Modeling, Assessment & Awareness Project

White Paper

Recommendations for:
Hydrologic Methods in Harris County

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Notes:
This white paper outlines processes and procedures for developing hydrologic models in Harris County. The subject matter covered includes discussion of rainfall, infiltration losses, sub-area delineation, development of unit hydrograph parameters, hydrograph routing, and model calibration. Also discussed are requirements for GIS data development related to hydrologic modeling.

White Paper
#11

The Harris County Flood Control District (HCFCD) Standard Method

The HCFCD Standard Method was developed after Harris County joined the National Flood Insurance Program in the late 1970s. The Standard Method provides the time of concentration (Tc) and storage coefficient (R) for the Clark Unit Hydrograph Method. The methodology, which was developed using available USGS gage data for Harris County watersheds, relates Tc and R to the following eight (8) parameters:

- Watershed Length (L)
- Length to Centroid (Lca)
- Channel Slope (S)
- Overland Slope (So)
- Percent Land Urbanization (DLU)
- Percent Channel Improvement (DCI)
- Percent Channel Conveyance (DCC)
- Percent Ponding (DPP)

An adjustment was made to the methodology in connection with the Tropical Storm Allison Recovery Project (TSARP) to add Percent Urban Development Affected by Detention to the original list of watershed parameters.

Need for Change

From a scientific standpoint, the Standard Method has been very successful in terms of providing statistically reliable hydrologic data and matching recorded data from historical storms. However, the Standard Method involves a number of relatively complex variables that can be interpreted in different ways, leading to a significant degree of subjectivity and therefore a wide variety of possible Tc and R values for a given drainage area. In addition, the Standard Method was created for the purpose of completing watershed studies at a level of detail consistent with the production of Flood Insurance Rate Maps for Harris County, and is appropriate for application only to drainage areas of one square mile or greater extent. It is not appropriate for analyzing relatively smaller sub-areas, and it is not easily adaptable for use in completing drainage impact analyses. Furthermore, the Standard Method exhibits some idiosyncrasies, such as a discontinuity at 18% urban development where the calculated flow rate will actually decrease as the Percent Urban Development is to greater than 18%. Finally, because the Standard Method is complex and not easily understood, it lacks the type of transparency that is consistent with good public policy. For these reasons, HCFCD has developed an alternative method for assessing and validating urbanization runoff within a watershed using the Basin Development Factor (BDF).

Overview of the Basin Development Factor Methodology

In 1983, V. B. Sauer, W. O. Thomas, Jr., V.A. Stricker, and K.V. Wilson produced USGS Water-Supply Paper 2207, titled “Flood Characteristics of Urban Watersheds in the United States.” That document introduced the BDF as a measure of urbanization and the efficiency of the drainage system within a given watershed. This factor provides a simple means of accounting for urbanization and related drainage improvements by assigning arithmetic values to a set of indices that account for changes in drainage infrastructure. Values of BDF vary from 0 (undeveloped conditions) to 12 (fully developed conditions), and the BDF approach accounts for four drainage improvement indices: storm sewers, curb and gutter streets, channel improvements, and channel linings.

The BDF methodology was evaluated in 2008-2009 by consultants selected by the HCFCD to investigate factors that affect drainage and flooding in Harris County. That effort was designated the “FloodWise” project. Methods and equations were developed to adapt the BDF approach for use in Harris County, with the ability to develop Clark Unit Hydrograph parameters. Follow-up research was performed between 2009 and 2014, and additional research has been completed in 2018. Research products produced via these efforts include memoranda on study results, application and training manuals, PowerPoint® presentations, technical white papers, and other documents.

Justification for a Change to the BDF Method

The BDF method is simple, transparent, and easy to understand, and it produces very reasonable results with less subjectivity as compared with the Harris County Standard Method. In short, it is user friendly. The BDF method provides limited parameters for adjustment, and thus is limited in terms of modeling conditions that stray significantly outside of the range of typical situations in Harris County. On the other hand, research has shown that the BDF approach is robust, can be successfully applied to small or large watersheds, is very applicable to studies of historical events for validation, and is readily adaptable for use in the completing drainage impact analyses. Following are a number of justifications for using the BDF method alternative, which has been developed through years of study and testing of the methodology in Harris County watersheds.

- **The time is right**. Hurricane Harvey caused Harris County, the City of Houston, and other local jurisdictions to make significant changes in analytical and design requirements. This creates an opportunity for a change in the Harris County hydrologic methodology as well.
- **Transparency is needed**. The Harris County Standard Method is relatively complex and not easily understood. The more straightforward, easily understood, and less subjective BDF approach will be beneficial in improving the level of public trust in the HCFCD's management of Harris County watersheds.
- **Consistency is required**. Consistency among impact studies related to proposed developments is critical to a successful drainage regulatory program. The BDF method provides a simple, reproducible approach that will promote and improve consistency of application and results.
- **Limit the loopholes**. The simplicity of the BDF approach should make the impact identification process more direct and reduce the likelihood of having new developments fall into loopholes where impacts are not indicated (e.g., re-development with upgraded drainage systems, but no new impervious cover).
- **Added detail is possible**. The Standard Method is applicable to watersheds where a channel is present and the drainage area is at least one square mile. The BDF method, on the other hand, provides a means for analyzing smaller sub-watersheds, providing for more detailed analyses with a larger number of sub-areas.
- **New models require flexibility**. As the BDF method is not dependent on underlying assumptions such as the presence of a channel, and minimum sub-area size is as little as 0.01 square mile, it provides for more flexible modeling approaches suitable for the newer 1D/2D, unsteady-flow models.
- **Discrete is neat**. With smaller sub-areas, it is possible to discretize sub-watersheds in a way that individual drainage areas are more homogeneous. This reduces the need to combine different land uses, vegetative conditions, development types, drainage system types, detention/non-detention areas, etc.

In summary, the BDF method is flexible enough to apply to watershed studies, unsteady flow 1D/2D model studies, and impact analyses, and it has been shown to provide good results when calibrating models to historical events. This flexibility and the ability to utilize the method for a wide variety of drainage applications are perhaps the greatest and most significant justifications for its adoption as the new Harris County hydrologic methodology.

Hydrology-Related White Papers Prepared for MAAPnext

A series of white papers has been developed in connection with the MAAPnext effort to provide guidance to consultants selected to complete modeling and mapping activities. The following white papers apply specifically to hydrologic studies.

- Rainfall Data for Harris County Hydrologic Models
- Impervious Cover Updates in Harris County

- Replacing Green & Ampt Loss Function in HEC-HMS with Initial & Constant Loss Method
- Tc & R Using BDF Approach
  - Base Tc and R Methodology
  - Slope Adjustment
  - Detention Adjustment
  - Ponding Adjustment
- Flood Flow Frequency Data for Harris County Streams
- Upper Watershed Flows in Harris County
- Calibration Methods

These white papers provide a technical basis for updating hydrologic models for Harris County. Note that the Modified Puls routing method previously used in Harris County will be discontinued due to the adoption of 1D/2D hydraulic models that directly account for storage and thus do not require routing reaches. Runoff hydrographs from HEC-HMS models will be input to HEC-RAS 1D/2D models, which will account directly for storage volume within areas inundated by each studied flood event. However, in order to provide hydrologic models that can be run independent from HEC-RAS and provide consistent results, the Muskingum routing method will be implemented in the HEC-HMS models with coefficients determined via model calibration for historical storm events.

Rainfall Data

Rainfall data from NOAA Atlas 14 will be used for analyses of hypothetical storm events. Depth-duration-frequency data has been developed for three (3) rainfall regions as defined in the "**Rainfall Data**" white paper referenced above. Partial Duration Series (PDS) data will be utilized, with 24-hour storm duration unless otherwise directed by the project management team. No area adjustment will be applied to the rainfall depths obtained from Atlas 14. The balanced hyetograph option will be used to distribute rainfall, with maximum rainfall intensity at 67% of total storm duration.

Sub-Area Delineation

Sub-area delineation for updated hydrologic models will be based on 2018 LiDAR data. Watershed delineations should initially be completed in coordination with study consultants for adjacent watersheds for tie-in and/or overflow conditions. Sub-areas may be created and defined as needed for the purposes of completing the watershed study. Even though the minimum sub-area size for the Basin Development Factor method is very small, the number of sub-areas created and used for study purposes should generally be maintained at the minimum value needed to model streams with an appropriate level of detail. The following approach may be used to establish watershed and sub-area boundaries.

- Begin with M3 watershed maps and sub-area delineations.
- Use 2018 LiDAR data to delineate updated drainage boundaries.
- Coordinate with adjacent study teams in revising watershed boundaries.
- Identify additional stream miles and determine where sub-watersheds need to be revised or subdivided.
- Establish analysis points / reaches and establish sub-area boundaries as required.
- Import drainage boundaries into GIS for use in automated hydrologic parameter calculations.
- Compute drainage areas and impervious cover values.

The use of LiDAR data and automated digital processing to establish drainage boundaries is acceptable; however, those boundaries are based only on surface topography, and adjustments may be required to account for storm sewer systems that influence flow patterns.

Due to the likely use of smaller sub-areas than were delineated for the Tropical Storm Allison Recovery Project and subsequent Harris County watershed studies, the numbering scheme for MAAPnext HEC-HMS sub-areas must be revised to provide for more than the 26 main stream sub-areas provided in the current system (Stream Designation + Letter Designation - e.g., P100A). The new system substitutes numbers for letters (Stream Designation + Sub-Area Number (e.g., P100_01 or P14001_01 for tributaries to tributaries). This approach provides for as many as 99 sub-areas along a given stream. Nodes are currently denoted as Stream Designation + Stream Station _ J (with stream station in hundreds of feet) where the Stream Designation uses the full 8-digit number (e.g., K1000000_0040_J), and routing reaches are denoted as Stream Designation + Stream Station _R (e.g., K1000000_0040_R). The proposed sub-area designation is sufficiently different from the junction and reach designations to avoid confusion.

Clark Unit Hydrograph Parameters

Clark unit hydrograph parameters (time of concentration and storage coefficient) will be computed using relationships developed for applying the BDF methodology to Harris County watersheds. The following steps and processes shall be used to establish the required unit hydrograph parameters.

- Establish a BDF value for each study sub-watershed. For early work and the initial approximate modeling submittal, BDF values can be estimated using the following relationship involving Harris County Standard method parameters and TSARP sub-watersheds from M3 models.

  $$BDF = [(DLU \times 6) + (DCI \times 3)] / 100$$

  For subsequent, more detailed modeling and submittals, use GIS data or traditional map reviews to determine a BDF value for each individual sub-watershed. The traditional BDF approach involves a step-wise approach that may be used to define a BDF value to the nearest 0.5 BDF unit. This approach involves dividing each sub-basin into thirds, estimating the value (from 0 to 1) of each BDF index (curb and gutter streets, storm sewers, channel improvements, and channel linings) for each third, and totaling all individual index values to get the overall BDF value.

  The following table provides typical BDF index values for various types and ages of drainage infrastructure. Age of infrastructure is important in Harris County because storm sewer systems designed before 1984 typically do not satisfy more recent design standards and therefore do not operate at the level of capacity and efficiency consistent with full values of the BDF storm sewer index. Additionally, areas with roadside ditch drainage reflect improved drainage, but the degree of improvement is less than would be realized with storm sewers and streets properly graded to provide sheet flow capacity. The following table provides adjusted BDF index values for these areas.

Table 1: Typical BDF Index Values for Individual Thirds of a Watershed

Drainage System Description	BDF Index Value
Undeveloped Property with No Drainage Improvements	0.0
Storm Sewers Constructed Prior to 1984	0.5
Storm Sewers Constructed In or After 1984	1.0
Curb-and-Gutter Streets Constructed Prior to 1984	0.5
Curb-and-Gutter Streets Constructed In or After 1984	1.0
Unimproved / Natural Channels	0.0
Improved Earthen Channels	1.0

Concrete Lined Channels	**1.0**
Streets with Roadside Ditches (Where Significant Longitudinal Flow Capacity Exists)	**0.5**
Roadside Ditches	**0.5**

Each third of the watershed illustrated in **Figure 1** is drained by curb-and-gutter streets and storm sewers constructed prior to 1984, and the channel that drains the entire area is improved, but not concrete-lined. As indicated in the table in the lower left-hand corner of the figure, the total BDF index value is 2 for each third (1 for channel improvements and 0.5 each for curb and gutter streets and storm sewers). The overall BDF value for this drainage area is 6.0. A simple, homogeneous area such as this one requires only a very basic additive BDF calculation. Other watersheds may be complex and will require more effort and diligence to develop an appropriate BDF value.

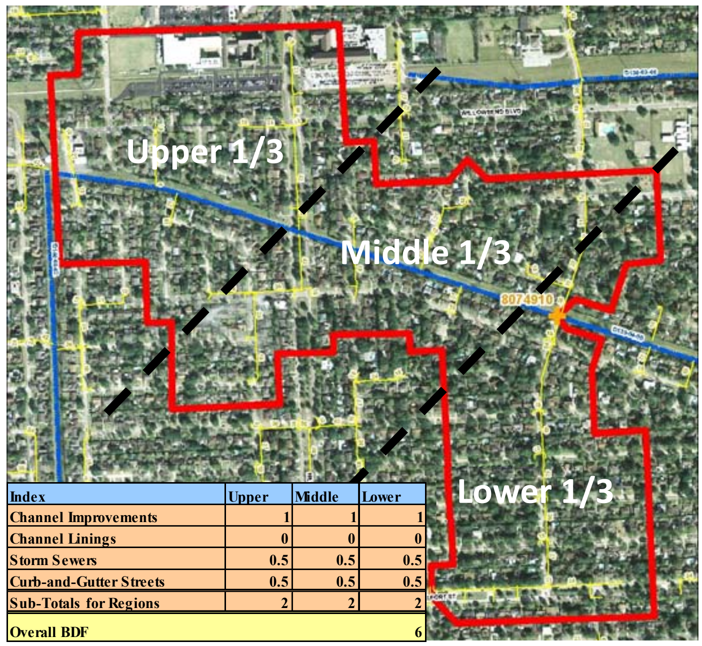


Figure 1: Step-Wise BDF Calculation for a Homogeneous Sub-Basin

An alternative to the original step-wise method illustrated above involves a weighted BDF approach that may be used by applying the following relationship, in which percentages of the total drainage area and channel/storm sewer length are multiplied by corresponding BDF values and totaled.

BDF = Σ(% of Total Area x Base BDF Index Value)

This relationship may also be expressed as follows, with individual channel/conveyance system lengths totaled and multiplied by index channel and land use BDF values.

Wtd. BDF = { Σ(Channel BDF x Length) / Σ(Channel Lengths) } + { Σ(Land Use BDF x Area) / Σ(Area) }

For this weighted approach, the following table of BDF values may be used to identify index values for typical land uses and drainage system types.

Table 2: BDF Values for Basic Land Uses in Harris County

Majority Major Conveyance System	BDF
No Channel/Natural	0
Improved	3
Concrete	6
Land Cover	**BDF**
Undeveloped	0

Open Space (graded)	1
Roadside Ditch Drainage	1.5
Curb-and-Gutter with Storm Sewers Pre-1984	3
Curb-and-Gutter with Storm Sewers Post-1984	6

The sub-basin illustrated in **Figure 2** is drained by an improved, but unlined channel. U.S. Highway 59 and the area west of the highway are drained by storm sewers constructed prior to 1984. The area east of U.S. Highway 59 is drained predominately by open ditches, with a few storm sewers. If the sub-basin was a separate drainage area, the BDF value for a sub-basin similar to area west of U.S. 59 is 6.0 (3.0 for improved open ditch, plus 1.5 for curb-and-gutter streets and 1.5 for storm sewers built prior to 1984). Likewise, the area east of U.S. 59 would have a BDF value of 4.5 (3.0 for improved earthen channel and 1.5 for roadside ditch drainage with limited longitudinal capacity in the roadway). Approximately 35% of the total area is within or west of the U.S. 59 right-of-way. The weighted BDF value for this sub-basin as a whole would be computed as follows.

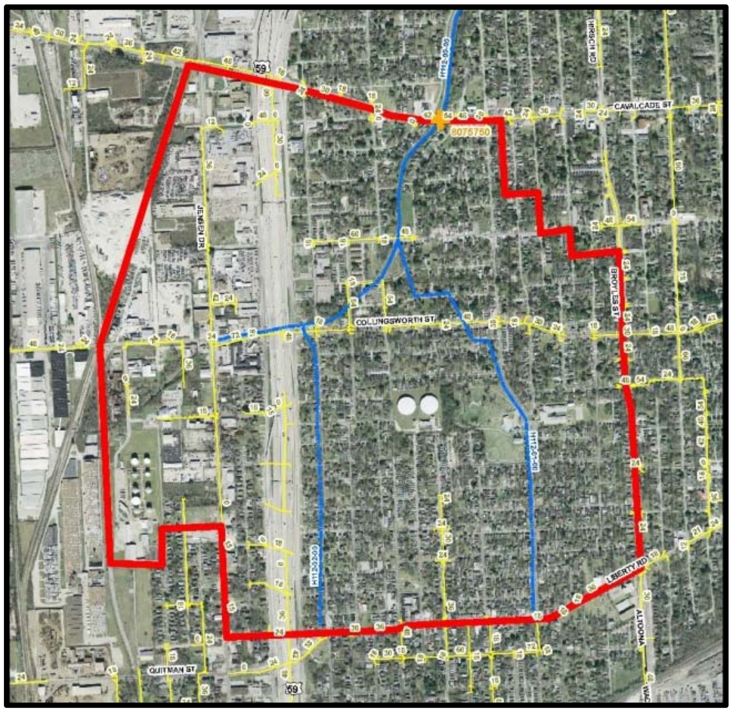


Figure 2: Area-Weighted BDF Calculation for a Non-Homogeneous Sub-Basin

BDF = (0.35 x 6.0) + (0.65 x 4.5)

BDF = 5.03

This weighted average BDF value is representative of the sub-basin as a whole. When using the weighted average method, round the BDF value to the nearest 0.01 unit as opposed to the nearest 0.5 unit for the step-wise approach. Note that because the sub-area is not divided into thirds for this approach, the individual BDF values are three times the corresponding values used when the watershed is divided into thirds.

For small watersheds lacking an actual drainage channel, the central roadside ditch or trunk storm sewer may be treated as the channel. Otherwise, BDF values for developed areas may be underestimated by failing to account for the values associate with the Channel Improvement and Channel Linings indices. For the sample in **Figure 3**, the storm trunk line is highlighted with a blue line and arrow to demonstrate the flow direction. Assuming that all storm sewers in this area were constructed post-1984 and considering the trunk storm sewer as improved and concrete-lined, the BDF value for this homogeneous sub-basin would be 12 (3.0 for improved channel, 3. 0 for channel linings, 3.0 for storm sewers, and 3.0 for curb-and-gutter streets). If the streets and storm sewers were constructed pre-1984, the BDF value would be reduced to 9 (3.0 for improved channel, 3.0 for channel linings, 1.5 for storm sewers and 1.5 for curb-and-gutter streets). Again, note that because the sub-area is not divided into thirds for this approach, the individual BDF values are three times the corresponding values used when the watershed is divided into thirds.

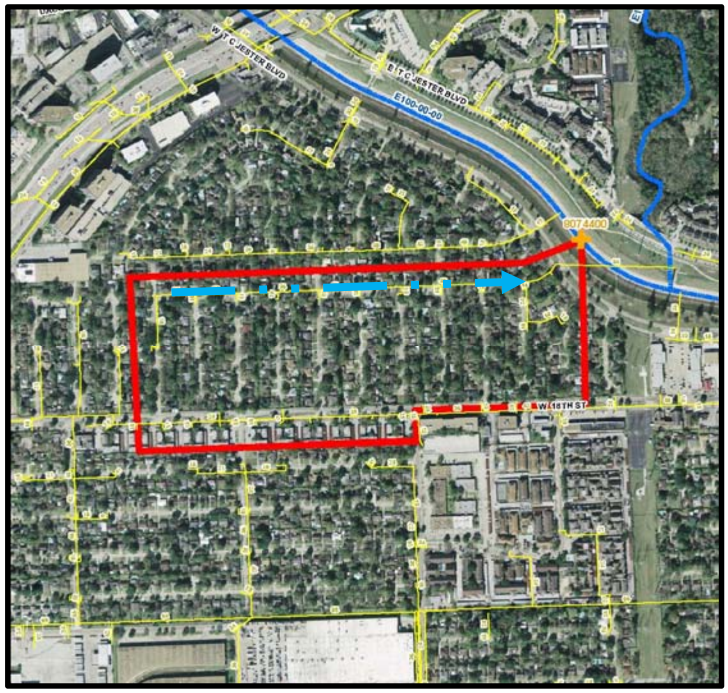


Figure 3: Subbasin with Storm Sewer Trunk Line Treated as Channel

- Compute base Clark Tc and R values using the equations developed for application of the BDF method in Harris County in connection with the FloodWise program.

$$\mathbf{Tr = 10^{[(-0.05228xBDF) + 0.4028 \log_{10}(A) + 0.3926]}}$$

$$\mathbf{Tc_{BDF} = Tr + (A^{0.5})/2}$$

$$\mathbf{R_{BDF} = 8.271e^{-0.1167*BDF} (A^{0.3856})}$$

where: A = Drainage Area (square miles)
BDF = Basin Development Factor

- Adjust Tc and R values for slope using the following relationships developed for Harris County for the MAAPnext project. This adjustment is required because the data used to develop the basic equations for Tc and R were normalized to relatively flat slopes of 5 feet per mile and 10 feet per mile for channel and overland slope, respectively, while slope values in some portions of Harris County significantly exceed those base values.

$$\mathbf{Ks = -0.162 \times \ln(SxSo) + 1.5232 \quad for\ SxSo >= 26}$$

$$\mathbf{Tc_{ADJ} = K_S \times Tc_{BDF}}$$

$$\mathbf{R_{ADJ} = K_S \times R_{BDF}}$$

Values of the "channel" slope S should be measured along the main channel and principal tributaries within the sub-basin, following channel, storm sewer, and/or open ditch from the sub-basin outlet to the upstream drainage boundary. It is recommended that a GIS approach be used for estimating the watershed slope (S_o) for catchments. This approach is implemented using ArcGIS's Spatial Analyst Slope tool to compute the slope from LiDAR and Zonal Statistics to summarize these slopes into a mean value for individual catchments. Slope is to be computed from LiDAR data resampled to a 660x660 foot pixel which allows for an approximation of slope over an approximately 10-acre sized pixel.

The slopes computed using the re-sampled LiDAR at a 660x600 cell size produce results generally within 10-percent of manually computed values. These slopes are generally higher than manually computed values, as watershed wide computation picks up more of the localized effects. With the approximately 10-acre generalization of the surface, these localized effects are valid for consideration. Use of this method greatly improves consistency in the calculations in addition to a reduction in the effort required for model building. The 660x660 slope surface for the entire 2018 LiDAR data set (660slope.TIF) will be provided to modeling and mapping consultants by the project management team. Consultants will only need to run the Zonal Statistics using their developed catchments to derive the S_o values for each sub-basin.

Note that the following separate equations were originally developed for adjusting Tc and R to account for slope. However, noting the similarity between the two equations (see graph below), the single equation provided above was subsequently developed for Tc and R adjustments.

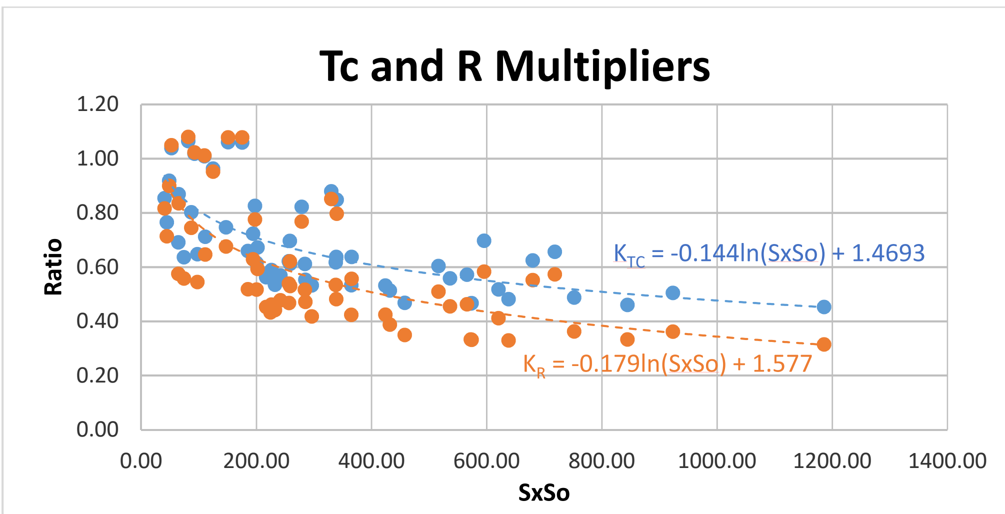


Figure 4 – Tc and R Multipliers

It should be noted that no correction should be made for S x So less than 26. Set S x So values less than 26 equal to 26 when calculating Tc_{ADJ} and R_{ADJ}.

- Adjust Tc and R values for on-site detention using the procedure and equations provided in the On-Site Detention Methodology section of the "**Tc and R"** white paper.

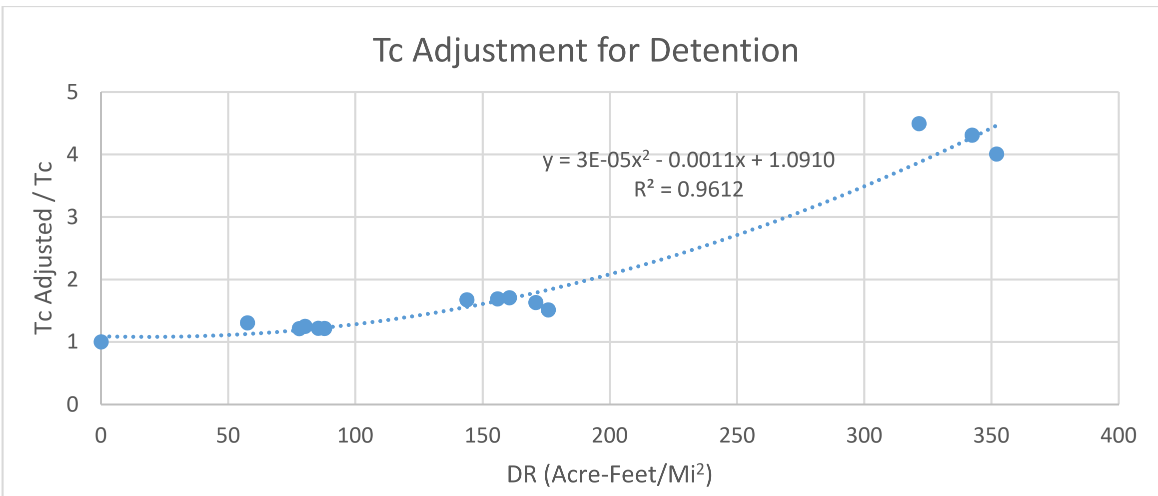
$$\mathbf{C\mathit{f} = 0.00003\,(DR)^2 - 0.00095(DR) + 1.0 \text{ for } DR > 10}$$

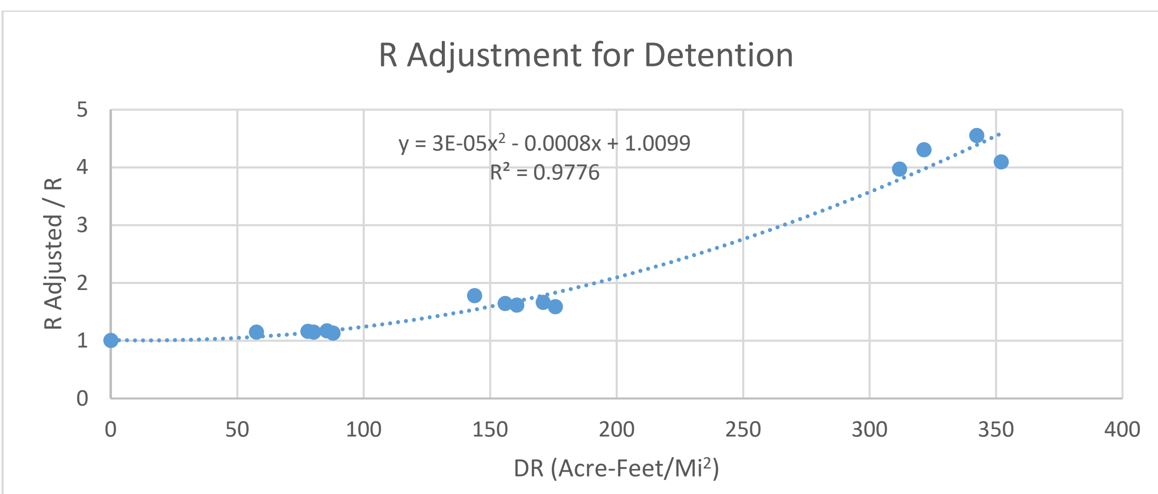
$$\mathbf{Tc_{DET} = Tc_{ADJ} \times C\mathit{f}}$$

$$\mathbf{R_{DET} = R_{ADJ} \times C\mathit{f}}$$

The detention rate (DR) is computed by determining the total detention storage for development basins within a given sub-area and dividing that volume by the drainage area. DR is expressed in units of acre-feet per square mile of drainage area. Note that detention basins located within the 100-year floodplain are accounted for in the hydraulic modeling process and should therefore be excluded from consideration in this hydrologic adjustment for the model subbasin. In addition, large storage volumes outside of the floodplain, such as sand pits, should have their total volume discounted or excluded from the drainage area. The modeler should review these large storage areas and determine if there is sufficient contributing drainage to prevent skewing of the DR ratio for the catchment in question.

Note that following separate equations were originally developed for adjusting Tc and R to account for detention. However, noting the similarity between the two equations (see graphs below), the single equation provided above was subsequently developed for Tc and R adjustments.





Figures 5 & 6 – Tc and R Adjustments for Detention

- Ponding areas are defined in the same way as they were for the Harris County Standard Method. If a ponding area(s) exists within a given sub-area, use the following storage coefficient adjustment relationships to account for the effects of the ponding area by adjusting (increasing) the Clark Storage Coefficient (R) for the subbasin in question.

  The application of ponding adjustment factors results in similar percent changes in peak discharges for the Standard and BDF methods. Therefore, it is recommended that the Standard Method ponding adjustment factors and equations be retained for use with the BDF Method. Below are the recommended equations.

Table 3: Ponding Correction Equations:

Storm Event	RM
(50%) 2-year	1.33 x $DPP^{0.242}$
(20%) 5-year	1.31 x $DPP^{0.214}$
(10%) 10-year	1.28 x $DPP^{0.199}$
(4%) 25-year	1.25 x $DPP^{0.171}$
(2%) 50-year	1.23 x $DPP^{0.153}$
(1%) 100-year	1.21 x $DPP^{0.132}$
(0.5%) 200-year	1.19 x $DPP^{0.113}$
(0.2%) 500-year	1.17 x $DPP^{0.086}$

For these equations:

- DPP = Percent Ponding (Percentage of Drainage Area Affected by Ponding)
- RM = Ponding Adjustment Factor.

Adjusted storage coefficients (R) are computed using the following relationship.

$$\mathbf{R_{PONDING} = R \times RM}$$

The value of R used in this relationship is the adjusted value for which slope and detention adjustments have been made.

A Microsoft Excel® spreadsheet template developed for use in determining weighted BDF values, calculating Clark Tc and R values, and making necessary adjustments to base Tc and R values will be provided to all modeling and mapping consultants involved in the MAAPnext project.

Loss Function Parameters

The Green-Ampt loss function is recommended for use in Harris County. The following table provides a summary of the Green-Ampt parameters to be used for each of the county's 22 major watersheds. Impervious cover values may be computed manually or by using GIS with the Harris County impervious cover layer acquired by the HCFCD. The latter is the recommended approach.

Table 4: Recommended Green-Ampt Loss Function Parameters

Watershed(s)	Predominate Soil(s)	Hydrologic Soil Group	Initial Canopy Storage (inches)	Max. Canopy Storage (inches)	Crop Coefficient	Initial Moisture Content	Saturated Content	Suction (inches)	Conductivity (inches/hour)
Spring Creek	Sandy Loam	B	0.0	0.5	1.0	0.059	0.46	2.286	0.181
Cypress Creek, Little Cypress Creek, Willow Creek, Addicks Res.	Sandy Loam	C	0.0	0.5	1.0	0.048	0.46	4.33	0.079
White Oak Bayou, Greens Bayou, San Jacinto River, Luce Bayou	Loam	D	0.0	0.1	1.0	0.024	0.46	3.50	0.024
Brays Bayou, Buffalo Bayou, Sims Bayou, Barker Reservoir, Jackson Bayou, Goose Creek, Cedar Bayou, Armand Bayou,	Clay	D	0.0	0.1	1.0	0.075	0.46	12.45	0.024

Impervious cover values for typical development types in Harris County are summarized below.

Table 5: Recommended Impervious Cover Values for Typical Development Types

Land Use	Description	Revised Percent Impervious
Undeveloped	unimproved, natural, or agricultural	0%
Residential - Rural Lots	≥ 5-acre ranch or farm	5%
Residential - Large Lots	> 1/2 acre new residential with storm sewers or roadside ditches with adequate capacity, OR > 1/4-acre older neighborhoods with limited capacity roadside ditches	25%
Residential - Small Lots	≤ 1/4-acre	40%
School	schools with non-paved areas	40%
Developed Green Areas	parks or golf courses	15%
Light Industrial/Commercial	office parks, nurseries, airports, warehouses, or manufacturing with non-paved areas	65%
High Density	commercial, business, industrial, or apartments	85%
Isolated Transportation	highway or major thoroughfare corridors	80%
Water	detention basins, lakes, and channels	100%

Routing Data Development

The Muskingum Method is recommended for approximating routing reaches. The insertion of Muskingum routing reaches allows the development of HEC-HMS models that yield peak runoff rates consistent with those computed using HEC-RAS 1D/2D models with BDF-based input hydrographs. Each individual Muskingum routing reach coincides with a defined channel reach, or segment, with end points typically located at tributary confluences or crossing structures such as roads and railways. The Muskingum method requires that values of three (3) parameters be determined, as described in the following paragraphs:

The Muskingum routing coefficient K (Travel Time) can be estimated by comparing the time of peak inflow to the reach to the time of peak outflow from the reach. Travel time can also be estimated using simple Manning calculations, reviewing results of prior model studies, or estimating flow velocities based on channel condition and experience, then dividing the reach length by the estimated velocity. The K coefficient is expressed in hours.

The Muskingum routing coefficient X is a dimensionless weighting coefficient ($0.0 \leq X \leq 0.5$) that represents the attenuation effect of storage within the reach. If the reach provides significant storage or is controlled by downstream conditions such that there is a strong correlation between storage and outflow (i.e., outflow is strongly influenced by storage), a value of X=0.0 would be appropriate. If there is minimal storage and an assumption of inflow = outflow is appropriate, than a value of X=0.5 would be appropriate. Varying degrees of storage influence on discharge rates may be represented by varying values of X from 0.0 to 0.5, with values typically rounded to the nearest tenth. Reviewing the watershed topography and anticipated floodplain extents allows modelers to make reasonable estimations of appropriate values of the X coefficient.

The number of routing steps (NSTPS) can be determined by dividing the K value travel time by the model computation time interval if the estimated flood wave velocity exceeds 1 foot per second (fps). For velocities less than 1 fps, a routing step of 1 should be assigned to simulate a strong correlation between storage and flow rate. Experience in Harris County strongly indicates that when flow velocities are less than 1 fps, the effects of storage are very similar to level-pool routing through a reservoir, a condition which is best modeled using a single routing step.

Once routing coefficients are assigned, the modeler should compare hydrographs computed in HMS to those computed in the corresponding 1D/2D RAS model. Better matches may be achieved by adjusting the locations at which a hydrograph is inserted in HEC-RAS or HEC-HMS, or by changing the means of assigning the catchment hydrographs, perhaps from a uniform distribution over the length of a stream segment to a point inflow at a given location along that segment, or vice versa. For example, a catchment hydrograph that is uniformly distributed over a reach in HEC-RAS may be assigned instead as a point inflow at the upstream end of a reach in HEC-HMS. Conversely, a catchment flow hydrograph input at the lower end of a reach in HEC-RAS may have to be input at the upstream end of a reach in HEC-HMS or distributed uniformly over the entire reach for better agreement between HMS and RAS results. In making decisions as to where and how hydrographs are input, account for actual inflow locations, local geography, topography and terrain, and possible backwater effects from roads, railways, etc.

A Microsoft Excel® spreadsheet template has been developed for the purpose of computing values of the Muskingum routing coefficients using computed inflow and outflow hydrographs for a given routing reach. The hydrographs may be obtained from HEC-HMS models (i.e., inflow and routed hydrographs for Modified Puls reaches) or from HEC-RAS models (combined inflow and outflow hydrographs). This spreadsheet will be provided to all MAAPnext modeling and mapping consultants for use in developing Muskingum routing coefficients for HEC-HMS models.

Model Calibration

Hydrologic and hydraulic models must be calibrated for a minimum of three (3) historical events. One of those events will be Hurricane Harvey. Two other events will be prescribed by the HCFCD and the MAAPnext project management team. Rainfall data will be provided in the form of grid-based, time-variable rainfall data processed by Vieux and Associates, Inc. Rainfall data will correspond to TSARP sub-watersheds reflected in the current M3 models for Harris County. In completing the calibration process, the following hydrologic modeling parameters may be modified in order to adequately reflect historical results.

- BDF values may be modified within a range of acceptable values for given land uses and drainage system conditions.
- Impervious cover values may be modified within a range of acceptable values for given land uses. Justification for modifying values provided in the county-wide layer should be provided.
- Overflows from and to adjacent watersheds may be taken into account. Coordination with study consultants for the adjacent watersheds will be required if overflows are suspected or known.

Even though the use of unsteady-flow, 1D/2D HEC-RAS models will in effect eliminate the need for routing data, the provision of a self-contained HEC-HMS model for each watershed will be very beneficial by allowing a means for completing simple impact analyses and watershed management studies. Therefore, the Muskingum routing method should be used to simulate storage routing reaches in the HEC-HMS model to approximate recorded peak flow rates at gage locations. The methods described in the previous section should be used to establish the required Muskingum routing parameters.

More information on the hydrologic model calibration process is provided in the MAAPnext white paper titled "**Model Calibration Requirements and Procedures for Harris County, Texas**."

BDF Approach Demo & Sample Calculations

A PowerPoint presentation developed to illustrate the basic steps involved in establishing BDF values and computing Clark Tc and R coefficients is attached for review. That presentation outlines a 12-point process as follows. It is assumed that sub-area boundaries have been identified in GIS.

1. Identify the main channel into which storm runoff from the sub-watershed drains. Develop GIS line work that identifies the main channel. Categorize the main channel as natural, improved earthen, or improved concrete.
2. Identify principal tributaries within the sub-watershed. Develop GIS line work that identifies these tributary channels. Categorize each tributary as natural, improved earthen, or improved concrete.

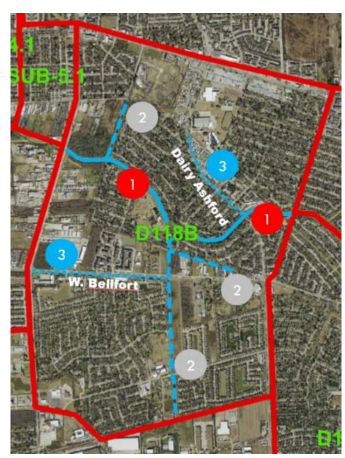


Figure 7: Steps 1-3 (Channel BDF)

3. Add storm sewer trunk lines, typically including only major sewers located along major thoroughfares or within dedicated easements, and only storm sewers that are of significantly greater size than neighborhood systems typical of the systems within the sub-watershed. These may be pre-1984 or post-1984 storm sewers.
4. Add land use polygons for the following land uses.
    - Undeveloped (Areas with No Drainage Improvements)
    - Open Space (Graded, such as Golf Courses, Athletic Fields, etc. with Limited Drainage Improvements)
    - Developed Areas with Roadside Ditch Drainage
    - Developed Areas with Curb-and-Gutter Streets and Storm Sewers (Pre-1984)
    - Developed Areas with Curb-and-Gutter Streets and Storm Sewers (Post-1984)

Figure 8: Step 4 (Land Use BDF)

5. Compute the weighted BDF value by multiplying channel lengths and development areas by corresponding BDF values from Table 2, dividing by the total channel / trunk line sewer length and total development area, and adding the channel and development values.

Weighted BDF = { Σ (Channel BDF x Length) / Σ (Channel Lengths) } + { Σ (Land Use BDF x Area) / Σ (Area) }

6. Compute Tc & values for Clark's Unit Hydrograph using the equations previously presented in this paper.
7. Adjust the base Tc and R values for Slope & Detention using the equations previously presented in this paper.
8. Use HEC-HMS to compute runoff hydrographs for each model sub-watershed.
9. Insert computed hydrographs into the watershed RAS model.
10. Calibrate the HEC-RAS model using three (3) historical storm events that significantly impacted the study watershed.
11. Adjust the initial BDF values to increase or reduce flow rates per calibration results. The following adjustments may be made to influence the BDF values.
    - Add / Deduct Storm Sewer Length
    - Add / Deduct Channel Length
    - Modify Land Use Polygons
    - Sub-Divide Drainage Area
12. Re-calibrate the HEC-HMS model. Repeat as needed, increasing or reducing BDF values, re-computing Tc & R values and runoff hydrographs, and re-inserting the hydrographs into the HEC-RAS model.

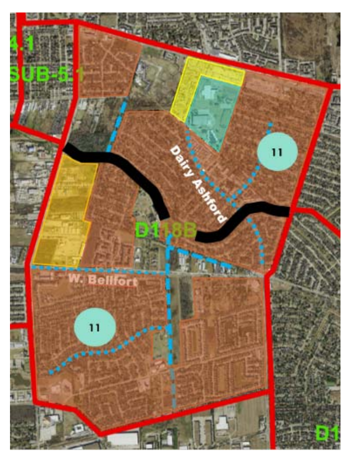


Figure 9: Step 11 (Adjust BDF)

A PowerPoint presentation is attached to illustrate the progressive steps and calculations required to establish the final BDF value for a given sub-watershed and compute the required Tc and R values. In addition to the PowerPoint presentation, a set of sample BDF calculations for the Hunting Bayou watershed is attached for the purpose of illustrating the process of determining BDF values and calculating values of the Clark Tc and R coefficients for use in HEC-HMS.

GIS Standards for BDF Documentation

This section provides GIS standards that are required to backup Basin Development Factor (BDF) TC&R calculations. The GIS shape files should document the engineer's Conveyance System and Land Use lengths and areas that were input in the watershed's TC&R table. These features will also allow potential reviewers to understand how current values were obtained while facilitating future updates to these values.

Conveyance System

Submit GIS line features that represent the channels and storm sewers that were used to determine the conveyance system BDF value.

The conveyance feature lines should be assigned their corresponding channel descriptions in the "Substrate" attribute. For consistency, pick from the following: (1) Natural, (2) Improved, or (3) Concrete. Each of these conveyance types will be line features with linear footage calculated in the "Length ft" attribute. Populate the "FeatID" attribute with a unique identifier for any conveyance features if needed for reference to the engineer, reviewer, or future user. The table below summarizes the line features within the Conveyance System shape file.

Feature Name	Conveyance_System.shp				
Type	Line Features				
Attributes	Field Type	Field Length	Description	Valid Field Values	Attribute Status
Feat_ID	Text	20	Unique Identifier for each feature		Required
Substrate	Text	40	Description of feature substrate.	"Natural", "Improved", "Concrete"	Required
Length_ft	Double		Linear Feet of feature		Required

Land Use

Submit a GIS polygon feature that represents the breakdown of areas that was used to determine the land use BDF values.

The land use feature polygons should be assigned their corresponding land use descriptions under the "LC_Type" attribute. Use the following field names for consistency, (1) Undeveloped, (2) Open Space (Graded), (3) Roadside Ditch Drainage, (4) Curb-and-Gutter with Storm Sewer Pre-1984, (5) Curb-and-Gutter with Storm Sewer Post-1984. Each of these land uses will be created as a polygon to allow for acreages to be calculated.

The table below summarizes the line features within the Land Cover shape file.

Feature Name	Land_Cover.shp				
Type	Polygon Features				
Attributes	Field Type	Field Length	Description	Valid Field Values	Attribute Status
LC_Type	Text	50	Description of Land Cover Type	"Undeveloped","Open Space(Graded)", Roadside Ditch Drainage", "Curb-and-Gutter with Storm Sewers Pre-1984", "Curb-and-Gutter with Storm Sewers Post-1984"	Required
Acreage	Double		Acreage of Land Cover Polygon		Required

Detention Adjustments

In order to properly document the data used to compute detention adjustments to BDF-based unit hydrograph parameters, a GIS layer should be created with detention basin locations and attributes. The information required for each detention basin included in the detention adjustment calculations is as follows.

1. Provide a unique identifier for each detention facility. The recommended format is K100_01_D1, where D1 is a counter and K100_01 is the sub-area within which the detention basin is located.
2. Provide the computed storage volume for the detention basin in units of acre-feet.
3. Provide the water surface elevation or top of bank elevation used to define the "top" of the storage in the basin.

As an example, assume that data is being developed for the 10th detention basin in sub-area W140_03. The computed storage in the basin is 15.3 acre-feet. The minimum top of bank elevation around the basin is being used to identify the top of the storage, and the elevation is 85.5 feet. The required documentation is as follows.

- Identifier: W140_03_D10
- Storage: 15.3 acre-feet
- Elevation: 85.5 feet

Each detention basin should be identified using a polygon that "bounds" the basin and can be included in a detention shape file. Following are the appropriate GIS attributes for the detention basin polygons.

Feature Name	**Detention.shp**				
Type	Polygon Features				
Attributes	Field Type	Field Length	Description	Valid Field Values	Attribute Status
Basin_ID	Text	50	Description of Land Cover Type	**Sample "W140_03_D10"**	Required
Elevation	**Double**		**Elevation at "Top" of Storage in feet**		**Required**
Volume	Double		**Storage Volume in acre-feet**		Required

Attachments

- **Watershed Slope Classification Paper**
- **GIS Standards for BDF Back-Up Documentation**
- **Sample BDF Determination Calculations – Hunting Bayou Watershed**
- **PowerPoint with Directions on BDF Determinations & GIS Documentation**

Recommendation for:
Watershed Slope Classification within Harris County
(Created 02/28/2019)

Goal: To identify a standard method for approximating the catchment mean watershed slope.

Recommended Procedure: It is recommended that a GIS approach be used for estimating the watershed slope (S_o) for catchments. Standard practice of estimating the mean slope by sampling various portions of the watershed using engineering judgement is prone to variation between engineers. The following approach will standardize the estimation for consistency across Harris County. This approach is done using ACR-GIS's Spatial Analyst Slope tool to compute the slope from LiDAR and Zonal Statistics to summarize these slopes into a mean value for individual catchments. Slope is to be computed from LiDAR data resampled to a 660x660 foot pixel which allows for an approximation of slope over an approximately 10-acre sized pixel.

Testing: The following assumptions are made to generalize the LiDAR surface and provide a better approximation of catchment watershed slopes. Note channel slopes (S) will still be required to be approximated manually.

- The Slope tool was ran using the 2018 LiDAR with 3x3 pixels and resampled to 100x100 and 330x330 and 660x660 pixels
- Preliminary testing indicated that pixel sizes less than 200x200-feet tended to greatly overestimate the mean slope of the catchments. This was attributed to the high slope values that were being computed along edges of channels and basins. These cells high slope values were providing greater weight than the cells in the over bank areas and resulting in over estimation of S_o.
- Pixel sizes of 330x330 vs 660x660 were found to generally provide average slopes within 6-feet/mile of each other with the 330x330 in all cases being higher.
- The slopes computed for Cypress and Little Cypress using this method were compared to the slopes in the effective model TC&R spreadsheet. These watersheds have a large range of watershed slopes that encompass the maximum and minimum expected slopes for most watersheds in Harris County.
- When compared to the effective S_o values both the 330 and 660 slope results derived in GIS were found to be, on average, 8- to 22-percent flatter than those previously presented in the effective model TC&R spreadsheet. This comparison excluded several comparisons where differences were greater than 100-percent.
- Approximately 20% of the watersheds were randomly selected and S_o manually recomputed. These values were compared to the 330 and 660 slopes and found to be on average 25- and 9-percent flatter than those computed by GIS.
- **Table 1** provides a comparison of the slopes based on the 330 and 660 resampled LiDAR to the effective and manually re-evaluated catchments.

Conclusion: The slopes computed using the re-sampled LiDAR at a 660x600 cell size produced results generally within 10-percent of manually computed values. These slopes are generally higher than that of manually computed values as watershed wide computation picks up more of the localized effects. With the approximately 10-acre generalization of the surface, these localized effects are valid for consideration. Use of this method greatly improves consistency in the calculations in addition to a reduction in the effort required for model building.

The 660x660 slope surface for the entire 2018 LiDAR data set (660slope.TIF) will be provided. Consultants will only need to run the Zonal Statistics using their developed catchments to derive the S_o values for each sub-basin.

Figure 1 Zonal Statistic (Spatial Analyst Tool)

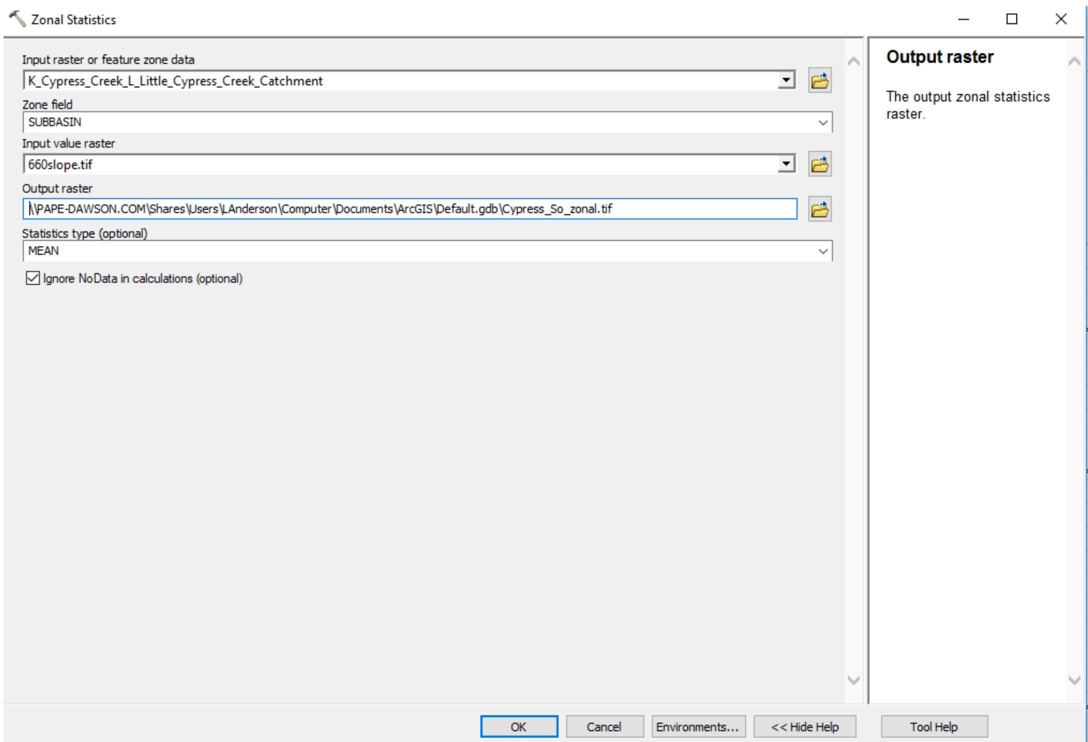
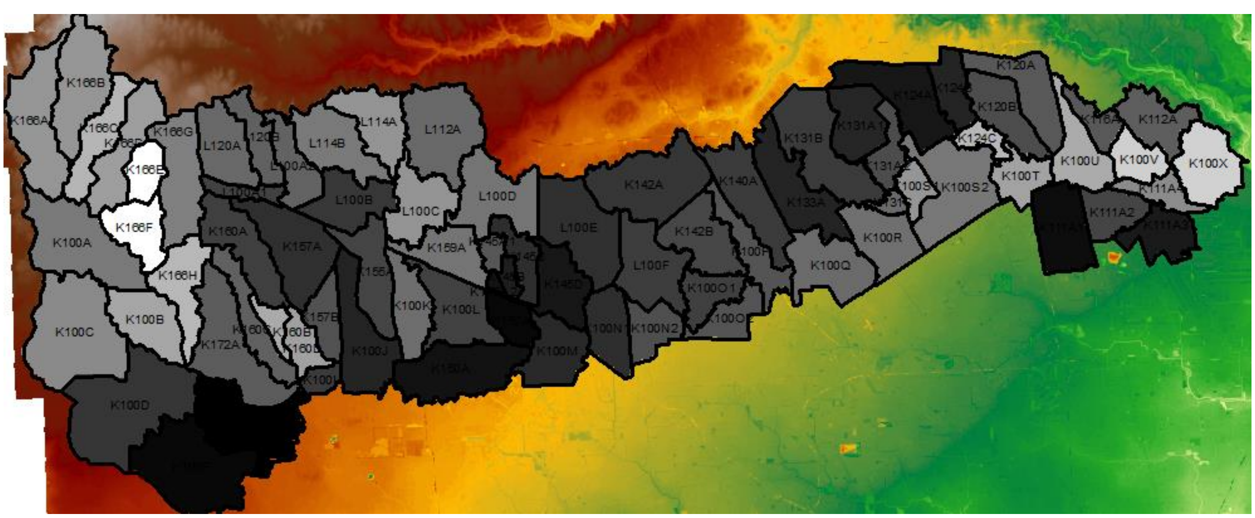


Figure 2 Resulting Catchment Mean Slope Raster



Harris County Flood Control District

FEMA
TC&R values
Cypress & Little Cypress Creek
HCFCD TC&R

Subwatershed	**Overland Slope effective (ft./mi.)**	Mean 330x330		Mean 660x660		Manual Re-Calculation of Watershed S_o		
	So	Overland Slope(ft./mi.)	%diff vs effective	Overland Slope(ft./mi.)	%diff vs effective	Overland Slope(ft./mi.)	%diff vs 330	%diff vs 660
k100a	40.9	29.1	-29%	20.8	-49%	20.57	-29%	-1%
k100b	42.9	33.6	-22%	26.3	-39%			
k100c	29.1	27.8	-4%	22.8	-21%			
k100d	13.1	13.1	0%	12.3	-6%	11.28	-14%	-9%
k100f	5.1	7.8	53%	6.9	37%			
k100g	5.3	7.0	32%	5.7	7%			
k100h	13.2	6.2	-53%	5.0	-62%	4.97	-19%	0%
k100i	28.4	23.7	-17%	12.9	-55%			
k100j	8.8	11.3	29%	10.3	18%			
k100k	34.4	23.0	-33%	19.3	-44%			
k100l	16.3	20.5	25%	14.0	-14%			
k100m	27.6	17.9	-35%	11.0	-60%			
k100n1	42.1	15.7	-63%	11.5	-73%			
k100n2	49.9	20.8	-58%	15.5	-69%			
k100o1	37.6	20.0	-47%	13.8	-63%			
k100o2	52.2	19.2	-63%	16.1	-69%			
k100p	38.7	23.4	-40%	16.1	-58%			
k100q	48.7	24.3	-50%	19.0	-61%			
k100r	19.7	27.4	39%	19.6	0%	10.10	-63%	-49%
k100s1	31.2	30.8	-1%	24.1	-23%			
k100s2	28.4	25.1	-11%	20.6	-27%			
k100t	39.1	33.7	-14%	25.8	-34%			
k100u	48.9	35.7	-27%	26.6	-46%			
k100v	47.5	42.8	-10%	31.3	-34%	32.77	-23%	5%
k100x	25.7	40.7	59%	31.3	22%			
k111a1	9.4	11.9	27%	7.6	-19%			
k111a2	25.1	19.7	-21%	14.3	-43%			
k111a3	27.9	16.7	-40%	9.1	-67%			
k111a4	37.3	27.2	-27%	23.0	-38%			
k112a	14.8	21.7	47%	17.3	17%			
k116a	44.8	23.5	-48%	16.7	-63%	20.00	-15%	20%
k120a	15.0	23.4	56%	16.9	12%			
k120b	38.3	23.5	-39%	15.3	-60%			
k124a	15.9	15.4	-3%	8.8	-44%			
k124b	35.6	15.5	-57%	10.2	-71%			
k124c	68.3	47.3	-31%	28.4	-58%			
k131a1	33.5	17.9	-47%	10.5	-69%			
k131a2	37.6	22.3	-41%	15.2	-59%			
k131b	17.9	19.9	12%	13.0	-27%			
k131c	53.3	27.8	-48%	18.9	-65%			
k133a	26.9	15.2	-43%	10.2	-62%			
k140a	46.7	19.8	-58%	13.2	-72%			
k142a	37.2	19.1	-49%	12.4	-67%			
k142b	42.9	20.4	-52%	14.6	-66%	10.21	-50%	-30%
k145a1	25.0	21.1	-16%	16.6	-33%			
k145a2	14.0	13.8	-1%	8.3	-41%			
k145b	14.0	19.2	37%	9.5	-32%			
k145c	25.0	15.8	-37%	11.4	-54%			
k145d	14.0	13.7	-2%	8.6	-39%			
k150a	6.1	16.3	165%	8.2	34%			
k152a	15.3	11.4	-26%	6.9	-55%			
k155a	18.7	20.7	11%	14.3	-23%			
k157a	6.1	14.4	136%	11.9	95%			
k157b	9.7	16.0	65%	15.8	63%			
k159a	50.2	25.5	-49%	20.1	-60%			
k160a	3.6	16.7	368%	13.7	283%	12.30	-27%	-10%
k160b	47.9	32.0	-33%	26.8	-44%			
k160c	22.1	21.6	-2%	17.6	-20%			
k160d	20.1	34.5	72%	25.5	27%	18.95	-45%	-26%
k166a	43.0	30.6	-29%	24.1	-44%			
k166b	47.9	30.9	-35%	24.4	-49%			
k166c	36.5	38.8	6%	28.0	-23%			
k166d	33.7	36.4	8%	25.1	-25%			
k166e	60.3	49.4	-18%	36.9	-39%			
k166f	44.1	47.6	8%	38.9	-12%	44.47	-6%	14%
k166g	46.5	29.1	-37%	21.4	-54%			
k166h	44.7	38.9	-13%	28.4	-36%			
k172a	7.8	20.0	156%	17.0	117%			
l100a1	16.0	20.6	29%	13.9	-13%			
l100a2	2.6	20.0	657%	18.1	584%	15.70	-22%	-13%
l100b	32.0	17.0	-47%	12.7	-60%			
l100c	34.0	32.6	-4%	23.8	-30%			
l100d	27.0	23.6	-13%	20.3	-25%			
l100e	15.0	16.9	13%	11.7	-22%			
l100f	13.0	19.9	53%	13.4	3%	9.60	-52%	-28%
l112a	38.0	22.2	-42%	18.6	-51%			
l114a	26.0	26.2	1%	23.9	-8%			
l114b	16.7	22.0	32%	20.8	25%			
l120a	9.1	22.6	150%	18.8	108%	18.84	-17%	0%
l120b	2.6	19.5	637%	17.6	568%	11.24	-42%	-36%
Average % Difference			-8%		-22%		-25%	-9%

637% Red cells excluded from average % Difference

Memo

Date:	Friday, March 01, 2019
Project:	MAAPnext
To:	Duane Barrett, PE, CFM
From:	Alex Yescas, PE, CFM, ENV SP
Subject:	**Draft GIS standard nomenclature**

Overview

The hydrology pre-processing information associated with the MAAPnext project involves assessing several different layers of GIS data. The goal of this summary is to standardize the GIS nomenclature associated with the various layer types that will be used to assess the watersheds. The two specific layers that require a level of standardization is for conveyance facilities and land uses within the watershed. These are important to establish the standardization to have consistency amongst the different watersheds and consistency in the pre-processing calculations for the Basin Development Factor (BDF). The pre-processing of the hydrology includes entering conveyance facility and land use type. These two allow for the determination of the TC and R adjustments per the BDF for each watershed. A list of conveyance and land use types have been identified and are shown below.

Conveyance System

The following conveyance features have been listed for consistency include No Channel/Natural, Improved, and Concrete. Each of these conveyance types will be line features to allow for linear footage to be calculated. The line feature will be entered into a GIS shapefile as a text field with up to 40 characters. This field will not be case sensitive, to limit processing errors within GIS. The table below summarizes the line features within the Conveyance System shapefile.

Feature Name	Conveyance_System.shp				
Type	Line Features				
Attributes	Field Type	Field Length	Description	Valid Field Values	Attribute Status
Feat_ID	Text	20	Unique Identifier for each feature		Required
Substrate	Text	40	Description of feature substrate.	"No Channel/Natural", "Improved", "Concrete"	Required
Length_ft	Double		Linear Feet of feature		Required

Land Use

The land use features shapefile will be standardized to allow users to enter information associated with the land use in each watershed and sub watershed. The following field names will be used for the land use Undeveloped, Open Space (Graded), Roadside Ditch Drainage, Curb-and-Gutter with Storm Sewer Pre-1984, Curb-and-Gutter with Storm Sewer Post-1984.

Each of these land uses will be created as a polygon to allow for acreages to be calculated. The maximum field length for this description will be set to 50 characters.

Feature Name	Land_Cover.shp				
Type	Polygon Features				
Attributes	Field Type	Field Length	Description	Valid Field Values	Attribute Status
LC_Type	Text	50	Description of Land Cover Type	"Undeveloped","Open Space(Graded)", Roadside Ditch Drainage", "Curb-and-Gutter with Storm Sewers Pre-1984", "Curb-and-Gutter with Storm Sewers Post-1984"	Required
Acreage	Double		Acreage of Land Cover Polygon		Required

Memorandum

Date: Monday, January 07, 2019

To: Brian Edmondson, P.E., CFM

From: Duane Barrett, P.E., CFM – HDR Engineering, Inc.

Project: MAAP*next* Hydrology

Subject: BDF Values for Hunting Bayou Pilot Study

This memorandum describes the development of BDF values for preliminary HEC-HMS modeling of the Hunting Bayou watershed. The BDF method is proposed for use in the upcoming MAAP*next* effort for hydrologic modeling of Harris County watersheds.

Introduction

The Hunting Bayou watershed is located in the northeastern quadrant of the area circumscribed by Loop 610 and covers an area of approximately 31.0 square miles. The watershed is almost fully developed, with most of the development occurring in the middle portion of the 20th century. Drainage is provided by open channels, which are predominately earthen with some concrete-lined segments, open ditches and storm sewers.

The M3 model of the Hunting Bayou watershed was developed using the Harris County Standard Method with Modified Puls routing reaches between analysis points. The watershed was divided into twenty (20) sub-areas for purposes of developing the M3 model. Following is a summary of 100-year peak flow rates computed using the M3 HEC-HMS model of the Hunting Bayou watershed. These results were obtained using HEC-HMS Version 3.3.

M3 Model 1% Flows - Hunting Bayou Watershed

HEC-HMS Node	Total DA (sq mi)	Station (ft)	Q_{100} (cfs)
H1000000_0020_J	30.98	2000	10,567.7
H1000000_0020_R	29.58	2000	10,154.9
H1000000_0097_J	29.58	9700	10,200.6
H1000000_0097_R	24.08	9700	8,248.7
H1000000_0270_J	24.08	27000	8,298.8
H1000000_0270_R	19.13	27000	6,863.9
H1000000_0319_J	19.13	31900	6,869.6
H1000000_0319_R	17.41	31900	6,566.0
H1000000_0403_J	17.41	40300	6,615.6
H1000000_0403_R	14.99	40300	6,079.3
H1000000_0558_J	14.99	55800	6,308.1
H1000000_0558_R	13.65	55800	5,658.7
H1000000_0567_J	13.65	56700	5,657.5
H1000000_0567_R	9.42	56700	4,309.7
H1000000_0643_J	9.42	64300	4,589.2
H1000000_0643_R	4.48	64300	2,228.5
H1000000_0668_J	4.48	66800	2,266.6
H1000000_0668_R	2.35	66800	1,094.4
H1000000_0730_J	2.35	73000	1,310.5

Initial BDF Estimates

Initial estimates of BDF values for the twenty (20) sub-areas in the Hunting Bayou M3 model were developed via the following procedure.

1. Superimpose M3 watershed and sub-area boundaries on a 2018 aerial photograph of the Hunting Bayou watershed.
2. Compute BDF values using the equation BDF = (6 x DLU_{DET}) + (3 x DCI). This equation was previously developed in connection with testing of the BDF method and has been found to yield reasonable results.
3. Develop a Microsoft Excel workbook in which drainage improvement indices are quantified via user-input percentages of total area.
4. Use Google Maps to view development patterns, channel condition, type of drainage system (storm sewer vs. open ditch) for each sub-area.
5. Use City of Houston GIMS data to determine and/or verity what areas are drained by storm sewers versus open ditch systems.
6. Input data to the Excel workbook to compute BDF values, base Tc and R values, and adjusted Tc and R values.

The Excel workbook is divided into two sheets, the first for data input and base BDF value calculations, and the second for computing base Tc and R values plus slope and detention adjustments, as well as any adjustments required to account for ponding. A copy of each of those worksheets is attached, along with an annotated map of the Hunting Bayou watershed. For this exercise, the following standardized BDF values were used for various land uses.

Drainage System Description	Avg. BDF Value
Undeveloped with No Drainage Improvements	0.0
Roadside Ditch Drainage	1.5
Curb-and-Gutter with Storm Sewers Pre-1984	3.0
Curb-and-Gutter with Storm Sewers Post-1984	6.0

Estimated BDF values range from 4.05 to 8.55. Note that the BDF values presented in these worksheets are preliminary and represent initial estimates. Model calibration and validation work is required to adjust and finalize these preliminary values. Following are notes on BDF value development for each of the twenty (20) sub-areas in the Hunting Bayou M3 model.

- **H100A**. This area is fully developed (mixed commercial and residential), with about one-half of the sub-area drained by storm sewers and one-half drained by roadside ditches. The receiving channel is earthen and improved. The composite BDF is 5.25.
- **H100B**. This area is entirely developed as a residential area. Because the length of the Hunting Bayou channel segment within this sub-area is so short, the main trunk line storm sewer is assumed to account for 2/3 of the total channel length. The composite BDF for this area is 7.71, in part due to the “lined” channel.
- **H100C**. This area is entirely developed as an industrial / commercial area. Most of the area is served by storm sewers, most of which have been upgraded and are treated as “post 1984) systems with full index value of 6.0 to include storm sewers and curb-and-gutter streets. The composite BDF value is 8.55.

- **H100D**. This area is fully developed, with combination of rail yard and residential areas. About 70% of the area is drained by roadside ditch systems, with the remainder drained by pre-1984 storm sewer systems. The composite BDF is 4.95.
- **H100E**. Hunting Bayou drains through this area, which is about 90% developed, with refineries, industrial and commercial areas, along with limited residential development. About 60% of the area is drained by roadside ditches, with another 30% drained by storm sewers. The composite BDF value is 4.80.
- **H100F**. This area is approximately 70% developed, about 50% with roadside ditch drainage and 20% via storm sewers. Development is mostly industrial and commercial, and the channel of Hunting Bayou passes through the area. The composite BDF value for this area is 4.35.
- **H100G**. This sub-area encompasses significant commercial and residential development along Loop 610, along with a large undeveloped area. The area is roughly evenly divided in terms of drainage between undeveloped, pre-1984 storm sewer, and post-1984 storm sewer. The composite BDF value is 6.00.
- **H100H**. This area lies at the downstream end of Hunting Bayou, where it outfalls to the Houston Ship Channel. About 70% of the area is developed, mostly as industrial but with a little single-family residential development. Drainage in developed areas is via open ditch systems. The composite BDF value is 4.05.
- **H101A**.This area lies south of Loop 610 and encompasses significant industrial and single-family residential development. The area is entirely developed, and storm sewer trunk lines are assumed to form about 50% of the channel length. Drainage is evenly split between pre-1984 storm sewer and open ditch. BDF = 6.75.
- **H102A**. This sub-area comprises the area draining to a Hunting Bayou tributary south of Loop 610. The area is evenly divided between undeveloped and residential development with roadside ditch drainage. The tributary channel is concrete lined. The composite BDF value for this area is 6.75.
- **H103A**. This area is entirely developed as a commercial / industrial area with mixture of roadside ditch (40%) and storm sewer (60%) drainage. Storm sewers appear to be pre-1984 vintage. The area is drained by an improved earthen channel. The composite BDF value is 5.40.
- **H103B**. This area is almost entirely developed as a single-family residential area and is roughly bisected by Loop 610. The area north of 610 is drained by storm sewers, while the area south of 610 is drained by a mixture of roadside ditches, storm sewers, and concrete-lined swales. The composite BDF is 5.70.
- **H106A**. This area is predominantly developed as single-family residential with mixture of open ditch and pre-1984 storm sewer drainage. A long trunk storm sewer in the western portion of the sub-area is treated as a concrete-lined channel, and about 2/3 of the channel is thus lined. The composite BDF is 6.96.
- **H108A**. This area is drained by a combination of open ditches (80%) and storm sewers (20%). One-half of the channel length is assumed concrete-lined due to the presence of long trunk line storm sewers. Development is nearly all single-family residential. The composite BDF value is 6.30.
- **H110A**. Approximately 2/3 of the channel draining this area is concrete lined. The sub-area is otherwise drained by roadside ditches and is developed as single-family residential (80%) and commercial/industrial (20%). The composite BDF value for this area is 6.51.
- **H112A**. This area is drained by improved earthen ditches. The area west of US59 (about 35% of the total) is drained by storm sewers and is industrial/commercial, while the area east of US59 (65% of total) consists of single-family development with roadside ditch drainage. The composite BDF value for this area is 5.03.

- **H118A**. This area is predominantly single-family residential with the exception of the US59 right-of-way. Drainage is provided by improved earthen channels, with open ditches draining roughly 90% of the total area. Pre-1984 storm sewers drain the remaining 10%. The composite BDF is 4.65.
- **H118B**. This area is mostly developed as a single-family residential area, with limited commercial areas. Outfall drainage is provided by improved earthen channels. About 70% of the area is drained by open ditches, with the remaining 30% drained by pre-1984 storm sewers. The composite BDF value is 4.95.
- **H119A**. This area is comprised of a large rail yard and single-family residential development, plus about 20% undeveloped area. Drainage is provided by improved earthen channels, with local drainage provided by roadside ditches (60%) and PRE-1984 storm sewers (20%). The composite BDF value is 4.50.
- **H125A**. This sub-area lies in the south-central portion of the watershed, encompassing areas on either side of Hunting Bayou. Development consists of a mixture of undeveloped (20%), single-family, and commercial/industrial. Drainage is provided by open ditches (20%) and storm sewers (60%). BDF = 5.10.

The following table summarizes the BDF values obtained using the equation approach and the worksheet. Individual values differ significantly, most frequently due to the fact that development in the Standard Method is not divided into pre-1984 and post-1984 areas as is done for the BDF method, and channel lining was not accounted for in the formula. However, the average BDF value for the two methods is very similar.

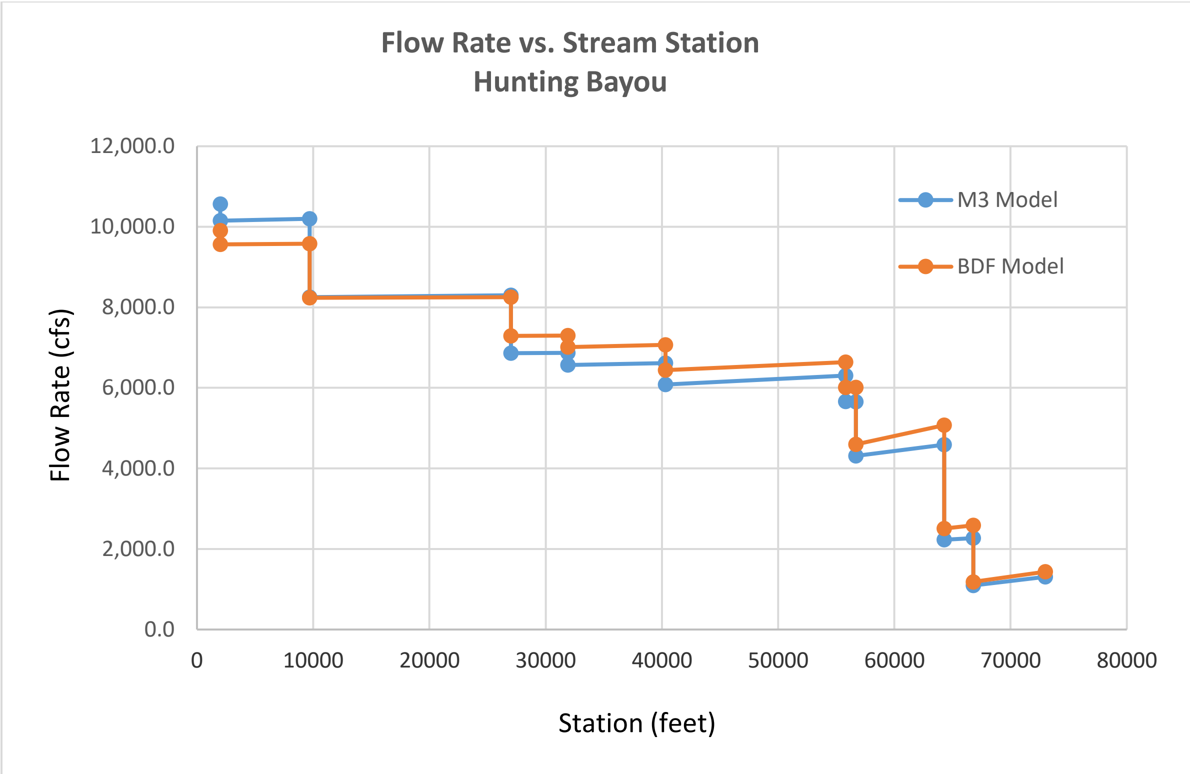
Sub-Area Name	Composite BDF	Equation BDF	Difference (Units)	TC (hours)	R (hours)
H100A	5.25	7.18	-1.93	1.77	4.28
H100B	7.71	7.68	0.03	1.55	3.53
H100C	8.55	7.47	1.08	1.37	3.04
H100D	4.95	8.27	-3.32	2.10	5.19
H100E	4.80	6.92	-2.12	2.73	6.61
H100F	4.35	3.84	0.51	2.46	6.11
H100G	6.00	4.18	1.82	2.42	5.66
H100H	4.05	3.48	0.57	2.19	5.41
H101A	6.75	7.48	-0.73	1.19	2.57
H102A	6.75	5.05	1.70	2.25	5.12
H103A	5.40	6.94	-1.54	2.06	5.02
H103B	5.70	7.91	-2.21	1.68	3.86
H106A	6.96	6.42	0.54	1.86	4.29
H108A	6.30	6.80	-0.50	2.37	5.43
H110A	6.51	8.14	-1.63	1.38	3.14
H112A	5.03	7.73	-2.70	2.01	4.98
H118A	4.65	7.55	-2.90	2.32	5.75
H118B	4.95	7.80	-2.85	1.84	4.61
H119A	4.50	6.82	-2.32	2.42	6.01
H125A	5.10	4.73	0.37	2.54	6.12
Averages	**5.71**	**6.62**	**-0.91**	**-----**	**-----**

Preliminary HEC-HMS Results

The TC and R values computed from the BDF values were adjusted for slope, detention, and ponding as necessary, and those values were then copied into the M3 HEC-HMS model of the Hunting Bayou watershed. The following table and graph summarize M3 and revised model results.

HEC-HMS Node	Total DA (sq mi)	Station (ft)	M3 Q_{100} (cfs)	BDF Q_{100} (cfs)	Difference (%)
H1000000_0020_J	30.98	2000	10,567.7	9906.0	-6.26%
H1000000_0020_R	29.58	2000	10,154.9	9559.9	-5.86%
H1000000_0097_J	29.58	9700	10,200.6	9580.5	-6.08%
H1000000_0097_R	24.08	9700	8,248.7	8236.9	-0.14%
H1000000_0270_J	24.08	27000	8,298.8	8253.8	-0.54%
H1000000_0270_R	19.13	27000	6,863.9	7289.6	6.20%
H1000000_0319_J	19.13	31900	6,869.6	7295.2	6.20%
H1000000_0319_R	17.41	31900	6,566.0	7015.2	6.84%
H1000000_0403_J	17.41	40300	6,615.6	7068.4	6.84%
H1000000_0403_R	14.99	40300	6,079.3	6437.7	5.90%
H1000000_0558_J	14.99	55800	6,308.1	6640.2	5.26%
H1000000_0558_R	13.65	55800	5,658.7	6014.4	6.29%
H1000000_0567_J	13.65	56700	5,657.5	6013.4	6.29%
H1000000_0567_R	9.42	56700	4,309.7	4599.1	6.72%
H1000000_0643_J	9.42	64300	4,589.2	5072.2	10.52%
H1000000_0643_R	4.48	64300	2,228.5	2510.5	12.65%
H1000000_0668_J	4.48	66800	2,266.6	2588.8	14.22%
H1000000_0668_R	2.35	66800	1,094.4	1184.7	8.25%
H1000000_0730_J	2.35	73000	1,310.5	1437.1	9.66%

As indicated in the table and on the following graph, the range of differences between computed 100-year flow rates ranges from -6.26% to +14.22%, and the BDF-based flow rates reasonably reflect the Standard Method results. Again, the BDF values developed and presented in this memorandum are preliminary. At this point, flows would be input to a 1D/2D model, and hydrologic and hydraulic models would be calibrated and validated, with changes made to the BDF calculations, underlying assumptions, values, and resulting Tc and R values.



Conclusion

As indicated previously, the calculations and results presented in this memorandum represent a preliminary stage of development in the hydrologic modeling process. In actual practice, different assumptions and approaches might be taken. For example, different analysis points may be selected for hydrographs, and the approach, assumptions, calculations, and results for the BDF-based hydrology may change significantly. Keep in mind that in determining BDF values, the definition of the main channel, tributary systems, etc. is conditional upon the location of the analysis point and the type and layout of drainage systems included within each individual sub-area. Consult the white papers prepared in connection with the MAAP*next* project for additional information on the BDF method.

Sample BDF Calculations
Hunting Bayou Watershed Pilot Study
7-Jan-19

This Excel worksheet is a preliminary version that uses percentage estimates to compute weighted BDF values. The later, final version of the BDF worksheet is described in the "Tc and R" white paper and will be provided for use by all MAAPnext modeling and mapping consultants.

Subwatershed	Drainage Area (acres)	Drainage Area (sq.mi.)	Channel Improvements (% of Total Length)			BDF Includes or Excludes Stream	Undeveloped Area (No Drainage Improvements)		Developed with Roadside Ditch Drainage		Developed with Storm Sewer (Pre 1984)		Developed with Storm Sewer (Post 1984)		Composite BDF	Area Check
			Unimproved	Earthen	Concrete		Area (%)	BDF	Area (%)	BDF	Area (%)	BDF	Area (%)	BDF		Area (%)
H100A	716.8	1.12		100.00%		Includes	0.00%	0.0	50.00%	1.5	50.00%	3.0	0.00%	6.0	5.25	100.00%
H100B	723.2	1.13		33.00%	67.00%	Includes	0.00%	0.0	20.00%	1.5	80.00%	3.0	0.00%	6.0	7.71	100.00%
H100C	640.0	1.00		100.00%		Includes	0.00%	0.0	10.00%	1.5	0.00%	3.0	90.00%	6.0	8.55	100.00%
H100D	857.6	1.34		100.00%		Includes	0.00%	0.0	70.00%	1.5	30.00%	3.0	0.00%	6.0	4.95	100.00%
H100E	1548.8	2.42		100.00%		Includes	10.00%	0.0	60.00%	1.5	30.00%	3.0	0.00%	6.0	4.80	100.00%
H100F	1100.8	1.72		100.00%		Includes	30.00%	0.0	50.00%	1.5	20.00%	3.0	0.00%	6.0	4.35	100.00%
H100G	1478.4	2.31		100.00%		Includes	33.00%	0.0	0.00%	1.5	34.00%	3.0	33.00%	6.0	6.00	100.00%
H100H	896.0	1.40		100.00%		Includes	30.00%	0.0	70.00%	1.5	0.00%	3.0	0.00%	6.0	4.05	100.00%
H101A	640.0	1.00		50.00%	50.00%	Includes	0.00%	0.0	50.00%	1.5	50.00%	3.0	0.00%	6.0	6.75	100.00%
H102A	1427.2	2.23			100.00%	Includes	50.00%	0.0	50.00%	1.5	0.00%	3.0	0.00%	6.0	6.75	100.00%
H103A	908.8	1.42		100.00%		Includes	0.00%	0.0	40.00%	1.5	60.00%	3.0	0.00%	6.0	5.40	100.00%
H103B	870.4	1.36		90.00%	10.00%	Includes	0.00%	0.0	40.00%	1.5	60.00%	3.0	0.00%	6.0	5.70	100.00%
H106A	966.4	1.51		33.00%	67.00%	Includes	10.00%	0.0	50.00%	1.5	40.00%	3.0	0.00%	6.0	6.96	100.00%
H108A	1516.8	2.37		50.00%	50.00%	Includes	0.00%	0.0	80.00%	1.5	20.00%	3.0	0.00%	6.0	6.30	100.00%
H110A	640.0	1.00		33.00%	67.00%	Includes	0.00%	0.0	100.00%	1.5	0.00%	3.0	0.00%	6.0	6.51	100.00%
H112A	787.2	1.23		100.00%		Includes	0.00%	0.0	65.00%	1.5	35.00%	3.0	0.00%	6.0	5.03	100.00%
H118A	1017.6	1.59		100.00%		Includes	0.00%	0.0	90.00%	1.5	10.00%	3.0	0.00%	6.0	4.65	100.00%
H118B	627.2	0.98		100.00%		Includes	0.00%	0.0	70.00%	1.5	30.00%	3.0	0.00%	6.0	4.95	100.00%
H119A	1100.8	1.72		100.00%		Includes	20.00%	0.0	60.00%	1.5	20.00%	3.0	0.00%	6.0	4.50	100.00%
H125A	1388.8	2.17		100.00%		Includes	20.00%	0.0	20.00%	1.5	60.00%	3.0	0.00%	6.0	5.10	100.00%
														Averages	5.71	

Note: Cell shading indicates a required data input. 640.00

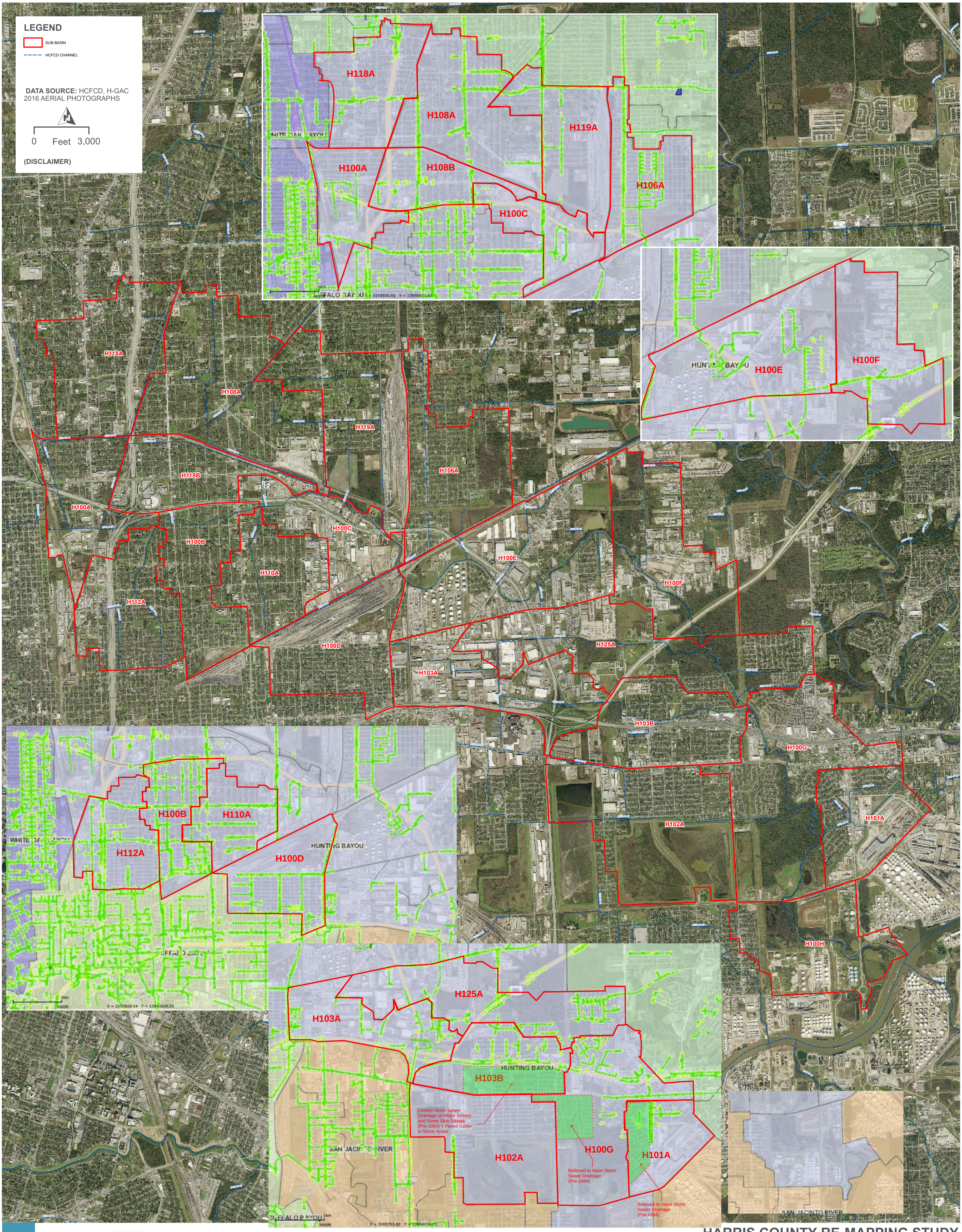
BDF Values for Basic Land Uses in Harris County	
Drainage System Description	Average BDF Value
Undeveloped with No Drainage Improvements	0.0
Roadside Ditch Drainage	1.5
Curb-and-Gutter with Storm Sewers Pre-1984	3.0
Curb-and-Gutter with Storm Sewers Post-1984	6.0

Notes

Notes on BDF Value Assignments

BDF values for Undeveloped areas may be greater than 0 if drainage improvements are present. Typical range is 0.0 to 3.0.

Roadside Ditch values may vary from 1.5 to 3.0 for Unstudied Streams and from 4.5 to 6.0 for Studied Streams.



HARRIS COUNTY RE-MAPPING STUDY

HUNTING BAYOU WATERSHED

EXHIBIT 1

PATH: C:\WORKSPACE\HC REMAPPING\GIS\HUNTINGBAYOU.MXD - USER: JBLEVINS - DATE: 7/9/2018

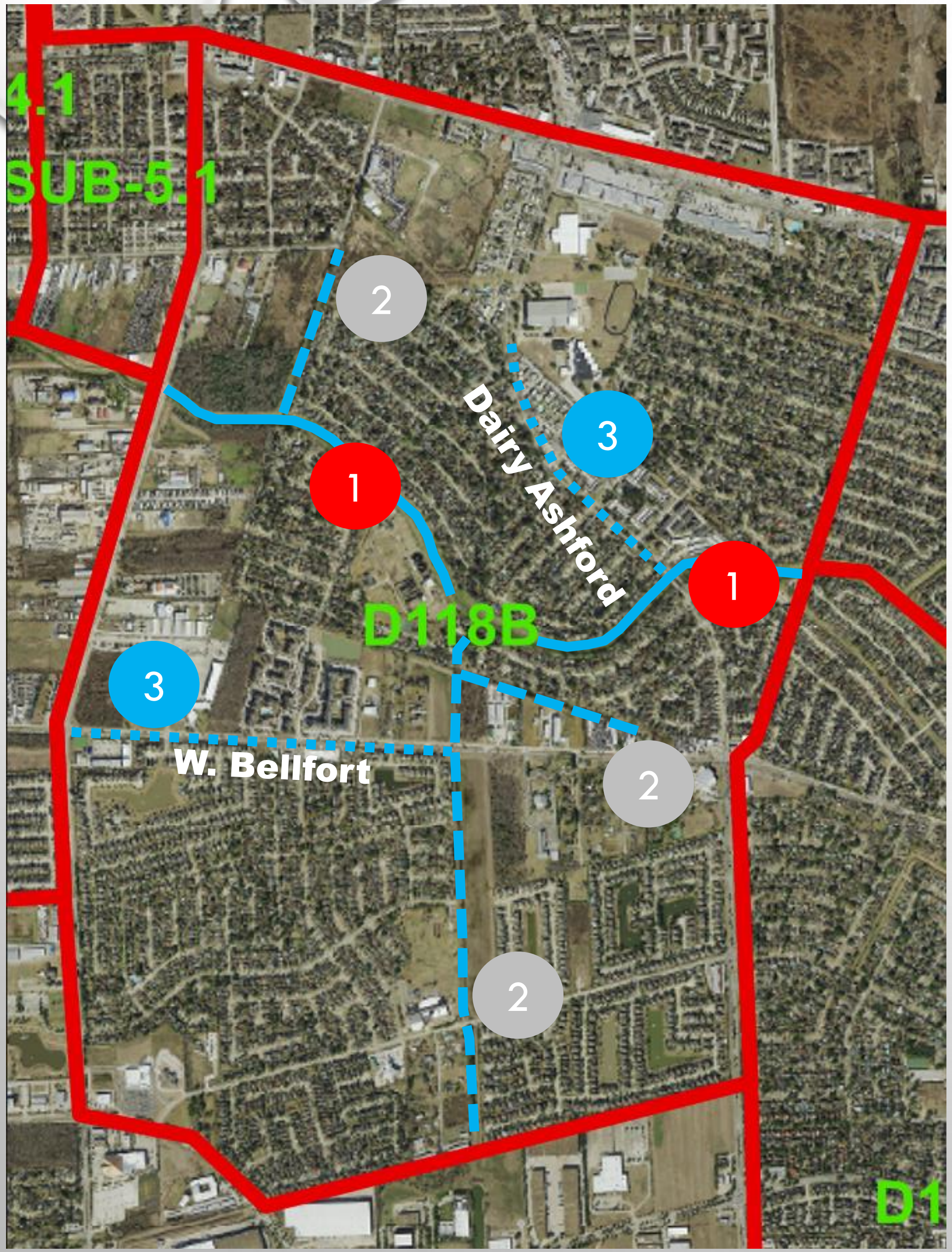
MAAP*next* MAPPING, ASSESSMENT, & AWARENESS PROJECT

BDF Demonstration

HARRIS COUNTY FLOOD CONTROL DISTRICT

FEBRUARY 15, 2019

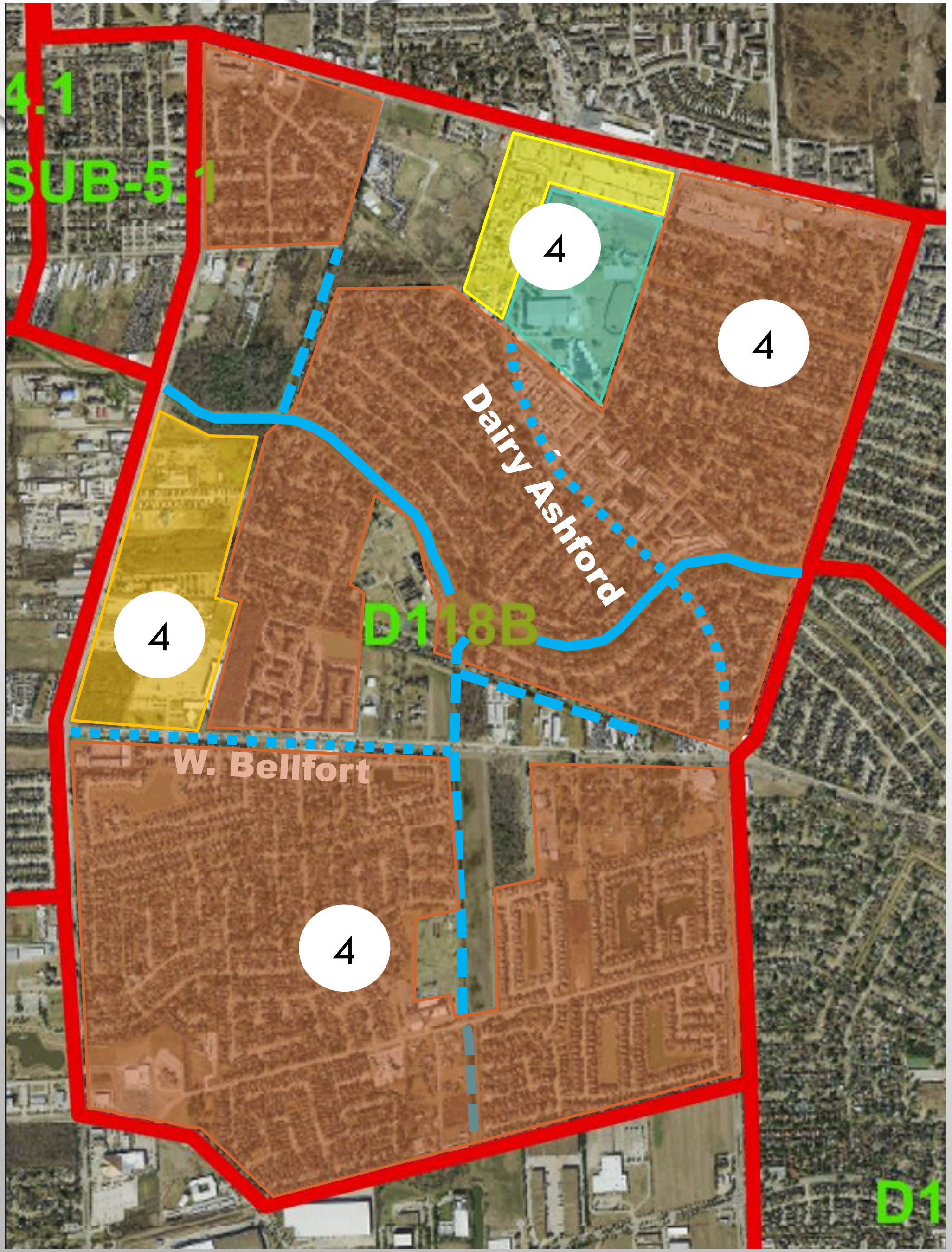
BDF Determination



1. **Identify Main Channel**
2. **Identify Principal Tributaries**
3. **Add Storm Sewer Trunk Lines**

Identify the main channel, principal tributaries, and storm sewer trunk lines in a way that characterizes the existing drainage systems & drainage patterns in the sub-watershed. Typically, the selected channels and sewers will represent an evenly-spaced system of drainage components.

The initial set-up should include the main channel and significant tributaries. Include storm sewer trunk lines along major thoroughfares. Exclude neighborhood storm sewer systems, which are accounted for in the land use polygons.



BDF Determination

4. Add Land Use Polygons & Areas
5. Compute Weighted BDF (Area/Length)

Use channel & storm sewer lengths to compute a weighted channel BDF factor. Use land use polygon areas to compute a weighted development BDF factor. Add the two to get the total BDF value.

BDF Values for Basic Land Uses in Harris County	
Drainage System Description	
Majority Major Conveyance System	BDF
No Channel/Natural	0
Improved	3
Concrete	6
Land Cover	BDF
Undeveloped	0
Open Space (graded)	1
Roadside Ditch Drainage	1.5
Curb-and-Gutter with Storm Sewers Pre-1984	3
Curb-and-Gutter with Storm Sewers Post-1984	6

BDF Determination

6. **Compute Tc&R Values**
7. **Adjust for Slope & Detention**

$$Tr = 10^{[(-0.05228xBDF)+0.4028\log10(A)+0.3926]}$$

$$TC = Tr + (A^{0.5})/2$$

$$R = 8.271e^{-0.1167*BDF}(A^{0.3856})$$

$$Tc_{ADJ} = TC \times K_s \times Cf$$

$$R_{ADJ} = R \times K_s \times Cf$$

$$Ks = -0.162\ln(S0xS)+1.5232 \text{ FOR } SxS_0>=26$$

$$Cf = 3 \times 10^{-5} x (DR)^2 - 0.00095(DR) + 1.0 \text{ FOR } DR>10$$

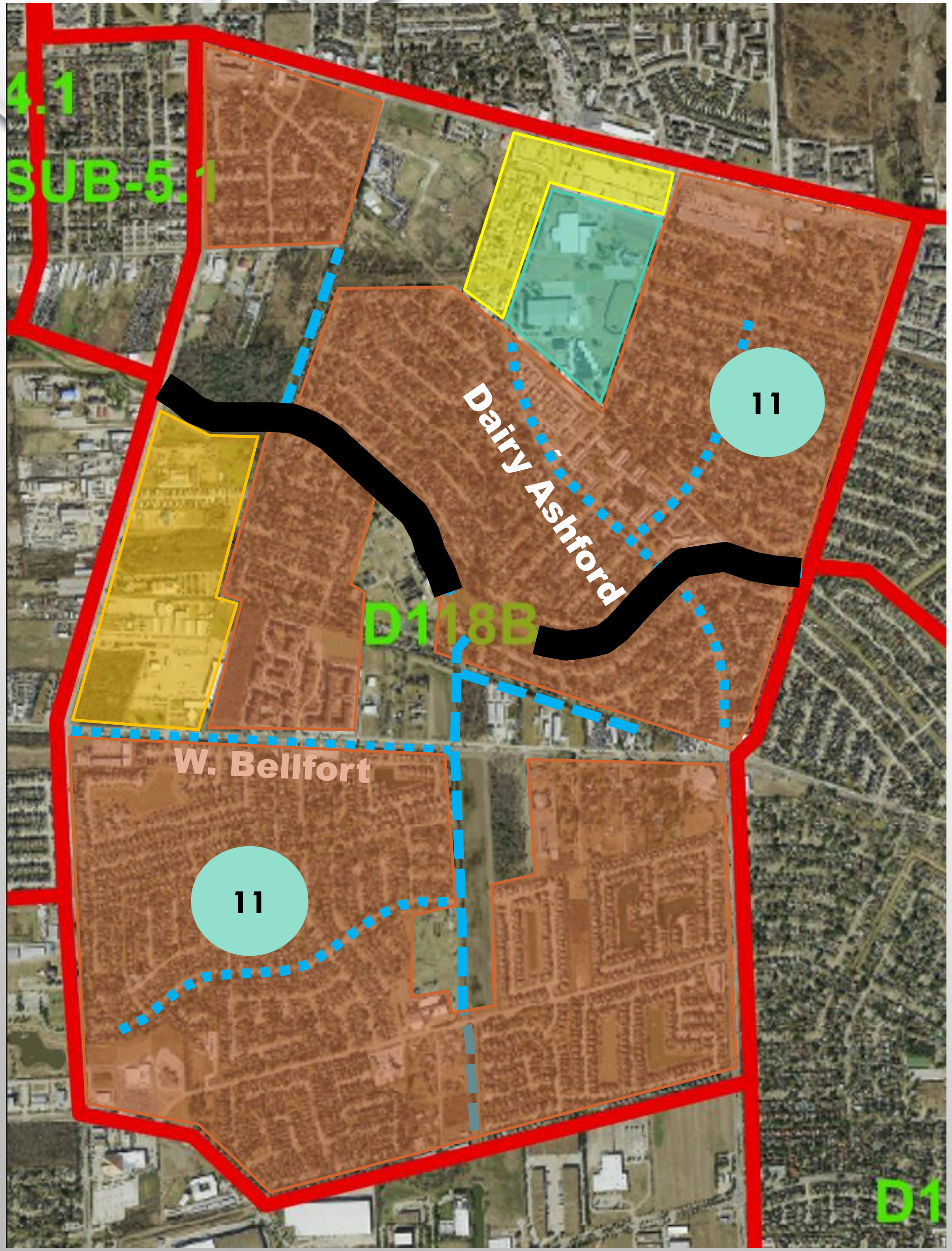
A = Drainage Area (square miles)

Tc = Time of Concentration (hours)

R = Storage Coefficient (hours)

Ks = Slope Correction Factor

Cf = Detention Correction Factor



Execute Model & Calibrate

8. Use HEC-HMS to Compute Hydrographs
9. Insert Hydrographs Into RAS Model
10. Calibrate RAS Model
11. Adjust BDF Per Calibration Results
    - Add / Deduct Storm Sewer Length
    - Add / Deduct Channel Length
    - Modify Land Use Polygons
    - Sub-Divide Drainage Area

- Re-Calibrate & Repeat As Needed

Adjustments related to calibration must be defensible and consistent with a reasonable characterization of the drainage systems witin the sub-watershed.

DISCUSSION

BDF is a characterization of drainage system efficiency. Include tributary systems as necessary to describe the system and its efficiency, but don't get too detailed, and don't over-think. Use calibration results to check your BDF number and identify necessary adjustments.