers does not produce the large increase in discharge observed in the other models — the layout of the sewers in this model was not uniform and followed the authors best guess of the sewer alignments that make sense for the watershed. The shape of the watershed (along with an internal lake) complicated the logical alignment of a subsurface sewer system. Nevertheless the addition of sewers increases peak discharge values and reduces lag time as intuition would suggest.

Considering the rule of thumb developed from the generic hypothetical models, this watershed falls short of the rule of fourfold increase in discharge from undeveloped to developed, instead displaying an increase of 1.5 to 3.0 depending on the magnitude of the rainfall; this watershed model was the least sensitive of the three semi-realistic models to rainfall forcing in terms of the ratio of peak discharge produced for high or low value of basin development factor.

To summarize the lessons of the semi-realistic models the findings are similar in nature as the generic hypothetical models except that the runoff generation modeling must be well thought out to agree with observed discharges[18]. Generally the behavior observed in the generic hypothetical cases was preserved in the semi-realistic models; sewers are the most important components in impacting peak discharge values and lag times at a watershed outlet.

As with the generic hypothetical the results of the semi-realistic watershed studies are plotted on a log-log axis and compared with the current site runoff curves for 10% chance, and 1% chance storms.

Figure 33 is such a plot for the 10% change rainfall. The three analog watersheds under varying levels of development (as reflected by basin development factor) are plotted as circles, the size of the circle proportional to the value of BDF. In this plot, the model results are within the current knowledge represented by the site development curves. With the exception of the largest analog (Woodlands Ditch A, with a known topographic low) the plots more or less follow the site runoff curves, with a narrower range of values. The larger watershed plots low relative to the current site runoff curves — the authors think this result is because of the on-watershed storage conferred by the internal topographic low

[18]This statement is not inconsequential. Truly synthetic hydrology, where models without any nearby measurements are created, will contain substantial error regardless of the tools used. Current hydrologists are likely aware of such limitations and use personal experience and sound engineering judgement to adjust such models — such behavior needs to continue and be encouraged until reliable alternatives are developed

value[19].

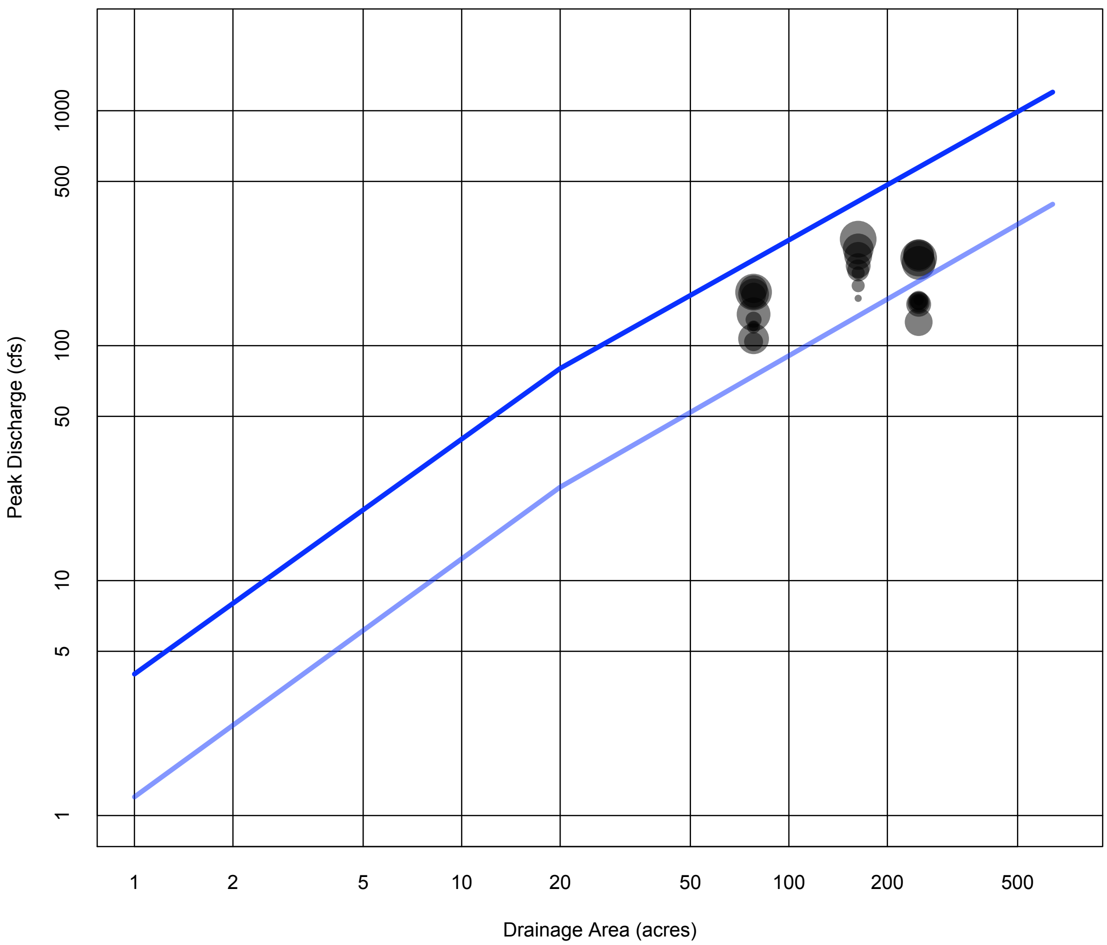

Figure 33: Relation between simulated peak discharges and drainage area for 3 semi-realistic watershed models. Symbol size is proportional to model basin development factor (BDF) — smaller symbols are "less developed", larger symbols are "developed"; Lines are 85% and 0% impervious cover adapted from HCFCD Site Runoff Curves for 10% rainfall exceedance probability.

[19] In other words the actual contributing area is smaller than plotted,and the markers should be somewhere to the left. The effect of contributing area is beyond the scope of this present work but is one plausible explanation for the seemingly inconsistent plot.

Figure 34 is such a plot for the 1% change rainfall. Similar results are observed. An additional important observation is that the larger watershed plots closer to the existing site runoff curves – the authors suspect that this "better agreement" is a manifestation of the impact of topographic behavior dominating the watershed response when engineered drainage systems are overwhelmed.

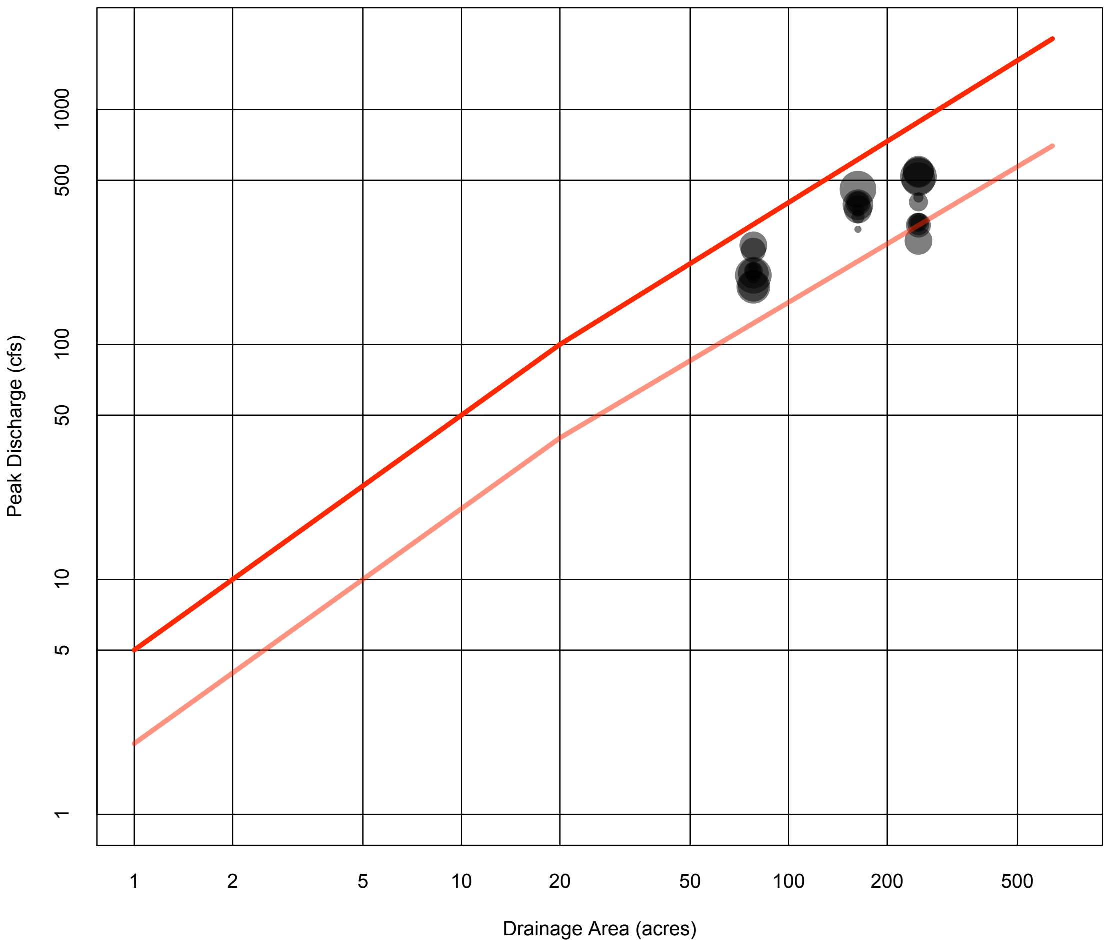

Figure 34: Relation between simulated peak discharges and drainage area for 3 semi-realistic watershed models. Symbol size is proportional to model basin development factor (BDF) — smaller symbols are "less developed", larger symbols are "developed"; Lines are 85% and 0% impervious cover adapted from HCFCD Site Runoff Curves for 1% rainfall exceedance probability.

4 Discussion, Interpretation, and Conclusions

4.1 Interpretive Analysis and Discussion

The effects of slope, basin development factor, and scale are examined by exploratory data analysis and ordinary log-linear regression. The equations developed and reported in this section are **for interpretative purposes only** and are an attempt to infer mathematical structure. They are **not intended for design use**.

Figure 35 is a four-panel plot of all the results from both the generic modeling and the semi-realistic models. The upper-left panel is a plot of the relationship of peak discharge Q_p, in cubic feet per second, and excess precipitation P, in inches. The "cloud" of markers increases towards the upper right as intuition would suggest (more excess should produce comparatively higher peak values). The upper-right panel is a plot of the ratio of peak discharge and excess precipitation, $\frac{Q_p}{P}$, in cubic feet per second per inch of excess depth, plotted against the watershed area, A, in acres. The authors selected the ratio representation to remove the impervious cover as an explanatory variable[20] in the interpretative analysis. The relationship plots towards the upper right of the chart, indicating the intuitive result that as drainage area is increased peak discharge increases for a given excess depth.

The lower-left panel is a plot of the relationship of basin lag time T_l, in minutes, versus basin development factor BDF. This relationship plots towards the lower right as one would intuitively anticipate — if the curvature is ignored, the relationship suggests that development of drainage infrastructure as modeled in this report reduces basin response time by a factor of ≈5, thus if an undeveloped condition responds in one hour, the fully developed will respond in $\frac{1}{5}$ of an hour.

The lower right panel is a plot of $\frac{Q_p}{P}$ versus basin development factor BDF. The marker cloud plots slightly upward to the right. As with the T_l, if curvature is ignored, the relationship suggests ≈4-fold increase in $\frac{Q_p}{P}$ as the watershed changes from an undeveloped to a fully developed drainage structure. As suggested earlier in this report, the first doubling (≈2-fold increase) is attributed to the act of development itself, without any modification of the drainage infrastructure – just a change in the runoff production. The second doubling (additional ≈2-fold increase) is attributed to the drainage infrastructure improvement, for a combined total effect of the ≈4-fold increase in $\frac{Q_p}{P}$.

Watershed slope is not considered in this analysis — exploratory data analysis suggested that slope is not a useful explanatory variable as compared to area A, or basin development factor BDF.

[20]Incidentally this decision produces some comparability to the excess rational method of (Asquith, 2008).

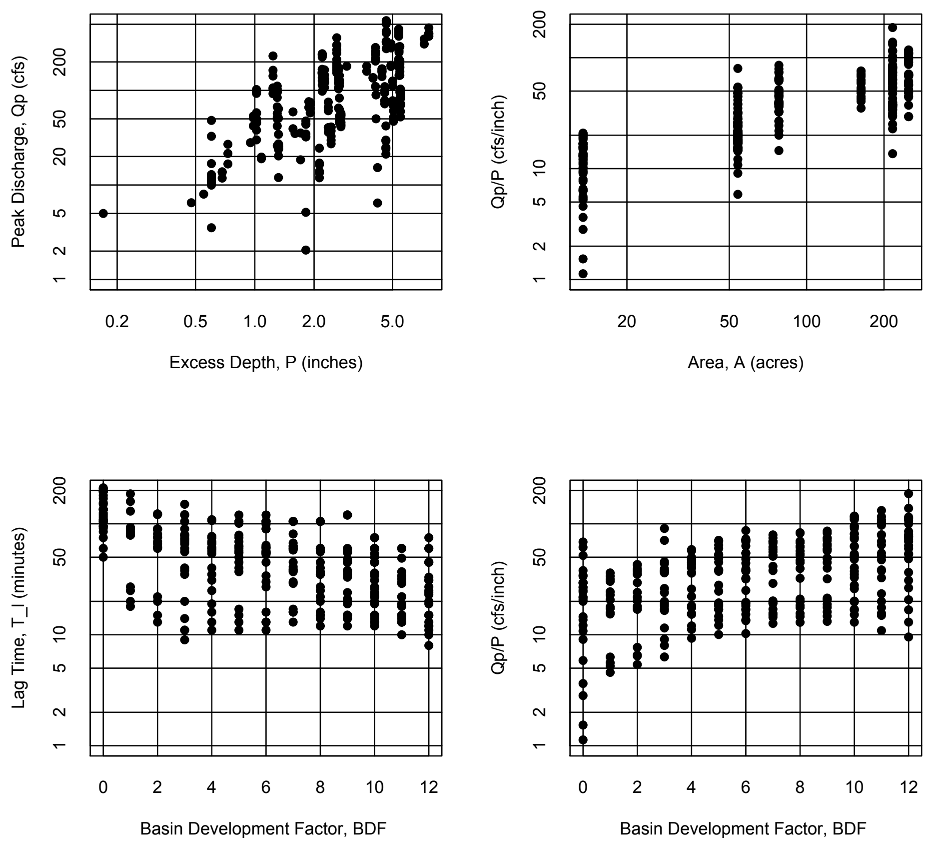

Figure 35: Exploratory analysis plots using hypothetical and semi-realistic model output as "data." Upper left panel is peak discharge versus excess depth, upper right panel is peak discharge/excess depth versus excess depth, lower left panel is peak discharge/excess depth versus area, and the lower right panel is peak discharge/excess depth versus basin development factor.

Using these plots as a guideline, a regression model is postulated using the watershed area A, in acres and the basin development factor BDF, as explanatory variables. [21] and is stated as

$$log10(\frac{Q_p}{P}) = \beta_0 + \beta_1 log10(A) + \beta_2 BDF \quad (1)$$

Determination of the coefficients is accomplished by ordinary least squares regression in the **R** (R Development Core Team, 2008) statistics package. The value of β_1 represents the exponent on area in a power-law sense [22] The value of β_2 represents the change in $log10(\frac{Q_p}{P})$ per unit change in BDF

The regression analysis using **R** is displayed below.

```
> lm1<-lm(log10(peak/excess)~log10(area)+bdf)
> summary(lm1)

Call:
lm(formula = log10(peak/excess) ~ log10(area) + bdf)

Residuals:
      Min        1Q    Median        3Q       Max
-0.726871 -0.089528  0.007824  0.098895  0.290420

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 0.083756   0.039294   2.132   0.0339 *
log10(area) 0.615529   0.019167  32.115   <2e-16 ***
bdf         0.039696   0.002238  17.736   <2e-16 ***
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1

Residual standard error: 0.145 on 297 degrees of freedom
Multiple R-squared: 0.8253,Adjusted R-squared: 0.8241
F-statistic: 701.3 on 2 and 297 DF,  p-value: < 2.2e-16
```

When inverse transformed into arithmetic space, the model, parameterized by the coefficients obtained from the regression analysis is

[21] This model is strictly ad-hoc and represents a guess at a mathematical relationship.

[22] Watershed area and a characteristic length are thought to be related by this exponent, a concept explored by (Lienhard and Meyer, 1967) and (Cleveland et al., 2006).

$$\frac{Q_p}{P} = 10^{\approx 0.08 + \approx 0.04 \times BDF} \times A^{\approx 0.6} \tag{2}$$

The values are intentionally displayed as approximate to discourage use of this equation for anything other than assessing the relative relationships in comparison with other Block B team findings. Uncertainty analysis is not performed and the reader is reminded this equation is strictly for comparative purposes.

As an illustration of the meaning conveyed in the equation, Figure 36 is a plot of the relationship expressed by equation 2 as a function of drainage area and basin development factor. The basin development factor increases upward in the figure, thus the two red lines represent the lower and upper envelope of $\frac{Q_p}{P}$. This set of curves has similar structure to curves in (Asquith, 2008) although the numerical values of discharge, when multiplied by rainfall excess are about one-third smaller. This difference is irrelevant for this discussion, more importantly the curves are very nearly parallel on one another – thus the change in discharge per change in BDF is about the same, in this case ≈0.04 per unit change in BDF.

The purpose of this interpretative analysis is to determine if the relative change in discharge peak is consistent with that of the other Block B teams. This analysis suggests that nearly one half log cycle of increase in Q_p for a change in BDF from 0 (undeveloped) to 12 (developed, sewers and other drainage features) would be anticipated, and this finding is consistent with that of the other Block B researchers.

4.2 Conclusions

The results of this modeling study are summarized in the following statements:

1. Watershed development, whether drainage features such as ditches, streets, and sewers are created during development have impacts on both peak discharge and total volume from a watershed. Based on the generic models, and supported in concept by the semi-realistic models, the act of development as simulated by a change in impervious cover (or a reduction in Green-Ampt saturated conductivity) causes at least a two-fold increase in runoff, if not more. Mitigation of this runoff, which is an actual increase and not a result of reduced travel times will have to be accomplished by either some kind of on watershed storage or by some kind of increased, although concentrated, loss strategy[23].

[23] The on-watershed storage is the detention approach that is well documented and is being systematically applied. An increased loss approach may not be technologically feasible, the only obvious tool being infiltration basins whose use in Harris County is infeasible because of soil type. Injection systems do not make economical sense in the authors' opinion.

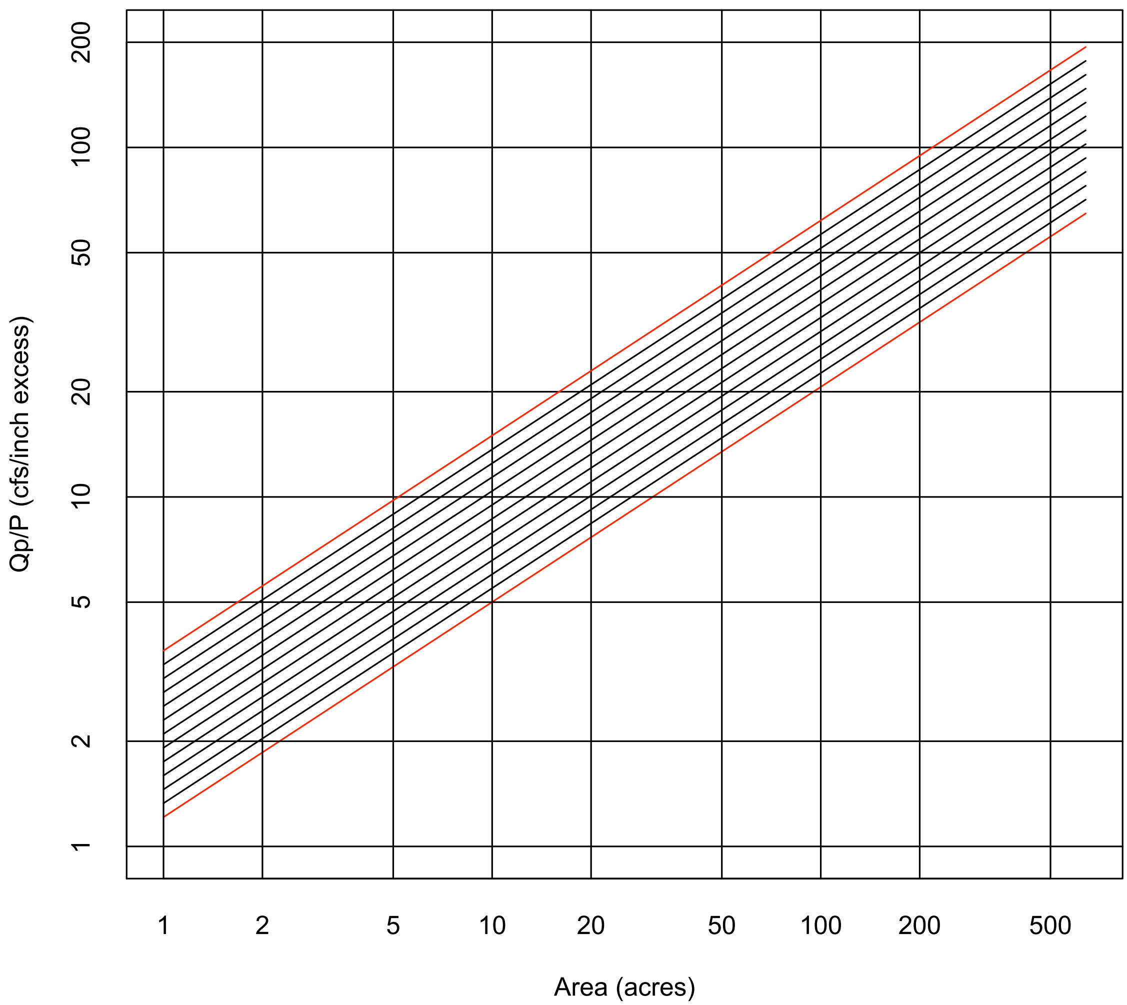

Figure 36: Relation between peak discharge per unit depth of excess $\frac{Q_p}{P}$, in cubic feet per second per inch, and watershed area, A, in acres. Lines represent different values of BDF, increasing moving upward. Lower red line is $BDF = 0$, upper red line is $BDF = 12$.

2. Once the discharge doubling for any kind of development is acknowledged, internal drainage improvements (drainage using streets, ditches, and or sewers as conveyance tools) results in a reduced watershed response time and an increased peak discharge rate. The largest time reduction is caused by a storm sewer system at least for the lower magnitude, more common (in a probabilistic sense) rainfall events. Sewers and other engineered conveyances noticeably reduce response time for the 50% and 10% chance events.

3. The largest magnitude events (1% chance rainfall) in this study appear to be topographically dominated and the reduction in response time conferred by the engineered systems is proportionally smaller that the response time explained by simple surface topography. Engineering strategies to mitigate effects from these rainfall inputs must significantly impact topography[24].

4. Basin Development Factor used as a surrogate for development appears to have the ability to capture the inclusion or absence of sewers and should be a meaningful small watershed approach in lieu of SWMM models or similar tools. While not well tested in this study, the authors believe that BDF will scale up to several square mile range (if not further) and results will aggregate sufficiently for use in larger hydrologic models.

5. Based upon exploratory data analysis and a power law model fit of the modeled results the relative change in peak discharge as basin development factor is increased is on the order of one-half a log cycle (log10) for an increase from 0 to 12. This result is consistent with results from other Block B team members and arrived at through relatively independent interpretations using specific-to-author computational infrastructure.

[24]These strategies would have to change topography over a relatively large area – not impossibly large but on the order of several acres per 200 acres.

5 References

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Table 16: Characteristics and Responses for Hypothetical Watershed Models.

[MODEL_ID, is a model identification code; AREA, is nominal drainage area in acres; SLOPE is dimensionless main channel or longitudinal slope; %IC is fraction of impervious cover used in the runoff generation (Green-Ampt) model; Q_{peak}, peak (largest) discharge at the outlet, in cubic feet per second; T_{lag} is lag time from peak excess precipitation to peak outlet discharge, in minutes; BDF, is basin development factor; Scenario, is a description of the conceptual watershed.

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
54-2	54	0.001	0	0.602	3.53	169	0	Undeveloped
54-2	54	0.001	0	0.602	10.45	81	1	Street 1/3
54-2	54	0.001	0	0.602	10.2	81	2	Street 1/3; Imp. 1/3 channel
54-2	54	0.001	0	0.602	9.96	80	3	Street 1/3; Line 1/3 channel
54-2	54	0.001	0	0.602	10.61	76	4	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	0	0.602	11.24	69	5	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	0	0.602	11.79	64	6	Street 2/3; Line 2/3 channel
54-2	54	0.001	0	0.602	12.15	63	7	Streets 3/3; Line 2/3 channel
54-2	54	0.001	0	0.602	12.63	60	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-2	54	0.001	0	0.602	12.88	59	9	Streets 3/3; Line 3/3 channel
54-2	54	0.001	0	0.602	16.82	36	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-2	54	0.001	0	0.602	32.71	32	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-2	54	0.001	0	0.602	48.14	31	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
54-2	54	0.001	30	1.319	11.98	180	0	Undeveloped
54-2	54	0.001	30	1.319	20.29	85	1	Street 1/3
54-2	54	0.001	30	1.319	23.78	62	2	Street 1/3; Imp. 1/3 channel
54-2	54	0.001	30	1.319	24.07	60	3	Street 1/3; Line 1/3 channel
54-2	54	0.001	30	1.319	24.1	57	4	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	30	1.319	25.56	50	5	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	30	1.319	25.15	54	6	Street 2/3; Line 2/3 channel
54-2	54	0.001	30	1.319	25.62	37	7	Streets 3/3; Line 2/3 channel
54-2	54	0.001	30	1.319	26.61	40	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-2	54	0.001	30	1.319	27.17	38	9	Streets 3/3; Line 3/3 channel
54-2	54	0.001	30	1.319	34.3	23	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-2	54	0.001	30	1.319	50.73	22	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-2	54	0.001	30	1.319	63.82	24	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
54-2	54	0.001	10	0.683	11.82	79	1	Street 1/3
54-2	54	0.001	10	0.683	13.79	76	2	Street 1/3; Imp. 1/3 channel
54-2	54	0.001	10	0.683	13.61	78	3	Street 1/3; Line 1/3 channel
54-2	54	0.001	20	1.08	18.93	61	4	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	20	1.08	19.57	55	5	Street 2/3; Imp. 2/3 channel
54-2	54	0.001	20	1.08	19.7	55	6	Street 2/3; Line 2/3 channel
54-10	54	0.001	0	1.707	18.45	155	0	Undeveloped
54-10	54	0.001	10	1.817	32.31	93	1	Street 1/3
54-10	54	0.001	10	1.817	32.24	89	2	Street 1/3; Imp. 1/3 channel
54-10	54	0.001	10	1.817	34.59	72	3	Street 1/3; Line 1/3 channel
54-10	54	0.001	20	2.361	36.25	68	4	Street 2/3; Imp. 2/3 channel
54-10	54	0.001	20	2.361	40.18	62	5	Street 2/3; Imp. 2/3 channel
54-10	54	0.001	20	2.361	40.44	56	6	Street 2/3; Line 2/3 channel

Continued on next page

Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
54-10	54	0.001	30	2.688	45.69	38	7	Streets 3/3; Line 2/3 channel
54-10	54	0.001	30	2.688	47.21	35	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-10	54	0.001	30	2.688	47.41	33	9	Streets 3/3; Line 3/3 channel
54-10	54	0.001	30	2.688	53.17	27	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-10	54	0.001	30	2.688	62.97	29	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-10	54	0.001	30	2.688	83.01	31	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
54-100	54	0.001	0	4.125	50.11	108	0	Undeveloped
54-100	54	0.001	10	4.567	72.09	83	1	Street 1/3
54-100	54	0.001	10	4.567	78	66	2	Street 1/3; Imp. 1/3 channel
54-100	54	0.001	10	4.567	78.05	79	3	Street 1/3; Line 1/3 channel
54-100	54	0.001	20	5.01	77.75	77	4	Street 2/3; Imp. 2/3 channel
54-100	54	0.001	20	5.01	73.55	75	5	Street 2/3; Imp. 2/3 channel
54-100	54	0.001	20	5.01	76.43	60	6	Street 2/3; Line 2/3 channel
54-100	54	0.001	30	5.452	78.45	58	7	Streets 3/3; Line 2/3 channel
54-100	54	0.001	30	5.452	79.53	58	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-100	54	0.001	30	5.452	80.19	55	9	Streets 3/3; Line 3/3 channel
54-100	54	0.001	30	5.452	82.67	22	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-100	54	0.001	30	5.452	95.79	13	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-100	54	0.001	30	5.452	144.1	12	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
216-2	216	0.0005	0	0.476	6.49	361	0	Undeveloped
216-2	216	0.0005	10	0.73	16.68	186	1	Street 1/3
216-2	216	0.0005	10	0.73	21.52	123	2	Street 1/3; Imp. 1/3 channel
216-2	216	0.0005	10	0.73	26.92	38	3	Street 1/3; Line 1/3 channel
216-2	216	0.0005	20	0.983	42.12	107	4	Street 2/3; Imp. 2/3 channel
216-2	216	0.0005	20	0.983	51.13	79	5	Street 2/3; Imp. 2/3 channel
216-2	216	0.0005	20	0.983	53.46	61	6	Street 2/3; Line 2/3 channel
216-2	216	0.0005	30	1.237	92.31	67	7	Streets 3/3; Line 2/3 channel
216-2	216	0.0005	30	1.237	102.85	56	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
216-2	216	0.0005	30	1.237	106.35	48	9	Streets 3/3; Line 3/3 channel
216-2	216	0.0005	30	1.237	141.82	26	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
216-2	216	0.0005	30	1.237	163.04	30	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
216-2	216	0.0005	30	1.237	231.15	27	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
216-10	216	0.0005	0	1.563	39.33	199	0	Undeveloped
216-10	216	0.0005	10	1.911	57.85	159	1	Street 1/3
216-10	216	0.0005	10	1.911	74.93	122	2	Street 1/3; Imp. 1/3 channel
216-10	216	0.0005	10	1.911	71.76	121	3	Street 1/3; Line 1/3 channel
216-10	216	0.0005	20	2.259	107.26	54	4	Street 2/3; Imp. 2/3 channel
216-10	216	0.0005	20	2.259	119.9	40	5	Street 2/3; Imp. 2/3 channel
216-10	216	0.0005	20	2.259	122.51	34	6	Street 2/3; Line 2/3 channel
216-10	216	0.0005	30	2.607	153.09	29	7	Streets 3/3; Line 2/3 channel
216-10	216	0.0005	30	2.607	163.12	27	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
216-10	216	0.0005	30	2.607	165.65	24	9	Streets 3/3; Line 3/3 channel
216-10	216	0.0005	30	2.607	211.87	34	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
216-10	216	0.0005	30	2.607	268.2	37	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
216-10	216	0.0005	30	2.607	299.8	23	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
216-100	216	0.0005	0	3.984	134.6	134	0	Undeveloped

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
216-100	216	0.0005	10	4.424	159.61	130	1	Street 1/3
216-100	216	0.0005	10	4.424	169.16	121	2	Street 1/3; Imp. 1/3 channel
216-100	216	0.0005	10	4.424	167.35	120	3	Street 1/3; Line 1/3 channel
216-100	216	0.0005	20	4.915	178.73	109	4	Street 2/3; Imp. 2/3 channel
216-100	216	0.0005	20	4.915	183.38	101	5	Street 2/3; Imp. 2/3 channel
216-100	216	0.0005	20	4.915	183.89	99	6	Street 2/3; Line 2/3 channel
216-100	216	0.0005	30	5.38	203.81	30	7	Streets 3/3; Line 2/3 channel
216-100	216	0.0005	30	5.38	212.67	22	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
216-100	216	0.0005	30	5.38	214.37	21	9	Streets 3/3; Line 3/3 channel
216-100	216	0.0005	30	5.38	287.86	31	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
216-100	216	0.0005	30	5.38	373.77	22	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
216-100	216	0.0005	30	5.38	391.17	19	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
54-10	54	0.005	0	1.707	35.46	104	0	Undeveloped
54-10	54	0.005	10	1.817	44.34	79	1	Street 1/3
54-10	54	0.005	10	1.817	43.76	61	2	Street 1/3; Imp. 1/3 channel
54-10	54	0.005	10	1.817	47.49	66	3	Street 1/3; Line 1/3 channel
54-10	54	0.005	20	2.361	60.95	69	4	Street 2/3; Imp. 2/3 channel
54-10	54	0.005	20	2.361	66.06	63	5	Street 2/3; Imp. 2/3 channel
54-10	54	0.005	20	2.361	75.2	62	6	Street 2/3; Line 2/3 channel
54-10	54	0.005	30	2.688	111.27	41	7	Streets 3/3; Line 2/3 channel
54-10	54	0.005	30	2.688	119.93	35	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-10	54	0.005	30	2.688	120.31	35	9	Streets 3/3; Line 3/3 channel
54-10	54	0.005	30	2.688	128.74	19	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-10	54	0.005	30	2.688	127.22	19	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-10	54	0.005	30	2.688	143.73	20	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
54-100	54	0.005	0	4.125	89.52	91	0	Undeveloped
54-100	54	0.005	10	4.567	94.39	90	1	Street 1/3
54-100	54	0.005	10	4.567	99.51	75	2	Street 1/3; Imp. 1/3 channel
54-100	54	0.005	10	4.567	109.51	74	3	Street 1/3; Line 1/3 channel
54-100	54	0.005	20	5.01	110.99	66	4	Street 2/3; Imp. 2/3 channel
54-100	54	0.005	20	5.01	123.59	57	5	Street 2/3; Imp. 2/3 channel
54-100	54	0.005	20	5.01	125.58	53	6	Street 2/3; Line 2/3 channel
54-100	54	0.005	30	5.452	158.3	39	7	Streets 3/3; Line 2/3 channel
54-100	54	0.005	30	5.452	176.03	37	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
54-100	54	0.005	30	5.452	173.93	37	9	Streets 3/3; Line 3/3 channel
54-100	54	0.005	30	5.452	190.53	22	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
54-100	54	0.005	30	5.452	205.88	18	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
54-100	54	0.005	30	5.452	290.93	13	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
216-10	216	0.003	0	1.563	59.26	211	0	Undeveloped
216-10	216	0.003	10	1.911	64.45	90	1	Street 1/3
216-10	216	0.003	10	1.911	70.9	89	2	Street 1/3; Imp. 1/3 channel
216-10	216	0.003	10	1.911	71.96	69	3	Street 1/3; Line 1/3 channel
216-10	216	0.003	20	2.259	132.35	31	4	Street 2/3; Imp. 2/3 channel
216-10	216	0.003	20	2.259	145.29	37	5	Street 2/3; Imp. 2/3 channel
216-10	216	0.003	20	2.259	164.75	27	6	Street 2/3; Line 2/3 channel
216-10	216	0.003	30	2.607	174.33	81	7	Streets 3/3; Line 2/3 channel

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
216-10	216	0.003	30	2.607	181.54	20	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
216-10	216	0.003	30	2.607	192.75	19	9	Streets 3/3; Line 3/3 channel
216-10	216	0.003	30	2.607	247.44	24	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
216-10	216	0.003	30	2.607	302.26	34	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
216-10	216	0.003	30	2.607	359.79	33	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
216-100	216	0.003	0	3.984	136.71	207	0	Undeveloped
216-100	216	0.003	10	4.424	139.9	81	1	Street 1/3
216-100	216	0.003	10	4.424	155.8	69	2	Street 1/3; Imp. 1/3 channel
216-100	216	0.003	10	4.424	159.83	56	3	Street 1/3; Line 1/3 channel
216-100	216	0.003	20	4.915	281.05	67	4	Street 2/3; Imp. 2/3 channel
216-100	216	0.003	20	4.915	295.68	63	5	Street 2/3; Imp. 2/3 channel
216-100	216	0.003	20	4.915	310.73	57	6	Street 2/3; Line 2/3 channel
216-100	216	0.003	30	5.38	427.4	63	7	Streets 3/3; Line 2/3 channel
216-100	216	0.003	30	5.38	443.15	57	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
216-100	216	0.003	30	5.38	443.61	56	9	Streets 3/3; Line 3/3 channel
216-100	216	0.003	30	5.38	436.17	54	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
216-100	216	0.003	30	5.38	429.18	49	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
216-100	216	0.003	30	5.38	415	25	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
13.5-100	13.5	0.01	0	4.2	15.27	110	0	Undeveloped
13.5-100	13.5	0.01	10	4.63	24.18	18	1	Street 1/3
13.5-100	13.5	0.01	10	4.63	29.81	15	2	Street 1/3; Imp. 1/3 channel
13.5-100	13.5	0.01	10	4.63	42.1	9	3	Street 1/3; Line 1/3 channel
13.5-100	13.5	0.01	20	5.061	60.85	13	4	Street 2/3; Imp. 2/3 channel
13.5-100	13.5	0.01	20	5.061	68.8	13	5	Street 2/3; Imp. 2/3 channel
13.5-100	13.5	0.01	20	5.061	69.03	13	6	Street 2/3; Line 2/3 channel
13.5-100	13.5	0.01	30	5.491	86.05	13	7	Streets 3/3; Line 2/3 channel
13.5-100	13.5	0.01	30	5.491	100.68	12	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
13.5-100	13.5	0.01	30	5.491	103.14	12	9	Streets 3/3; Line 3/3 channel
13.5-100	13.5	0.01	30	5.491	93.06	12	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
13.5-100	13.5	0.01	30	5.491	82.02	13	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
13.5-100	13.5	0.01	30	5.491	71.35	10	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
13.5-100	13.5	0.002	0	4.2	6.45	125	0	Undeveloped
13.5-100	13.5	0.002	10	4.63	21.19	25	1	Street 1/3
13.5-100	13.5	0.002	10	4.63	24.95	20	2	Street 1/3; Imp. 1/3 channel
13.5-100	13.5	0.002	10	4.63	29.22	11	3	Street 1/3; Line 1/3 channel
13.5-100	13.5	0.002	20	5.061	47.09	19	4	Street 2/3; Imp. 2/3 channel
13.5-100	13.5	0.002	20	5.061	50.81	17	5	Street 2/3; Imp. 2/3 channel
13.5-100	13.5	0.002	20	5.061	51.88	16	6	Street 2/3; Line 2/3 channel
13.5-100	13.5	0.002	30	5.491	69.41	17	7	Streets 3/3; Line 2/3 channel
13.5-100	13.5	0.002	30	5.491	71.1	16	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
13.5-100	13.5	0.002	30	5.491	72.43	15	9	Streets 3/3; Line 3/3 channel
13.5-100	13.5	0.002	30	5.491	71.24	14	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
13.5-100	13.5	0.002	30	5.491	59.86	14	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
13.5-100	13.5	0.002	30	5.491	52.43	11	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
13.5-10	13.5	0.01	0	1.816	5.14	115	0	Undeveloped
13.5-10	13.5	0.01	10	2.128	13.4	20	1	Street 1/3

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
13.5-10	13.5	0.01	10	2.128	16.38	13	2	Street 1/3; Imp. 1/3 channel
13.5-10	13.5	0.01	10	2.128	24.49	11	3	Street 1/3; Line 1/3 channel
13.5-10	13.5	0.01	20	2.441	37.34	11	4	Street 2/3; Imp. 2/3 channel
13.5-10	13.5	0.01	20	2.441	41.03	11	5	Street 2/3; Imp. 2/3 channel
13.5-10	13.5	0.01	20	2.441	40.67	11	6	Street 2/3; Line 2/3 channel
13.5-10	13.5	0.01	30	2.737	52.48	16	7	Streets 3/3; Line 2/3 channel
13.5-10	13.5	0.01	30	2.737	54.22	14	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
13.5-10	13.5	0.01	30	2.737	57.21	14	9	Streets 3/3; Line 3/3 channel
13.5-10	13.5	0.01	30	2.737	55.01	13	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
13.5-10	13.5	0.01	30	2.737	54.71	13	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
13.5-10	13.5	0.01	30	2.737	56.6	12	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
13.5-10	13.5	0.002	0	1.816	2.05	50	0	Undeveloped
13.5-10	13.5	0.002	10	2.128	11.91	27	1	Street 1/3
13.5-10	13.5	0.002	10	2.128	13.96	22	2	Street 1/3; Imp. 1/3 channel
13.5-10	13.5	0.002	10	2.128	17.04	14	3	Street 1/3; Line 1/3 channel
13.5-10	13.5	0.002	20	2.441	27.25	16	4	Street 2/3; Imp. 2/3 channel
13.5-10	13.5	0.002	20	2.441	29.69	15	5	Street 2/3; Imp. 2/3 channel
13.5-10	13.5	0.002	20	2.441	32.7	13	6	Street 2/3; Line 2/3 channel
13.5-10	13.5	0.002	30	2.737	41.31	16	7	Streets 3/3; Line 2/3 channel
13.5-10	13.5	0.002	30	2.737	42.59	15	8	Streets 3/3; Line 2/3, Imp. 1/3 channel
13.5-10	13.5	0.002	30	2.737	43.95	14	9	Streets 3/3; Line 3/3 channel
13.5-10	13.5	0.002	30	2.737	45.8	13	10	Streets 3/3; Line 3/3 channel; Sewer 1/3
13.5-10	13.5	0.002	30	2.737	42.71	10	11	Streets 3/3; Line 3/3 channel ; Sewer 2/3
13.5-10	13.5	0.002	30	2.737	45.92	8	12	Streets 3/3; Line 3/3 channel; Sewer 3/3
LZB-2-M1B12	78	0.0047	30	1.3	111	15	12	Validation
LZB-2-M1B11A	78	0.0047	30	1.3	103	15	11	–
LZB-2-M1B11	78	0.0047	30	1.3	84	15	11	–
LZB-2-M10A	78	0.0047	30	1.3	95	20	10	–
LZB-2-M1B10	78	0.0047	30	1.3	67	15	10	–
LZB-2-M1B9	78	0.0047	30	1.3	97	20	9	–
LZB-2-M1B3	78	0.0047	30	1.3	57	40	3	–
LZB-2-M1B6	78	0.0047	30	1.3	42	55	6	–
LZB-2-M1B5	78	0.0047	30	1.3	50	60	5	–
LZB-2-M1B4	78	0.0047	30	1.3	52	40	4	–
LZB-2-M1B0	78	0.0047	30	1.3	26	95	0	Pre-development (all backyard sections)
LZB-2-M1B0A	78	0.0047	0	0.55	8	95	0	Pre-development; all pervious
LZB-10-M1B12	78	0.0047	30	2.66	169	15	12	Validation
LZB-10-M1B11A	78	0.0047	30	2.66	166	15	11	–
LZB-10-M1B11	78	0.0047	30	2.66	136	15	11	–
LZB-10-M10A	78	0.0047	30	2.66	164	15	10	–
LZB-10-M1B10	78	0.0047	30	2.66	107	15	10	–
LZB-10-M1B9	78	0.0047	30	2.66	174	15	9	–
LZB-10-M1B3	78	0.0047	30	2.66	121	35	3	–
LZB-10-M1B6	78	0.0047	30	2.66	104	45	6	–
LZB-10-M1B5	78	0.0047	30	2.66	129	45	5	–
LZB-10-M1B4	78	0.0047	30	2.66	120	35	4	–

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
LZB-10-M1B0	78	0.0047	30	2.66	65	75	0	Pre-development (all backyard sections)
LZB-10-M1B0A	78	0.0047	0	1.60	35	105	0	Pre-development; all pervious
LZB-100-M1B12	78	0.0047	30	5.4	197	15	12	Validation
LZB-100-M1B11A	78	0.0047	30	5.4	201	50	11	–
LZB-100-M1B11	78	0.0047	30	5.4	176	15	11	–
LZB-100-M1B10A	78	0.0047	30	5.4	252	25	10	–
LZB-100-M1B10	78	0.0047	30	5.4	177	35	10	–
LZB-100-M1B9	78	0.0047	30	5.4	264	15	9	–
LZB-100-M1B3	78	0.0047	30	5.4	212	20	3	–
LZB-100-M1B6	78	0.0047	30	5.4	205	30	6	–
LZB-100-M1B5	78	0.0047	30	5.4	222	55	5	–
LZB-100-M1B4	78	0.0047	30	5.4	194	25	4	–
LZB-100-M1B0	78	0.0047	30	5.4	144	60	0	Pre-development (all backyard sections)
LZB-100-M1B0A	78	0.0047	0	4.1	110	85	0	Pre-development ; all pervious
WDAB10-2	249.25	0.003	30	1.02	97	60	10	Channel, Concrete, Curb/Gutter, Sewer (validation at data collection)
WDAB8-2	249.25	0.003	30	1.02	58	105	8	Reduce BDF , remove channel lining
WDAB7-2	249.25	0.003	30	1.02	57	105	7	Reduce BDF , remove (1/3) sewer
WDAB6-2	249.25	0.003	30	1.02	49	90	6	Reduce BDF , remove (2/3) sewer
WDAB5-2	249.25	0.003	30	1.02	46	120	5	Reduce BDF , remove (3/3) sewer
WDAB11-2	249.25	0.003	30	1.02	99	60	11	Increase BDF, extend channel
WDAB12-2	249.25	0.003	30	1.02	102	60	12	Increase BDF, line extension
WDAB3-2	249.25	0.003	30	1.02	38	150	3	Reduce BDF, remove channel, remove sewer
WDAB6A-2	249.25	0.003	30	1.02	45	120	6	Reduce BDF, remove channel, keep sewer
WDAB9-2	249.25	0.003	30	1.02	50	120	9	Reduce BDF, remove channel lining, keep extension
WDA10A-2	249.25	0.003	30	1.02	93	60	10	Same as reference BDF, remove relief sewer from node 69 (topographic sump)
WDAB30-2	249.25	0.003	30	1.02	30	195	0	Pre-development (all backyard sections)
WDAB0A-2	249.25	0.003	0	0.17	5	150	0	Pre-development (all backyard sections); all pervious
WDAB10-10	249.25	0.003	30	2.2	240	75	10	Channel, Concrete, Curb/Gutter, Sewer (validation at data collection)
WDAB8-10	249.25	0.003	30	2.2	150	105	8	Reduce BDF , remove channel lining
WDAB7-10	249.25	0.003	30	2.2	152	105	7	Reduce BDF , remove (1/3) sewer
WDAB6-10	249.25	0.003	30	2.2	156	105	6	Reduce BDF , remove (2/3) sewer
WDAB5-10	249.25	0.003	30	2.2	153	105	5	Reduce BDF , remove (3/3) sewer
WDAB11-10	249.25	0.003	30	2.2	225	60	11	Increase BDF, extend channel
WDAB12-10	249.25	0.003	30	2.2	236	60	12	Increase BDF, line extension
WDAB3-10	249.25	0.003	30	2.2	156	105	3	Reduce BDF, remove channel, remove sewer
WDAB6A-10	249.25	0.003	30	2.2	152	105	6	Reduce BDF, remove channel, keep sewer
WDAB9-10	249.25	0.003	30	2.2	126	120	9	Reduce BDF, remove channel lining, keep extension

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
WDA10A-10	249.25	0.003	30	2.2	244	60	10	Same as reference BDF, remove relief sewer from node 69 (topographic sump)
WDAB30-10	249.25	0.003	30	2.2	114	135	0	Pre-development (all backyard sections)
WDAB0A-10	249.25	0.003	0	0.95	28	195	0	Pre-development (all backyard sections); all pervious
WDAB10-100	249.25	0.003	30	4.65	540	75	10	Channel, Concrete, Curb/Gutter, Sewer (validation at data collection)
WDAB8-100	249.25	0.003	30	4.65	322	105	8	Reduce BDF , remove channel lining
WDAB7-100	249.25	0.003	30	4.65	325	105	7	Reduce BDF , remove (1/3) sewer
WDAB6-100	249.25	0.003	30	4.65	331	105	6	Reduce BDF , remove (2/3) sewer
WDAB5-100	249.25	0.003	30	4.65	330	105	5	Reduce BDF , remove (3/3) sewer
WDAB11-100	249.25	0.003	30	4.65	505	60	11	Increase BDF, extend channel
WDAB12-100	249.25	0.003	30	4.65	519	75	12	Increase BDF, line extension
WDAB3-100	249.25	0.003	30	4.65	422	90	3	Reduce BDF, remove channel, remove sewer
WDAB6A-100	249.25	0.003	30	4.65	404	90	6	Reduce BDF, remove channel, keep sewer
WDAB9-100	249.25	0.003	30	4.65	276	120	9	Reduce BDF, remove channel lining, keep extension
WDA10A-100	249.25	0.003	30	4.65	546	60	10	Same as reference BDF, remove relief sewer from node 69 (topographic sump)
WDAB30-100	249.25	0.003	30	4.65	319	120	0	Pre-development (all backyard sections)
WDAB0A-100	249.25	0.003	0	2.93	180	135	0	Pre-development (all backyard sections); all pervious
WDCB2-2	162.84	0.0041	0	1.88	66	90	2	Channel, Unlined, Pre-Development (all backyard sections); all pervious
WDCB4-2	162.84	0.0041	0	1.88	76	75	4	Increase BDF, Line Channel
WDCB4A-2	162.84	0.0041	30	2.2	98	60	4	Increase %IC
WDCB7-2	162.84	0.0041	30	2.2	136	60	7	Increase BDF, curb/gutter all streets, entire watershed
WDCB8-2	162.84	0.0041	30	2.2	149	60	8	Increase BDF, sewer east side of ditch
WDCB9-2	162.84	0.0041	30	2.2	156	60	9	Increase BDF, sewer upper end of ditch
WDC10-2	162.84	0.0041	30	2.2	166	45	10	Increase BDF, sewer remaining portion
WDC10A-2	162.84	0.0041	30	2.2	167	45	12	Increase BDF, remove upper end sewer, extend channel in place of sewer
WDCB2-10	162.84	0.0041	0	3.7	159	90	2	Channel, Unlined, Pre-Development (all backyard sections); all pervious
WDCB4-10	162.84	0.0041	0	3.7	180	75	4	Increase BDF, Line Channel
WDCB4A-10	162.84	0.0041	30	4.1	204	60	4	Increase %IC
WDCB7-10	162.84	0.0041	30	4.1	209	45	7	Increase BDF, curb/gutter all streets, entire watershed
WDCB8-10	162.84	0.0041	30	4.1	219	45	8	Increase BDF, sewer east side of ditch
WDCB9-10	162.84	0.0041	30	4.1	241	45	9	Increase BDF, sewer upper end of ditch
WDC10-10	162.84	0.0041	30	4.1	258	45	10	Increase BDF, sewer remaining portion
WDC10A-10	162.84	0.0041	30	4.1	284	45	12	Increase BDF, remove upper end sewer, extend channel in place of sewer
WDCB2-100	162.84	0.0041	0	7.25	309	60	2	Channel, Unlined, Pre-Development (all backyard sections); all pervious

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Table 16: Characteristics and Responses for Hypothetical Watershed Models. — Continued

MODEL_ID	AREA	SLOPE	%IC	Pe	Qp	T_{lag}	BDF	Scenario
WDCB4-100	162.84	0.0041	0	7.25	351	60	4	Increase BDF, Line Channel
WDCB4A-100	162.84	0.0041	30	7.65	373	60	4	Increase %IC
WDCB7-100	162.84	0.0041	30	7.65	401	60	7	Increase BDF, curb/gutter all streets, entire watershed
WDCB8-100	162.84	0.0041	30	7.65	399	60	8	Increase BDF, sewer east side of ditch
WDCB9-100	162.84	0.0041	30	7.65	380	45	9	Increase BDF, sewer upper end of ditch
WDC10-100	162.84	0.0041	30	7.65	401	45	10	Increase BDF, sewer remaining portion
WDC10A-100	162.84	0.0041	30	7.65	458	45	12	Increase BDF, remove upper end sewer, extend channel in place of sewer