City of Houston, Texas
Department of Public Works and Engineering
Technical Paper No. 100
(TP-100)

Storm Sewer Design Applications for the City of Houston, Texas, Capital Improvement Plan Projects

October 19, 2005

Abstract

This Technical Paper No. 100 (TP-100) serves as a guideline for the latest stormwater design criteria outlined in Chapter 9 of the City of Houston Design Manual[1]. This paper includes a discussion of the methods that are to be utilized in the design process for Capital Improvement Plan (CIP) projects including storm drainage improvements, particularly Street and Bridge and Stormwater projects. The guidelines provided herein are intended to serve as supplemental information to the manual to aid the design engineer in adhering to the stormwater design requirements and criteria. TP-100 is intended for use by City Project Managers as well as consultants working on CIP projects.

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[1] City of Houston Department of Public Works and Engineering Infrastructure Design Manual, Revision 3, October 1, 2004

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1. PURPOSE

The purpose of this technical paper, TP-100, is to provide a guide for City Project Managers and consultants for use in designing CIP projects that comply with the stormwater design requirements and criteria outlined in Chapter 9 of the City of Houston Infrastructure Design Manual.

2. DESIGN PHILOSOPHY

The issue of storm water management has become a heightened subject of interest to the Houston community. The City has established updated criteria on storm water design in response to the severity and frequency of our local storms which lead to habitual drainage and flooding problems. The need has been identified for a higher level-of-service for our storm water infrastructure which would result in improved flood reduction. The City is currently implementing the following solutions:

- Increasing public awareness about flooding
- Devising and Implementing planning processes internal to the City and with other agencies such as the Harris County Flood Control District and the Corps of Engineers to identify flood reduction actions and projects which can be implemented
- Implementing Chapter 9 of the Department of Public Works and Engineering Infrastructure Design Manual to require a higher level-of-service storm sewer design to improve flood reduction in both public and private projects

2.1. Storm Sewer Design Criteria

Chapter 9 defines the design criteria for all CIP and development projects involving the design of stormwater facilities within City of Houston jurisdiction. This chapter outlines the standard stormwater design requirements including:

- Design frequency
- Velocity considerations
- Pipe sizes and placement
- Starting water surface and hydraulic gradient
- Manhole locations
- Inlets

The design criteria can be obtained via hard copy from the City Department of Public Works and Engineering or is available for download in *.pdf format at:

http://www.publicworks.cityofhouston.gov/documents/Design%20Manuals/dmanual.PDF

It should be noted the current version of the Design Manual dated February 1, 2005 includes recent additions to Chapter 9 as follows:

- The required use of HouStorm as the design analysis tool for CIP projects (9.05.A.1)
- The introduction of 4 Methods to be used for the Consideration of Overland Flow (9.05.D.2)
- Definition of a Maximum Ponding Elevation (MPE) established to prevent structural flooding (9.05.D.4.g.1)

2.2. Design Process

In addition to providing a guideline regarding the Chapter 9 design criteria, this paper will introduce the suggested design process that a project will follow based on the typical City of Houston scope of services, divided into Phase 1-Preliminary Engineering and Phase 2- Final Design. It should be noted that certain aspects of a project may be performed in a different sequence as directed by the Project Manager. These steps are discussed in detail in Sections 3.0 and 4.0 that follow.

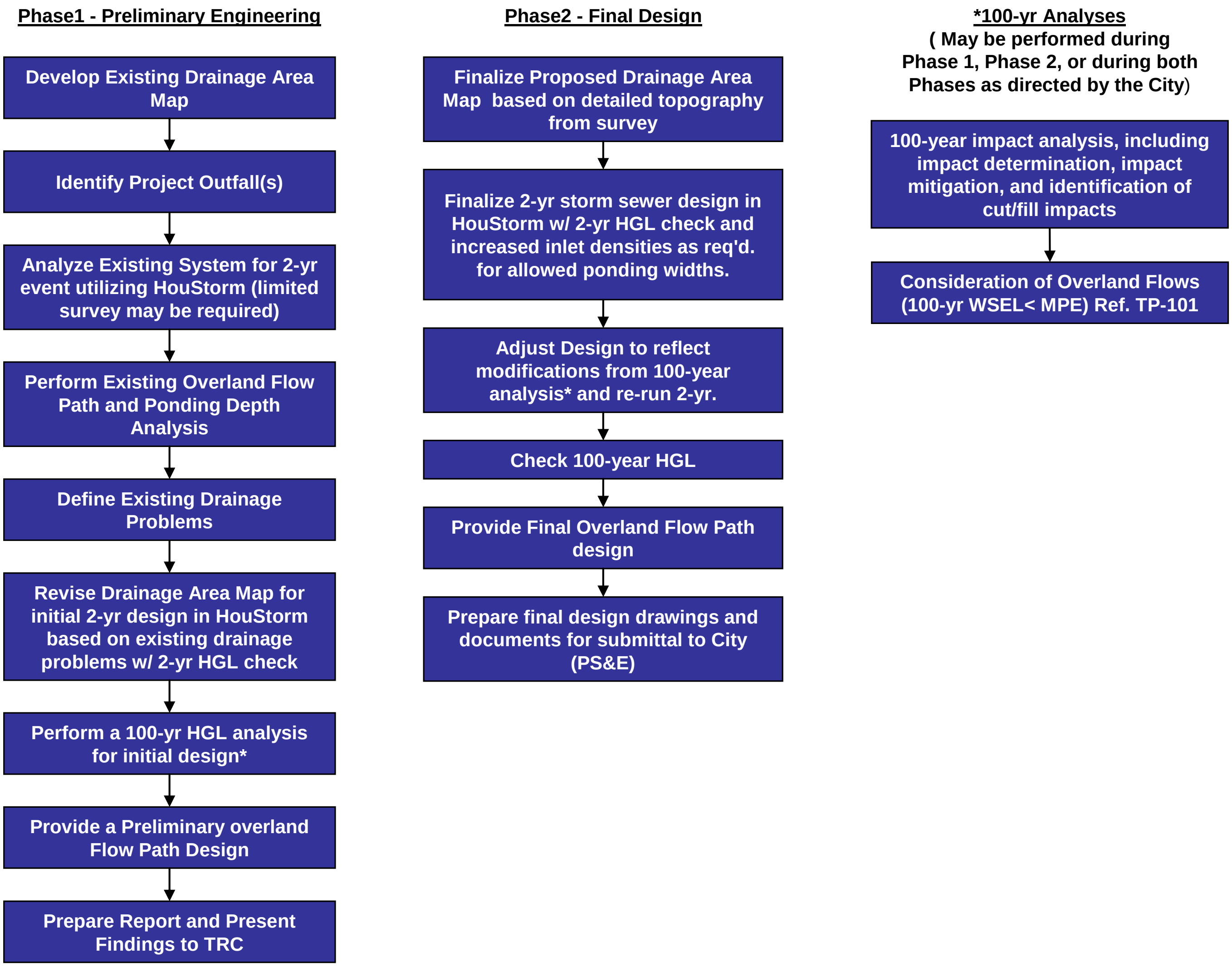

Figure 2.1 – Design Process for CIP Projects

3. PHASE 1 – PRELIMINARY ENGINEERING

As mentioned in Section 2.2, the typical City of Houston contract for a CIP project is divided into two phases for professional services; Phase 1 - Preliminary Engineering and Phase 2 - Final Design. In this section we will discuss the design services to be performed for the storm sewer design during Phase 1-Preliminary Engineering.

3.1. Development of Drainage Area Maps

The first step in any storm sewer project is the development of the drainage area map. This drainage area map delineates the region that contributes storm water runoff to a known point of interest, typically the project outfall(s). Recent practice, stemming from concerns over inlet capacities and roadway ponding extents, has resulted in drainage area maps being subdivided and delineated to the point of interception; i.e. an inlet, ditch culvert, etc. For City CIP projects, it is recommended that the Drainage area map be divided to this level (inlet level) for input into HouStorm as discussed in Section 3.3 and 3.6.

Various sources of information are available that can aid today's designer in the development of a project drainage area map. The Harris County Flood Control District's (HCFCD) Tropical Storm Allison Recovery Project (TSARP) products include Light Detection and Ranging (LiDAR) data and 2-foot contours for all of Harris County. This LiDAR data is a free, geographic information system (GIS)-based product made available by HCFCD and its technical partner, the Federal Emergency Management Agency (FEMA). An example LiDAR plot is included as Figure 1. Watershed and subwatershed boundaries were also developed as part of the TSARP project for all 22 watersheds within Harris County. These data are helpful on project's that traverse such boundaries. An additional data source is the United States Geological Survey's (USGS) digital elevation models available online at www.usgs.gov.

Figure 1 – Example of LiDAR Elevations (software: ArcGIS 8.x, spatial analyst, ArcHydro; Data: LiDAR)

3.1.1. Contour Maps

The City may require the use of LiDAR and USGS digital elevation models to generate other contour maps and maps with flow path directions, if this is applicable to the project scope and size. Development of these maps is particularly helpful not only in the generation of more accurate drainage area maps, but also in the consideration of overland flow discussed in Sections 3.4, 3.8, and 4.4 of this paper.

3.1.2. Existing Construction Drawings

In addition to the above data sources, traditional sources of data are still very important in the development of the project drainage area maps including past construction plans, drainage studies, and City GIMS information. This information can be used to define the project drainage divides within the watershed which can be further subdivided to the appropriate level (i.e., inlet-level) based on pavement vertical points of intersection or other features as determined by the specific project conditions (roadside ditches, culverts, etc.).

3.1.3. 100-year Floodplain Maps

Once the preliminary Drainage Area Map is developed, this information will be supplemented with Storm Water Investigative Survey discussed in Section 3.3.2 below in order to verify the resulting drainage area delineations. The drainage area maps shall include 100-year floodplain limits (show both the Effective FIRM limits and TSARP limits if different). The resulting drainage areas and 2-year storm sewer runoff rates shall be included on the drainage area map. For ease of review, flow direction arrows shall be included on the drainage area maps.

3.2. Identification of Outfalls

Project outfalls can usually be identified in the field with the naked eye; however, LiDAR can also be used to pinpoint and confirm the receiving channel(s) that collect runoff from the project area. Once the project's outfall channel(s) has been identified, the hydrologic and hydraulic models (if any) associated with the channel should be obtained and reviewed in order to determine the various WSEL's in the stream. The effective (or current) models should be obtained directly from FEMA. The draft TSARP models are available on DVD from HCFCD.

Flood insurance rate map (FIRM) panels for the project area—both effective and TSARP—should also be reviewed and compared. The effective FIRM panels for Harris County are available online at www.efloodmap.com; the TSARP project's FEMA Preliminary FIRM Panels are available at www.tsarp.org. The TSARP web site also offers a GIS viewer that allows the user to overlay the effective and TSARP flood plains.

The City and its consultant teams should coordinate with HCFCD in order to gain insight into any planned channel improvement projects, local buyout program participation, and the existence of regional detention basins, etc.

When the identified project outfall is an existing storm sewer, it is not necessary to analyze the entire downstream storm sewer system(s) to the receiving stream. Typical practice is to begin the analysis of the 2-year HGL of the proposed system at the top-of-pipe of the receiving storm sewer. However, there may be situations in which the scope may require the analysis of the downstream storm sewer; for instance, if the continuation to the receiving stream is a relatively short distance, and/or if the existing storm sewer is deemed incapable of conveying the contributing flows, even when pressure flow (head) is considered. As such, further analysis may be required at the direction of the project manager.

3.3. Existing System Analysis (HouStorm)

Using the City of Houston Comprehensive Drainage Plan, GIMS data, and construction plans for the project area, a preliminary HouStorm model of the existing system shall be created. Data can be imported from GIMS into a spreadsheet format for data entry into HouStorm, though it is generally recommended to input the data by hand as import of data can be complex and/or erroneous. This will include the entry of all drainage area information (name, acreage, "C" value and time of concentration), node data (type, associated drainage area, critical elevation, and other appropriate data such as inlet information), and link information (lengths, flowline or soffit elevations, material, n value, size, etc.). Once this model is constructed and analyzed for a 2-yr frequency, existing storm sewer system inadequacies can be defined such as insufficient capacities or deficient inlet density.

When entering the drainage area information into HouStorm, the Time of Concentration (Tc) may be entered using the City of Houston formula defined in Section 9.05.3.b. This formula is provided as an option for calculating Tc; however, it is recommended that Tc be calculated using one of many reference manuals available on the subject (i.e. HEC22 - See reference 2 of this paper). It is also recommended that a Minimum Tc of 10 minutes be used for all projects.

3.3.1. An Overview of HouStorm

HouStorm is a derivative software program based upon the Texas Department of Transportation's (TxDOT's) WinStorm computer program. The City of Houston has a license agreement with TxDOT to utilize this derivative software and make modifications to the computer code to meet specific requirements of the City.

HouStorm simulates storm drainage systems using a drainage network comprised of three basic drainage components:

- Drainage areas
- Nodes (junctions)
- Links (conduits)

The user describes the components of the system by proceeding through a series of dialogue windows defining each portion of the drainage components.

The computational features within HouStorm include the following:

- Computing peak discharges associated with the drainage areas
- Designing and/or analyzing seven types of storm drain inlets
- Designing and/or analyzing various conveyance elements (links) including pipes, box culverts, arch pipes, elliptical pipes, semicircular arches, and ditches
- Optionally, junction loss computations can be performed at the nodes
- Graphical visualization of the hydraulic gradeline for a selected reach
- Runoff computations using SCS TR20 Method or the Rational Method are provided. HouStorm is capable of designing and analyzing a system simultaneously when sizes of features are specified. Additionally, two frequency storms can be simulated concurrently in order to evaluate the performance of a system during different events, or a system can be designed based on one event and analyzed under a different event.

The HouStorm program and User's Manual are free to the public and can be downloaded at www.swmp.org.

3.3.2. Storm Water Investigative Survey

Detailed topography is not necessarily required during Phase 1- Preliminary Engineering. The City may require a limited preliminary or storm water investigative survey, in conjunction with field investigations, to gather existing storm sewer and overland flow information. This survey shall include the location of all storm sewer features (i.e. inlets, manholes, culverts, and ditches) to be adequately identified on available block maps to display their respective geometric position within the right-of-way. Furthermore, the identification of high points in roadways and ditches shall be determined from the design engineer's best judgment during the field investigations. All surveys conducted shall be based upon the 88NGVD, 2001 adjustment (TSARP) vertical datum, or as directed by the Project Manager. All available monuments in and around the project area shall be tied in to this survey.

The following is a list of the suggested items to be included in the storm water investigative survey:

- Manhole rim elevations
- Inlet top of curb and gutterline elevations
- Inlet types and sizes
- Storm sewer sizes, including inlet lead sizes and flow directions for connectivity
- Flow lines of storm sewers into manholes and inlets (from measure downs)
- Natural ground elevations on both sides of the right-of-way at manhole and/or inlet locations
- Key high point (vpi) elevations within roadway sections as needed to identify road channel and overland flow patterns as further described below
- Slab finished floor elevations for selected homes/structures in the project area to be approved by the project manager
- Ditch information: flowlines at high and low points, material, side slopes, bottom width, and depth. Also associated culvert information (excluding driveway culverts)

It is also recommended that typical sections of pavements in the project area be obtained. In determining overland flow characteristics of the project area (overland flow, in this case, is also intended to include channel flow within the streets as well as sheet flow from off-site areas), it may be necessary to identify key high point elevations of unique or particular street grades (VPI's) via vertical surveys. The general grade trends of the streets in the project area impacting the storm sewer performance are also should be identified. The intent is to verify the surface drainage, ponding (storage), and overland flow behavior of the system.

3.4. Existing Overland Path and Ponding Depth Analysis

LiDAR is very helpful in identifying low-lying depressions (where ponding occurs), land-locking, and natural or man-made flow paths. LiDAR data and 2-foot contour data DVD's can be obtained from HCFCD:

- LiDAR DVD titled: Harris County Digital Elevation Model release December 2002, version 1
- 2-foot contour DVD titled: Harris County 2-foot Contours, released June 2003

The Hydrologic Engineering Center's Geospatial Hydrologic Modeling Extension, or HEC-GeoHMS for ArcView GIS, uses ArcView and Spatial Analyst to analyze digital terrain information and identify drainage paths, among other custom capabilities. HEC-GeoHMS is available for free download at www.hec.usace.army.mil. Ponding maps can be generated using "fill sink" functions; overland flow paths can also be identified. The ArcGIS Hydro data model and tools, created by the University of Texas at Austin's Center for Research in Water Resources, can also be used to develop these project tools. The ArcHydro data model is available for free download at www.crwr.utexas.edu. Otherwise, proprietary versions of the software ArcView GIS 3.x, and/or ArcGIS 8.x or 9.x (with Arc Hydro), and spatial analyst can be purchased from http://www.esri.com.

Examples of LiDAR-based GIS output are shown in Figures 2 and 3. The design engineer shall generate a similar map exhibiting the existing overland flow patterns and locations where ponded water occurs due to topographical features, structures, and/or pavement grades.

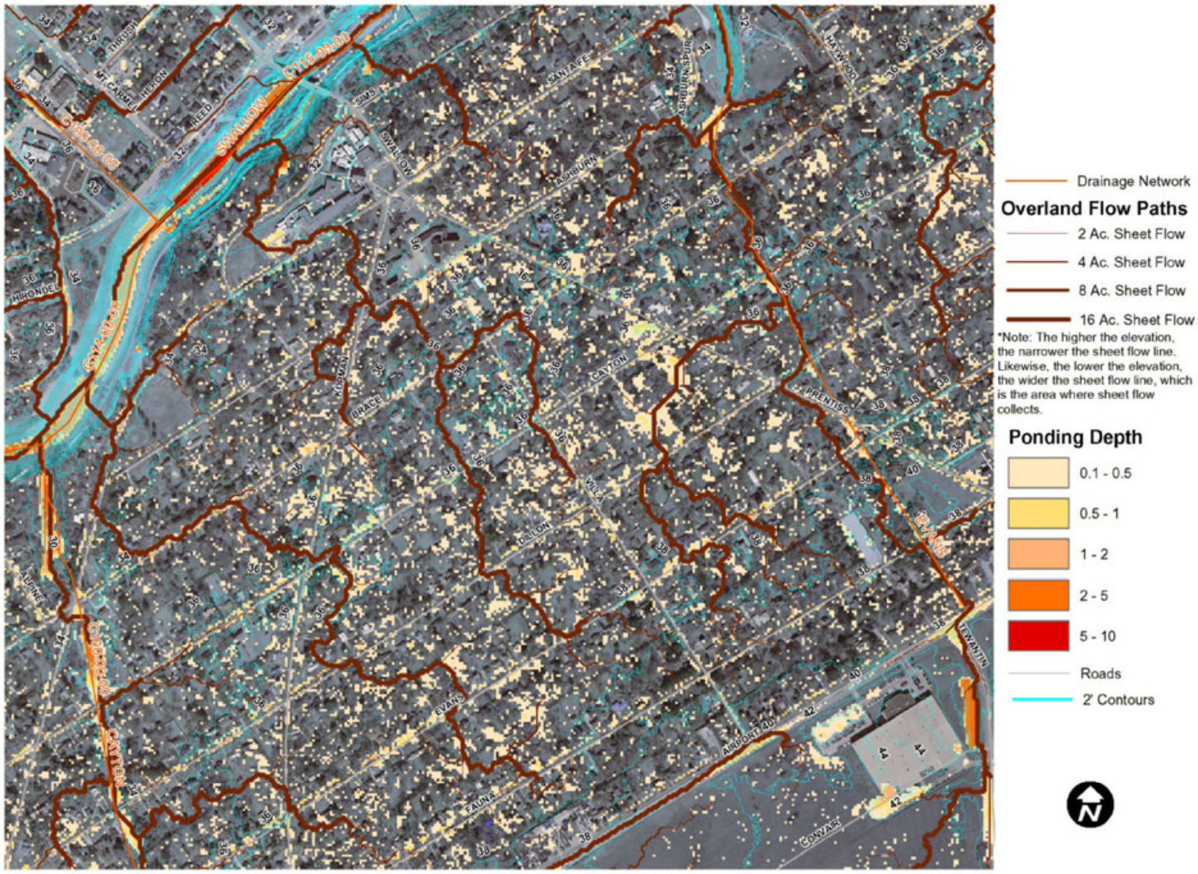

Figure 2 – Example of Overland Flow and Ponding Patterns (software: ArcGIS 8.x, spatial analyst, ArcHydro; data: HGAC Aerials, LiDAR, & 2-foot contours)

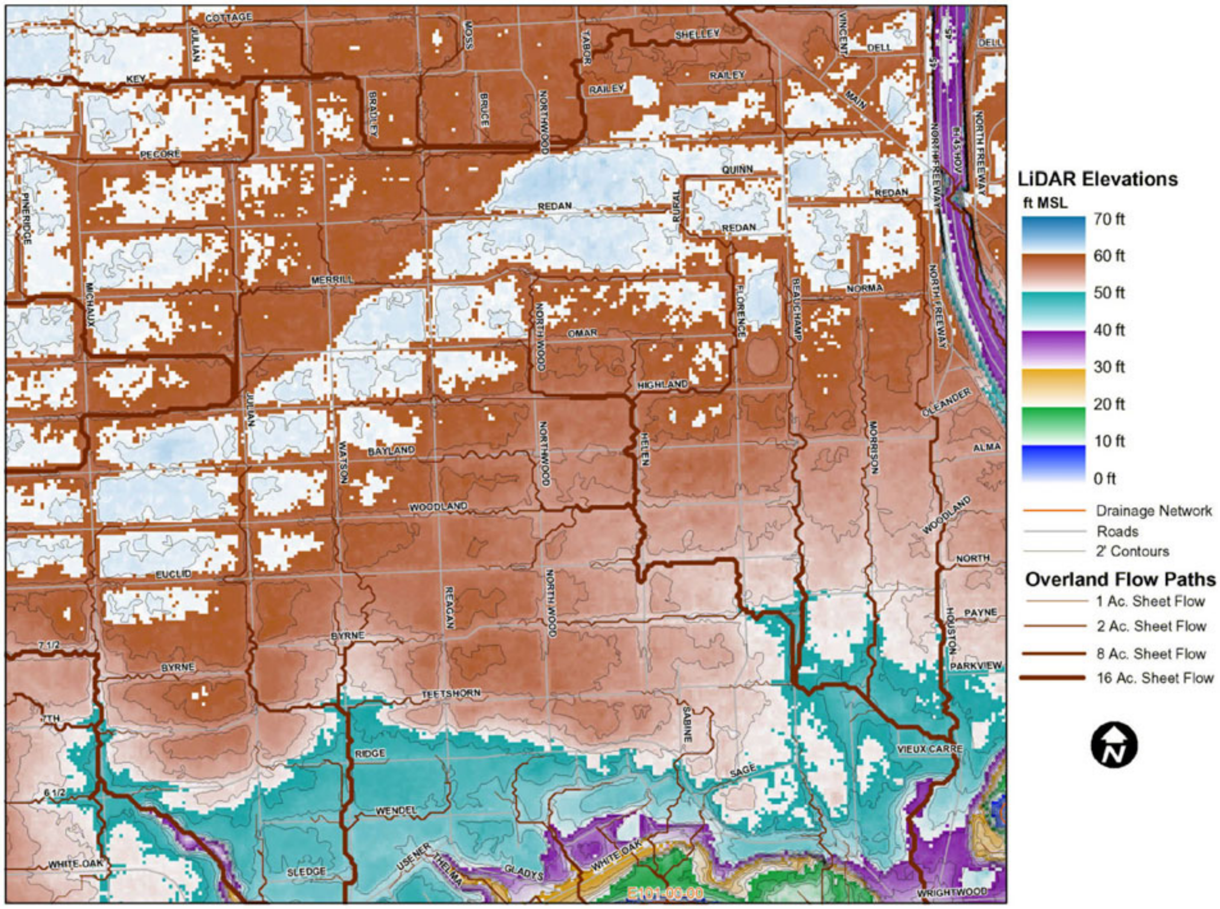

Figure 3 – Example of LiDAR Elevations with Overland Flow Paths (software: ArcGIS 8.x, spatial analyst, ArcHydro; data: LiDAR)

3.5. Definition of Existing Drainage Problems

Based on the existing system analysis using HouStorm, the existing overland path and ponding depth analysis, and outfall information obtained (specifically tailwater and floodplain elevations relative to the project) the design engineer can identify the source(s) of the existing drainage problems including:

- Underground infrastructure inadequacies
- Surface inlet inadequacies
- Overland flow
- Tailwater implications, and/or
- Any combination thereof

Once this is known and defined, the design engineer can develop a preliminary design for improvements that will address the specific problems.

3.6. Initial Storm Sewer Design (HouStorm)

The initial storm sewer design shall be performed in HouStorm using the 2-year design event. The intent of this design effort is to produce a suitable and efficient storm sewer system that addresses the existing drainage problems identified and also maintains the HGL at or below the gutter line for depressed curb-and-gutter roadway sections within the project reaches for the project design event. The HGL analysis may be performed at this time assuming that gutterline elevations were obtained in the limited survey and/or from available construction drawings. HouStorm can also be used to design open channel systems such as in projects with open-ditch roadway cross sections. The starting water surface elevation for the 2-year HouStorm run shall be entered in the "Project Information" tab by selecting the "tailwater elevation option" button titled "set TW at soffit" in concurrence with Section 9.05.C.4.a of the Design Manual.

After the storm sewer system HGL is checked in HouStorm, if sufficient data is available, the inlet design shall be checked as well to insure that the street ponding width and depth at the inlets is suitable in accordance with the project street ponding criteria discussed in Section 4.2 of this paper.

At this step, there is no need for significant refinement of the system as initially designed as impact mitigation analyses and other design processes described in Section 5 of this technical paper will likely modify the initial storm sewer/ditch system design.

3.7. 100-year HGL Analysis

Once the project's design storm criteria are met, the system should be analyzed for a more extreme rainfall event. If a dynamic, unsteady state analysis is performed, a 100-year, 24 hour rainfall with a 100-year variable tailwater condition should be used. This variable tailwater is typically applied by developing a time versus stage relationship from available models such as HEC-1 (HEC-HMS) and HEC-2 (HEC-RAS) for the outfall. If a static, steady state analysis is performed such as HouStorm, then an analysis with a fixed tailwater applies and should be based on one of the following:

1. 100-year rainfall with a 10-year tailwater condition (per TP-101); or,
2. In some instances, the City may require a 100-year rainfall with a tailwater condition as determined from TxDOT Hydraulic Design Manual Chapter 5 regarding "Frequencies of Coincidental Occurrence" (p. 5-16 and 5-17)[2]

If a lower tailwater elevation is needed to perform the 100-year HGL analysis as described above, engineering judgment and general reasonableness should be used based upon best available data. Knowing that the intent is to evaluate the performance of the storm sewer system, the design engineer should analyze various tailwater scenarios and the resulting hydraulic profiles to develop a given tailwater condition for the 100-year HGL analysis. Since we are typically dealing with common scenarios whereby the 10-year WSEL (or other WSEL as established by criteria 2 above) is too high to allow for a suitable 100-year HGL analysis of the storm sewer system, rules-of-thumb have been used successfully in the past in establishing such

[2] Texas Department of Transportation, *Hydraulic Design Manual*, March 2004.

starting WSEL's. These include using a WSEL 2-feet below the top-of-bank at the outfall and in some cases whereby the soffit of the outfall conduit is almost at the top-of-bank, the soffit elevation itself is reasonably used. However, the lowest WSEL utilized for the 100-year analysis should not be below the soffit of the outfall conduit at the outfall channel or receiving outfall conduit.

In cases whereby lowered tailwater conditions are justified as discussed herein, the design engineer should provide suitable documentation to the City project management staff to justify and support this recommendation. With approval by the City staff, a lowered tailwater condition may be utilized. The intent of lowering the tailwater is to stress the storm sewer system with an extreme event (i.e. the 100-year event) and check the performance of the system via examination of the hydraulic profile. Noted inefficiencies of the system which would cause elevated WSEL's in exceedance of the MPE can therefore be remedied.

In other extreme cases where the outfall channel level-of-service is too poor to perform an adequate 100-year analysis with a reduced tailwater as described above, a more frequent rainfall (i.e. 50-, 25-, or even 10-year) with a lesser tailwater condition may be used. It is not commonplace to apply a more frequent rainfall; however, if the engineer determines that it is necessary to do so in order to reasonably analyze a project's performance, the supporting data justifying the usage of the more frequent rainfall event shall be presented to the City's engineering management for approval prior to finalizing the project design. Again, the intent is to stress the designed system to check its performance for behavior in an extreme storm event when out-of-bank flooding at the outfall is not the controlling factor affecting WSEL's as related to the MPE.

In determining the tailwater elevation to be used, the Harris County Flood Insurance Study (FIS) provides the 10-, 50-, 100-, and 500-year frequencies (10, 2, 1, and 0.2%, respectively) for modeled streams. If the desired tailwater is a non-published frequency, an estimate of the starting WSELs may be necessary from known WSEL's. In this case, a direct linear interpolation is not appropriate and a log-linear, log-log, or linear probability approximation should be investigated. Note that care should be taken near structures (bridges, culverts, pipelines, weirs, etc.) and bayou mouths (downstream boundaries), as the hydraulic conditions at these locations may affect interpolated results at varying frequencies.

3.8. Preliminary Overland Flow Path Design

After the extreme event HGL analysis is performed, the designer should verify that an overland flow path(s) exists leading to the project outfall. This analysis can result in either the development of a preliminary path profile or a plan view drawing indicating the intended overland flow path direction. It should be noted that this step does not require a pavement design or detailed topography, but can be performed based on construction plans, field investigations, limited survey and LiDAR data/maps. The existing conditions overland flow paths will have been identified as discussed in Section 3.4 above, thus the design should insure that no adverse changes to those paths or problematic flow paths are addressed in the design, if possible.

In the Houston area, the proper consideration of the overland flow path to the project outfall or outlet is critical since it is not uncommon for an extreme storm event to render storm sewer systems ineffective due to high tail water conditions, despite the best design practices employed for the storm sewer system. Overland flow path determination is perhaps the most important step in checking for the provision of flood protection to the project area.

The overland flow path may need to be provided by the design of the roadway profile of a given project in a cascading manner to the project storm sewer outfall or outlet. However, there are many areas where an adequate overland flow path does not exist, and excessive ponding may result during extreme events and potentially threaten structures. If at all reasonably possible and feasible, corrections to deficient overland flow paths identified in the CIP project area shall be designed.

3.9. Prepare Report and Present Recommendations at TRC

Once the Phase 1-Preliminary Engineering services are nearing completion, a date for the presentation of the findings, results, and recommendations to the Technical Review Committee shall be scheduled. This presentation shall include the provision of color photos, color exhibits, and a written summary of alternatives considered and the recommended alternative. Additionally, a report shall be compiled including all analyses and data collected during Phase 1. Refer to Section 9.07.A for all required submittals.

4. PHASE 2 - FINAL DESIGN

Phase 2 services are typically authorized following the TRC review of the Phase 1 findings. This phase includes the final design functions and the preparation of the final construction plans to be bid and let for construction. The following is a discussion of the steps and products to be completed in this phase.

4.1. Drainage Area Maps

Once detailed topography has been obtained, the drainage area map developed in Phase 1 should be taken to the final level. Overall boundaries and sub-boundaries (to the inlet level) should be re-checked and finalized based on the actual elevations from the survey. This map will become the final drainage area map in the construction plans for bid. Like the preliminary map, the drainage area maps shall include 100-year floodplain limits (show both the Effective FIRM limits and TSARP limits if different), the drainage area sizes and 2-year storm sewer runoff rates, and flow direction arrows for ease of review (Section 9.07.B.4).

4.2. Storm Sewer Design (HouStorm)

In Phase 2, both the Existing Conditions and Initial Storm Sewer Design HouStorm Models developed in Phase 1 shall be updated by adjusting data to the correct vertical datum established in the survey. Once the models are updated in HouStorm, re-evaluate the hydraulic performance of both the existing and proposed storm sewers and inlets for the 2- year frequency with a starting tailwater at the top of the outfall pipe. The HouStorm output will include the 2-year HGL compared to the gutterline for the entire system with these bounding elevations entered as the critical elevation at each node in HouStorm. In cases where the typical sections have roadside ditches, the 2-year HGL's shall be compared to the natural ground elevation at the right-of-way entered in the same manner.

The updated proposed HouStorm model will become the final model and output will serve as the design calculations required in Section 9.07.B.2 and 3 to be put on the Hydraulic Data Sheet(s) in the construction plans as discussed in section 4.5 below.

With the drainage area map be delineated to the inlet level, the design engineer can check for proper inlet capacity, inlet sizing, ponded width, and total head in HouStorm. This inlet analysis is critical to the storm sewer design process since inadequate inlet density and/or capacities are a major contributing factor to ponding depth problems. If a HouStorm analysis indicates that inlet capacity is exceeded, the solution is often to simply provide a larger inlet, but in the event that HouStorm indicates exceeded ponded width, the only solutions are to either modify the roadway geometry (cross or transverse slope), or to add more inlets, thus subdividing the drainage areas further. The reason for this is that ponded width or spread flow in a gutter is a function of flow and slope, thus providing a larger inlet at a problem location will not solve the ponding width problem. This can be seen in Manning's spread flow equation as calculated by HouStorm and as defined in the latest WinStorm user manual[3] (which also serves as the current HouStorm user manual):

$$Q = (Kg / n)(Sx^{1.67})(So^{0.5})(T^{2.67})$$

$$T = \frac{y}{S_x}$$

where:

Q	=	flow rate in gutter (cfs)
n	=	Manning's roughness coefficient
Kg	=	0.56 (English) and 0.376 (Metric)
S_x	=	transverse slope (or cross slope) (ft/ft)
S_o	=	longitudinal slope (ft/ft)
T	=	ponded width (ft)
y	=	ponded depth (ft)

and where the following definitions are applied:

Ponded Width - allowable distance water may accumulate into the roadway. HouStorm reports a warning if gutter flow exceeds this ponding width measured from the curb face.

Ponded Depth - depth of water at the curb face.

[3] Texas Department of Transportation, WinStorm 3.05, *Storm Drain Design User's Manual*

Chapter 9 does not specifically cover allowable lane ponding, technically termed the spread[4]. The lane ponding, or spread, is a function of desired access for a given storm event. In most cases, it is desired to keep at least one lane free from ponding during a 2-year storm event; however, more stringent criteria may be established for ponding. The allowable ponding width is entered into HouStorm for inlets as *maximum allowed ponded width* for inlets on grade. For inlets in sag, both the *maximum allowed ponded width* and the *maximum allowed head* are entered as constraints. For example, in a typical residential street with a 27-foot face-to-face curb-and-gutter section 13.5 feet would confine the spread to the crown of the pavement which relates to a 0.57-foot maximum head at any standard Type BB inlet with a 1.5-foot gutter depression width and a 0.33-foot gutter depression depth (12-feet x 2% slope + 0.33-feet = 0.57-feet).

4.3. 100-year HGL Analysis

Similar to the 2-year analysis of the storm sewer design HouStorm model, the proposed system shall be analyzed for a 100-year frequency by applying the 100-year rainfall with a 10-year tailwater. For the 100-year analysis, the 100-year HGL is compared to the natural ground elevation at the ROW elevations entered as the critical elevation at each node in HouStorm for this run. The purpose of this exercise is to determine whether or not the system as designed for a 2-year event when stressed with a 100-year rainfall meets the criteria of the 100-year HGL below the Maximum Ponded Elevation (in the case of a CIP project, typically natural ground at the ROW). If the 100-year HGL exceeds the critical depth (as flagged in HouStorm) at only a few locations, the design engineer may elect to increase selected reaches of storm sewer where excessive headloss occurs (as indicated by the friction slope output in HouStorm) to bring the project into compliance with the criteria. This is Method 1 of the Consideration of Overland Flow for the extreme event as discussed in Chapter 9, Section 9.05.D. Otherwise one of the other methods discussed in this section and TP-101 will need to be used to insure that the design does not increase the structural flooding potential and/or reduces the threat of flooding to structures (Section 9.02.B).

4.4. Final Overland Flow Path Design

Based on the detailed topography obtained in the survey as well as the known project design features such as modified paving grades, ditch or swale construction, detention ponds, etc., the overland flow path design needs to be addressed to insure that no adverse changes are being made that will affect overland flow. Additionally, any existing defects in the existing overland flow paths that can be addressed within the bounds of the project should be done to the extent possible without adversely impacting the project area. The final design shall include the proper consideration of the overland flow path to the project outfall or outlet (Section 9.05.D.4.a). This is critical in terms of flood protection to the project area and is achieved by designing the roadway profile in a cascading manner to the project storm sewer outfall or outlet. In some cases, the storm sewer may not track readily with the overland flow path(s) which is not necessarily a negative as long as the design accommodates this condition. While the roadway

[4] Federal Highway Administration, 2001. Hydraulic Engineering Circular No. 22 (HEC22); *Urban Drainage Design Manual*, Chapter 4.4

serves as the primary overland flow mechanism, the means by which overland flow will be routed from the roadway to an outlet such as an open channel via a storm sewer easement (Section 9.05.D.4.d) should also be considered. Again, Section 9.05.D of the Design Manual discusses this criteria and methods for use in this analysis while TP-101 serves as a guideline on this topic for further information.

If in Phase 1- Preliminary Engineering, a detailed hydraulic profile was not required thus checking the overland flow path(s), then such a detailed profile shall be provided in the final design and submitted separately to the Project Manager and may be included in the hydraulic calculation sheets of the plan set. This profile shall include paving grades, natural ground elevations and tailwater elevations along the overland flow path(s) to the project outfall.

4.5. Final Design Drawings

In terms of storm sewer design, the final design drawings to be inserted into the 100% construction plans for bid include:

- Drainage area maps
- Hydraulic data sheets
- Storm sewer plan & profile drawings
- Detention pond layouts (if applicable)
- Storm sewer details
- Other applicable design drawings

Drainage Area Maps are described in Section 4.1 above. Hydraulic data sheets containing the HouStorm calculations for the inlet design and the design event storm sewer HGL shall be included. The standard, formatted HouStorm output can be copied directly into project plan sheets. This format and presentation of Hydraulic Data Sheets will result in consistency between projects in terms of the information provided. This will aid document and plan reviewers and help expedite the process of PER and plan review.

Storm Sewer P&P's, Detention Pond Layouts (if applicable), Storm Sewer Details, and other applicable design drawings shall comply with the City of Houston Standard Specifications and Standard Details as defined in the Design Manual. Refer to Section 9.07.B for all submittals required in Final Design.

5. HYDRAULIC IMPACT DETERMINATION AND MITIGATION

Hydraulic Impact Determination and Mitigation may be performed during either Phase 1 or Phase 2 of a project, or during both phases with a preliminary analysis during Phase 1 and a final analysis during Phase 2. This is dependent on a project-by-project basis to be determined by the Project Manager. The step of determining and mitigating hydraulic impacts is an important aspect of the design process for City of Houston storm sewer CIP projects given the heightened focus on flooding problems. Improvement projects consist of not only the construction of new facilities on raw land, but also the alteration of existing impervious levels and drainage characteristics in previously developed areas, and the rehabilitation of existing storm water facilities. As such, new development, channel and storm sewer modifications, roadway reconstructions, and other common civil works projects may lead to the creation of undesirable hydraulic impacts. The identification, quantification, and mitigation of such impacts to the receiving outlet channels or conduits and adjoining properties are the primary focus in this step.

An exception is for CIP Projects in which regional detention is available and the impact determination and mitigation process has typically been performed previously. As such, design modifications to the initial storm system design will not apply and this step will not be a part of the project scope.

The term “impact” is used extensively in hydraulic engineering, defining all changes to the behavior of the existing storm water flows as routed from or through a project area. These impacts may be negative or positive. The alteration of an existing watershed’s drainage characteristics, as caused by a typical urban storm water project, often leads to increased flow rates to the receiving outlet or downstream collection system. In many cases, these increased flow rates equate to rises in open channel water surface elevations or the surcharging of existing storm sewer systems, which may relate to increased levels of surface flooding.

While the elimination or significant reduction of increased surface flooding is desired, not all increases in flow rates from a given project area are necessarily negative impacts. This would be the case if an outlet system had sufficient capacity to accommodate these increased flows without any effect on or alteration to levels of surface flooding. Provided that no onsite, upstream, or downstream flooding conditions are created or worsened as caused by the increased discharges and/or increased water surface elevations from the project, it can be argued that no negative impacts have occurred. This approach is subject to interpretation and can only be applied in certain watersheds, to be determined by the applicable floodplain administrator. If an outlet system has no excess hydraulic capacity, and an increase in flows would result in surface flooding, possibly causing physical flood damage, then this increase in flow rate and corresponding increase in water surface elevation would be considered a negative impact. In addition to increased surface flooding, a negative impact might include erosion, or other such physically damaging phenomena.

Once a CIP project storm sewer design is completed using either advanced or conventional means, an impact analysis should be performed to ascertain if any hydraulic impacts exist. If negative impacts do exist, then mitigation measures should be undertaken. The determination and mitigation of hydraulic impacts can entail a rather complex analysis utilizing unsteady flow computer modeling tools that take into account the effects of storage and timing although more simplified approaches can also be employed in many cases.

Complex modeling can be achieved using computer models such as the EPA’s Storm Water Management Model (SWMM)[5], and DHI Water and Environment’s MOUSE. These are dynamic models that analyze unsteady flow utilizing the complete St. Venant equations for free surface flow, as well as pressurized closed conduit flow that take into account the aspects of

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[5] U.S. Environmental Protection Agency. *U.S. Environmental Protection Agency’s Storm Water Management Model (SWMM)*, Retrieved May 1, 2003 from http://www.epa.gov/ednrmrl/swmm/

storage and time. Other methods that do not use such complex algorithms can still take storage and time into account. These methods involve generating hydrographs and routing flows through the system, although they do not take into account partial flows, flow reversal, back water effects, etc. Computer models such as the Army Corps of Engineers' HEC-HMS can be utilized for this. Other methods for hydrograph generation and routing are the Small Watershed Method, Modified Puls Method, and the National Resource Conservation Service's TR-55. In order to generate water surface profiles or HGLs, a steady state model such as HouStorm is typically used, which generates a steady state, non-uniform flow HGL that allows for partial flow in conduits. Hand calculations usually involve a comparison of volumes generated by determining the area under hydrographs. HGL hand calculations are generally steady state, uniform flow considering only full flow in conduits. Combinations of these methods and others can be used to obtain various levels of complexity (or simplicity). In addition, there are other commercially available proprietary software computer programs that handle various levels of analysis of storm sewer systems.

The basic steps in performing the impact analysis are as follows:

- Perform the design of the storm water management improvements as based upon the 2-year design event
- Model the existing conditions using computed contributing drainage areas and peak discharges
- Change the drainage area characteristics, if needed, to reflect proposed conditions
- Model the new or proposed conditions by incorporating all of the designed storm water facilities (ditches, storm sewers, streets, inlets, etc.) into the proposed model.
- Compare the existing model results to those of the new or proposed model.
- Identify adverse hydraulic impacts (increases in peak flows, water surface elevations, etc.)
- Determine and analyze mitigation methods (detention, in-line restriction, etc.).
- Refine/change the base design within the new or proposed model to reflect the incorporated mitigation measures.
- Remodel the new or proposed conditions to demonstrate the mitigation results.

In summary, the fundamental approach is to analyze the existing conditions, compare those hydraulic conditions to the new or proposed conditions that would result due to project improvements, and mitigate any impacts as required.

5.1. Impacts by Fill Within the 100-year Floodplain

For projects located within the 100-year floodplain, any proposed fill within the floodplain will result in reductions in floodplain storage and will have to be mitigated by the creation of a like amount of storage within the floodplain. These cut/fill calculations must be demonstrated, if applicable, to document that equivalent excavation to either the outfall channel, a detention pond, or cut within the project rights-of-way will be provided to offset any proposed fill within the floodplain.

5.2. Impact Analysis and Mitigation Examples

One means of identifying hydraulic impacts from a storm water management project is the comparison of the existing condition outlet discharge hydrograph to that of the new or proposed condition outlet discharge hydrograph. The base design, as previously described, is performed using the storm event with the required synthetic design reoccurrence interval. Hydraulic impacts are analyzed for not only the lesser storm frequency events but more importantly for the extreme storm frequency events such as the 10-, 25-, 50-, and 100-year frequency events. This is to ensure that the project design performs adequately in such extreme events without inducing adverse hydraulic impacts such as increased structural flooding in or near the project area.

One of the most common forms of mitigation employed is the utilization of a detention basin within the project design. There are numerous detailed references on detention design[6] , but the basic fundamental sizing of a detention basin is based on the comparison of the existing and proposed discharge hydrographs at the outlet, whereby the needed storage volume is determined from the area between the proposed and existing hydrographs as illustrated in Figure 10.1

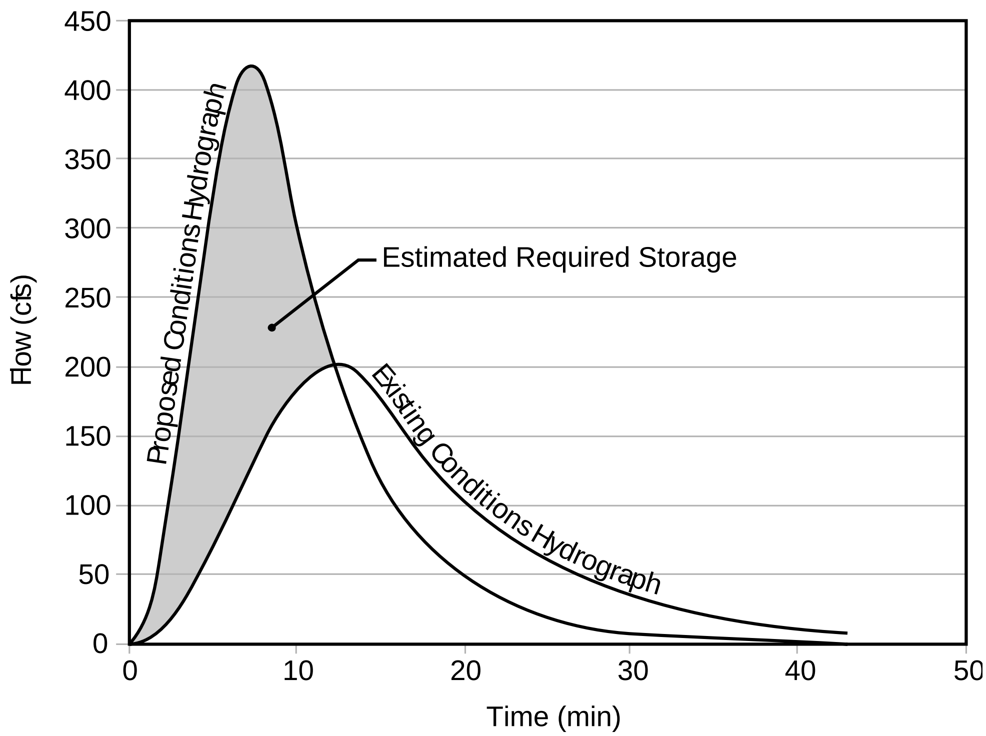

Figure 10.1 – Detention Basin Sizing

Figure 10.2 illustrates an urban project area's existing condition discharge hydrograph overlaid with that of the proposed condition discharge hydrograph at the outlet to the receiving stream. The peak flow of the proposed condition hydrograph is higher in amplitude as compared to the

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6 Stahre, P.,and Urbonas, B.,1990. *Stormwater Detention for Drainage, Water Quality, and CSO Management,* Prentice Hall, Englewood Cliffs, NJ.

existing condition hydrograph. To address this hydraulic impact of increased flow relative to existing conditions, in–line restrictors and storm sewer upsizing was employed to make use of available pressure head freeboard which is a different approach and subsequent result than adding the required detention volume in the pipes. However, other means could have been considered to ameliorate the impact such as a detention basin or other routing means to attenuate the flow. After several iterations of re-sizing the restrictors and upstream storm sewers, the peak of the proposed condition discharge hydrograph was reduced, as seen in Figure 10.3, to mimic the existing conditions peak. The proposed condition hydrograph was then input into the stream hydrologic and hydraulic models and routed downstream to ensure that no rises in water surface elevations were caused by the project improvements.

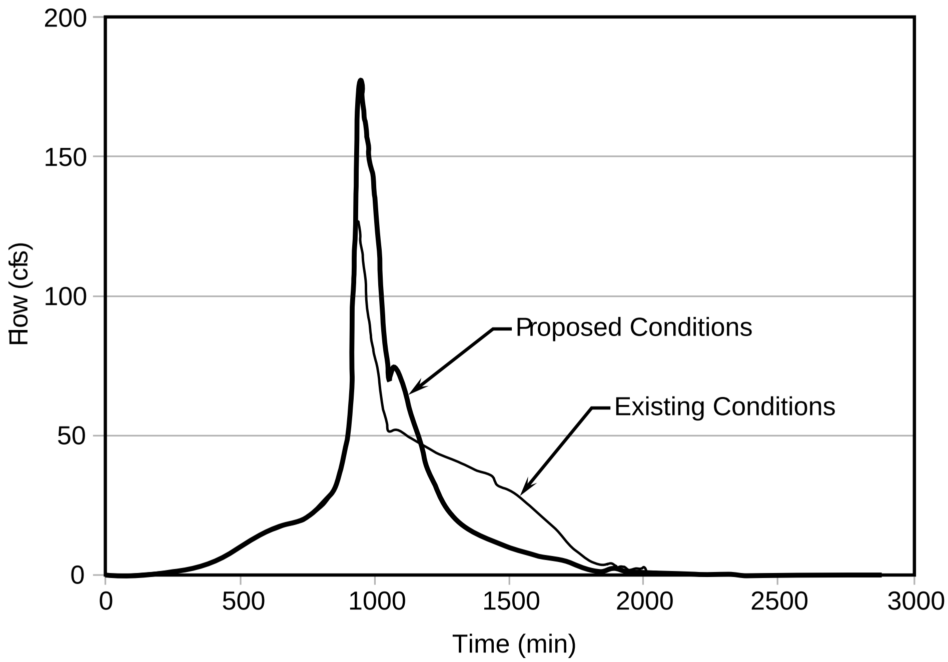

Figure 10.2 – Existing Versus Proposed Discharge Hydrographs

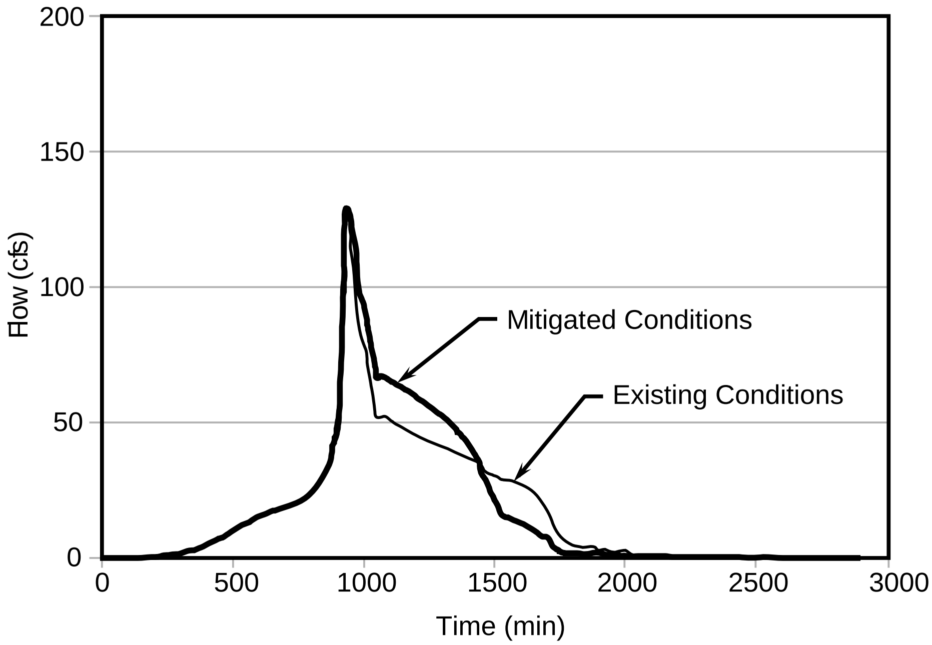

Figure 10.3 – Estimated Versus Mitigated Discharge Hydrographs

Mitigation measures are often not easily employed in densely developed urban areas such as within the City of Houston. In many cases, available land for detention basins does not exist or available land is simply too costly. As is often the case, a complex balance of manipulating available storage within storm sewers, ditches, and even depressed curb-and-gutter streets in conjunction with adjusting the routing of flows within the storm drainage system is required to successfully mitigate adverse hydraulic impacts resulting from the proposed improvements. For these reasons, complex modeling techniques using sophisticated computer software are often required to properly analyze the project conditions, make an accurate determination of hydraulic impacts, and adequately design the needed mitigation measures. However, on simpler systems where such complex analyses and software may not be necessary, simpler methodologies (such as those previously mentioned or hand calculations) may be utilized to properly analyze the project.

6. SUMMARY

Some changes to the City of Houston design criteria have been made recently. This paper identifies these changes and outlines how these changes affect the design process. In summary, the storm sewer design process for City of Houston CIP Projects shall incorporate the following:

- Develop project drainage area map and collect existing conditions drainage infrastructure and outfall information
- Analyze existing system (storm sewer & inlets) for a 2-year event using HouStorm
- Identify existing storm sewers with insufficient capacities and existing inlets with excessive ponding widths
- Check overland flow paths using readily available data such as LIDAR & DEM's for more accurate determination of ponded areas and flow directions (these tools can also be used in the delineation of drainage areas).
- Define source of drainage problems: infrastructure, overland flow, tailwater effect, or combination thereof
- Perform initial 2-year storm sewer proposed design with new &/or improved storm sewers and/or inlets
- Add new inlets as necessary to account for excessive ponding widths
- Check that all 2-year HGL's are below gutterline for curb-and-gutter roadways, or natural ground at the ROW for open-ditch sections
- Determine if regional detention or local real estate is available for mitigation.
- Perform 100-year impact analysis
- Address the consideration of overland flows for the extreme event
- Identify mitigation measures and overland flow improvements
- Modify original design to include mitigation and overland flow components as necessary
- Adjust HouStorm design and re-run 2-year
- Re-check 2-year HGL's
- Select final design
- Produce hydraulic data sheets, drainage area maps, and all applicable storm sewer final design documents

This design process will provide storm water designs based on the latest criteria offering a higher level-of-service for our storm water infrastructure and improved flood reduction. This technical paper provides a snapshot of the intended process to be applied.