# Analyzing the Impact of Land Use Changes on Urban Flood Risk in Northwest Houston, Texas, and Prediction of Future Flood Vulnerability

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**Abstract:**

In the United States, fluvial flood risk is managed by the National Flood Insurance Program (NFIP), which delineates areas that have a 1% chance of flooding each year (i.e. the 100-year floodplain). However, there is a disconnect between NFIP risk delineation, and observed flood losses that can be attributed in part to changing land cover impacts on watershed response. Development within and adjacent to riverine floodplains exacerbates losses by increasing peak discharge, shortening the time to peak, and altering the extent of the floodplain. This paper proposes a novel methodology for evaluating the impacts of future development on the 100-year floodplain by considering both regional trends in development and site-scale development policies. The framework advanced in this paper integrates future development scenarios from a machine learning land use projection model with distributed hydrologic modeling and coupled 1D/2D unsteady hydraulic modeling to produce future floodplain estimates. Current site-scale detention requirements are represented within the hydrologic model to evaluate the regional effectiveness of these policies under future development conditions in 2050. Results indicate that the 100-year floodplain can expand by 25% as a result of projected development in 2050 using current stormwater mitigation policies. This study serves as a step forward in understanding how incremental land use changes can significantly alter the reality of flood risk in urbanizing watersheds, and how to increase flood resilience through land use policy.

## Problem and Research Objectives:

In the US, fluvial flood risk is characterized and managed through the National Flood Insurance Program (NFIP), which delineates a regulatory 100-year floodplain (the area that has a 1% chance of flooding each year), known as the Special Flood Hazard Area (SFHA). However, there is often a disconnect between the SFHA and observed flood damage (NRC, 2014) that can be attributed in part to outdated floodplain maps, which do not take into account changing land cover impacts on watershed response (Blessing et al., 2017). For example, one study found that over 60% of floodplain maps were at least 10 years old (Birkland et al., 2003). In high-growth areas like Houston, TX (located along the upper Texas Gulf coast) substantial land development can occur within a span of 10 years that can significantly alter the hydrologic behavior and undermine the SFHA's capability to accurately represent current flood risk. Since NFIP map revisions cannot keep pace with changing watershed conditions, development may be occurring in areas that are vulnerable to flooding but have not been designated as SFHAs yet. This results in development policies that are reactionary rather than proactive. The consequences of this approach have been evident in Harris County, TX, where development restrictions have typically been implemented in response to major flooding events, rather than keeping pace with urbanization trends. This paradigm poses a critical challenge to planners and engineers who seek to design long-term flood management strategies in the face of future development uncertainty.

In order to evaluate the long-term effectiveness of flood management infrastructure and quantify evolving riverine flood risk, it is necessary to integrate land use projection modeling with hydrologic and hydraulic modeling. Although there have been many studies documenting the increase in peak flows and runoff volumes associated with historical urbanization (Doubleday et al., 2013; Rose and Peters, 2001; Sheng and Wilson, 2009; Vogel et al., 2011), these impacts do not uniformly translate to increases in floodplain extent (Wheater and Evans, 2009). There is still limited understanding of floodplain sensitivity to increases in overland runoff rates and volumes, since topographic factors, stream characteristics, and the presence of existing flood infrastructure influence the ability of a watershed to accommodate or attenuate increases in overland flow. There has also been little research conducted on the regional effectiveness of site-scale development policies to offset future impacts of urbanization. These policies, such as on-site detention/retention requirements, aim to mitigate the impacts of development at the site-scale. Although there have been some studies examining the local runoff response of these site-scale detention features (Mogollón et al., 2016), there has been no consideration of their efficacy at the regional scale.

This study aims to address the limited understanding of watershed sensitivity to future development and the regional impacts of site-scale mitigation by developing an integrated framework to quantify floodplain increases under a range of future development conditions. By linking land use projection modeling with hydrologic/hydraulic analysis, this paper provides a comprehensive approach to floodplain management that effectively considers the crucial feedback loop between anthropogenic activities, environmental response, and natural hazard management. First, a land use projection model for the region is developed to characterize the likelihood of development in 2050, and ultimately produce future development scenarios. These scenarios are represented within a distributed hydrologic model to evaluate the impact of urbanization patterns as well as site-scale development requirements on 100-year overland flows. Flow hydrographs are linked to an unsteady hydraulic model to assess development impacts on water surface elevations, and ultimately produce current and future 100-year floodplain depths and extents. Floodplain results are analyzed to characterize watershed response to future development, identify potentially vulnerable regions of the watershed, and provide information about the effectiveness of existing policies in mitigating future flood risk. This framework is applied to a case study watershed in northwest Harris County that has experienced rapid development in recent years, has been highly vulnerable to riverine flooding, and is expected to continue developing rapidly in the future.

## Materials/Methodology

### Study Area

The Cypress Creek watershed is located north of the city of Houston in northwest Harris County, along the upper Texas Gulf Coast (Figure 1). The watershed encompasses a 692 $km^2$ drainage area, features over 400 km of open drainage channels, and contains a population of 347,334 (HCFCD, 2017). The watershed is currently partially developed, with the majority of developed land located on the east side of the watershed. The western portion of the watershed is primarily composed of agricultural and natural prairie land (Figure 1). Cypress Creek serves as the primary drainage conduit for the watershed, draining east to west until flowing into the San Jacinto River. The stream is slow-draining since it has largely remained in its natural state, with vegetation lining the banks and natural meanders. However, due to the flat topographic slopes in the southwestern portion of the watershed and the limited conveyance capacity of the stream, water spills over the watershed divide and into the neighboring Addicks Reservoir watershed during high-intensity rain events (HCFCD, 2017). Inter-basin overflow can occur during rain events greater than a 5-yr magnitude (14.7 cm in 24hr), and result in significant volumes of overflow during higher intensity events (HCFCD, 2017). This complex hydraulic phenomenon is somewhat unique and poses a challenge for modeling the rainfall-runoff response of the watershed, since overflow rates depend on both rainfall intensity and downstream water surface elevations. Thus, traditional 1D models have been unable to simulate the runoff dynamics during extreme rain events and are unable to accurately represent the 100-year floodplain in this portion of the watershed.

The Cypress Creek watershed has experienced several major flooding events over the last few years that have inundated thousands of homes and resulted in substantial economic losses. During a storm event in April 2016, for example, over 2000 homes were flooded in the Cypress Creek watershed alone, and peak water elevations throughout the watershed far exceeded previous records (Lindner and Fitzgerald, 2016). More recently, during Hurricane Harvey, thousands of residents in the watershed experienced severe inundation over a period of several days (Sebastian et al., 2017), leaving hundreds stranded in their homes. These recent extreme precipitation events highlight the vulnerability of the watershed to repetitive flooding.

These recent flood events in the Cypress Creek watershed are even more concerning when considering the rapid development simultaneously occurring in the area. From 2000 to 2010, the population of the watershed grew by 70% on average, while development rates in the western portion were as high as 390% in one zip code (Zheng, 2011). The impact of this development is twofold: 1) new development is occurring inside areas already vulnerable to flooding and 2) the accompanying increase in impervious surface further exacerbates flood risk.

## Land Use Projection Model

This study utilizes output from a pattern recognition based model, known as a multi-layer perceptron artificial neural network (MLPNN) (Pijanowski et al., 2002). The MLPNN model for the Houston-Galveston region was set up and validated by Dr. Russell Blessing from Texas A&M Galveston. The ability of ANNs to generalize across regions is particularly useful for land cover modeling. More specifically, ANNs can address the oftentimes complex interacting nature of land use change drivers that operate over different spatial and temporal scales (Lambin et al., 2003). Spatially, drivers of change can be local or global, and temporally they can operate in subtle and graduate fashion (e.g. climate change) or they can exhibit the rapid changes due to major events (e.g. hurricanes and floods) (Lambin et al., 2003). In this study, an ANN is used to determine the potential of a given location to transition from a non-built classification to built (i.e. urban expansion) using regional drivers of change and historic land cover change dynamics.

A full description of the model set up and validation can be found in the forthcoming article (Gori et al., 2018). Essentially, the model is trained using historical land cover data from the NLCD from 2001 and 2006. Historical drivers of development are investigated and ultimately four drivers are shown to sufficiently explain regional urbanization patterns in the Houston-Galveston region: existing land cover type, distance to existing development, distance to downtown, and distance to schools. The model is validated using NLCD 2011 land cover data to ensure accurate prediction.

Transition potentials for 2050, or the likelihood that an area will become developed in the year 2050, are generated by the model. This yields a map of probability of development as well as a map depicting the model's "best guess" for 2050. Land use scenarios are developed by utilizing both maps to stipulate 15% less development than predicted by the best guess estimate for a low development scenario, and 15% more development than predicted for a high development scenario. These two development scenarios are modeled within a distributed hydrologic model.

## Hydrologic Model

This study utilizes Vflo®, a physics-based, distributed hydrologic model, to simulate the rainfall-runoff process. Vflo® solves conservation of mass and momentum equations using a finite-element approach, and represents the physical characteristics of a watershed in gridded-cell format (Vieux and Bedient, 2004). In the model domain each grid cell contains parameters that represent elevation, soil type, land cover characteristics, and a flow direction that is defined based on relative elevation compared to surrounding cells. Grid cells can be designated as overland or channel cells, and channel cross sections can be extracted from digital elevation data. The model performs rainfall-runoff calcaulations within each grid cell, and overland flow between cells is routed via the Kinematic Wave Analogy (KWA), which is a simplification of the 1D Saint-Venant equations. A full description of the KWA derivation is documented in (Vieux & Vieux, 2002). Infiltration is calculated at each grid cell using the Green & Ampt Equation, which depends on soil parameters of hydraulic conductivity, wetting front suction head, effective porosity, and soil depth (Rawls et al., 1983). In this study, Modified Puls routing is utilized to model channel flow since it is more suitable for representing channel storage in mild-sloped watersheds (Vieux and Bedient, 2004).

Distributed models are particularly useful for representing spatially-diverse land cover characteristics and modeling land cover evolution through time since calculations are made at the grid cell level. In contrast, traditional lumped modeling methods often rely on empirical parameters derived at a subbasin-scale, which may not be able to accurately represent localized development changes (Blessing et al., 2017). Vflo® has been successfully utilized to model development scenarios, low impact development features, and flood mitigation infrastructure (Doubleday et al., 2013; Fang et al., 2010; Juan et al., 2017). Additionally, Vflo® was chosen because it has been widely applied and validated in the Houston region for both inland and coastal watersheds (Blessing et al., 2017; Ray et al., 2011; Vieux and Bedient, 2004).

## Model Set up and Calibration

Vflo® model setup requires detailed elevation, soil type, and land cover information. The model domain was delineated based on the Harris County Flood Control District (HCFCD) watershed boundary and utilized a grid cell resolution of 91 m (300 ft), which was determined based on a maximum model size of roughly 100,000 cells. 2008 LiDAR Digital elevation (DEM) data was obtained from the Houston-Galveston Area Council (HGAC), and was utilized in the model to determine the slope of each cell and the overland flow direction grid, and to extract cross-section profiles for channel cells in the model. Soil type information was obtained the Texas Natural Resources Information System (TNRIS), and processed in ArcGIS according to Rawls et al., (1983) to obtain estimates of hydraulic conductivity, effective porosity, wetting front capillary pressure head, and soil depth.

Land cover data to represent current conditions in the watershed was obtained at 30 m resolution from a 2011 dataset within the National Land Cover Database (NLCD). Vflo® is able to represent land cover/use through a Manning's roughness coefficient and a percent imperviousness applied at each grid cell. Roughness coefficients indicate the amount of frictional losses between flowing water and ground surface, and impact the veloctiy of overland flow (Kalyanapu et al., 2009). Consequently, natural areas of high vegetation or forest will have higher roughness coefficients and lower flow rates, while concrete or pavement areas will have low roughness and high flow rate. Land cover categories from NLCD are converted to Manning's roughness coefficients based on Kalyanapu et al (2009), and impervious percentages are designated based on NLCD guidelines (NLCD, 2011).

The hydrologic model was calibrated using two significant rainfall events, one on April 17th 2016 and the other occurring on May 26th 2016. The first event in April 2016 was an extreme precipitation event that dropped over 38 cm in 12 hrs on some parts of the watershed, and resulted in the Tax Day flood described in the Study Area section (Lindner and Fitzgerald, 2016). This storm exceeded a 500-yr frequency event in the western portion of the watershed and a 100-yr frequency on average throughout the study area (Lindner and Fitzgerald, 2016). The second storm occurring on May 26th 2016 resulted in 12.7-17.8 cm across the watershed, corresponding to roughly a 10-yr frequency event. These two events were chosen because they represent a range of frequency storm magnitudes, and because they occurred during the same time period. This latter point is important in order to isolate and calibrate to the most recent development conditions.

Five USGS streamflow gages along Cypress Creek were used as calibration points (Figure 3a). The average peak flow difference and Nash-Sutcliffe Efficiency across the three gages was 2.1% and 0.80, and -1.2% and 0.74, for the April 2016 and May 2016 storms respectively (with negative values indicating under-prediction by the Vflo® model). Based on these performance metrics and the overall shape and timing of the comparison hydrographs, the authors believe these are satisfactory calibration results. Figure 3a shows hydrograph comparisons at the middle gage location, which is the most reliable gauge (based on rating curve measurements) in the watershed, and Figure 3b shows a comparison of modeled peak streamflow vs observed.

In order to ensure accurate comparison between current and future conditions, a 100-year design storm was applied to the current conditions Vflo® model to generate 100-year flow hydrographs. The 100-year rainfall hyetograph for this region corrseponds to 31.5 cm in 24 hrs, and was applied according to the Soil and Water Conservation Society (SWCS) guidelines for a Type-III 24 hr storm event, which is the same rainfall methodology applied by Harris County floodplain managers in modeling a 100-year event (Storey et al., 2010).

## Site-Scale Detention Modeling Methodology

Although roughness coefficients from Kaylanapu et al (2009) are used to represent frictional losses for current development in the watershed, these values were not applied to represent future development. These values assume no on-site detention measures, and thus represent development impacts under a no mitigation scenario. Instead, this study derives new roughness values based on development criteria from the HCFCD, which is the primary floodplain regulatory agency in Harris County, and the topographic conditions of the Cypress Creek watershed.

According to HCFCD's Policy, Criteria, and Procedure Manual (Storey et al., 2010), new developments must adhere to peak discharge rate restrictions that are defined for a 10-year and 100-year storm event. For developments smaller than 2.59 km$^2$, a simple Site Runoff Curve can be used to determine the maximum allowable peak discharge. For developments larger than 2.59 km$^2$, more rigorous hydrologic and hydraulic modeling is needed to determine the appropriate on-site detention requirements. As a point of reference, the size of each grid cell in the Vflo® model is 0.008 km$^2$. For the purposes of this study it was assumed that all new developments would be the size of a single Vflo® grid cell, so on-site detention could be modeled using the Site Runoff Curve equations to constrain the maximum discharge rate. These curves are determined based on the following equation:

$$Q = bA^m$$

Where Q is peak flow rate, A is development area, b is a factor based on impervious percent of the development, and m a factor based on the size of the development. For development areas less than 0.08 km$^2$, m is equal to one and the equation simplifies to a linear relationship. Using this equation, each grid cell in the Vflo® model that is projected to become developed in 2050 should have a peak discharge of less than 0.14 m$^3$/s. This methodology for calculating and applying the maximum discharge rate to each individual cell is appropriate because given the linear nature of the Site Runoff Curves, a group of developed cells would have a combined peak discharge that is still in compliance with the detention requirements for their collective area. For example, a new development the size of ten Vflo® grid cells has a maximum allowable discharge ten times that of an individual developed cell.

In order to achieve compliance with these detention requirements, a sub-grid parameterization was employed so that on-site detention features within a given cell could be represented by adjusting the overland roughness across the entire cell. Since calculated flow rates within the Vflo® domain depend on both the slope and roughness of the cell (Vieux, 1990), both of these parameters were examined when calculating a new representative roughness for on-site detention features. This process is outlined in figure 4 and involved the following steps: 1) calculating the distribution of overland slope values for all new development cells in the watershed, 2) selecting a representative slope value ($s_0$) based on the distribution, 3) determining a representative roughness ($r_0$) for a cell with slope $s_0$ which produces a 100-year peak flow of 0.14 $m^3/s$, and 4) applying the new $r_0$ to all cells within the watershed and checking a random sample of 100 cells to ensure that compliance is achieved.

Since steeper slope values produce higher flow rates, $s_0$ was chosen to be greater than 90% of cells within the watershed. Based on the distribution of slope values (figure xx), 90% was chosen as the threshold because the distribution has a heavy tail, with a few high slope outliers. Next, $r_0$ was determined by applying a 100-year rainfall hyetograph to a single cell with slope $s_0$, and increasing the roughness until the peak discharge was reduced to 0.14 $m^3/s$. The new $r_0$ was determined to be 0.2, compared to 0.0678 under a no mitigation scenario (Kalyanapu et al, 2009). This representative roughness was applied to all newly developed cells within the watershed and the 100-year peak flow for a random sample of 100 cells was tested to ensure compliance across the watershed. Of the 100 cells tested, 89 complied with peak flow requirements, and only 11 exceeded the peak flow threshold. However, most of these cells were within 5% of the required peak flow and all cells were within 10% of the requirement. Thus, this performance was deemed acceptable for modeling site-scale detention.

## Hydraulic Model

For this project, hydraulic analysis was conducted using a hydraulic model, HEC-RAS (Hydrologic Engineering Center – River Analysis System), developed by the U.S. Army Corps of Engineers. This model has been used in a wide variety of applications, including floodplain assessment, flood insurance studies, and dam breach analysis (Bass et al., 2017; Butt et al., 2013; Knebl et al., 2005; McLin et al., 2001). The primary function of HEC-RAS is to calculate water surface elevations at channel cross sections or modeled storage areas of interest for any given flow rate. The latest version of the software, Version 5.0.3 (Brunner, 2016), is capable of computing water surface profiles by performing one-dimensional (1D), two-dimensional (2D), or combined 1D/2D hydraulic calculations, based on energy and momentum equations.

In this study, the effective hydraulic model of Cypress Creek watershed developed by HCFCD was used as reference. This model is a 1D-steady model, and is used as the basis for generating the 100-yr FEMA floodplain. The model generates a static water surface profile (i.e., maximum water surface elevation) along the entire channel based on peak discharges inputted at specific channel cross sections. While a 1D-steady model is useful for floodplain assessment and floodway encroachment studies, it is insufficient to model the hydraulic performances of intricate systems where volume and timing are crucial, such as the Cypress Creek overflow area. In order to simulate the hydrodynamics at this particular location, the effective HCFCD model was modified and converted to a 1D/2D unsteady hydraulic model. The main advantage of an unsteady model compared to a steady model is that it can simulate the water surface profiles of entire storm hydrographs instead of just peak flows, which provides a better understanding of the system's flow and stage response over time. This is crucial for modeling the overflow area in Cypress Creek, because the overflow dynamics depend on both stage hydrograph timing and peak.

The HEC-RAS model was validated using the same two precipitation events that were used to calibrate the hydrologic model. There were a significant number of high water marks obtained for these events in addition to peak water levels recorded at gauges along Cypress Creek. Maximum water surface elevations modeled in HEC-RAS were compared to these high water marks for both the April 2016 and May 2016 storms. Additionally, for the April 2016 storm there were several high water marks recorded in the overflow area, which were used to ensure a good match between modeled overflow depths and observed depths. The average peak stage difference was -0.01 m and -0.3 m for the April 2016 and May 2016 storms respectively, with negative values indicating model under-prediction, and a comparison between modeled water depth and observed depth for both storms is shown in figure 5. Although the model slightly under-predicted stage for the May 2016 event, it produced good results for the April 2016 event, which is close to a 100-year magnitude.

## Principal Findings

### Future Development in Cypress Creek

As shown in figure 6, the Cypress Creek watershed is currently partially developed, with a majority of the watershed composed of agricultural and natural lands. Development projections for 2050 predict that new development will occur in areas adjacent to existing development, such as the undeveloped lands located in the middle and eastern portion of the watershed, and new development trends will push westward into areas currently dominated by natural and agricultural land cover. A comparison of current land use, 2050 low development, and 2050 high development shown in figure 6 illustrates the trend of westward development, and shows that the primary difference between the low and high development scenarios is the amount of development located in the western portion of the watershed.

Table 1 indicates that development in 2050 is projected to grow by 37%-54.5%, becoming the dominant land use type within the watershed. While developed land sees the largest gains in 2050, natural lands are projected to experience the highest losses, decreasing by 54%-61%. Agricultural lands remain relatively constant, shrinking by only 11%-24%. These results suggest that future development within the Cypress Creek watershed could disproportionately impact natural land, such as forests and wetlands, compared to pasture and crop land. Figure 6 demonstrates this trend further, showing that large areas of natural land are projected to become developed in 2050.

### Floodplain Extent Increase

Figure 7 illustrates the extent of the 100-year floodplain under each of the three scenarios: current conditions, 2050 low development, and 2050 high development. A comparison of the three floodplains illustrates that increases in floodplain extent are moderate along the middle and downstream portion of the watershed, but are more severe in the upstream portion, which is magnified in figure 7A. This magnified area corresponds to the inter-basin overflow area, where

Cypress Creek spills over its banks and into the neighboring Addicks Reservoir watershed. Figure 7B shows a portion of the midstream of Cypress Creek. In this region, floodplain increases are much less severe than in the overflow area.

Table 2 shows the change in 100-year floodplain extent and increase in inundated residential parcels between 2050 development scenarios and current conditions. The 100-year floodplain extent is projected to increase by 8.4-12.5% across the watershed, which corresponds to an increase in inundated area of 9-13 $km^2$. The impact to residential parcels is more severe, ranging from 12.3-18.8% increase compared to current conditions. Across the watershed, this corresponds to an additional 361-550 impacted parcels. These estimates only include existing residential parcels, and do not take into account newly developed parcels in 2050. Thus, it is likely that Table 2 under-estimates the true increase in residential flood risk across the watershed. Instead, it represents existing parcels that could become designated as special flood hazard areas (SFHAs) in the future due to growth of the floodplain extent.

Table 3 displays similar flood risk statistics as Table 2 for the overflow area alone. Within the overflow area, the floodplain extent is projected to increase by 16.4%-23%, and increase the number of inundated parcels by 21%-25%. These impacts are considerably greater than results across the entire watershed.

## Significance

The results indicate that the 100-year floodplain can expand by nearly a quarter of its original size as a result of nearly four decades of projected urbanization in the Cypress Creek watershed.

In general, across the watershed, a percent increase in development translated into about a 0.23% increase in the extent of the floodplain. However, floodplain sensitivity to projected development was found to be highly variable, which was driven in large part by spatially varying watershed characteristics and the heterogeneous pattern of future development. The overflow area in particular was much more sensitive to future urbanization, with impacts two times more severe than across the entire watershed. Even under a low development scenario, the floodplain is projected to increase by more than 20% in the overflow area, indicating that this region is highly sensitive to urbanization impacts. This impact likely would not have been as evident without the coupled 1D/2D unsteady hydraulic model that more accurately represents the complex hydrodynamics of the overflow area.

Another key finding is that the impact that development has on floodplain extent is location specific. Small increases in upstream urbanization can have large impacts on downstream floodplain extent due to specific physical characteristics of the downstream area. For example, although the majority of projected urbanization in 2050 (Figure 6) occurs in the middle and downstream portion of the watershed, the largest floodplain impacts are observed in the upstream overflow area. Under current conditions, 6% of land upstream of the overflow area is developed, and by 2050 increases to only 10% under a low development scenario. Yet, this small increase in upstream development results in a 20% increase in floodplain extent. In contrast, the middle and downstream portion of the watershed appear to be fairly resilient to increases in development, since they are able to accommodate large increases in future development without substantial increases in floodplain extent.

The difference in floodplain impacts between the overflow area and the middle/downstream portions of the watershed is also mediated by changes in slope and channel storage capacity. In the overflow region, the ground slope is mild and there is little storage capacity outside the channel. This results in a wide floodplain extent even under current conditions, since relatively small increases in water elevation result in large increases in inundation extent. Furthermore, since Cypress Creek already has limited storage capacity in this location (described in section 2), increases in runoff volume resulting from new development cannot be effectively stored or conveyed through the channel. Instead, excess runoff volume spills over the channel banks and drains through the overflow area, resulting in substantial increases to the 100-year floodplain in this area. In contrast, the middle and downstream portion of the channel has a large amount of overbank storage, which is able to constrain the floodplain extent. Previous studies have also shown that the presence of overbank storage capacity can improve flood wave attenuation by storing excess floodwater (Castellarin et al., 2011; Woltemade and Potter, 1994).

In addition to understanding overall watershed sensitivity to development, and identifying vulnerable locations, this study also evaluated the effectiveness of existing detention requirements to mitigate impacts from future development. Based on floodplain extent results, it is clear that on-site detention policies are unable to completely mitigate the impacts of future development. Previous studies have argued that on-site detention systems that are dispersed across a watershed can better alleviate the impacts from new development compared to large regional detentions systems, because they are better able to replicate pre-development hydrologic response (McCuen and Rawls, 1979). However, these systems are generally most effective for intermediate storms rather than extreme precipitation events (Konrad and Burges, 2001).

Roughness coefficients were increased substantially to replicate the effect of on-site detention standards for this area that were intended to preserve pre-development hydrologic conditions. However, the impact of increased imperviousness overwhelmed the study's on-site detention proxy resulting in increases in floodplain extents that disproportionately affected specific areas. These results suggest that in addition to limiting peak flow rates with on-site detention other hydrologic characteristics should be considered such as limiting runoff volume with on-site retention. Furthermore, the method presented in this study could be used to determine the necessary level of site-scale mitigation necessary achieve no adverse impacts at a regional scale. Development policies should be crafted by examining multiple spatial scales in order to properly quantify the cumulative impacts of development, and set mitigation criteria that produces no adverse impacts across the entire watershed.

The application of an integrated framework for land use projection modeling and hydrologic/hydraulic modeling to the Cypress Creek watershed highlights its usefulness for quantifying the impacts of future development trends and development policies. By taking into account both where development occurs regionally and how development is managed at the site-scale, this methodology is able to more accurately delineate areas of future risk. Specifically within the overflow area, which exhibits complex hydrologic effects, distributed hydrologic modeling coupled with 1D/2D hydraulic modeling methods are able to effectively represent evolving flood risk  Floodplain managers and engineers could utilize a similar framework to evaluate the long-term effectiveness of flood infrastructure or different development policies under nonstationary land use. Specifically, by considering a range of possible development conditions, decision-makers can understand the threshold level of development at which negative impacts are observed, and plan mitigation strategies based on this threshold.

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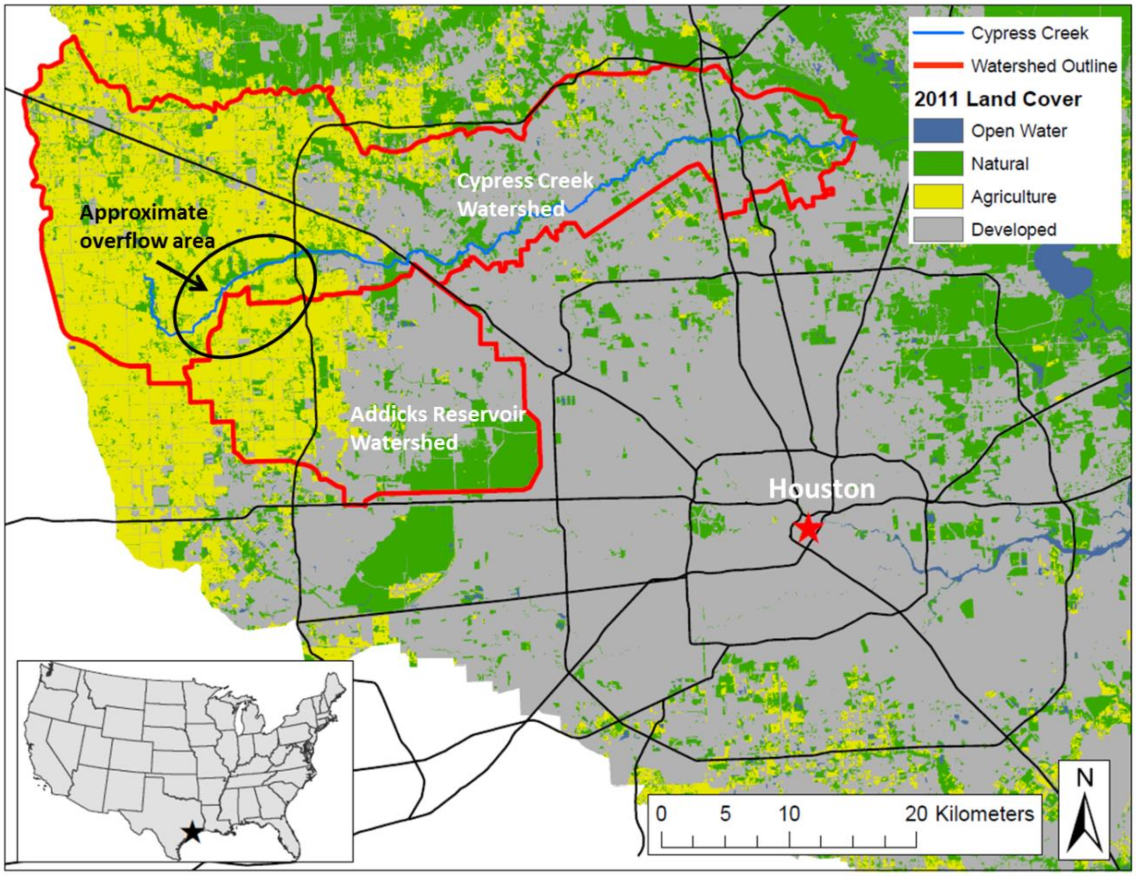


Figure 1: Cypress Creek watershed study area and regional land use

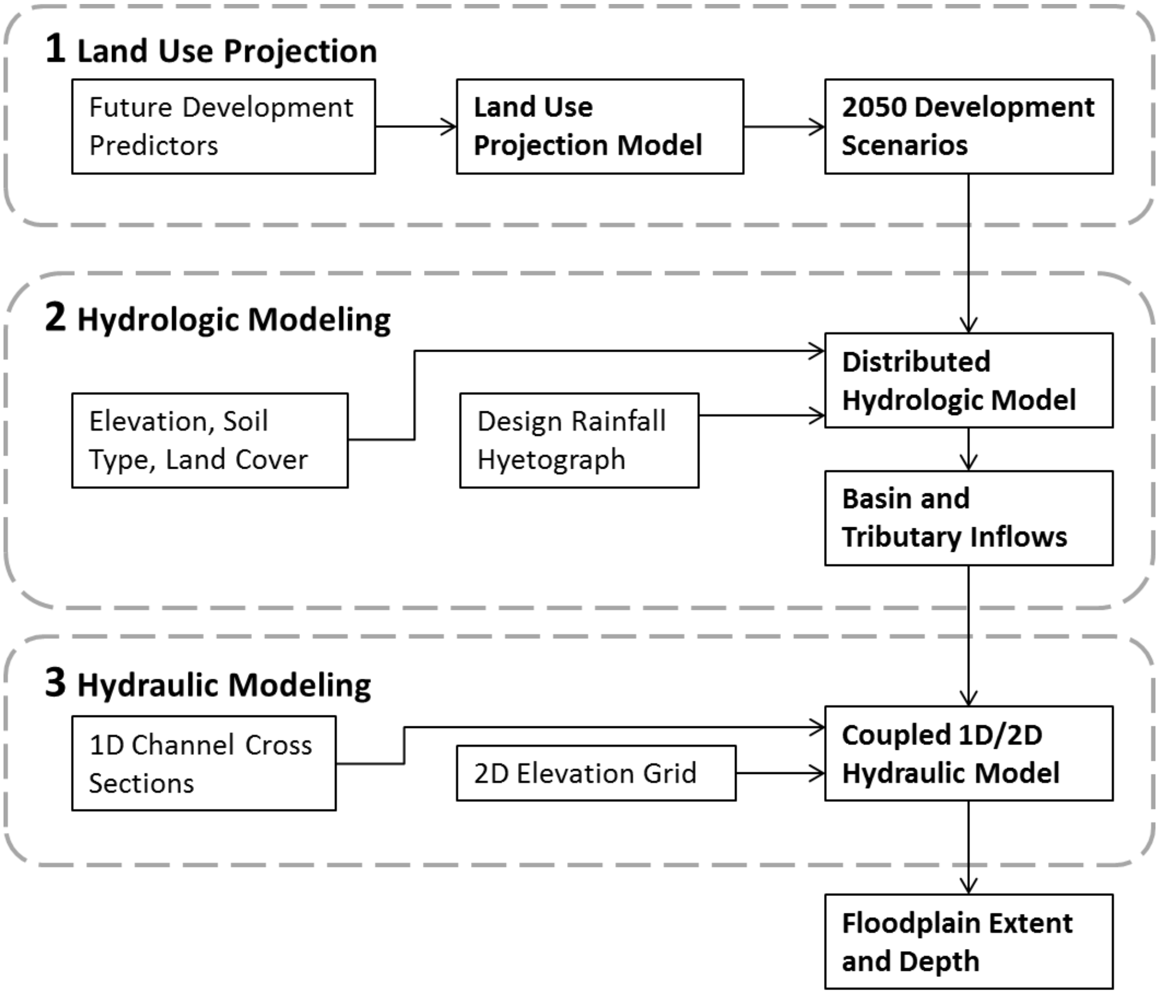


Figure 2: Integrated modeling framework overview

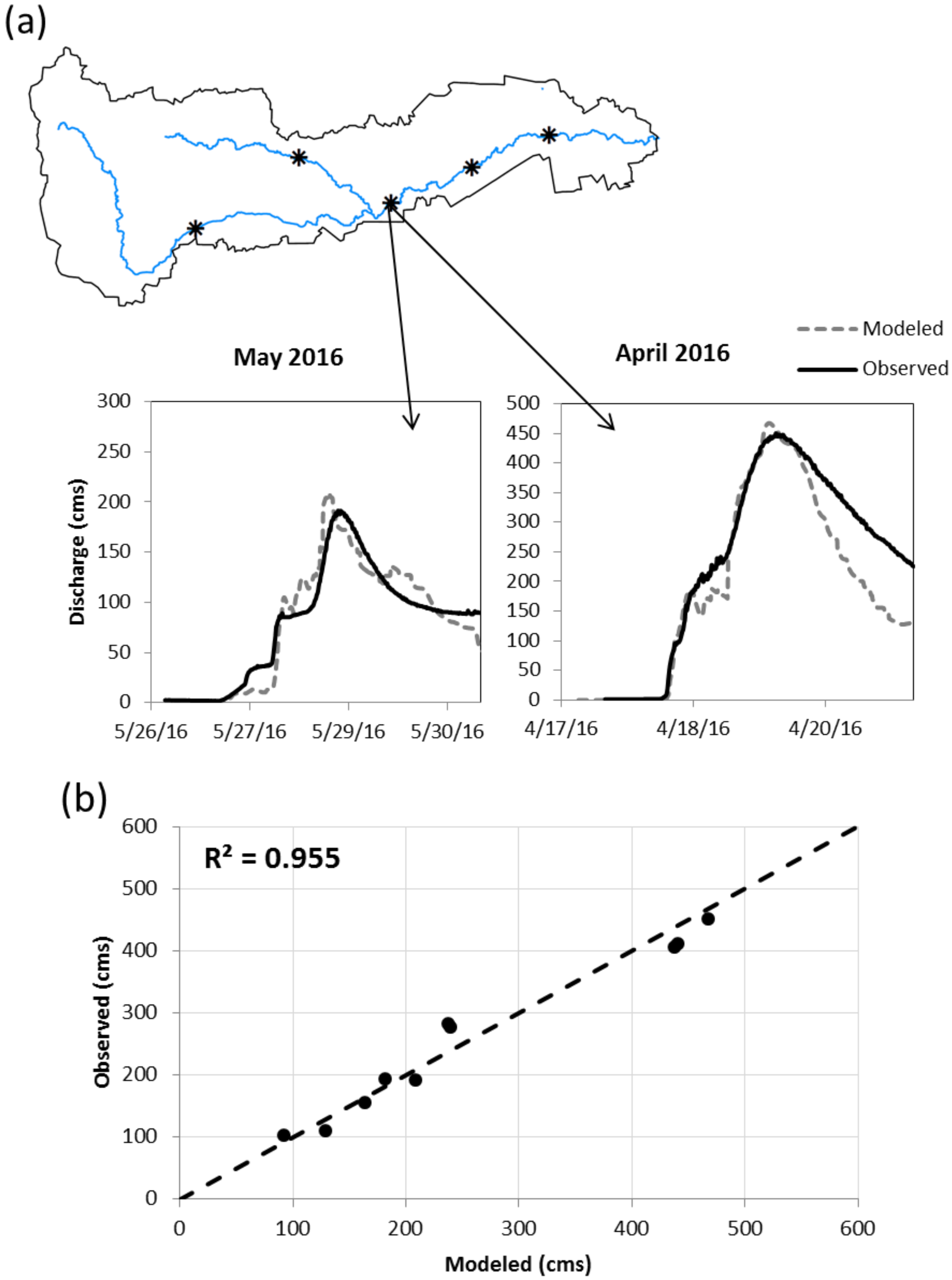


Figure 3: (a) Location of flow calibration points and hydrograph comparisons for a sample location in the middle of the watershed (b) modeled vs observed peak flow across all gages and storms

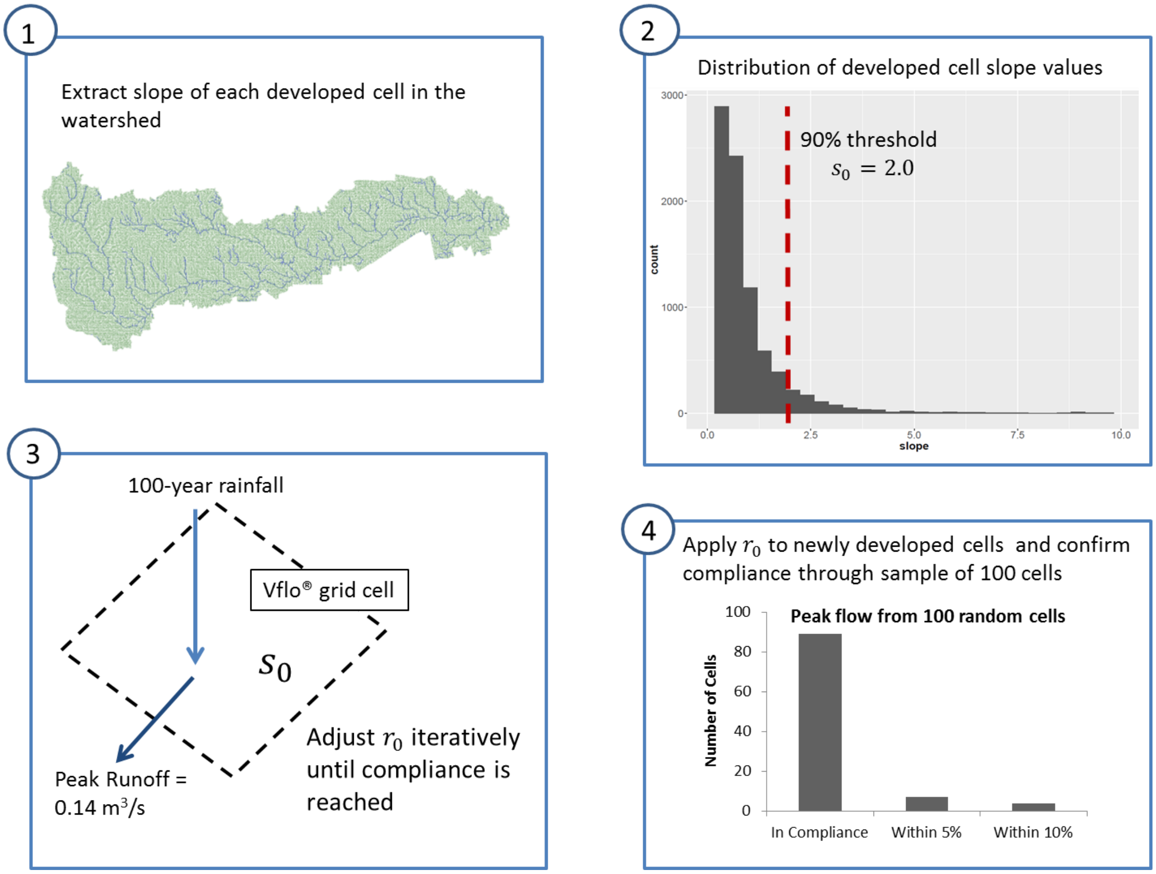
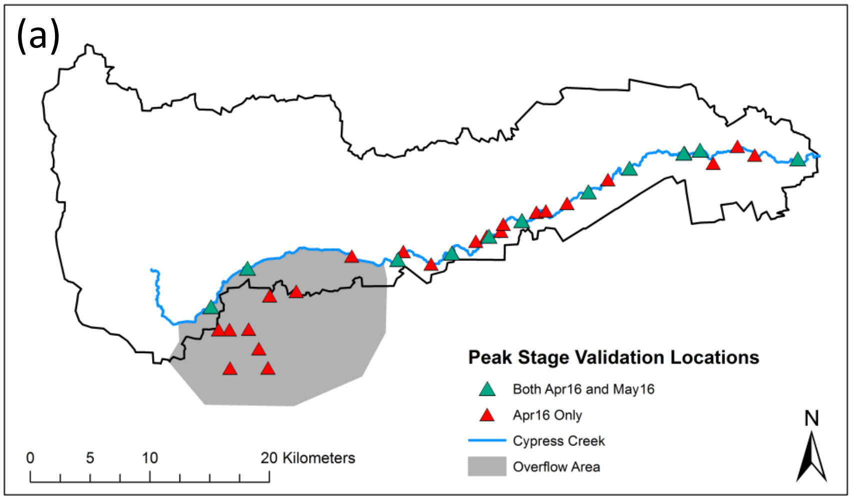


Figure 4: Process flowchart for determining representative roughness value to model on-site detention features of new development



(b) May 2016

(c) April 2016

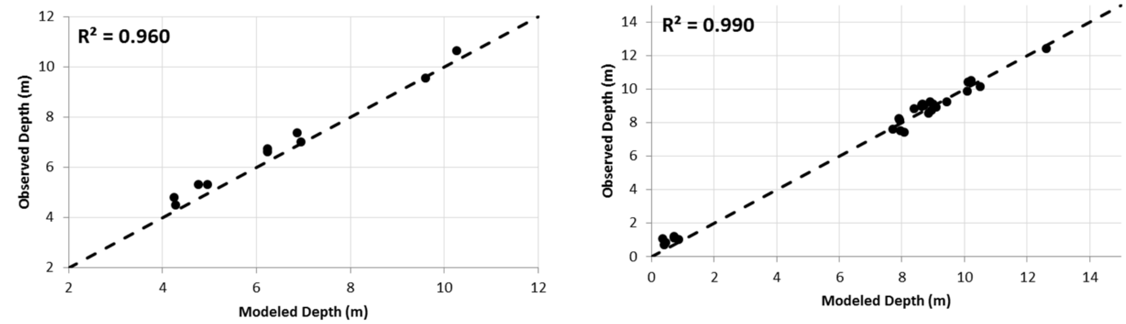


Figure 5: (a) peak stage validation locations (b) modeled vs observed peak stage for May 2016 event (c) modeled vs observed peak stage for April 2016 event

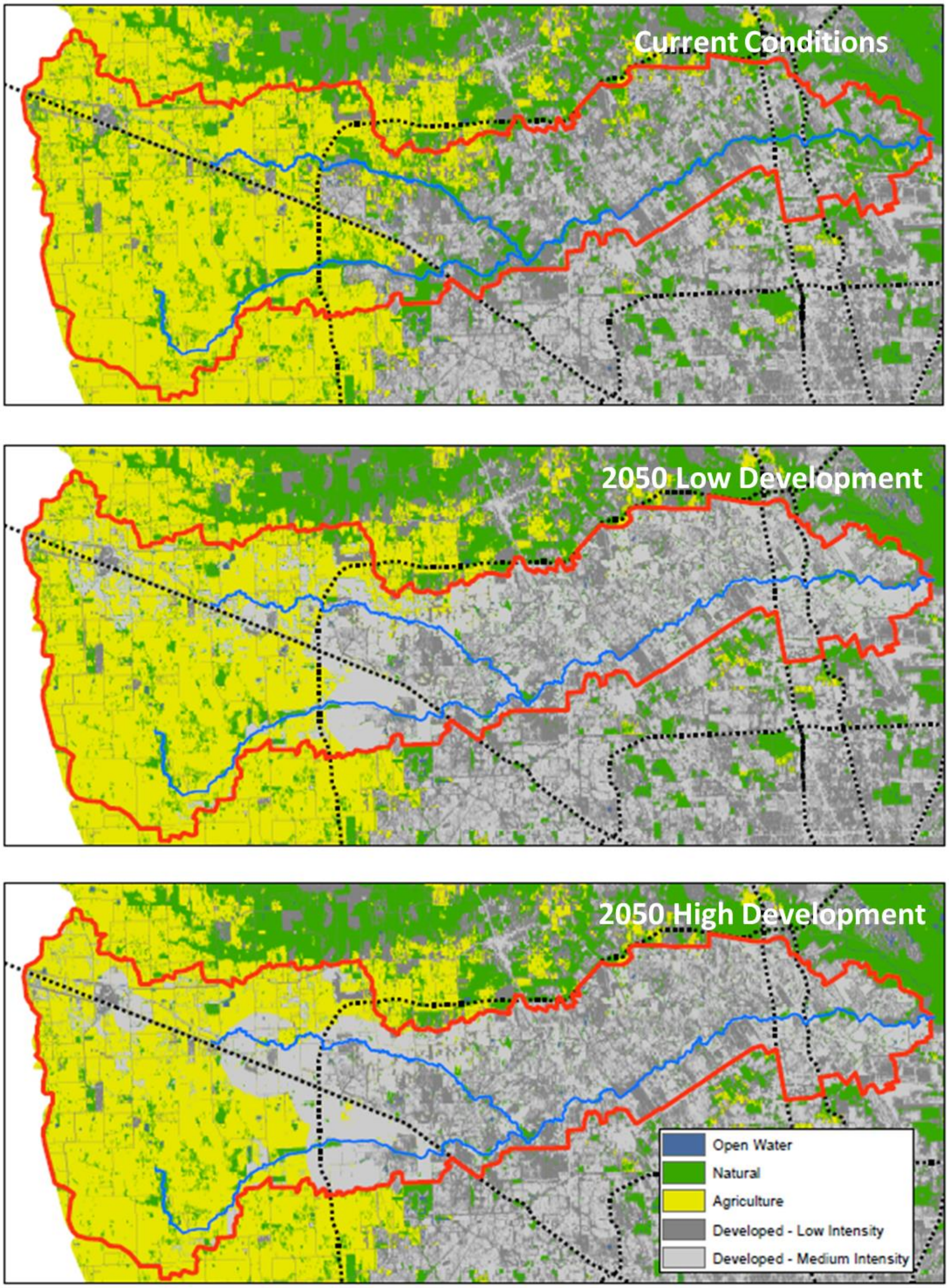


Figure 6: Land use evolution in Cypress Creek watershed for current conditions (top), 2050 low development scenario (middle), and 2050 high development scenario (bottom)

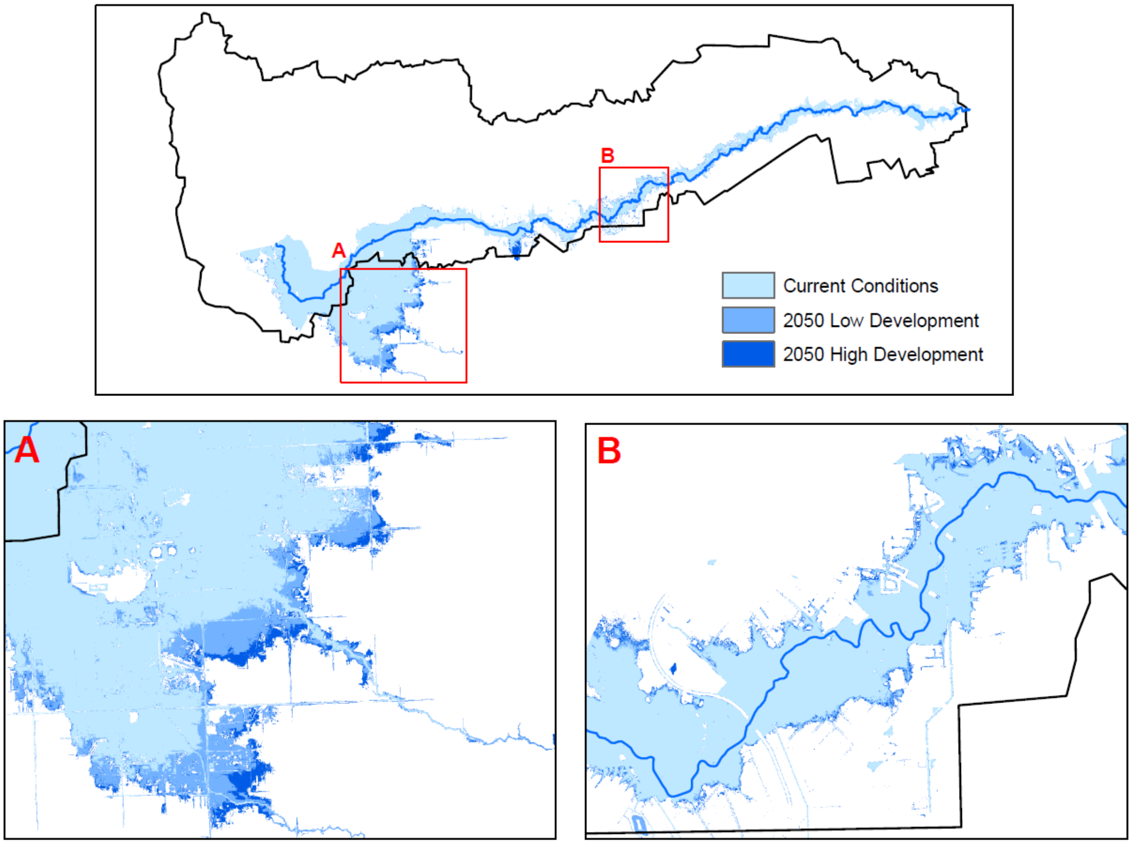


Figure 7: Current and 2050 projected 100-year floodplain comparisons

| | **Developed** | **Natural** | **Agriculture** |
|---|---|---|---|
| 2011 | 38.7% | 17.6% | 43.7% |
| 2050 (low) | 53.0% | 8.0% | 38.9% |
| 2050 (high) | 59.8% | 6.8% | 33.4% |
| Percent change from 2011 (low) | 37.0% | -54.5% | -11.0% |
| Percent change from 2011 (high) | 54.5% | -61.4% | -23.6% |

Table 1: Percent changes in land use type between 2050 projections and current conditions

| | **2011** | **2050 (low)** | **2050 (high)** |
|---|---|---|---|
| Floodplain Extent (km) | 106.5 | 115.5 | 119.8 |
| Percent Increase | - | 8.4% | 12.5% |
| Inundated Parcels | 2926 | 3287 | 3476 |
| Percent Change from 2011 | - | 12.3% | 18.8% |

Table 2: Floodplain extent increase and increase in inundated parcels for entire Cypress Watershed

| | 2011 | 2050 (low) | 2050 (high) |
|---|---|---|---|
| Floodplain Extent (km) | 38.5 | 44.8 | 47.3 |
| Percent Increase from 2011 | - | 16.4% | 23.0% |
| Inundated Parcels | 413 | 499 | 515 |
| Percent Increase from 2011 | - | 20.8% | 24.7% |

Table 4: Floodplain extent increase and increase in inundated parcels for overflow region of Cypress Creek watershed