Comparative Assessment of Flood Response to Impacts of Changes in Precipitation Extremes and Watershed Modifications

Carly Jo Phillips

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APPROVED:

Emad Habib, Chair
Department of Civil Engineering

Robert Miller
Department of Civil Engineering

Mohammad Jamal Khattak
Department of Civil Engineering

Haitham Saad
Department of Civil Engineering

Mary Farmer-Kaiser
Dean of the Graduate School

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Abstract

After flood events of the past decade, state agencies and local governments in Louisiana have been working to provide better drainage strategies and flood mitigation. The current study provides a comparative analysis of anthropogenic and natural factors which affect flood response and the implementation of flood mitigation methods to offset increases in flooding. The specific factors analyzed in this assessment include the impacts of land use changes, channel modifications, and precipitation changes to Coulee Ile des Cannes sub-watershed, a tributary of the Vermilion River watershed. Flood mitigation methods include the addition of detention ponds within Coulee Ile des Cannes watershed and a flood control structure on the Vermilion River, which would specifically operate during tropical storm events only. Hydrologic and hydraulic modeling efforts were used in this study to simulate the water surface elevation and flow rates in Coulee Ile des Cannes and its impacts to the Vermilion River. Findings from this study indicate that land use changes are not significantly impacting the maximum water surface elevation or flow rate within Coulee Ile des Cannes. Channel modifications managed to reduce the maximum water surface elevation but cause an increased flow rate to water draining into the Vermilion River, increasing the stage in the main river. Precipitation changes in this assessment looked at the impact of differences in design storms based on the data used to calculate precipitation depths associated with each storm. Design storm precipitation depths are calculated using data from a local rain gage to determine 24-hour 10, 50 and 100-year design storms for the area. Precipitation depths from a sample of this data were also calculated to investigate how the depth changes. This investigation indicates non-stationarity in the data and that over time precipitation rates have increased. Results from hydrologic and hydraulic modeling indicate that precipitation

changes have a significant impact to differences in water surface elevations and flow rates. For the flood mitigation methods, the detention ponds manage to reduce the water surface elevation in Coulee Ile des Cannes and reduce the flow rate. Reductions in the flow rate leads to reduction in the Vermilion River reversing the increase created by channel modifications. The flood control structure on the downstream end of the Vermilion River is found to potentially provide significant reduction in water surface elevation from downstream on the river all the way upstream to Coulee Ile des Cannes.

To each of my family members and friends,
though you may not understand the contents,
I would not have accomplished this without you.

Acknowledgements

The completion of this degree and the accomplishments I have made thus far in my life would not be possible without the strength and blessings I have received from God the Father. It is through His goodness that I have been given the abilities and opportunities to receive this education. I extend my sincerest gratitude toward my parents and sister for supporting and encouraging me through this degree and in every aspect of my life.

I would like to thank my advisor Dr. Emad Habib for his guidance and patience throughout my time obtaining my master’s degree. It is through his encouragement and confidence in me that I was able to complete this research. He has provided invaluable guidance into growing as a researcher and engineer. I would also like to thank Haitham Saad for his guidance and providing me with his knowledge throughout the completion of this thesis. I could not have accomplished this task without either of their encouragement. Thanks are also due to Dr. Robert Miller and Dr. Mohammad Khattak for supporting me and serving on my thesis committee. They have both been vital parts of my education here at the University of Louisiana at Lafayette.

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Chapter 1 Introduction

Background

In the state of Louisiana, flooding is a common natural disaster which frequently occurs due to high intensity inland storms and tropical storms coming from the Gulf of Mexico. Although common, flooding is not an issue isolated to Louisiana. Flood risk is increasing around the world due to precipitation events occurring more frequently and with higher intensities. Researchers associate the extreme weather conditions causing these flooding events with both anthropogenic and natural factors such as: urbanization, watershed modifications, and climate change. Globally, there were three times as many natural disasters between the years 2000 to 2009 as there were from 1980 to 1989 (Leaning & Guha-Sapir, 2013). These natural disasters are classified as geophysical (e.g., earthquakes, volcanos) and climate-related events having immediate and long-term effects. Climate-related events may be further classified into hydrologic (e.g., flooding, storm surge, landslides) and meteorologic (e.g., tropical storms, extreme temperatures, wildfires). Louisiana is a humid subtropical region with low-gradient topography, a combination that leaves a significant portion of the state vulnerable to flood risk. For this reason, it is necessary to understand the factors which contribute to increased flooding and changes to watershed hydrologic and hydraulic conditions.

As with many other areas of the United States and around the world, regional cities in Louisiana are continuing to expand and become more urbanized. Increased urbanization directly correlates to an increased area of impervious surfaces altering watershed hydrologic characteristics. These modifications to watersheds are having effects on local and downstream channel flows and water levels. For example, in Texas, efforts have been made to quantify the influence of urbanization on flooding and analyze the role climate change plays in this regard (Shao et al., 2020). This study suggests that urbanization reduces lag times and elevates flood peaks significantly and amplifies streamflow variability. In areas where there are little land cover changes, changing climate is found to be a major driver of variations in monthly maximum streamflows. Another study in Egypt investigated the effects of urbanization and climate change for the purpose of developing a GIS decision support system to create flood susceptibility maps (Mahmoud & Gan, 2018). Analyzing changes to annual rainfall and temperature allowed them to discover that even with a decline in rainfall, there was still an increase to the annual surface runoff due to the rapid urbanization of the study area. A different study in Texas focused on understanding the performance of different floodplain management approaches and their impact on the floodplain (Juan et al., 2020). This study compared two physically similar neighboring watersheds where one is channelized (i.e., modifications were made to increase the carrying capacity of the stream) and the other remains mostly in its natural state. The findings of this study indicate that the floodplain for both channels extended over time, but the channelized watershed had a larger floodplain increase than the natural channel. These studies, along with several others, give guidance for examining the effects of urbanization, channel modification, and changes in precipitation in Louisiana.

Within Louisiana, Lafayette is a parish in the south-central part of the state that is continuously urbanizing and expanding. With the expansions of the past few decades, the area has also seen an increase in flooding. A storm in August of 2016 left many parts of the City of Lafayette and surrounding areas with over 20 inches of rainfall, resulting in flooding homes and businesses. Many residents attribute the immense flooding to channels (referred to locally as coulees) being filled with debris which prevented them from draining properly. With this flooding event, members of the community have been working to investigate the leading causes of flooding in the area and what measures can be taken to prevent future flooding from occurring. This study will take recommendations and suggestions from other published studies on related topics to examine the contribution of land use change, channel modifications, and precipitation changes to increased flooding. The location focus of this study is on Coulee Ile des Cannes and the Vermilion River, both within the boundaries of Lafayette Parish. Coulee Ile des Cannes is a tributary of the Vermilion River which has undergone dredging and other channel modifications over the past few decades. The surrounding watershed is also part of an area of Lafayette that has increased urbanization and land use changes. In this assessment modeling software is used to examine the impact of changes to hydrologic and hydraulic factors and analyze whether future flood mitigation efforts could reverse the impacts of these changes. Future flood mitigation efforts examined include placing detention pond storage areas in Coulee Ile Des Cannes watershed and a flood control structure placed on the downstream end of the Vermilion River. The flood control structure modeling was completed as part of an assessment requested by the Vermilion Parish Police Jury. This assessment was conducted to examine the effect the structure has in tropical storms and preventing storm surge from damaging coastal communities. The impacts of the structure are also examined further upstream the Vermilion River at Coulee Ile Des Cannes in Lafayette Parish to determine if there are upstream benefits.

Literature Review

Assessing the regional flood risk in changing climate and urban conditions is not trivial due to the many variables contributing to flood events. Many areas of the world are seeing more frequent, extreme rainfall events that existing drainage structures and river networks are not equipped for. Understanding the flood response of watersheds during rainfall events is essential to developing effective flood management strategies. The rapid urbanization happening around the world is having increased implications on flood risk. An increase in impervious surfaces is increasing surface runoff volumes which puts pressure on drainage systems and raises water levels of local channels and rivers (Zhang et al., 2008). In response to the increased urbanization and changing climate, researchers are using land surface models with hydrodynamic models to directly examine flood inundation due to climate change (Modi et al., 2021). These models are using historical and future design storm peak discharges to estimate how flood risk is being altered in changing climates. The outcome of Modi et al., (2021) indicates that increased precipitation is not directly translating to an increase in flood risk for future climate scenarios. Therefore, using a coupled land surface model with a hydrodynamic model allows for investigation into antecedent soil moisture conditions and can provide insight into future flood risk. Another method found analyzed the effects of urbanization on floods was using a paired catchments approach for two adjacent river basins in south-central Texas (Shao et al., 2020). This analysis compared two physically similar basins, one with little land cover change and the other with considerable urbanization. Some of the variables examined in that study include peak flows of observed and simulated flood events, changes to the monthly maximum streamflow, and sensitivity of flood peak flows to various urban land cover conditions. Results published from that study indicate that changing climate is a driver of changes in streamflow patterns in areas with little land cover change. Similar to the study by Modi in 2021, it was found that urbanization can elevate flood peaks, lead to shorter lag times, and intensify the influence of antecedent soil moisture conditions.

Extreme precipitation events over the last few decades have also brought attention to nonstationary factors that influence the characteristics of hydrologic data. Stationarity in data implies that measured values are a result of a system that does not change over time. Therefore, nonstationary factors which influence hydrologic data can include climate change, urbanization, and other land use/land cover changes. Research suggests that warmer climates are expected to increase flood risk due to heavier precipitation amounts occurring (Trenberth et al., 2007) and as urbanization continues, greater volumes of runoff will occur due to the increase in impervious surfaces (Theobald et al., 2009). With this in mind, Gilroy and McCuen (2012) developed a method to adjust nonstationary measured flood data influenced by urbanization and climate change to a state that reflects stationary conditions for any design year. The results from this study would help engineers and policy makers understand that nonstationary factors such as climate change and urbanization have a significant influence on hydrologic data and need to be accounted for in flood frequency analyses.

A study following the same thought process of incorporating nonstationarity into flood frequency analyses was conducted by Regier et al. in 2021 to present a method for transferring the extreme precipitation from hurricane events to other geographical areas within their modeled landfall path. Hurricane Harvey, which hit the coast of Texas in 2017, was determined to have increased the 100-year peak flow for the region by 28% (McDonald and Naughton, 2018). Regier et al. used models of Hurricane Harvey to shift rainfall data to two probabilistic locations and simulate peak flows from the storm. Using the results from these simulations, they developed flood frequency statistics using Bulletin 17C methodologies and integrated the frequency statistics into a regional flood frequency analysis. Results of this analysis provide another example of how flood frequency statistics and regional flood analyses are intensified by climate change and extreme rainfall events. Applying the events of Hurricane Harvey on the two locations used in the study increased the 100-year peak flow by 17% and 66%. These results again signify the need to incorporate nonstationarity and extreme storms caused by climate change into the methods for calculating flood frequency statistics. It has been proven that extreme precipitation events are going to have an impact on design floods. The incorporation of changes to flood frequency statistics is necessary for responsible flood risk management and designing infrastructure to sustain such extreme storm events.

Overarching Goal and Objectives

The overarching goal of this research effort is to assess the relative contribution of anthropogenic factors and natural factors to the increased flooding in low-gradient watersheds, and whether future flood mitigation efforts can offset the effect of such factors. Anthropogenic factors of this research study include urbanization and channel modifications and natural factors include changes in precipitation extremes. Future flood mitigation efforts include detention pond storage areas and a flood control structure. The specific objectives of this study include:

- Analyze urbanization and land-use changes in Coulee Ile des Cannes watershed.
- Identify degree of channel modifications in Coulee Ile des Cannes watershed
- Analyze and quantify past changes in precipitation extremes over the same area

- Evaluate the relative contribution of each of three factors to flood risk to Coulee Ile des Cannes, and their collective impacts on flood risk.
- Quantify potential benefits of detention pond storage areas on Coulee Ile Des Cannes
- Quantify potential benefits of a proposed flood control structure placed at the downstream end of the Vermilion River for reducing flood risk along in Coulee Ile des Cannes.
- Assess tradeoffs and potential negative consequences of different mitigation measures on flood risk within the Coulee Ile des Cannes watershed as well as the main Vermilion River.

Chapter 2 : Methodology

Study Area

The Vermilion River is a major waterway in southern Louisiana, United States, that stretches approximately 70 miles from its headwaters to the Vermilion Bay, a large estuary in the Gulf of Mexico (**Figure 1**). The river runs through the city of Lafayette, the fourth-largest city in Louisiana, and its surrounding areas, including the towns of Abbeville and Maurice. The Vermilion River, being the fifth-largest river in Louisiana, drains a watershed of approximately 602 square miles. Throughout its length, the Vermilion River is fed by 15 main tributaries and bayous, including Coulee des Poches, Coulee Mine, Coulee Isaac Verot, Coulee Ile des Cannes, and Anslem Coulee. These five tributaries comprise the main drainage system of Lafayette Parish.

Coulee Ile Des Cannes watershed is approximately 52 square miles which makes it responsible for the drainage of ~20% of the Lafayette parish area (U.S. Census Bureau, 2020). The main stem of the coulee originates in the city of Scott, LA and travels predominantly south for ~16 miles before it drains into the Vermilion River (**Figure 1**). On the downstream end of the coulee, prior it joins the Vermilion River, a smaller coulee named coulee granges drains into coulee Ile des Cannes. The proximity of coulee granges to the outlet of coulee Ile des Cannes and its relatively significant drainage area makes it play an important role in the flood dynamics of coulee Ile Des Cannes. The main land cover in coulee Ile Des Cannes watershed and the Vermilion River watershed consists of pasture, cultivated crop, and developed land. The history of flooding within the drainage area of Coulee Ile Des Cannes indicates that flooding can occur during any season of the year (FEMA 2018). Floods occur due to limited stream capacities and because the nature of the terrain offers little relief. The existing channel capacities are exceeded by floods of low frequency that spread rapidly over the floodplains. Due to the flatness of the floodplains, they are entirely covered by floodwaters during the less frequent floods. After this condition occurs, increases in the discharges produce only minor increases in water-surface elevations. The principal sources of flooding in the area are from rainfall runoff and backwater from Coulee Ile des Cannes tributaries and West Coulee Mine (FEMA 2018). Additionally, with Coulee Ile des Cannes being one of the larger tributaries within the Vermilion River watershed, it is heavily influenced by flow and stage regimes in the Vermilion River. In this study, a large part of the focus is placed on the Coulee Ile Des Cannes and its watershed.

Since the late 1980s, Coulee Ile Des Cannes has been the subject of several drainage improvement projects. These have included drainage maintenance projects (i.e., debris/blockage removal), detention pond construction, and conveyance projects along the main channel as well as several of its lateral channels. Some of the recent drainage improvement projects have been focused on reshaping the channel to increase volume and reduce water surface elevations. Other projects include constructing detention ponds at various locations within the watershed. As a response to the August 2016 flood event, many drainage improvement projects and flood mitigation management plans are being put in place throughout Lafayette Parish and the state of Louisiana to prevent future flooding events.

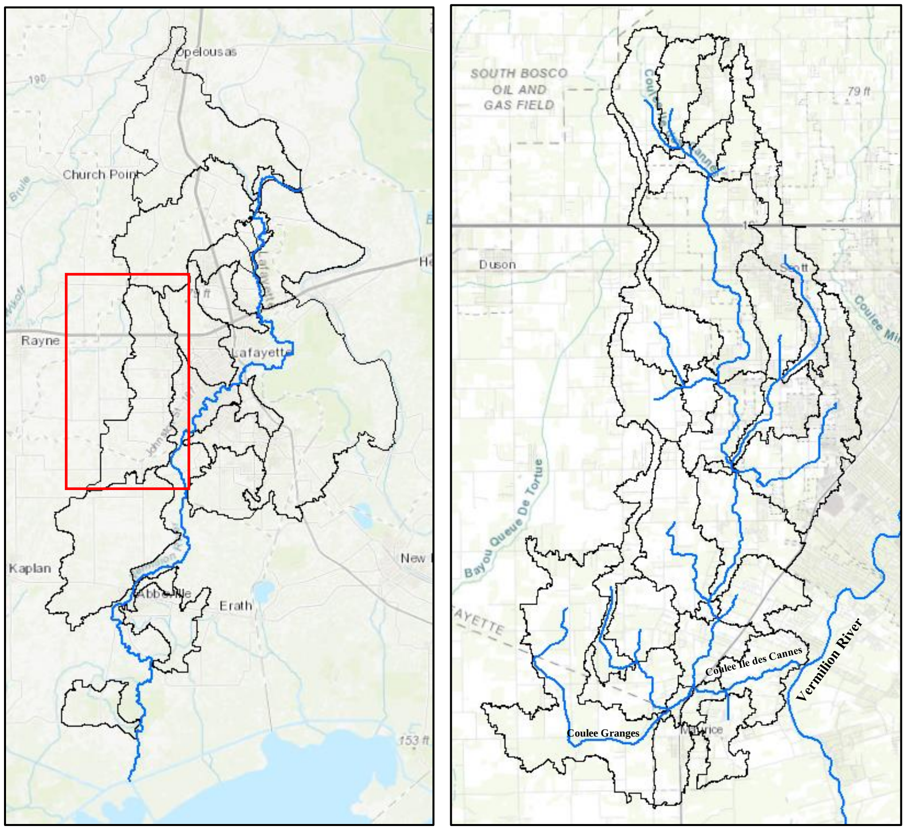


Figure 1. (Left) Vermilion River watershed with a red box signifying the location of Coulee Ile des Cannes in the watershed. (Right) A closer look at Coulee Ile des Cannes watershed which has been separated into subbasins. The main channel goes down the center of the watershed and has several lateral channels branching off.

Simulation Periods and Storms

Several sources of precipitation inputs were used for this study, including design storms as well as actual precipitation events. The study depended on the 10, 50, and 100-year return period design storms in addition to inland and tropical storms that have occurred in the past few years when performing retrospective runs. Precipitation data from the region was used to calculate rainfall depths associated with each of the return periods used in the study. The inland storms are used for the analysis of Coulee Ile Des Cannes. They include a storm from August of 2016 and May of 2014. Both storms produced widespread flooding in Lafayette and other parts of the state. The August 2016 event is comparable to a 100-year storm and the May 2014 event is comparable to a 10-year storm depending on the selected storm duration. To better understand the spatial distribution of the two inland rainfall events, a figure was created to show rain accumulation for the storms' duration (**Figure 2**). The figure shows the total accumulation of the rainfall received during each storm overlaying a map of the area. According to the figure, some areas received up to 658 mm (25.91 inches) of rain during the August 2016 storm, compared to the May 2014 storm where the maximum total rainfall recorded was about 320 mm (12.60 inches). The figure also reveals that the May 2014 storm was more concentrated over Coulee Ile des Cannes and upstream parts of the Vermilion River watershed, while the August 2016 storm has greater rainfall over the central-east side of watershed. The inland historical storms will only be used in simulations for analyzing changes in land use and channel modifications and for examining the impact of detention ponds. Changes in precipitation will rely on the design storms as the basis examining the impacts on the watershed. The tropical storms included in this study will be used to quantify flood mitigation benefits of a flood control structure placed on the downstream end of the Vermilion River. These tropical storms include Hurricane Barry of 2019 and Hurricane Laura of 2020. Hurricane Barry is comparable to a 2-year storm and had a moderate storm surge and flooding impacts on the Louisiana coast. Hurricane Laura is comparable to a 5-year storm and had higher storm surge and flooding impacts.

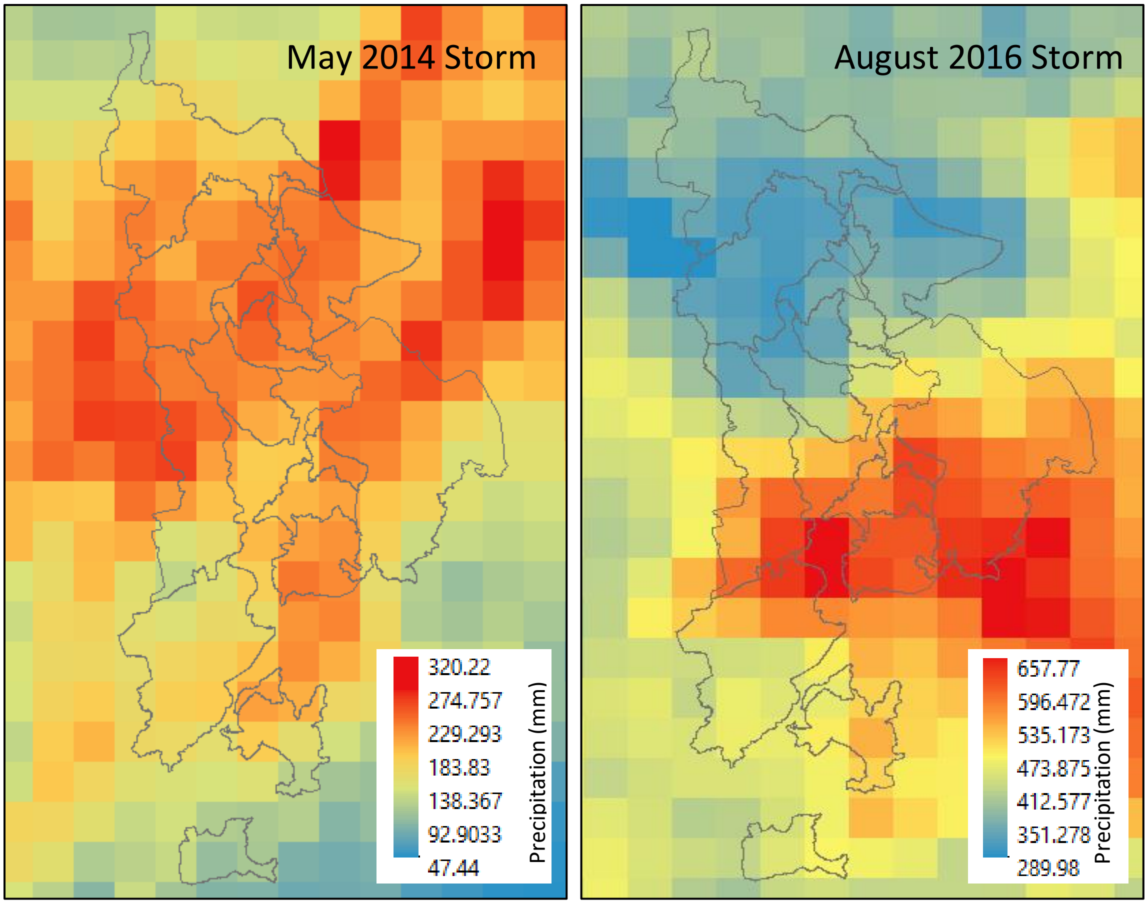


Figure 2. Spatial distribution map of the August 2016 storm and May 2014 storm over Vermilion River watershed showing the total accumulation of rainfall for each storm.

Hydrologic and Hydraulic Modeling

This study depended on both the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) in performing the hydrologic and hydraulic modeling for Coulee Iles Des Cannes respectively. The developed hydrologic and hydraulic models of Coulee Ile Des Cannes are used to simulate the impacts of changes to the watershed and proposed localized flood mitigation efforts on the flood dynamics along the coulee. The study also used another spatially expanded hydraulic model that covers the main stem of the Vermilion River along with the five main tributaries including coulee Ile Des Cannes. This model relies on the National Water Model (Blodgett, 2022) as hydrologic model to produce the runoff hydrographs required to run this model.

More details about this coupling will be discussed further in this section. This study will mainly depend on the spatially expanded hydraulic model of the Vermilion River to examine the impact of the flood control structure proposed near its downstream end. The hydrologic model of Coulee Ile Des Cannes is a distributed model where the model domain has been discretized dividing it into a large number of small grids at a spatial resolution of 2000 meters. Despite that, the HMS still requires the model domain to be delineated into subbasins where the solution of the hydrological processes is only available at the outlet of these subbasins. In order to establish such delineation, the delineation tools within HEC-HMS (V4.9) were utilized (USACE, 2018). These tools capitalize on the long-known GeoHMS tools that used to work as a toolbar inside ArcGIS software packages. These tools are widely used for hydrological simulations and have a number of tools to delineate and analyze watershed characteristics. The delineation process involved the identification of the watershed boundary and the calculation of the flow accumulation within the basin. The resulting model was comprised of 31 subbasins that were delineated based on factors such as topography, land use, and soil characteristics, which were all taken into consideration during the process. Subbasin elements for the hydrologic model consist of structured discretization, gridded deficit and constant loss method, and ModClark transform method. The gridded deficit and constant loss method involves the specification of several soil map parameters, including the initial deficit, maximum deficit, constant rate (hydraulic conductivity), and imperviousness. The soil data development toolbox from the Gridded Soil Survey Geographic Database (sSSURGO) (USDA, 2019) developed by the United States Department of Agriculture (USDA) was used to create the soil maps needed by the hydrologic model. Using the soil data development toolbox, maps for the available water storage and hydraulic conductivity could be developed. While preparing the required soil parameters, the study assumed that the initial deficit and maximum deficit are 25% and 50% of the available water storage respectively. The impervious data for the hydrologic model comes from the National Land Cover Database (NLCD) imperviousness product for 2001 and 2019 (Dewitz and USGS, 2021). Surface runoff calculations to produce the flow hydrographs were transformed using the ModClark method which uses a travel time index that is scaled by the overall time of concentration for each subbasin. Excess precipitation that falls on each grid cell is lagged by the scaled time index and routed through a linear reservoir (represented by the storage coefficient) (HEC-HMS User's Manual, 2018).

The hydraulic model for Coulee Ile Des Cannes developed in HEC-RAS consists of the output flow hydrographs from the HEC-HMS model for each subbasin routed using an unsteady one-dimensional setup. Figure 4 displays the setup of the hydraulic model of coulee Ile des Cannes, which in addition to the 1D cross-sections incorporates the main hydraulic structures (i.e., bridges and road crossings) encountered along the coulee. The hydraulic model is enforced by a downstream boundary condition, which is a stage-flow rating relationship applied at the junction of Coulee Ile Des Cannes and the Vermilion River. To develop this boundary condition, two rating curves were created using stage and flow data from the Vermilion River model at the outlet of Coulee Ile des Cannes. One of these curves is applicable for 10 and 50-year design storms, as well as the May 2014 storm, and was developed using data from the Vermilion River model during the May 2014 storm. The other curve is applicable for the 100-year and August 2016 storm and was developed using data from the Vermilion River during the August 2016 storm. These rating curves play a critical role in accurately modeling the flow dynamics of the system. The hydraulic model was used to estimate flow and stage hydrographs for various configurations of land use, channel bathymetry, precipitation, and detention pond setups.

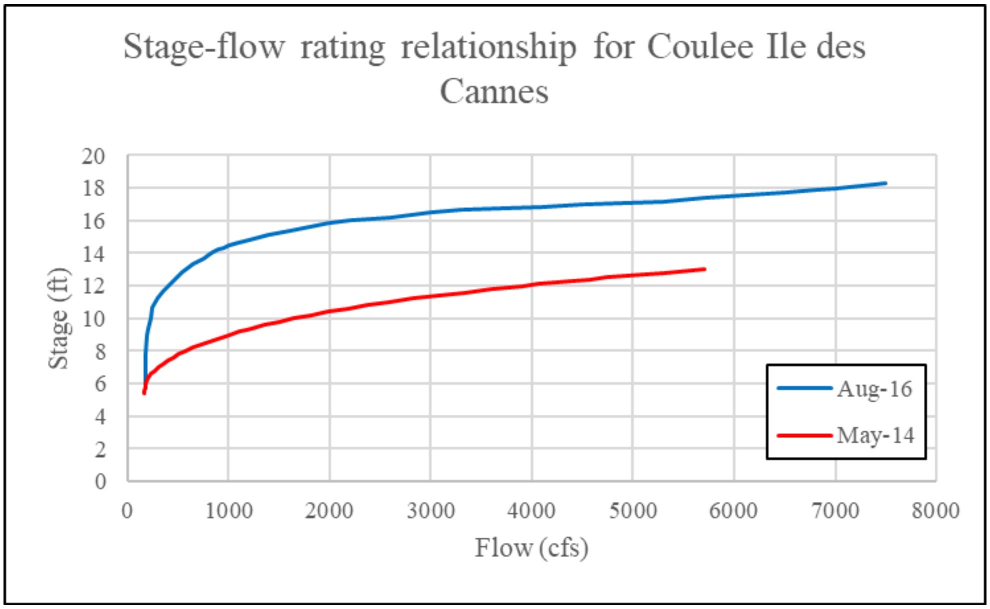


Figure 3. Stage-flow rating relationships used for the boundary condition in the standalone hydraulic model of Coulee Ile des Cannes. The red rating curve is applicable for the 10 and 50-year design storms, as well as the May 2014 storm. The blue rating curve is applicable for the 100-year and August 2016 storm. The rating curves were developed using data from May 2014 and August 2016 storms simulated in the full Vermilion River hydraulic model.

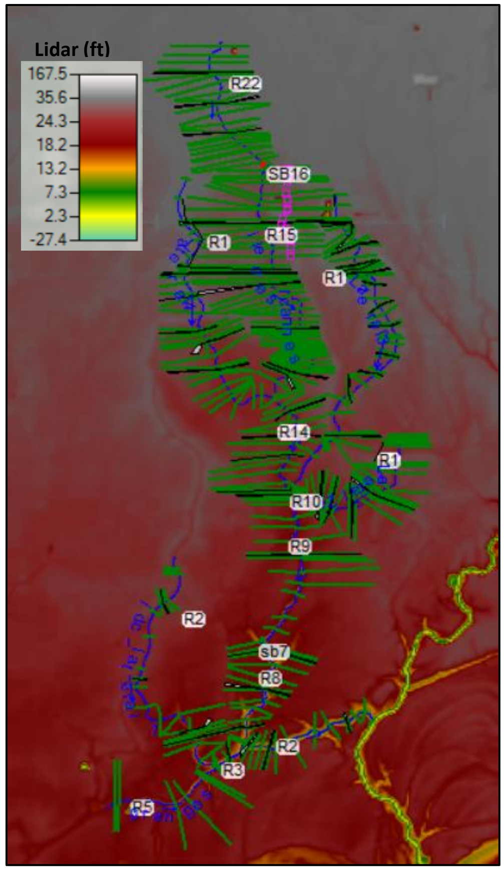


Figure 4. Hydraulic model set-up of Coulee Ile des Cannes in HEC-RAS with cross-section locations over the Lidar DEM.

A separate one-dimensional unsteady hydraulic model of the Vermilion River and its tributaries was used to examine the impacts changes to the channel bathymetry and detention ponds in Coulee Ile des Cannes to the Vermilion River. This model was also used to examine the impact of a flood control structure on the Vermilion River during tropical storm events as well. This model developed by (Saad et al., 2020) covers the entire Vermilion River, Bayou Tortue Swamp, and its five major tributaries. The main stem of the Vermilion in the model begins with receiving headwaters from Bayou Fusilier and flowing 69.2 miles where it intersects with GIWW and empties into the Vermilion Bay. Five of the major tributaries are included in the model while the other tributaries are represented by lateral streamflow hydrographs that are directly connected to the main stem of the river. The five major tributaries included in the model are Coulee des Poches, Coulee Mine, Coulee Isaac Verot, Coulee Ile des Cannes, and Anslem Coulee. Streamflow hydrographs from the National Water Model (NWM) Reanalysis (Blodgett, 2022) are used for the lateral streamflow hydrograph connections. The National Water Model (NWM), developed by (Gochis, et al., 2020), has been used by the National Weather Service (NWS) for operational flood forecasting since 2016. The latest version, NWM version 2.1, was implemented in June 2020. In order to investigate the performance of the NWM, retrospective analysis data for NWM version 2.1 were generated by the NWM team before its operational deployment. These retrospective analysis results, referred to as NWM-R3, are publicly available in Google Cloud Storage as of 2020.

The retrospective analysis results cover a 41-year period, from January 1979 to December 2020, and were generated using meteorological forcing data from the North American Land Data Assimilation System II (NLDAS2) datasets. The spatial resolution of the NLDAS2 datasets is 1/8th-degree with hourly temporal resolution. The NLDAS2 datasets utilize National Centers for Environmental Prediction (NCEP)/North American Regional Reanalysis (NARR) analysis fields for non-precipitation forcing fields, which are retrospective datasets while uses the gage-based NCEP/Climate Prediction Center (CPC) for the precipitation data. Prior to use in the retrospective analysis, the NWM team downscaled the NLDAS2 data and adjusted the precipitation data using the mountain mapper method (Hou et al., 2014) to account for climatological variation due to topography and wind directions (Rafieei Nasab et al., 2020). The resulting raster forcing dataset has a 1 km spatial resolution for each hour, containing incoming short- and longwave radiation, specific humidity, air temperature, surface pressure, near surface wind, and precipitation rate while the vectorized output dataset would include the flow hydrographs at 2.7M links across the United States. Each link in this dataset represents a unique and distinct stream reach. This study collected the streamflow information from this vectorized dataset at the stream links that corresponds to the Vermilion River main stem and tributaries to drive the Vermilion River hydraulic model.

The subbasins of the Vermilion River watershed and model configuration displaying the main river and storage areas along where streamflow hydrographs were connected can be viewed in **Figure 5**. Other elements of the model include hydraulic structures (i.e., bridges, road crossings), Bayou Tortue swamp (modeled as nine total storage areas), and Ruth Canal gate structure. Modeling of Bayou Tortue swamp in the model has proper storage-elevation relationships and inter-storage connectivity as well as direct precipitation from Stage IV radar rainfall over the swamp. A stage hydrograph is needed at the last cross-section of the Vermilion River to act as a downstream boundary condition for the whole model. The time-series for this location is collected from the Coastal Reference Monitoring System (CRMS) gauges network. The CRMS0552 station used as downstream boundary condition is located approximately 0.9 miles northeast of the intersection of the Vermilion River and the Intracoastal Waterway in Vermilion Parish, LA. Another two stage hydrographs are needed upstream of Fuselier Weir and Ruth Canal to represent conditions in Bayou Teche. The time-series at these two locations, along with the operation management for the gates, are provided by the Teche-Vermilion Freshwater District responsible for operation and monitoring the two structures.

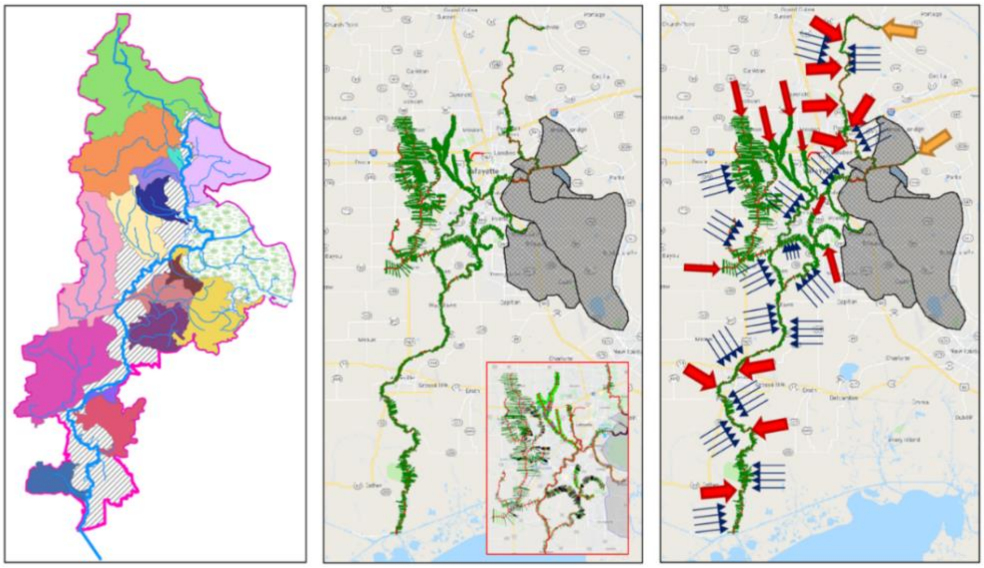


Figure 5. Left Panel: Main sub-watersheds of Vermilion River included in hydraulic model domain. Middle Panel: Layout of the main river and the five major tributaries modeled as 1D unsteady flow in the HEC-RAS model (Saad, Habib, and Miller, 2020). Hatched areas represent Bayou Tortue Swamp storage area within the model. (Right Panel): Representation of how the HEC-RAS model and the five tributaries are enforced by streamflow hydrographs. Thin multi-arrows represent laterally distributed hydrographs, while thick arrows are point-source hydrographs from sub-watersheds.

Analysis of Past Changes to the Watershed

Changes in Land use

To assess the impact of changes in land use on the flood dynamics of Coulee Ile Des Cannes, it is necessary to determine the extent of modifications in the watershed's landscape over time. In this study, these changes were quantified through analyzing the amount of alterations in the imperviousness of the area. The hydrologic model for coulee Ile Des Cannes requires the impervious area grid as an input parameter for the rainfall-runoff transformation calculations. To obtain the impervious area grid, the study utilized the National Land Cover Database (NLCD) of the United States Geological Survey (USGS), which is a publicly available dataset that provides land cover information for the entire country at a 30-meter pixel size resolution. The NLCD dataset includes information about the amount and location of impervious surfaces at different dates, which allowed the study to compare the changes in land use over time. The study retrieved two different versions of the impervious area grid from the NLCD dataset for the watershed area: one for the year 2001 and another for the year 2019. These two time periods were chosen to capture the changes in land use over an 18-year period. By comparing the two grids, the study was able to quantify the changes in the imperviousness of the Coulee Ile Des Cannes watershed (**Figure 7**). The 2019 impervious surface represents current conditions for the watershed and the 2001 surface is used to determine the effect of land use changes over the last couple of decades. The comparison of these two datasets will identify how the change of land use in the area is directly affecting surface runoff, water surface elevations and streamflow in Coulee Ile Des Cannes. As was previously mentioned in the section describing the study area, the three main land-use classes within this watershed are urban developments, pasture/hay, and cultivated crop areas. From 2001 to 2019, one of the most noticeable changes between the two land covers is the increased area of urban developments. **Figure 6** shows the two land cover maps released in 2001 and 2019 from NLCD. In the figure is also a map showing the differences between the two datasets. The difference between the two land covers is most visibly urban changes, represented by the magenta color on the map. Within the watershed, other apparent changes are classified as forest change, agriculture within class changes and water changes.

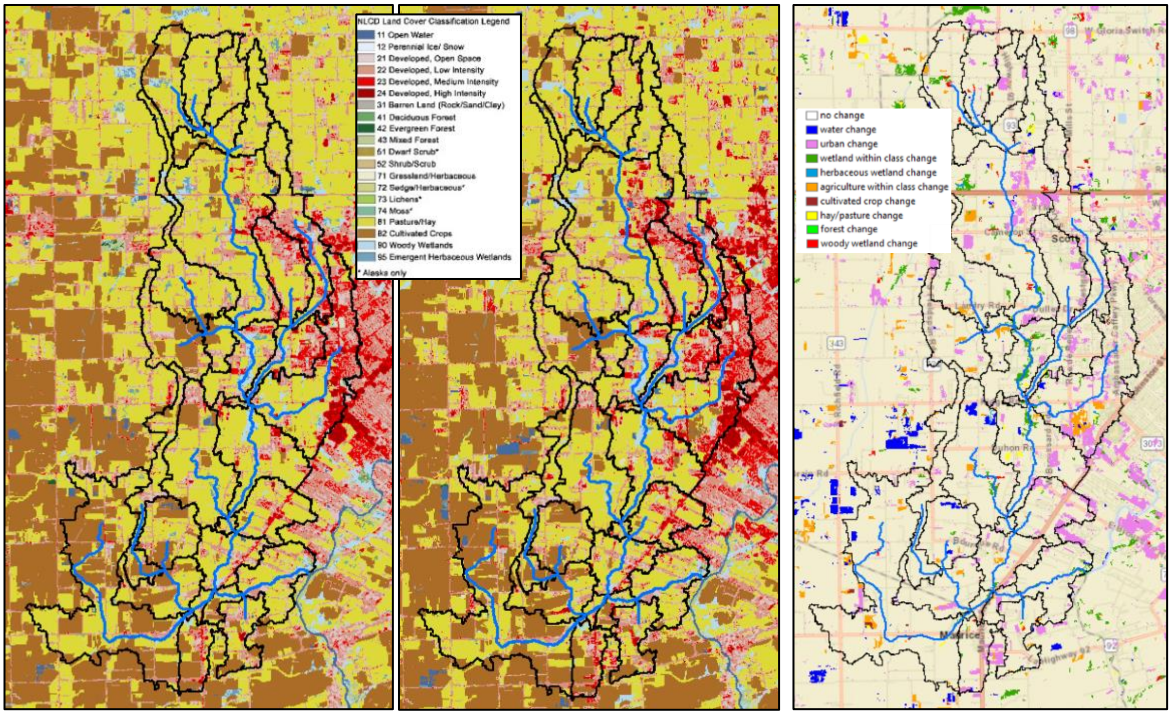


Figure 6. (Left Panel) NLCD land cover imagery from 2001, (Middle Panel) NLCD land cover imagery from 2019, and (Right Panel) changes in land cover between the two images for Coulee Ile des Cannes watershed.

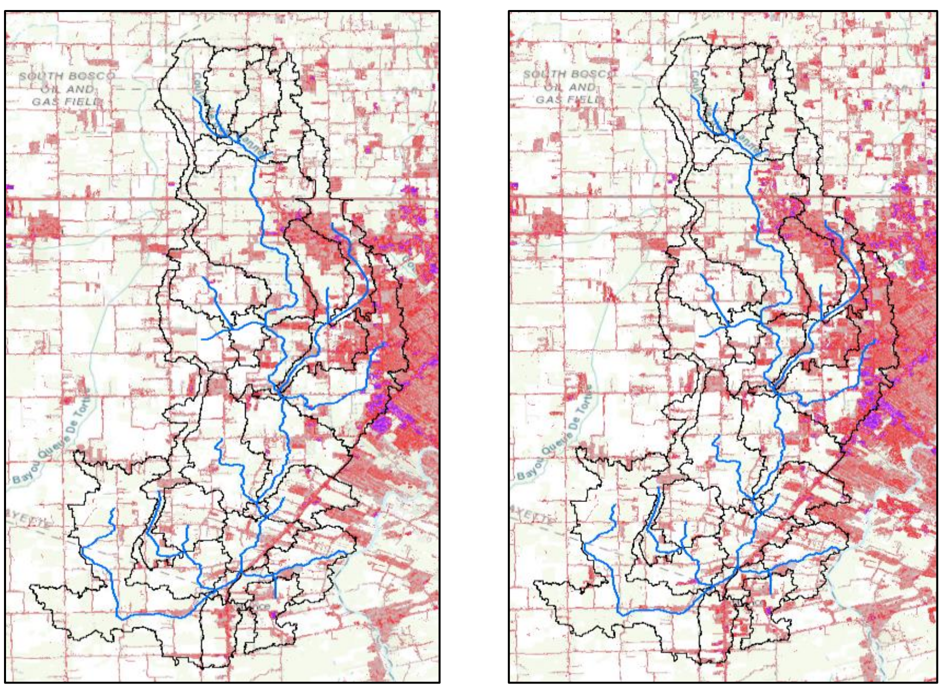


Figure 7. NLCD Imperviousness imagery for 2001 (left) and 2019 (right) which represents percent imperviousness. The darker magenta colors represent the highest percent impervious areas. This impervious data is incorporated into the hydrologic model to simulate changes in land use.

Channel Modifications

Analysis of channel modifications in this study is being completed by comparing the hydraulic modeling results of two channel bathymetries for Coulee Ile Des Cannes. These bathymetries represent two different channel conditions for the main stem of Ile Des Cannes. One of the bathymetries represents the current conditions of the channel. In the current conditions, parts of the channel have been dredged and widened to increase channel capacity. The second bathymetry that is used in this analysis comes from an older version of the current bathymetry that was worked on by the U.S. Army Corp of Engineers with the University of Louisiana at Lafayette in 2004. This bathymetry represents past conditions of the channel before some of the recent dredging and channel widening projects that took place. The two bathymetries were placed in separate geometry files of each of the HEC-RAS models used in this assessment. In the isolated model of Coulee Ile des Cannes, the pre-modified bathymetry is simulated for the design storms. The pre-modified bathymetry is simulated in the Vermilion River model with the two historical storms to examine the impact within Coulee Ile des Cannes and the impact of the modifications on the Vermilion River. By simulating the current and past bathymetries with the current precipitation data for design storms, the effect of watershed modifications can be isolated to better examine. Simulating the two geometries with the two real storms from May 2014 and August 2016 will show the difference of how the channel perform under actual events. The image below shows the two bathymetries along the main channel of the coulee. The green line is the past version of the coulee, and the black line is the current bathymetry. As can be seen in the **Figure 8**, the current channel is much smoother and deeper than the past version. The current channel is a result of dredging and widening projects conducted by LCG for drainage improvement. In **Figure 9**, four images at various locations along the main channel are displayed to show the difference between the two cross sections for the past and current channel bathymetries. The current channel is ~10ft deeper at the outlet of the coulee and ~3 to 6 ft deeper moving upstream along the channel.

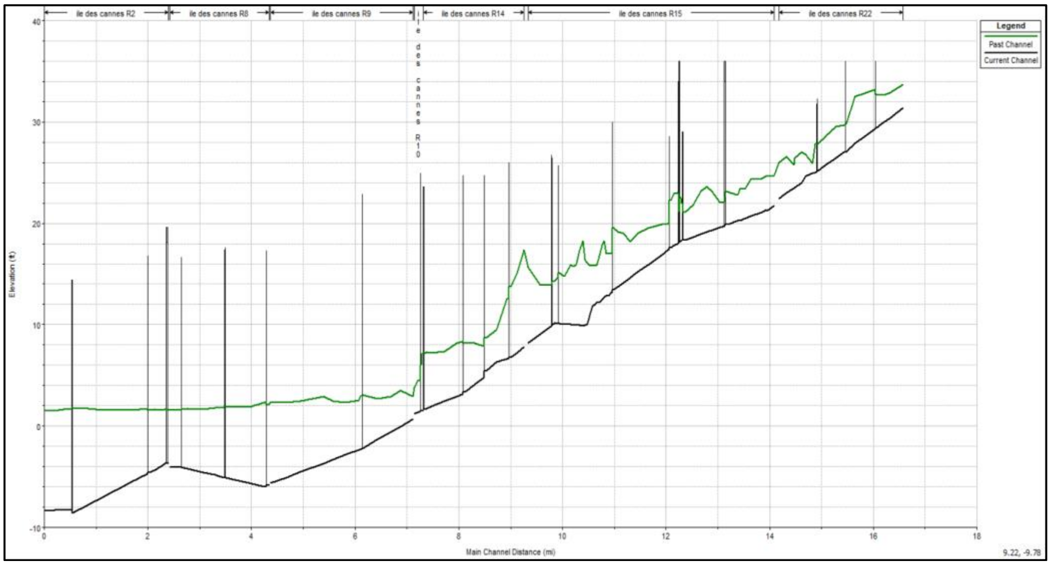


Figure 8. Profile image of the two bathymetries used in the HEC-RAS model. The green line represents the past channel bathymetry, and the black line represents the current channel bathymetry.

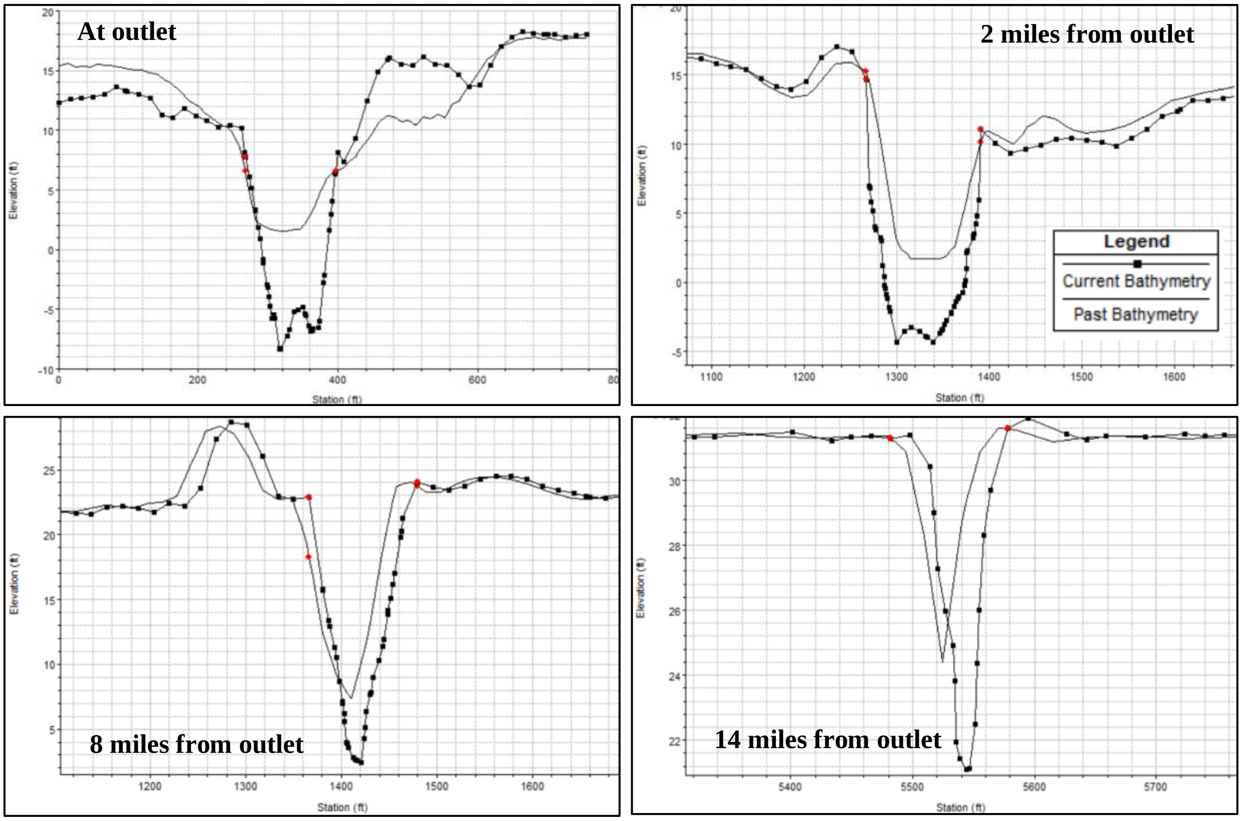


Figure 9. Cross sections at various locations along Coulee Ile des Cannes showing the difference between past and current conditions of the channel bathymetry.

Changes in Precipitation

The analysis of Coulee Ile Des Cannes includes using design storms and actual inland storm events. This section of the analysis uses hypothetical design storms input into the hydrologic model to simulate past 10, 50, and 100-year 24-hour storms. Typically, when using precipitation estimates, the National Oceanic and Atmospheric Administration (NOAA) Atlas-14 point precipitation estimates is the industry standard. For this study, a local precipitation gauge at Lafayette Regional Airport was used instead to calculate these estimates. This allows for insight into the time-series of the annual maximum precipitation, examination into trends of the data, and how the mean annual precipitation has changed over time. A rainfall frequency analysis was performed using precipitation gauge data from Lafayette Regional Airport to determine precipitation estimates for 10, 50, and 100-year return periods. The data from Lafayette airport included daily precipitation for a 129-year period starting in 1893 and ending in 2021. The daily rainfall was used to find the annual maximum precipitation for each year. A time series of the annual maximum precipitation can be found in Figure 10. The left image in the figure shows the whole time series of the data. To visualize the increase of the annual maximum precipitation, the right image in the figure shows the same data but without the data point from the 1940 precipitation event as it could be considered outlier. The annual maximum precipitation was then available to use to calculate design precipitation depths for the selected 24-hour storm period. These depths calculated using data from the entire data period will be referred to as "current precipitation." The equations for determining precipitation frequency depths are as follows:

$$K_T = -\frac{\sqrt{6}}{\pi}\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\} \quad (1)$$

$$y_T = \bar{y} + K_T * s_y \quad (2)$$

Where K_T represents the frequency factor, T is the return period, y_T is magnitude of the event, $\bar{y}$ is the sample mean of the hydrologic record, and s_y is the standard deviation of the hydrologic record.

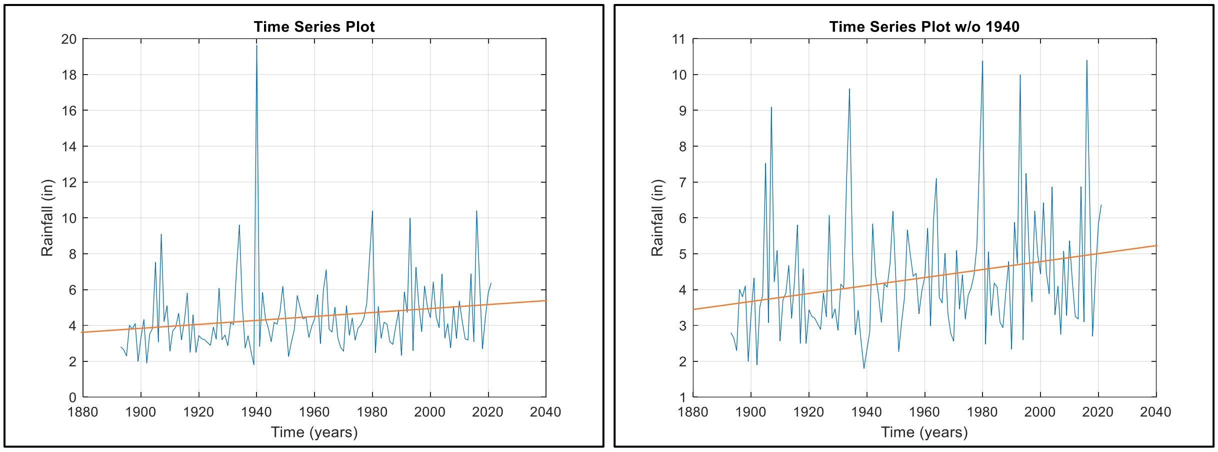


Figure 10. (Left): Lafayette Airport precipitation gauge annual maximum rainfall time series for daily precipitation data ranging from 1893 to 2021, (Right) Lafayette Airport gauge annual maximum rainfall without the 1940 precipitation event. Trendlines are placed on both figures showing the increase of the data over the course of the record.

Along with design storm precipitation depths calculated from the whole collection period of the Lafayette Regional Airport precipitation gauge data, 24-hour precipitation depths were also calculated using a sample of the data. This was a 40-year sample ranging from 1893 to 1932. This time frame of the sample was based off taking data from the beginning of the data record and before the 1940 extreme precipitation event. The 24-hour design storm precipitation depths were similarly calculated for 10, 50, and 100-year storms. Using this sample, a scenario is created to compare water surface elevations and flow rates along the main channel to current conditions. The scenario using a sample of the data, which will be referred to as "past precipitation," will show how much of an effect design storm precipitation depth has on the watershed.

Future Flood Mitigation Measures

Flood Detention Ponds

In recent years, and as a response to the extreme flooding events of August 2016, the Lafayette Consolidated Government has made measures for drainage improvement and flood mitigation by constructing detention pond storage areas around Lafayette. Detention ponds are commonly used as a stormwater management practice to capture and temporarily store excess runoff from urban and suburban areas, in order to reduce the peak flow rate and mitigate downstream flooding and erosion. A few of these ponds have plans to be placed at locations within the Coulee Ile Des Cannes watershed and some have already been constructed. In this study, the locations and storage area size of LCG proposed ponds were considered when adding detention pond storage areas to the hydraulic model. These detention pond storage areas were added to the hydraulic model to evaluate the impacts flood detention will have on Coulee Ile Des Cannes. In total, the study selected to test the impact of four proposed ponds along coulee Ile Des Cannes. The study believes that the location for these four detention ponds were strategically placed where one pond is proposed along the main stem of the coulee, two are proposed at downstream locations, while the last one is placed at the upstream end of the coulee (**Figure 11**). These locations suggest that the proposed ponds can effectively capture and store excess runoff before it reaches downstream areas or the Vermilion River. It is worth mentioning that the locations for two ponds out of the four were selected at excavated burrow pits. The use of excavated burrow pits as locations for detention ponds can be a cost-effective solution, as they already exist as depressions in the landscape and can be repurposed for stormwater management purposes.

Figure 11. Locations of the four detention ponds placed within Coulee Ile des Cannes watershed.

It is worth mentioning that it appears that the Lidar data used in the hydrologic model of Coulee Ile Des Cannes was collected between the years 2000-2004 (Cunningham et al., 2009), during which some of the burrow pits that the study is going to reuse as proposed detention ponds were not yet fully excavated. As a result, these ponds do not have a footprint in the acquired Lidar data (Check Figures 11, 12, and 13). To account for this, the model adopted the prismatic assumption, which assumes that the side walls of the pond are completely vertical and that the volume at any elevation can be calculated as the direct multiplication of the area footprint of the pond times the height difference between the elevation of interest and the bottom elevation of the pond. This approach can be useful in situations where the actual shape and dimensions of the pond are not known and can provide a conservative estimate of the storage volume. However, it is important to note that the prismatic assumption may not accurately reflect the actual shape and dimensions of the pond and may lead to an overestimation or underestimation of the storage volume.

The first of these detention ponds, labeled as Detention Pond 1 in **Figure 12**, has a surface area of ~190 acres with a bottom elevation of 7.00 ft and a weir crest elevation of 11.00 ft. The second of the ponds along Coulee Granges, Detention Pond 2 in **Figure 12**, has a surface area of ~23 acres with a bottom elevation of -10.00 ft and a weir crest elevation of 11.00 ft. In addition to the detention ponds being simulated in the hydraulic model of Coulee Ile des Cannes, the detention ponds were added to the complete Vermilion River hydraulic model which also contains Coulee Ile des Cannes. This was done to provide insight into any impact the detention ponds may have on the Vermilion River. In the Vermilion River model, the detention ponds were similarly simulated for the May 2014 and August 2016 storms. For Coulee Ile des Cannes in the complete Vermilion River model, flow hydrographs from the HEC-HMS simulations of Coulee Ile des Cannes for the two storms were input into the unsteady flow data. The rest of the complete Vermilion River model relies on flow hydrographs from the National Water Model as explained previously.

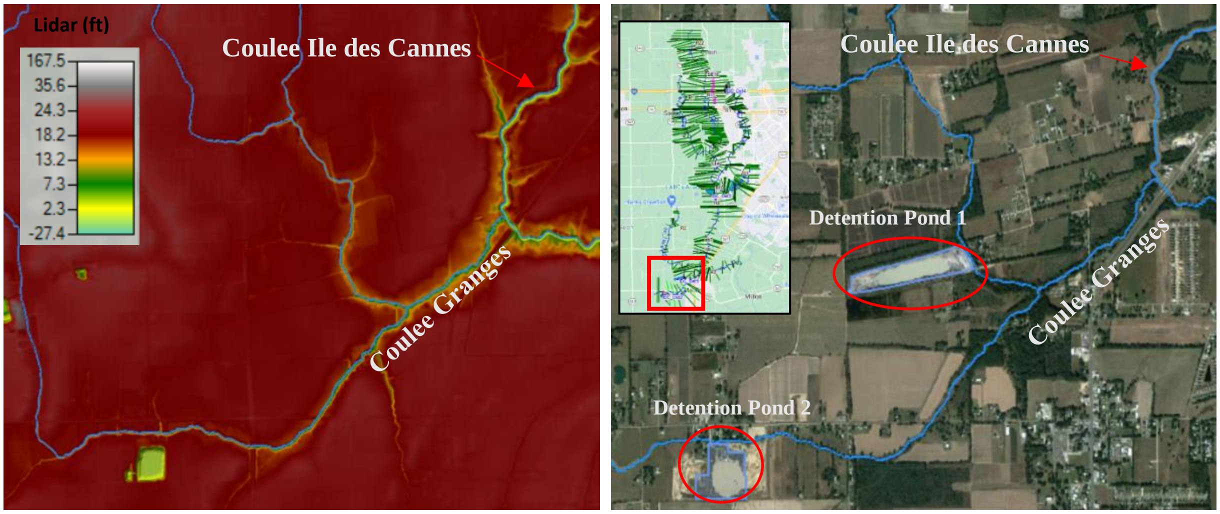


Figure 12. Location for the two detention ponds along Coulee Granges. The Lidar DEM on the left shows a deep hole in the ground reflecting the existence of a burrow pit.

The third detention pond, labeled as Detention Pond 3 in **Figure 13**, is placed along the main channel of Coulee Ile des Cannes. This detention pond has a surface area of ~90 acres with a bottom elevation of 15.00 ft and a weir crest elevation of 21.00 ft.

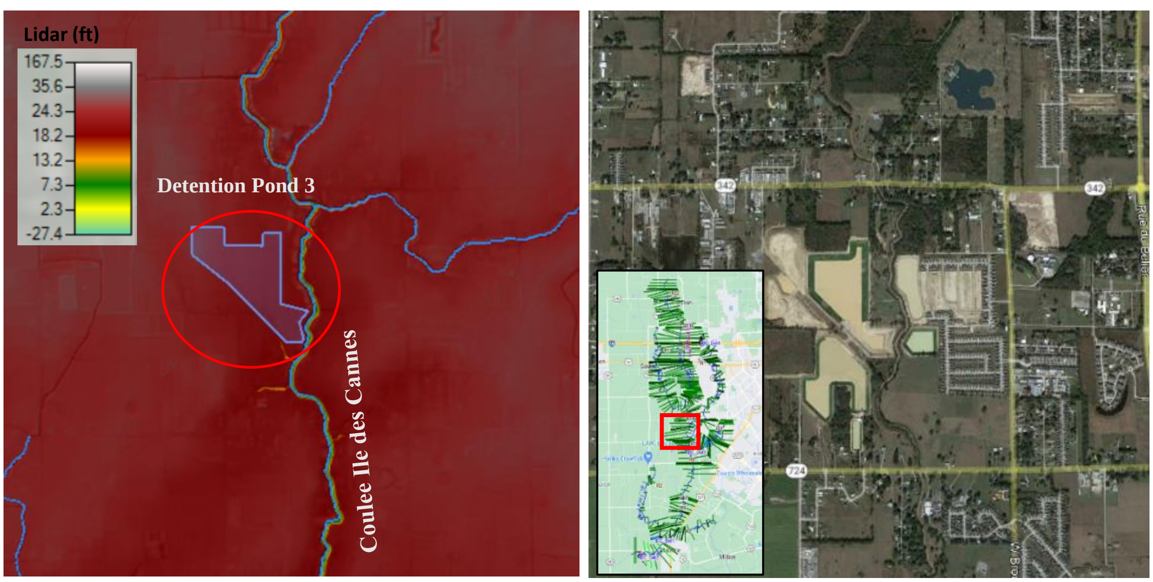


Figure 13. Location of detention pond along the main channel of Coulee Ile des Cannes. The satellite image on the right shows the current imagery of a constructed storage area.

The fourth pond, Detention Pond 4 in **Figure 14**, is placed at an upstream location in the watershed and has a bottom elevation of 9.00 ft with a weir crest of 30.00 ft. The surface area of this pond is ~18 acres and is already an existing pond within the watershed. The simulated scenario with the detention ponds in the hydraulic model will evaluate the impact of all ponds at the same time and compare it to the baseline scenario.

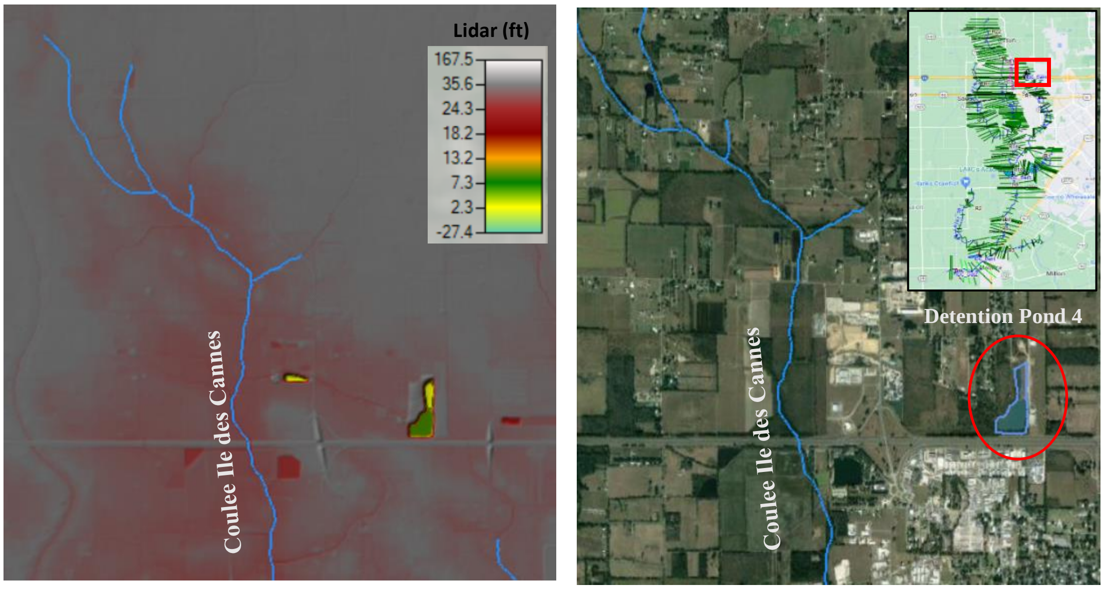


Figure 14. Location of detention pond on upstream end of the watershed. Left image shows Lidar DEM with a deep hole reflecting an existing pond.

Flood Control Structures

A flood control structure was modeled based on a request of the Vermilion Parish Police Jury (VPPJ) to evaluate the flood mitigation benefits of adding the structure near the downstream end of the Vermilion River. The proposed flood control structure that includes a flood gate and pumping station is intended to protect the upstream of gate communities during tropical storms and hurricane events. The flood gate would be closed as a tropical storm approach to prevent storm surge from entering the river system and causing flooding upstream. Once the storm has passed and water levels in the Gulf of Mexico have subsided, the gate would be opened to allow normal river flow to resume.

While the gate is closed, a pumping station would be used to divert upstream flows from the river upstream of the gate. The pumping station would be used to pump excess water over the gate and into the Gulf of Mexico, helping to maintain normal river flow and prevent flooding upstream. This approach can be effective in reducing the risk of flooding during tropical storms and hurricanes, particularly in areas where storm surge is a significant threat.

The location of the proposed gate, which can be seen in **Figure 15**, is situated south of Palmetto Island State Park which is 6 miles north of Vermilion Bay and 4 miles from GIWW. In the hydraulic model, the gate has dimensions of 400 ft width and 40 ft height at a -20 ft invert elevation (approximately the channel's bottom elevation). In the modeling study, various pumping scenarios and gate closure/opening times were examined using stage and flow hydrographs for two tropical storms, Hurricane Barry and Hurricane Laura. For each storm, simulations were performed to model the existing conditions (i.e., without the gate structure) of the river. The scenarios will be compared to the existing conditions to examine impacts to the stage and flow of the along the main reach of the Vermilion River. This structure's purpose is to protect downstream communities from tropical storms, but its impacts will also be examined upstream in Coulee Ile des Cannes. This is done to determine the impact to an upstream tributary and examine if upstream areas benefit from the structure. Finally, to connect the two flood mitigation measures and bring them together with the analysis on Coulee Ile des Cannes, the detention ponds have been added to the Vermilion River hydraulic model to examine their combined impact with the flood control structure. The detention ponds within Coulee Ile des Cannes will be simulated with the flood control structure also using the Hurricane Barry and Hurricane Laura. It should be noted though that for the simulated tropical storm events, the unsteady flow data uses lateral flow hydrograph connections from the National Water Model (NWM) and not the HEC-HMS connections used for the detention pond analysis in the Vermilion Model.

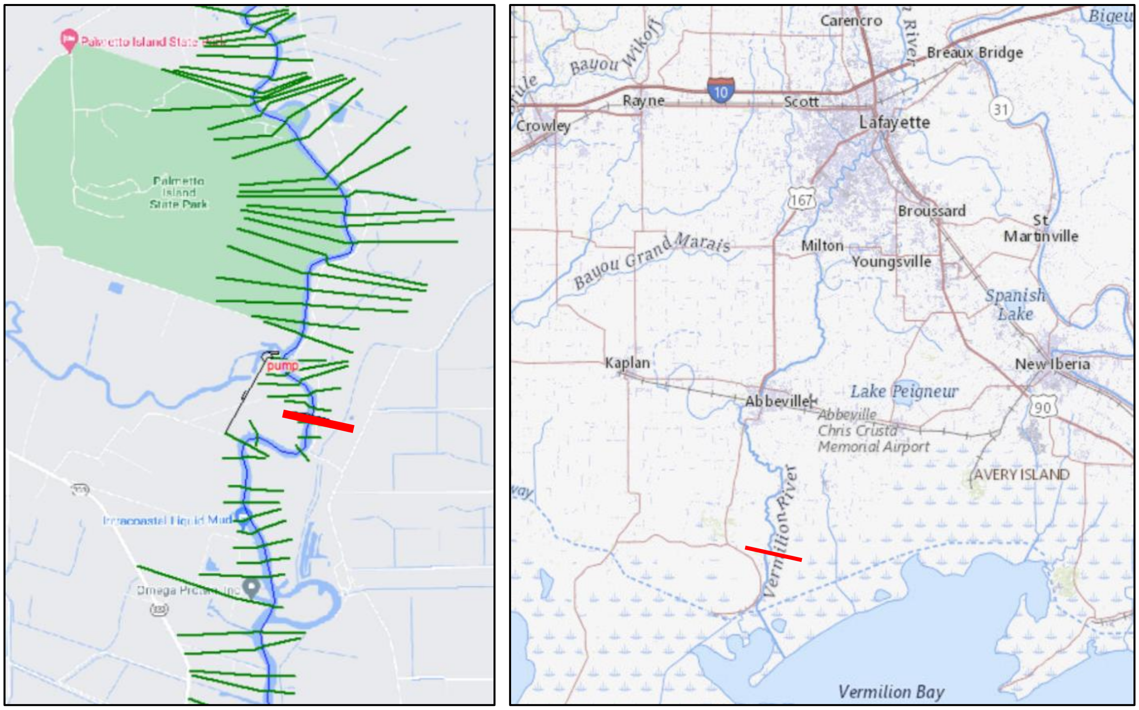


Figure 15. Location of proposed gate/pump structure within Vermilion River watershed. The proposed structure is placed just south of Palmetto Island State Park ~6 miles north of Vermilion Bay.

For Hurricane Barry, eight scenarios were first considered and analyzed in the model. The gate closing time was selected based on when river flows would reverse north upstream and before the water levels in the Gulf started to rise. From this closure time, pumping rates and duration of gate closure were selected. Some of the scenarios included pumping at a constant rate for the duration of gate closure, while others used a pumping rate that varied during gate closure. One of the scenarios (labeled as Test 4) will be discussed in the results section of this thesis. In this scenario, the gate closure starts at 06:00 on July 13, 2019, constant pumping at 3000 cfs will occur until the gate reopens at 00:00 on July 15, for a total of 42 hours of gate closure. For Hurricane Laura, a similar process was conducted. Based on the most effective results from the analysis of Hurricane Barry, pumping rates and gate closure/opening times were selected. Of the scenarios analyzed for Hurricane Laura, the results will be shown for the scenario labeled as Test 5. This scenario has gate closure starting at 00:00 on August 26, 2020, and starts with pumping at 2700 cfs, increasing to 4500 cfs, finally increasing to 6000 cfs before the gate opens at 15:00 on August 27, for a total of 39 hours of gate closure.

Simulation Scenarios

The variables being examined for this analysis of Coulee Ile des Cannes include land use change, channel modifications, and changes in precipitation extremes. Each of these variables have a "current" and "past" version. The past version of the variables will be isolated in the hydrologic and hydraulic model simulations to examine their individual impact to the water surface profile, as well as to stage and flow hydrographs. Hydrologic and hydraulic modeling using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) will be completed for several scenarios that vary in design storm magnitude, land use conditions, channel conditions, and for actual storm events. A summary of all the scenarios examined with the precipitation input used in the hydrologic and hydraulic models used is shown in Table 1 below. A baseline scenario is used to compare against each of the simulated scenarios. When simulating design storms, the baseline scenario is the existing conditions consisting of current land use (imperviousness), channel bathymetry, and current design storm precipitation estimates. When simulating actual storms, the baseline consists of the current land use (imperviousness), current channel bathymetry, and the Stage IV rainfall data for the selected storm. Along with isolating historical land use, pre-modified channel bathymetry, and past precipitation, a scenario was simulated that combined all past versions of the variables. All the design storm simulations for this analysis are completed in a standalone hydraulic model of Coulee Ile des Cannes. Simulations of the historical land use for May 2014 and August 2016 events are also completed in the standalone Coulee Ile des Cannes model. The pre-modified channel bathymetry analysis for the two historical storms is completed in the complete Vermilion River model. Both flood mitigation methods, detention ponds in Coulee Ile des Cannes and the flood control structure on the Vermilion River, are both simulated for the historical inland storm events and tropical storm events in the complete Vermilion River hydraulic model.

Table 1. Summary of hydraulic model simulation scenarios and the precipitation input used.

Scenario	HEC-RAS Model Used	
	Coulee Ile des Cannes	**Complete Vermilion River**
Baseline (Current Conditions)	Design Storms, May 2014, August 2016	May 2014, August 2016, Hurricane Barry 2019, Hurricane Laura 2020
Historical Land Use	Design Storms, May 2014, August 2016	
Pre-modified Bathymetry	Design Storms	May 2014, August 2016
Past Precipitation	Design Storms	
All Past Conditions	Design Storms	
IDC Detention Ponds		May 2014, August 2016, Hurricane Barry 2019, Hurricane Laura 2020
Flood Control Structure		Hurricane Barry 2019, Hurricane Laura 2020

Chapter 3 : Results

Baseline Simulations

Before analyzing the effects of changes in land use, channel modifications, and extreme precipitation patterns, it is important to evaluate the current conditions of Coulee Ile des Cannes and establish a baseline scenario by simulating it. The current state of the coulee will serve as the baseline scenario against which past conditions will be compared.

To determine the current conditions, maximum water surface profiles were generated for the main channel of Coulee Ile des Cannes under three design storms and two historical events, all of which were simulated using the existing conditions of the watershed and channels. These profiles are shown in **Figure 16** and **Figure 17**. Additionally, Table 2 shows the peak flow rate of the coulee at its outlet to the Vermilion River under all these events. Together, these figures and table provide the baseline conditions against which changes to the watershed will be evaluated. Water surface profiles and flow hydrographs will be compared to determine the impact of past changes to the watershed. For each simulation scenario, results will be presented showing the difference in maximum water surface elevation observed between such scenario and the baseline along the main channel. The difference in peak flow rate at the coulee outlet where it drains into the Vermilion River is also found and presented along with the flow hydrographs. It should be noted that the results for the baseline scenario suggest that the flow hydrograph at the outlet of the coulee estimated under the August 2016 storm exhibits double peaks. To recap, the hydraulic model of Ile des Cannes utilizes a rating curve as the boundary condition at the outlet of the coulee. Simulations of the 10-year and 50-year design storms and the May 2014 historical storm were carried out using a rating curve relationship obtained from the complete hydraulic model of the Vermilion River for the May 2014 storm. Meanwhile, the 100-year design storm and the August 2016 historical storm were simulated using a rating curve relationship derived from the same hydraulic model of the Vermilion River but for the August 2016 storm. This approach, although more realistic and representative of actual flood dynamics, yielded some results that exhibit discrepancies.

Notably, **Table 2** presents that the peak flow observed during the 100-year storm is less than the peak flow observed under the 50-year storm event at the coulee outlet. However, the maximum water stage observed at the same location is consistent, with the 100-year stage being higher than the 50-year water stage. This disparity is a direct consequence of the differences in rating curves that control the relationship between stage and flow at this location. Specifically, during the 100-year storm, the water stage in the Vermilion River itself (i.e., at the outlet of Coulee Ile des Cannes) is high, which creates a bottleneck for the flow from Ile des Cannes to drain freely, resulting in higher stages accompanied by lower flows.

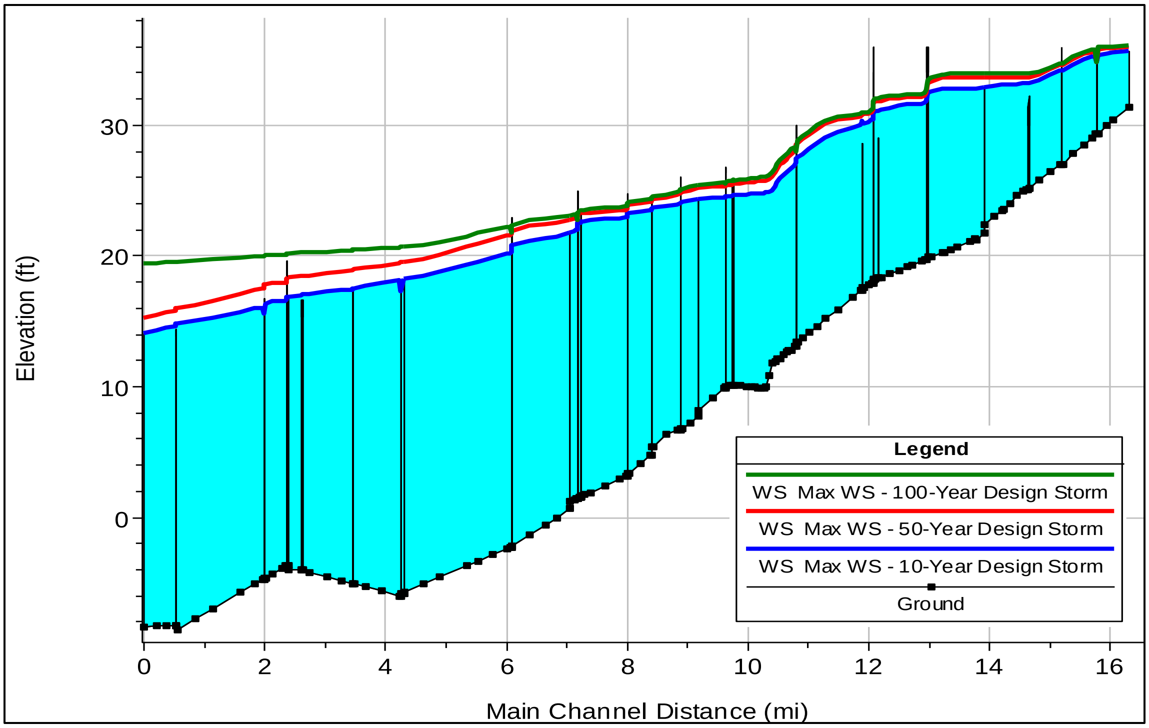


Figure 16. Maximum water surface profile in Coulee Ile Des Cannes for the baseline conditions for each the 10, 50, and 100-year design storms.

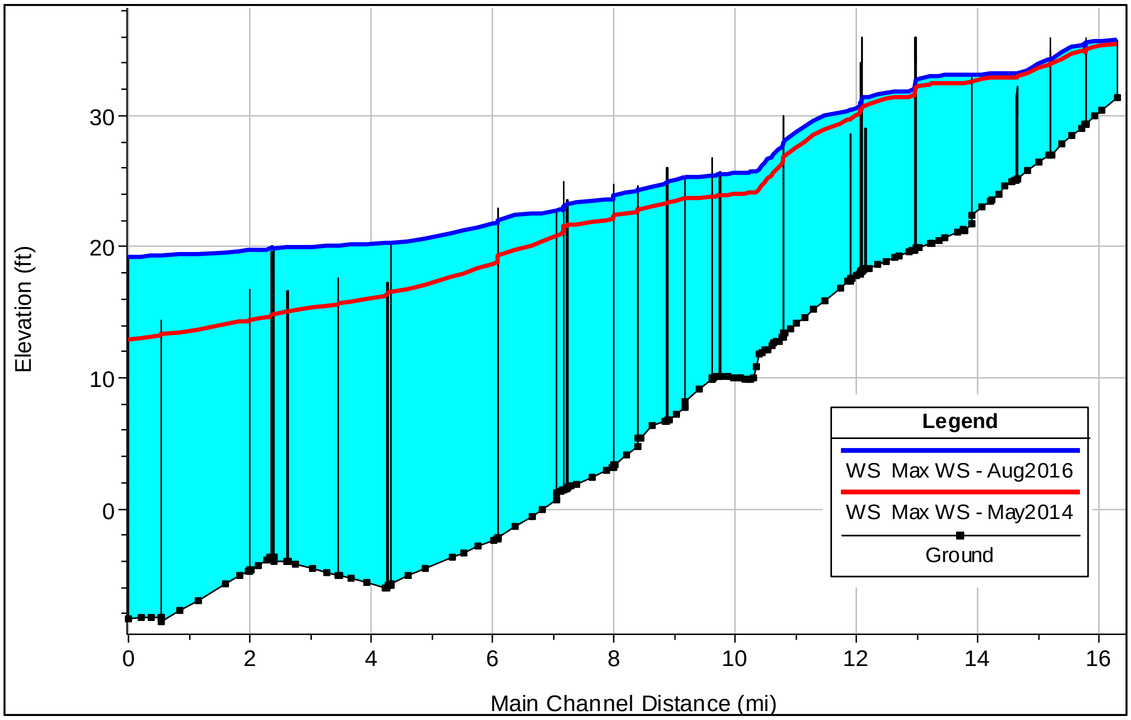


Figure 17. Maximum water surface profile in Coulee Ile des Cannes from the standalone model for the baseline condition for May 2014 (left) and August 2016 (right).

Table 2. Maximum flow rate at the outlet of Coulee Ile des Cannes for each precipitation event for the baseline condition.

Precipitation Event	Maximum Flow Rate at Outlet (cfs)
10-Year Design Storm	7847.10
50-Year Design Storm	10165.20
100-Year Design Storm	8861.80
May 2014 Storm	5404.72
August 2016 Storm	8425.56

Impact of Land Use Change

Land use changes in this study were examined using imperviousness grids from NLCD incorporated into the loss method of the hydrologic model. As previously stated, land cover in Coulee Ile Des Cannes watershed mainly consists of pasture/hay, cultivated crop cover, and urban developments. Over the past two decades, there has been an increase in urban areas in various parts of the watershed. These changes to land coverage will therefore be represented in the hydrologic model as changes in imperviousness grid values passed to the deficit and constant loss calculations within HEC-HMS. The past land use scenario used in this study is based on using an imperviousness grid information collected during 2001. The current land use baseline is using imperviousness grid information collected during 2019. Following that, the output hydrographs from the HMS from both cases, using the 2001 imperviousness layer and the 2019 imperviousness layer, is fed to the same hydraulic model setup to be routed through the coulee system until its outlet.

Overall, the results of the design storm scenarios reveal that land use changes are showing a relatively small impact on the water surface profiles observed along Coulee Ile des Cannes. Using the maximum water surface profiles obtained from both simulations, Figure 18, the differences between the current baseline condition and past land use condition was calculated. Table 3 shows these differences calculated at several locations along the main channel. Positive differences in the table represent an increase in water surface elevation compared to past conditions. Generally, the results show that the impact of the increase in urbanization extent is more pronounced during frequent storms compared to severe events. Between the three design storms, the largest difference between the past and current conditions was ~0.21 ft, which occurs at 6 miles from the outlet under the 10-year design storm. Inspection into the channel profile plots and stage hydrographs reveal that the current condition scenarios of land use have a slightly higher water surface elevation throughout the main reach compared to the scenarios with past land use.

Examining results of the historical storm scenarios show more differences in water stages compared to the design storms (Table 2). Results from the May 2014 storm, which is comparable to a 10-year design storm, show the difference in maximum water surface elevation along the channel is in the range of [0.18 – 0.33ft] occurring between Mile 2 and

Mile 8 along the main coulee main stem. These values are higher than the difference obtained under the 10yr design. Consistently, examination of the August 2016 storm results shows higher differences in the water surface elevations between the current and past conditions compared to the 100yr event. Between Mile 2 and Mile 8 the differences are in the range of [0.04 – 0.23ft] less than the current condition.

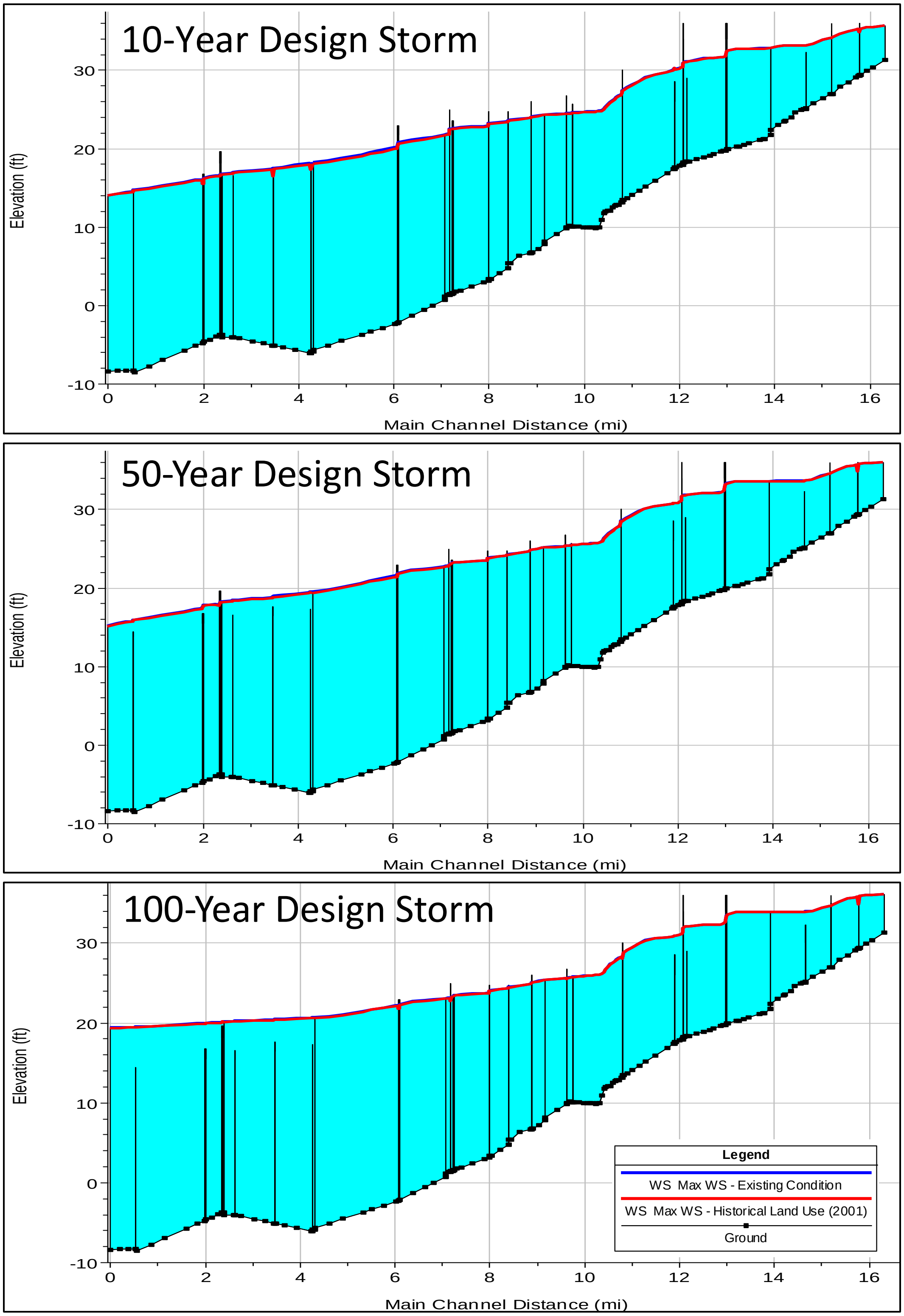


Figure 18. Maximum water surface profile in Coulee Ile des Cannes comparing the baseline condition to historical land use conditions for the 10, 50, and 100-year design storms.

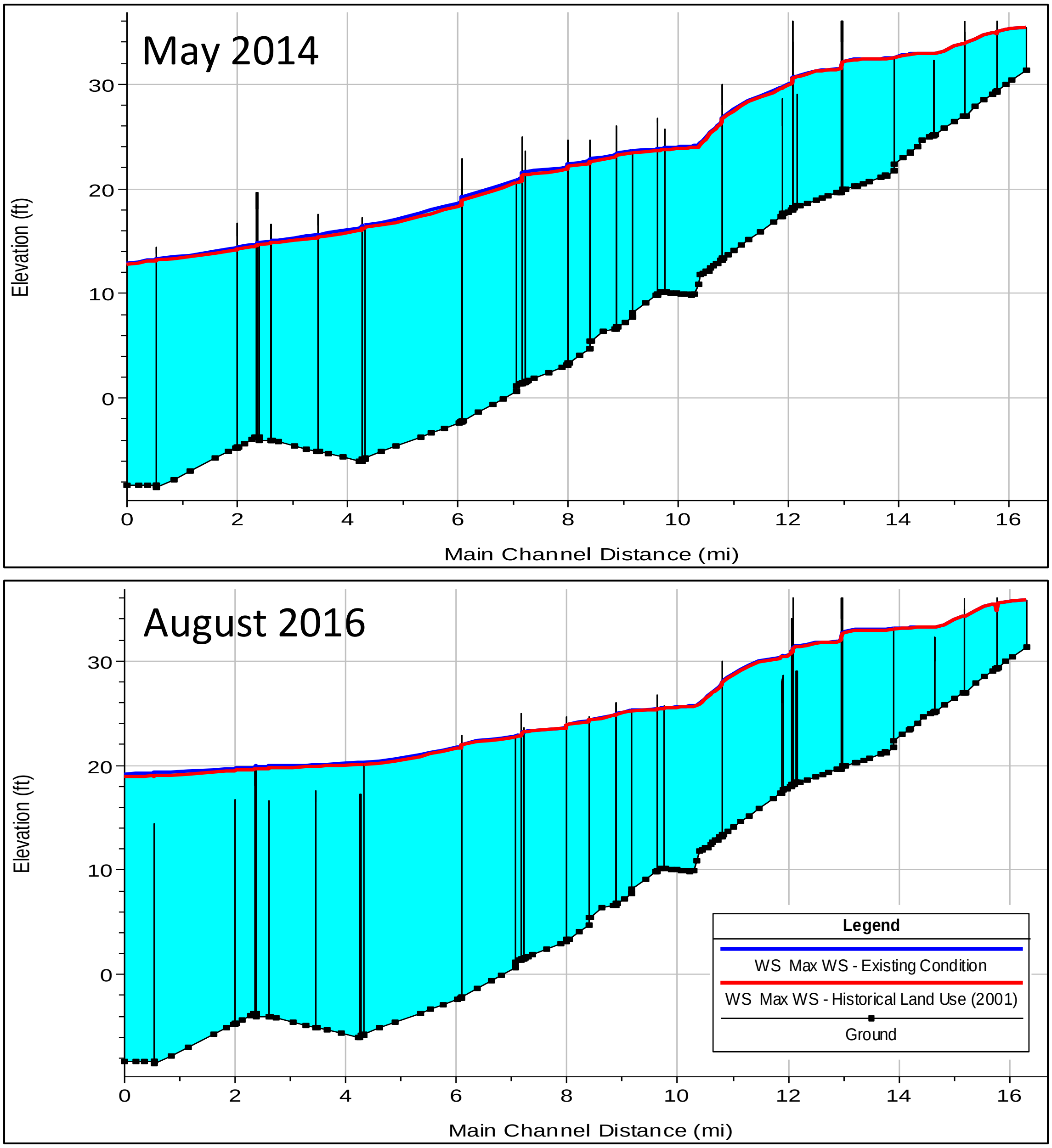


Figure 19. Maximum water surface profile in Coulee Ile des Cannes comparing the baseline condition to historical land use conditions for the May 2014 and August 2016 storms.

Table 3. Differences in water surface elevation along main channel distance in Coulee Ile des Cannes for changes in land use calculated as the difference of past conditions from baseline conditions.

Miles from IDC Outlet	Difference in water surface elevation (ft)				
	10-Year	50-Year	100-Year	May 2014	August 2016
Outlet	0.09	0.09	0.09	0.11	0.31
2	0.13	0.09	0.08	0.18	0.23
4	0.17	0.12	0.08	0.25	0.17
6	0.21	0.17	0.1	0.33	0.16
8	0.11	0.03	0.06	0.26	0.04
10	0.08	0.03	0.03	0.18	0.04
12	0.06	0.03	0.02	0.11	0.08
14	0.05	0.04	0.05	0.07	0.08
16	0.0	0.01	0.0	0.0	0.0

Flow hydrographs at the outlet of the channel for the impact of land use changes may be found in **Figure 20** and **Figure 21** for the design storms and historical storms. **Table 4** below gives the difference in peak flow rate at the outlet of the channel for each storm. Similar to the calculations for the difference in water surface elevation, the difference in maximum flow rate is taken as the subtraction of the past condition scenario from the baseline scenario representing the current condition. For the May 2014 storm, the flow hydrograph reveals that the flow rate in the main channel is about ~223 cfs higher for current conditions of land use versus past conditions at the outlet of Coulee Ile des Cannes. As mentioned, when introducing the existing conditions, the August 2016 flow hydrograph exhibits double peaks at the outlet of the coulee. For the impact of land use, the first peak shows an increase in flow rate with current conditions while the second peak shows a decrease in flow rate with current conditions compared to past land use conditions.

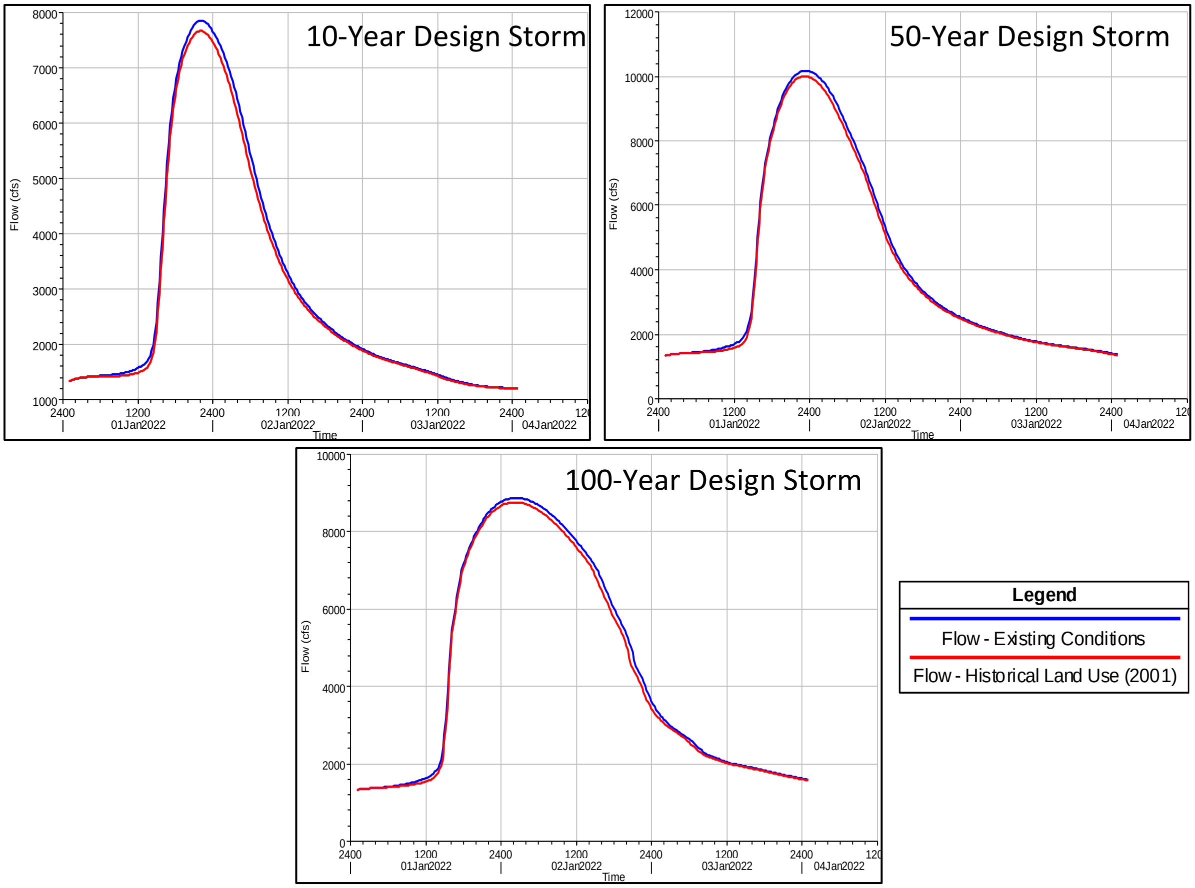


Figure 20. Flow hydrographs of the baseline and historical land use at outlet of Coulee Ile des Cannes for the 10, 50, and 100-year design storms.

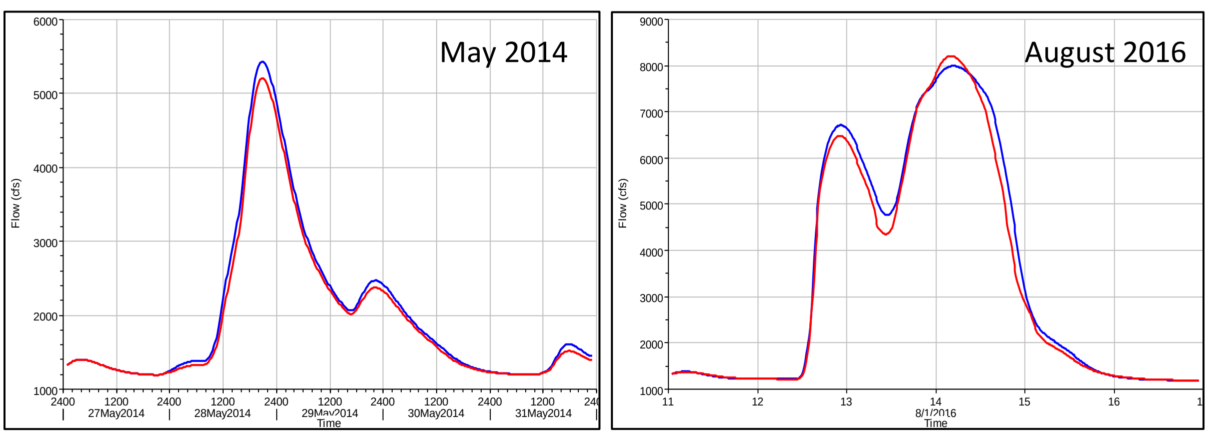


Figure 21. Flow hydrographs of the baseline and historical land use at outlet of Coulee Ile des Cannes for the May 2014 and August 2016 storms.

Table 4. Difference in maximum flow rate at outlet of Ile des Cannes for design and historical storm events for changes in land use calculated as the baseline flow rate minus past flow rate.

Precipitation Event	Difference in Maximum Flow Rate at Outlet (cfs)	Percent Increase
10-Year Design Storm	185.51	2.42%
50-Year Design Storm	180.46	1.81%
100-Year Design Storm	107.63	1.23%
May 2014	223.79	4.30%
August 2016	-216.51	-2.64%

Based on the hydrologic and hydraulic models where land use changes were examined in isolation, the analyses of water surface elevation and flow rates indicate that urbanization, as a land use change, is causing a minor impact on the flood dynamics of coulee Ile des Cannes. Examining the land cover maps produced by NLCD of 2001 and 2019 in **Figure 6** shows that even with the urban developments over the past two decades, land cover in the watershed remains largely covered by pasture and cultivated crops land. The increased urbanization in the northern portion of the watershed, and on the west side of the watershed, which is the outskirts of Lafayette, is not significantly affecting the overall landscape of the watershed. The difference in flow rates between the past and current conditions is only in the magnitude of 100 cfs to 200 cfs different for the simulated storms with peak flow rates under the current condition being between 5000 cfs and 10000 cfs depending on the storm severity.

Impact of Channel Modifications

Channel modifications in this study were examined by comparing two bathymetries of Coulee Ile des Cannes. One is current conditions of the channel representing the coulee conditions after the drainage improvement projects carried out over the past few decades which have included dredging and widening of the main channel, and the other past bathymetry is from a survey collected during an earlier work done in 2004 before many of these projects took place. Simulations were completed for the 10, 50, and 100-year design storms using the isolated hydraulic model of Ile des Cannes, while the complete Vermilion River model was used to simulate the August 2016 and May 2014 storms. Generally, the results show that the channel modifications, widening and dredging of the channel, yielded a reduction in the water surface profile along the coulee. These can be seen in **Figure 22** and **Figure 23** below for the design storms and historical storms. This difference in water surface elevation can be attributed to the current channel's increased capacity to hold larger volumes of water. Specific differences at several locations along the main channel for each of the storms can be found in **Table 5**. Positive differences within the table represent areas where the current water surface elevation has increased above the pre-modified bathymetries water surface elevation. Negative differences are vice versa, representing areas where the current condition has reduced the water surface elevation compared to pre-modified conditions. The design storm scenarios, due to the assumption of spatially uniform distribution of precipitation, represents the general impact of channel modifications to the coulee. Reductions in the water surface elevation vary throughout the main channel's distance for each design storm. A pattern can be seen in Table 5 with how there is a reduction from the channel's furthest end at Mile 16 up to Mile 8, where there is no reduction in the water surface elevation. After Mile 8, reductions start to show again until the channel's outlet where the current water surface elevation has increased. For the two historical storms, May 2014 and August 2016, there are more fluctuations in reduction of the current water surface compared to the design storms. In the simulation periods and storms section above, Figure 2 shows the spatial distribution of each of these storms which were simulated. In Figure 2, the storm from May 2014 has heavier rainfall specifically over Ile des Cannes and the northern portion of the Vermilion River watershed. The August 2016 storm has heavier precipitation over the south-east portion of the Vermilion watershed and Coulee Ile des Cannes receiving precipitation amounts on the lower to middle part of the scale. This is reflected in the outcome of the simulations gauging the impact of channel modifications. Figure 22 shows more reductions for the May 2014 storm, which has more precipitation over Coulee Ile des Cannes, compared to the August 2016 storm, which had more precipitation in other parts of the watershed. Similar to the design storms though, both historical storm events show an increase of the current water surface elevation at the outlet of the channel under the baseline scenario compared to the pre-modified conditions.

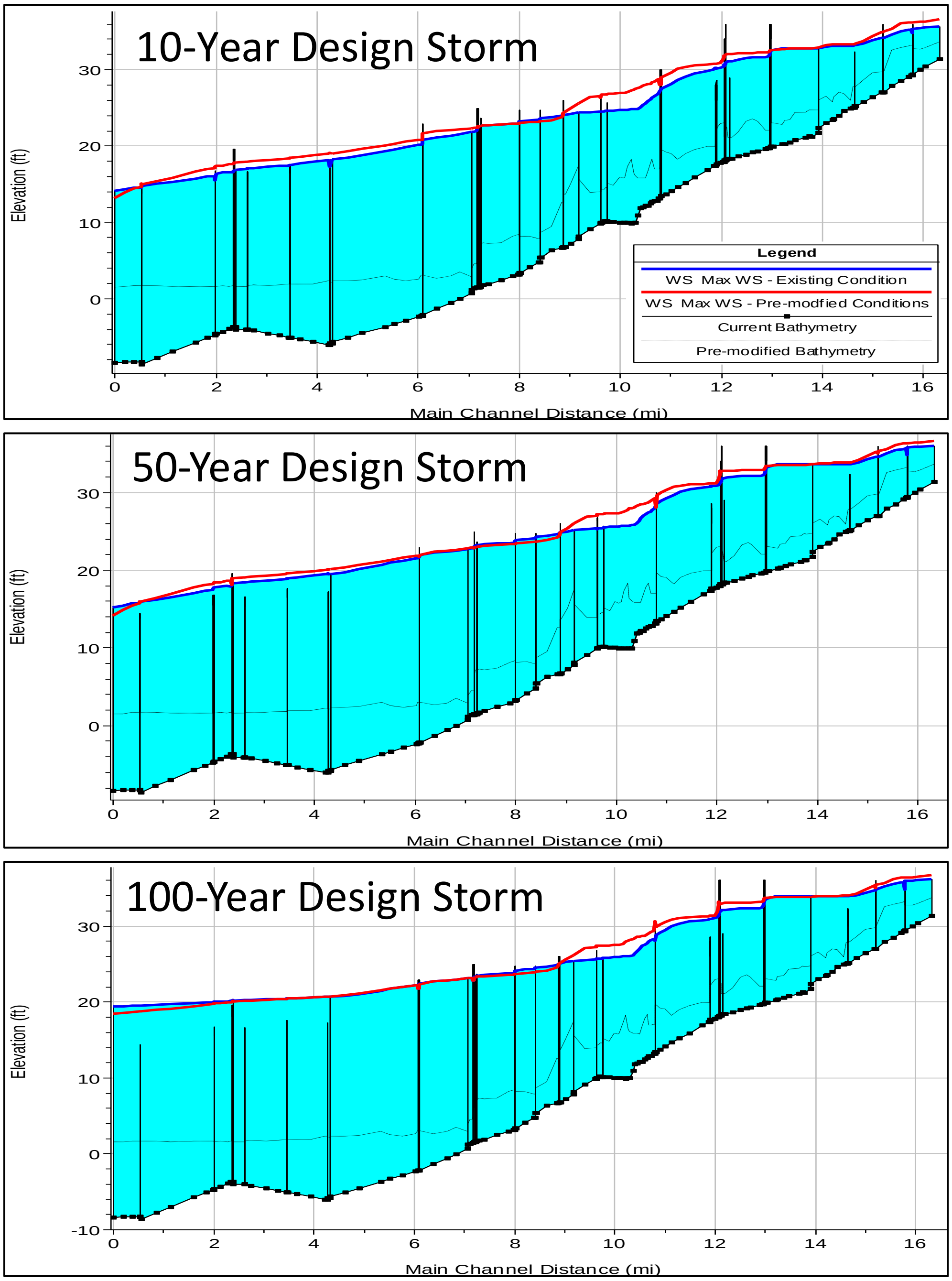
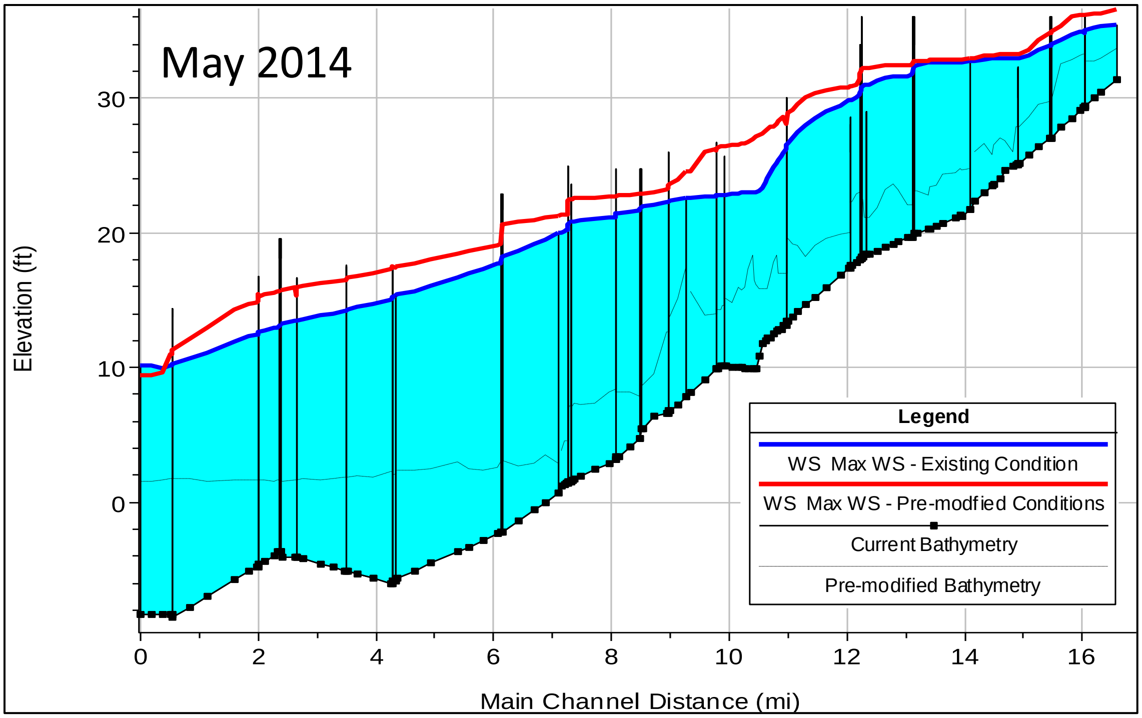


Figure 22. Maximum water surface profile in Coulee Ile des Cannes comparing the baseline condition to the pre-modified channel for the 10, 50, and 100-year design storms.



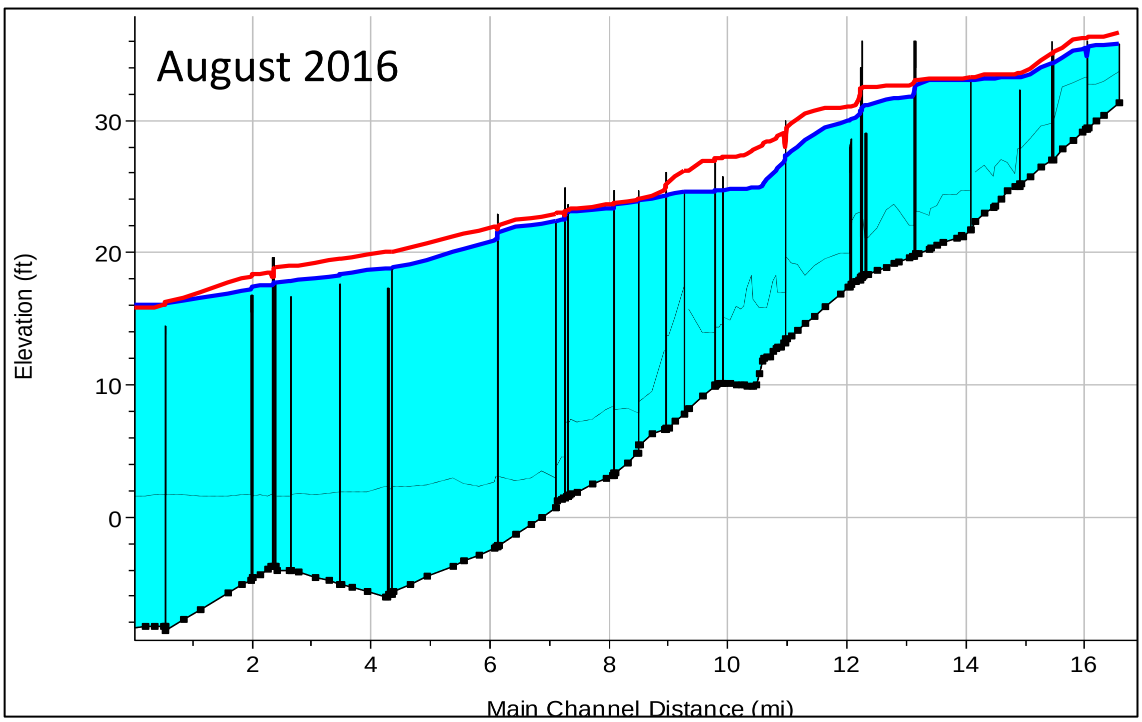


Figure 23. Maximum water surface profile in Coulee Ile des Cannes comparing the baseline condition to the pre-modified channel condition for the May 2014 and August 2016 storms.

Table 5. Difference in water surface elevation along main channel in Coulee Ile des Cannes due to channel modifications calculated as the baseline condition minus the pre-modified conditions.

Miles from IDC Outlet	Difference in water surface elevation (ft)				
	10-Year	50-Year	100-Year	May 2014	August 2016
Outlet	0.88	1.13	0.99	0.65	0.22
2	-1.06	-0.58	0.24	-2.6	-0.9
4	-0.85	-0.57	0.01	-2.29	-1.16
6	-0.63	-0.28	0.03	-1.4	-1.03
8	0.00	0.21	0.19	-1.63	-0.26
10	-2.05	-1.66	-1.6	-3.46	-2.3
12	-1.05	-0.6	-0.58	-1.54	-1.49
14	-0.01	0.04	0.07	-0.18	-0.16
16	-0.76	-0.53	-0.48	-0.98	-0.66

Impacts to the flow regime in the coulee due to channel modifications are much more significant compared to the impacts due to land use changes. Flow hydrographs for the design storms and historical storms may be viewed in **Figure 24** and **Figure 25**. In **Table 6**, the differences between the maximum flow rates are determined for the outlet of the main channel. Similar to the differences calculated for water surface elevations, positive differences in the flow rate represent an increase in flow rate from the pre-modified channel conditions to current conditions. Negative differences would represent a decrease in flow rate from the past to current conditions. On the downstream sections of the coulee at outlet, the flow of the current condition is ~1777 cfs and ~1196 cfs higher than the pre-modified condition flow rate for the 10-year design storm and May 2014 storm. The 100-year and August 2016 storms are ~1281 cfs and ~792 cfs higher than past condition flow rates. Along with the current condition having a higher flow rate, the flow hydrograph has both steeper rise and recession limbs compared to the past flow hydrograph. The current condition has increased flow rates for both peaks of the August 2016 flow hydrographs unlike the flow hydrograph from the impacts of land use change which only had an increase for one of the peaks.

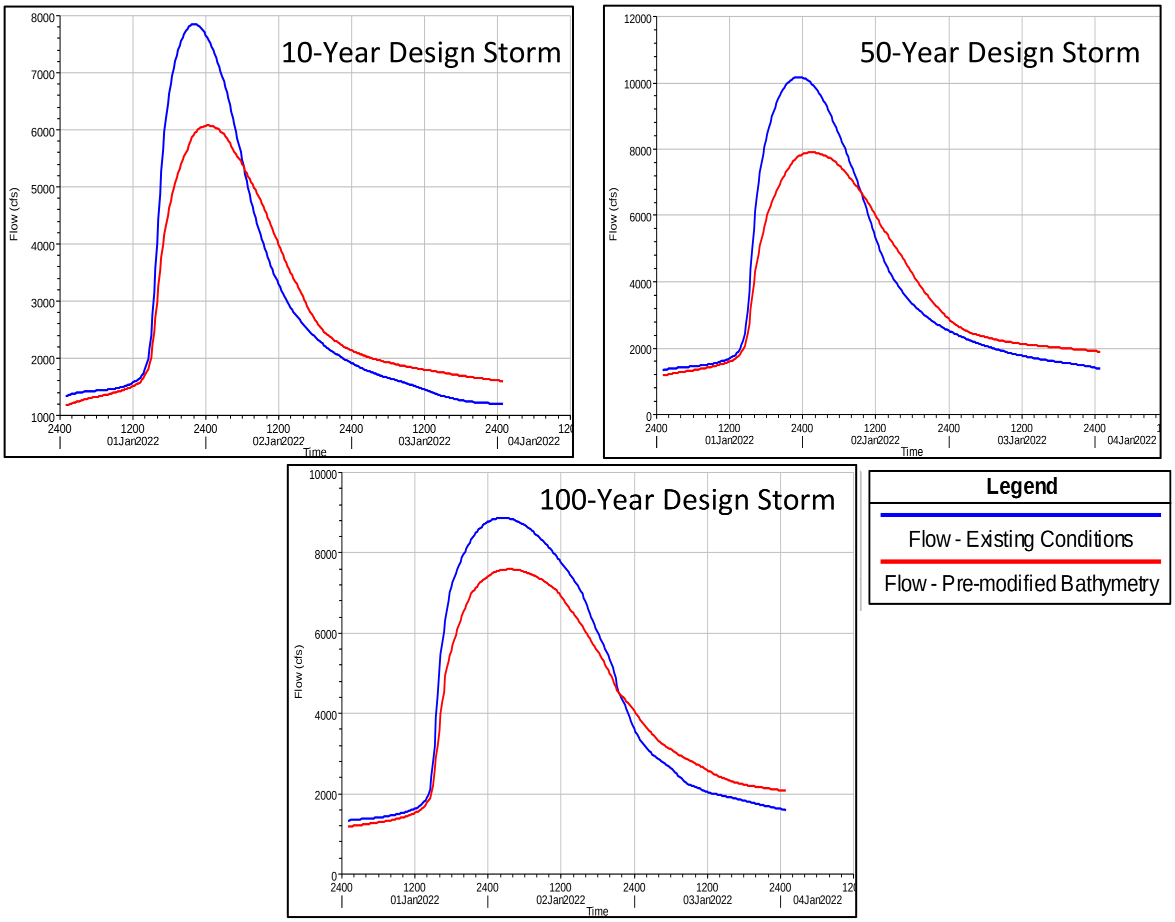


Figure 24. Flow hydrographs at outlet in Coulee Ile des Cannes of baseline and pre-modified channel for the 10, 50, and 100-year design storms.

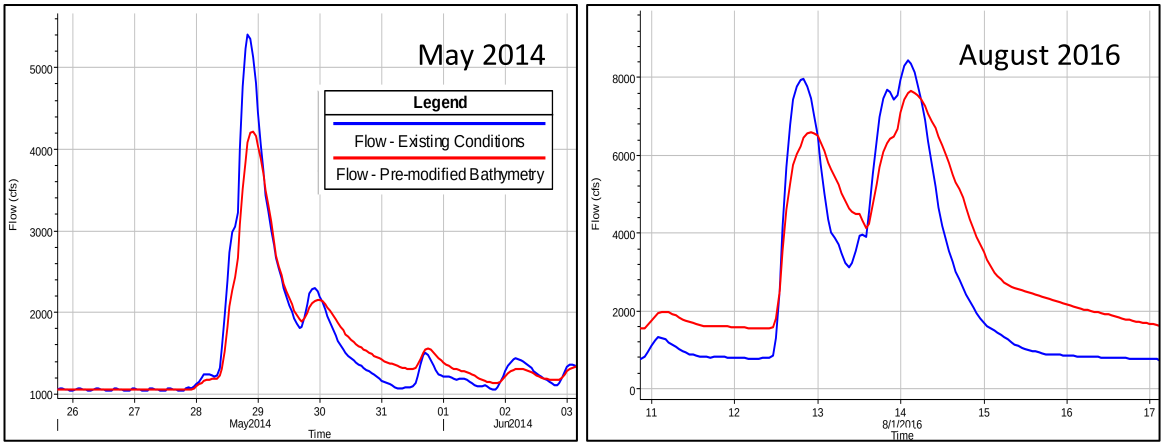


Figure 25. Flow hydrographs of baseline and pre-modified channel at outlet of Coulee Ile des Cannes for the May 2014 and August 2016 storms.

Table 6. Difference in maximum flow rate at outlet of Ile des Cannes for design and historical storm events for channel modifications calculated as the baseline flow rate minus past flow rate.

Precipitation Event	Difference in Maximum Flow Rate at Outlet (cfs)	Percent Increase
10-Year Design Storm	1777.02	29.28%
50-Year Design Storm	2274.4	28.82%
100-Year Design Storm	1280.64	16.89%
May 2014	1196.48	28.43%
August 2016	791.77	10.37%

Examining the impact that channel modifications have on the Vermilion River in Figure 25, stages in the Vermilion River at the reaches near the outlet of Ile des Cannes have increased. For these two historical storms, the increase, which was seen at the outlet of Ile des Cannes above, has translated into the Vermilion River itself. The modifications made to the channel bathymetry locally reduce the water surface elevation within Ile des Cannes, but due to these modifications, the flow rate that drains through the coulee has increased, bringing more water into the Vermilion River and with quicker response. The combination of these two processes leads to an increase in water surface elevation in the Vermilion River.

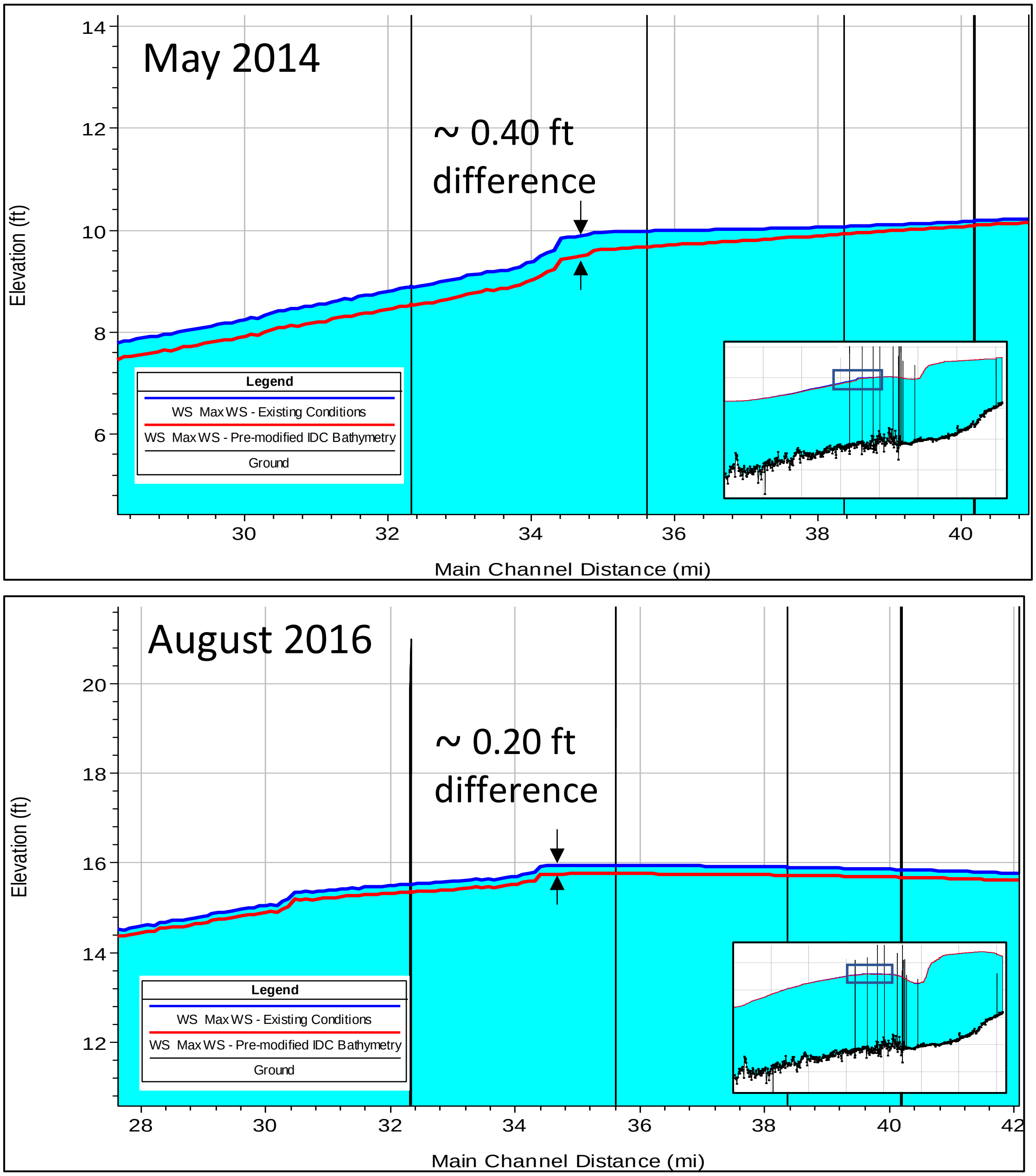


Figure 26. Differences in stage of the Vermilion River due to channel modifications in Coulee Ile des Cannes.

Impact of Changes in Precipitation Extremes

Examination of precipitation impacts in this analysis was completed by simulating two scenarios for the three 24-hour design storms. The current condition scenarios consisted of performing a rainfall frequency analysis using 129 years of recorded daily precipitation data from 1893 to 2021. The past condition scenarios are based on taking a 40-year sample of the 129-year record and performing a separate rainfall frequency analysis based on the smaller sample. The past condition sample period is from 1893 to 1932. Using a sample of the data from the beginning of the data record is not assuming that this would give actual past design storm rainfall depths, rather it is creating a theoretical number that the current conditions can be compared to. Performing the frequency analysis on a sample of the data resulted in a precipitation depth that is lower than the depth calculated using the whole sample. This lower depth can be attributed to a lower mean of the sample of the annual precipitation from 1893 to 1932. The frequency analysis performed to calculate the current and past precipitation depths for each design storm uses the mean of the annual precipitation of the sample provided. To show how the mean annual precipitation changes and can adjust the magnitude of a design storm a graph was created. **Figure 27** below shows how the mean fluctuates due to the increasing sample size. Starting at a sample size of 20 years, data from 1893 to 1912, mean annual precipitation was calculated. At each subsequent point, the next year's annual precipitation was added to the sample and a new average annual precipitation was calculated. The last point on the line is therefore the average annual precipitation for the whole data sample from 1893 to 2021 which was used to calculate the precipitation depths for the current design storms. The two lines in the graph contain the same data except the red line reflects calculations in which the outlying 1940 precipitation event was removed. This graph displays how the average annual precipitation changes yearly and can therefore change the precipitation depth of each design storm. The design storm precipitation depth for the current condition used the whole data sample without removing the 1940 outlying event. For this study, the past precipitation will represent a scenario of what a design storm may have been, to be compared to the increased depth that exists now. A summary of the calculated design storm depths for the past and current conditions included in the **Table 7** below. Included in the table are also the estimates provided by Atlas 14 to show how the calculated precipitation depths compare.

Table 7. Calculated 24-hour design storm precipitation depths for past and current conditions along with the value provided by Atlas 14.

Design storm	Past Depth (in.) -Pre 1940	Current Depth (in.) –Full Record	Atlas 14 (in.)
10-Year	5.63	7.30	7.71
50-Year	7.43	10.09	11.50
100-Year	8.19	11.28	13.40

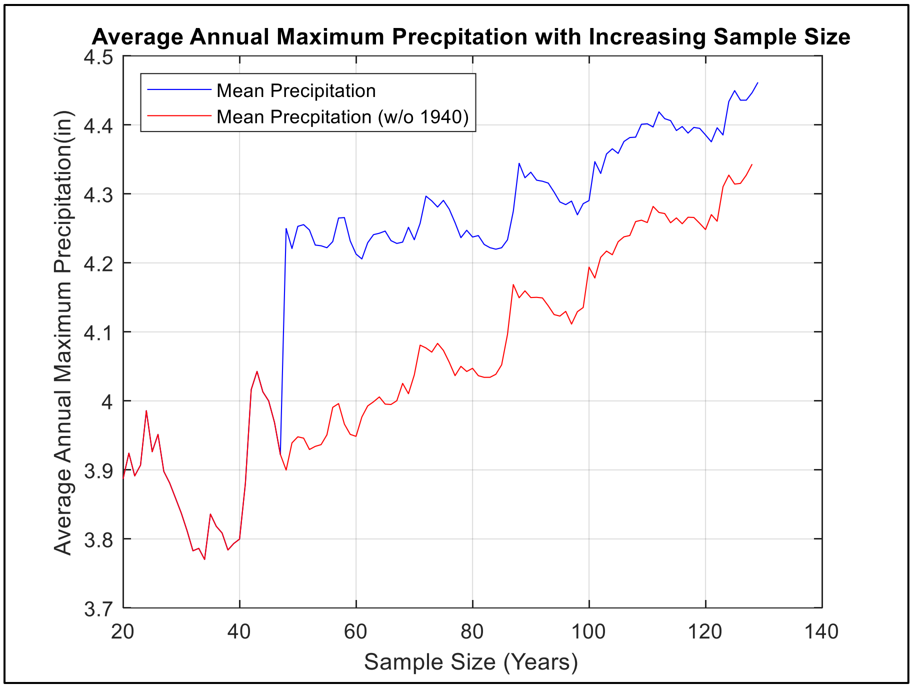


Figure 27. Average annual maximum precipitation for Lafayette airport rain gauge. The sample size of the average precipitation at the beginning of the graphs starts with 20 years (1893-1912), from the first sample size, subsequent annual maximum precipitation is added to the sample to calculate a new average.

In the hydrologic and hydraulic models, simulation of the past and current precipitation design storm conditions was both completed using current channel bathymetry and land use conditions. The inspection of the water surface profile for all three design storm magnitudes for the past precipitation reveals that the past precipitation water surface elevation is consistently lower than the baseline current condition. These water surface profiles are displayed in **Figure 28** for the three design storms. With the precipitation input for these scenarios being design storm hypothetical depths, which creates a uniform precipitation pattern, and the land cover and channel bathymetry being the same, there is an clear difference between the developed water surface elevations. Similar to the other two sections presenting the impacts of changes to the watershed, the differences in the water surface profile were calculated at the outlet and at key locations along the main channel. These differences are summarized in

Table 8. Positive differences represent an increase in water surface elevation of the current condition from the past condition. The past precipitation scenarios water surface elevation for the three design storms are more than a foot below the current condition for many sections of the channel.

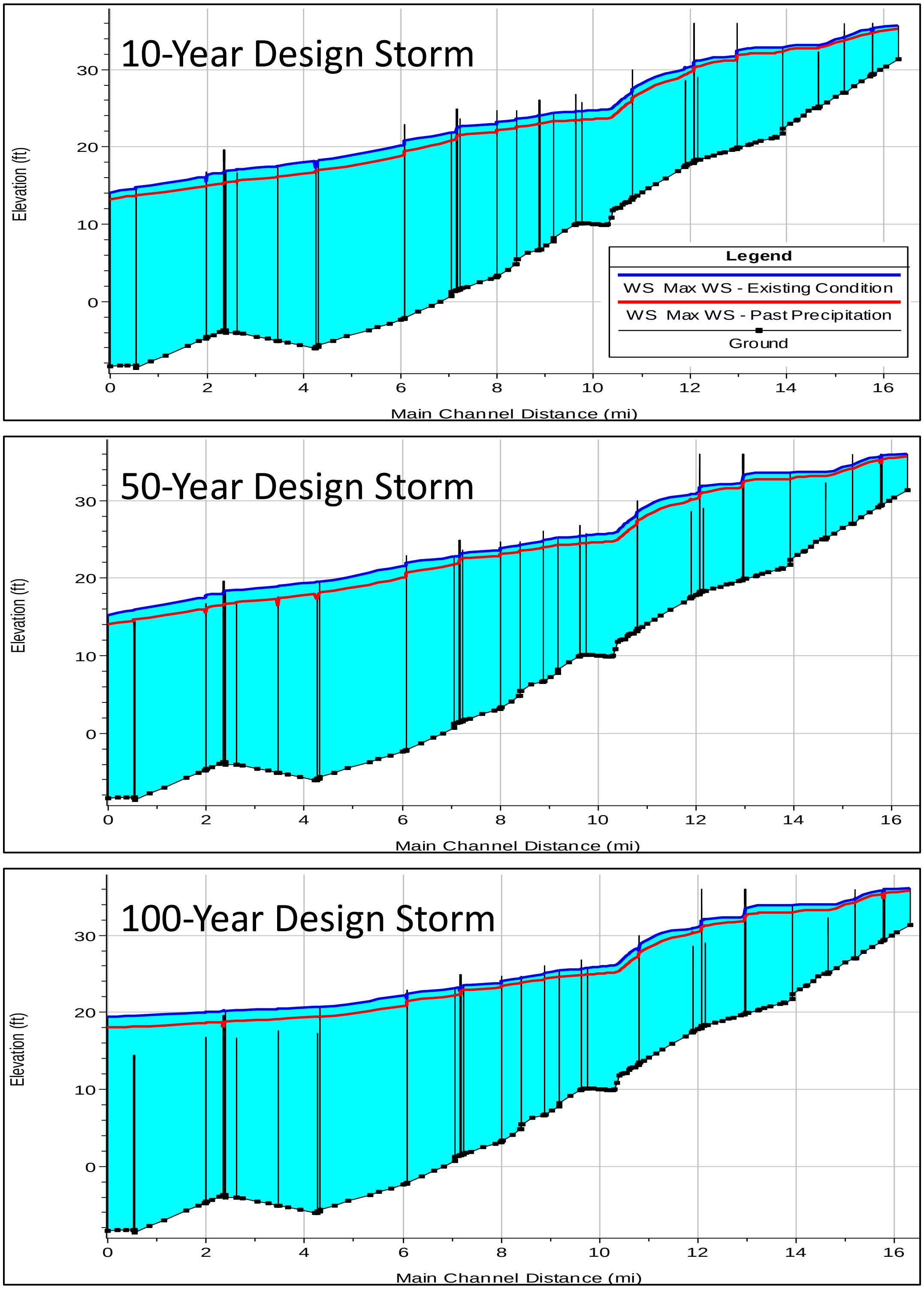


Figure 28. Maximum water surface profile comparing the baseline to past precipitation conditions in Coulee Ile des Cannes for the 10, 50, and 100-year design storms.

Table 8. Differences in water surface elevation along main channel distance in Coulee Ile des Cannes for changes in precipitation calculated as the baseline condition minus past condition.

Miles from IDC Outlet	Difference in water surface elevation (ft)		
	10-Year	50-Year	100-Year
Outlet	0.84	1.25	1.40
2	1.33	1.65	1.40
4	1.45	1.49	1.30
6	1.32	1.54	1.42
8	1.09	0.71	0.62
10	1.10	0.96	0.81
12	0.97	0.9	0.80
14	0.68	0.89	1.00
16	0.52	0.53	0.51

Flow hydrographs for the past and current precipitation scenarios are shown in **Figure 29**. The difference in flow rate was similarly calculated at the outlet of coulee Ile Des Cannes and displayed in **Table 9**. Positive differences in the flow rate represent an increase in flow rate from the past conditions of the maximum flow rate. Flow rates at the outlet of the current condition are approximately 1704 cfs to 2527 cfs above what they would be with the past precipitation conditions. The peak of the past condition, as can be seen in **Figure 29** below, are slightly lagged from the peak of the current condition.

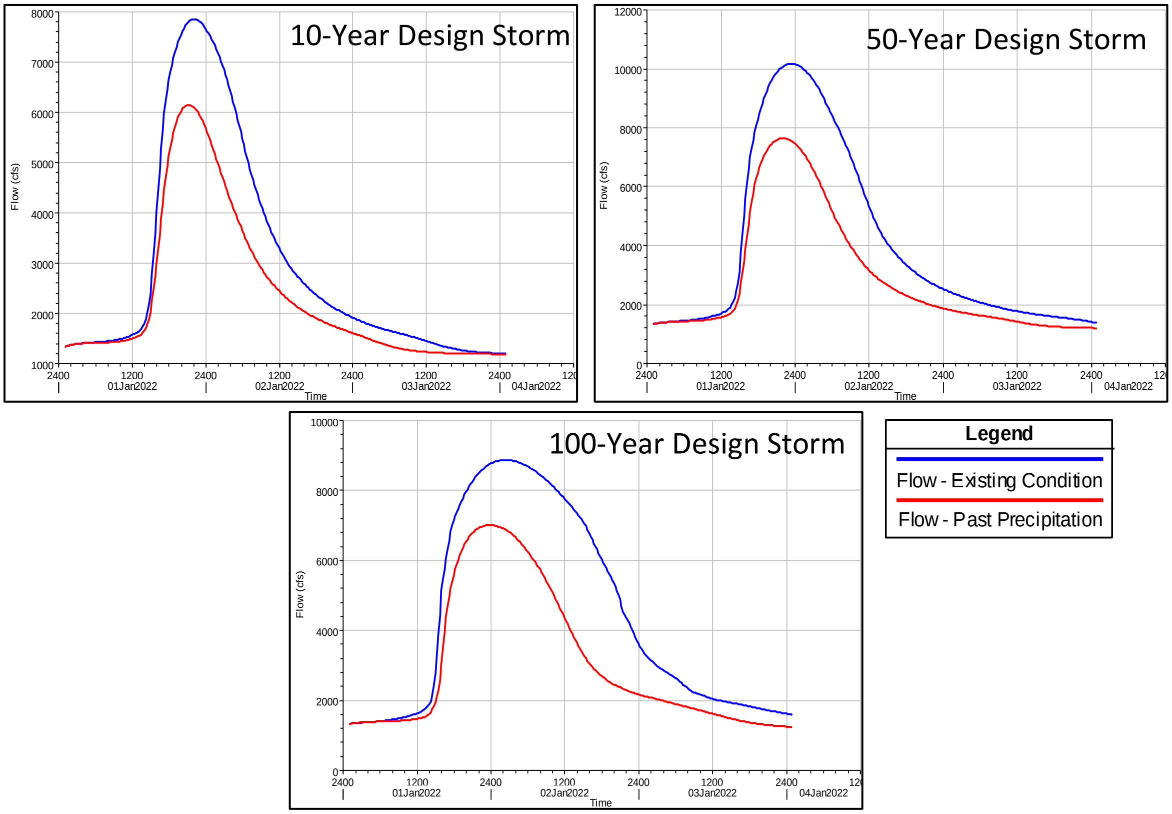


Figure 29. Flow hydrographs at outlet of Coulee Ile des Cannes of the baseline and past precipitation conditions for the 10, 50, and 100-year design storms.

Table 9. Differences in maximum flow rate at the outlet of Ile des Cannes for changes in precipitation calculated as the baseline flow rate minus past flow rate.

Precipitation Event	Difference in Maximum Flow Rate at Outlet (cfs)	Percent Increase
10-Year Design Storm	1704.38	27.75%
50-Year Design Storm	2526.98	33.08%
100-Year Design Storm	1859.25	26.55%

Impact of Combined Watershed Changes

Isolating the changes of land use, channel modifications, and precipitation shows their individual contribution of their impact on water surface elevations and maximum flow rates within Coulee Ile des Cannes. This section will show the results of combining the past versions of the three variables to create a scenario of all past conditions for the three design storms. This scenario compares the 2001 imperviousness, the pre-channel modification bathymetry, and the past design storm precipitation to the baseline scenario with all current conditions. **Figure 30** displays the water surface elevations of the current and all past conditions for the 10, 50 and 100-year design storms for Coulee Ile des Cannes. Just through visual inspections of the profile images, a reduction in water surface elevation is seen along the main channel's distance for the three design storms. Specific differences between the two scenarios may be found in **Table 10**. Similar to how the isolated impacts of changes to the watershed were presented, the positive difference represents an increase in the current water surface elevation from the past case. The largest differences may be found in the results from the 100-year design storm, the current condition is over one foot higher than past conditions until about 6 miles upstream from the outlet. The results follow a similar pattern in which they all have increases of the current water surface elevation around Mile 10 and Mile 16 at the furthest end of the channel. There is also a similar pattern at the channel's outlet where the largest reduction occurs at this location. This is most likely due to the rating curve imposed as the boundary condition of the channel.

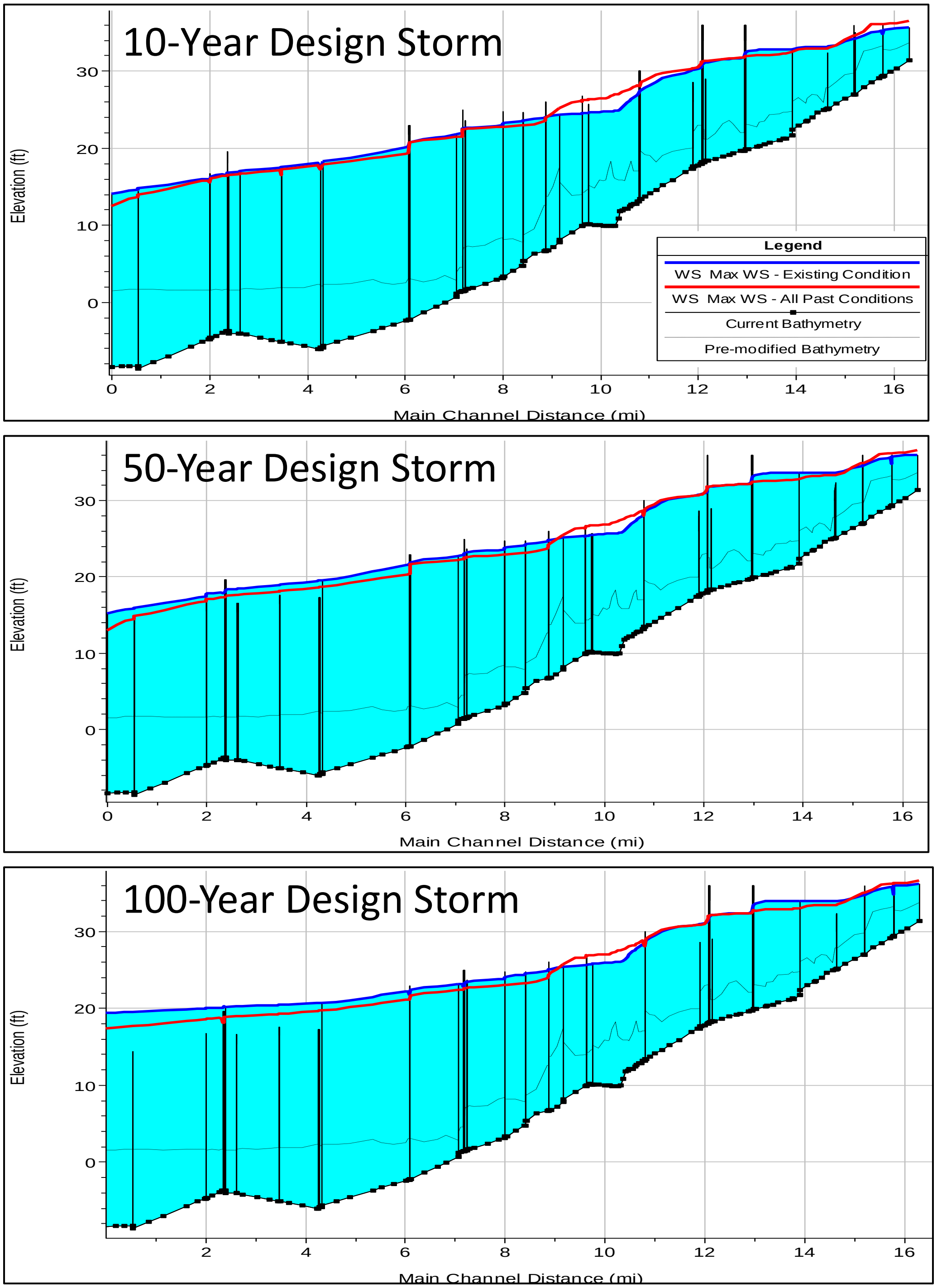


Figure 30. Maximum water surface elevation of all past conditions compared to the baseline for design storms along main channel of Coulee Ile des Cannes.

Table 10. The difference in maximum water surface elevation between all past conditions and the baseline condition along the main channel of Coulee Ile des Cannes calculated as the baseline minus the past.

Miles from IDC Outlet	Difference in water surface elevation (ft)		
	10-Year	50-Year	100-Year
Outlet	1.64	2.22	2.02
2	0.27	0.72	1.42
4	0.38	0.84	1.09
6	0.85	1.25	1.1
8	0.17	0.65	0.82
10	-1.62	-1.13	-1.03
12	-0.48	-0.02	0.02
14	0.59	0.91	1.00
16	-0.58	-0.26	-0.19

The flow hydrographs displayed in Figure 31 reveal a larger difference between the maximum flow rates of the two scenarios. The specific differences in the maximum flow rate at the outlet of the main channel may be observed in **Table 11**. The difference in maximum flow rate for all past conditions has the highest differences than any of the individual past conditions. For the all-past conditions scenario, the maximum flow rate ranges from ~3065 cfs to ~4481 cfs below the current maximum flow rate at the outlet of Coulee Ile des Cannes.

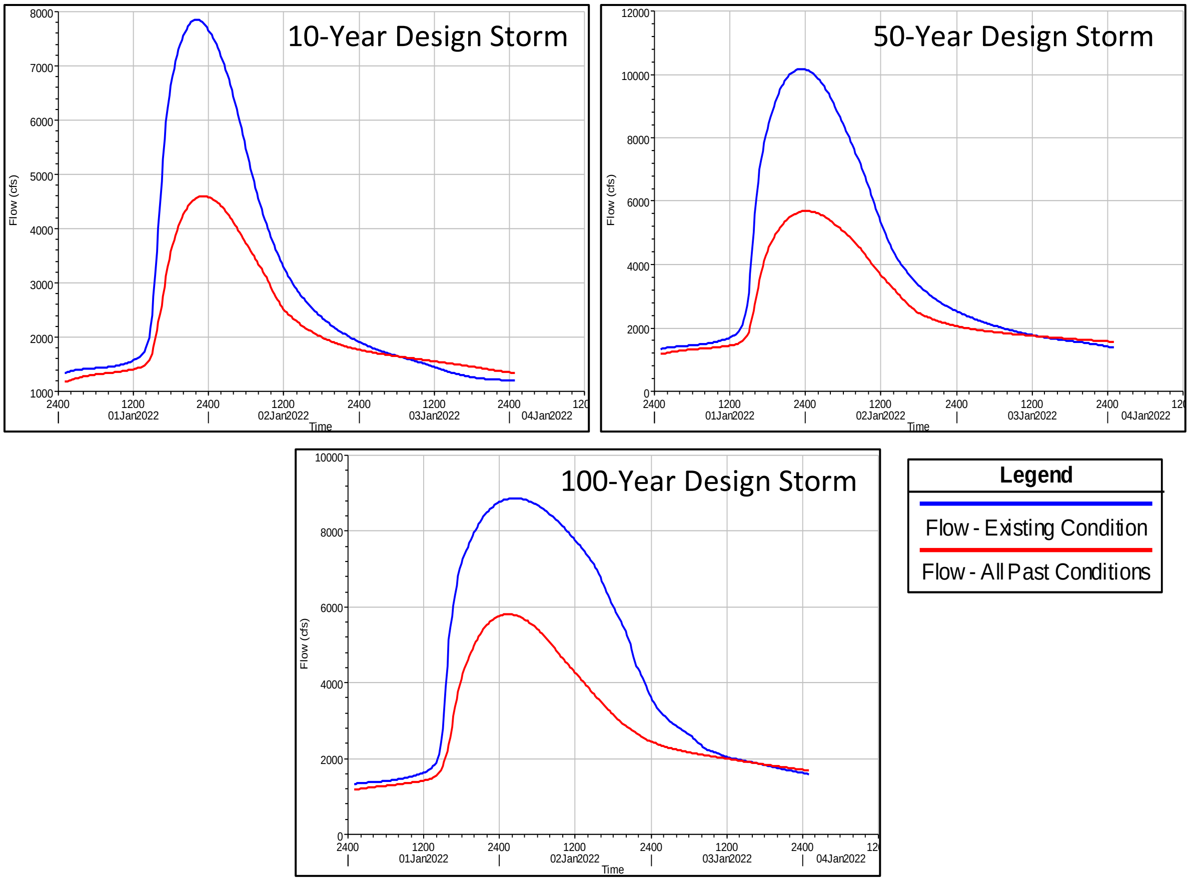


Figure 31. Flow hydrographs at outlet of Coulee Ile des Cannes comparing baseline conditions to past land use, past channel bathymetry, and past design storm precipitation for the 10, 50, and 100-year design storms.

Table 11. Differences in maximum flow rate at the outlet of Ile des Cannes for all past conditions calculated as baseline flow rate minus past flow rate.

Precipitation Event	Difference in Maximum Flow Rate at Outlet (cfs)	Percent Increase
10-Year Design Storm	3252.95	70.81%
50-Year Design Storm	4480.67	78.82%
100-Year Design Storm	3065.14	52.88%

Discussion

The isolation of land use changes, channel modifications, and precipitation is necessary to assess the relative contribution of each factor to water surface elevation and flow rates in Coulee Ile des Cannes. Separating the three factors gives insight into the role each of them play in drainage response during small and large storms which occur over the watershed. The three factors were simulated for three design storms and two historical storms.

The study's first objective was to investigate the impact of land use changes on flood dynamics along Coulee Ile des Cannes. To achieve this, the study utilized the National Land Cover Database's imperviousness layer to represent changes in land use across the watershed between two different years, namely 2001 and 2019. Using these layers, the study developed runoff hydrographs for 10, 50, and 100-year return period rain events, as well as two real-case events that occurred in May 2014 and August 2016, using the hydrologic model of Ile Des Cannes. Subsequently, these runoff hydrographs were used to drive the hydrodynamic model of Ile Des Cannes, and the resulting flood dynamics were evaluated to assess the impact of land use changes.

The study's findings indicate that the maximum difference in water surface elevations along Coulee Ile des Cannes was approximately 0.2ft during more frequent storms, such as the 10-year storm event. This difference gradually decreased as the storm return period increased, with the maximum difference in water surface elevation being around 0.1ft for the 100-year storm event. Such findings align with the observation that, as the storm event increases in size, the amount of rainfall becomes the dominant factor, reducing the impact of other factors, including land use changes. In severe storm events, various land uses may reach a state of saturation, behaving similarly to urbanized areas. Therefore, during such events, the impact of different land uses such as pasture or crops on flood dynamics may become insignificant, and the results may resemble those observed in urbanized areas. Additionally, the study's results demonstrated that for spatially uniform rainfall, the maximum water surface profile consistently occurred at the same location approximately six miles from the outlet of the coulee, regardless of the severity of the storm event.

The study's observations were further supported by the results obtained from running simulations for past storm events. The study found that during the severe storm event in August 2016, there were smaller differences in water surface elevations compared to the more frequent storm event in May 2014, aligning with the previously obtained finding. Additionally, and due to that the May2014 storm was spatially concentrated over the watershed of coulee Ile Des Cannes, the obtained results were similar to those obtained under design storms. The results show that under May2014 storm, the maximum difference in water surface elevation was observed at mile 6 from the coulee outlet with a value of 0.33ft. Interestingly, the study found that the differences in the maximum water surface profile observed in real past storm events were more significant compared to those obtained from design storms. The study's results revealed that the maximum difference in water surface elevation during the May 2014 storm event, which is comparable to the 10-year storm, was approximately 0.33ft, exceeding the value of 0.21ft obtained under the 10-year storm. Likewise, during the August 2016 storm event, the maximum water surface elevation difference was 0.23ft, while the 100-year storm, which is comparable to the August 2016 event, produced a maximum difference of 0.1ft. These results underscore the crucial role that the spatial distribution of rainfall events plays in flood dynamics. Furthermore, the findings suggest that the impact of land use changes or urbanization extends beyond the rainfall-runoff transformation mechanisms and can also alter storm dynamics.

Overall, assessing the results of the first experiment through testing the significance of the land use changes on the flood elevations along the coulee suggests that the land use or urbanization indeed impacts the shape and volume of produced runoff. However, and in comparison, with the results of the other experiments done under this study, it can be said that land use changes within Coulee Ile des Cannes have a less significant impact on the water surface elevation if specifically looking at conditions from 2001 compared to conditions from 2019. A few reasons for this result may be attributed to 1) the predominant land cover in the watershed being pasture/cultivated crop., and 2) time difference of the data analyzed. Given that the watershed's main land cover consists of pasture and cultivated crop land, the added amount of urbanization is not overwhelming the watershed with drainage issues. The examination of the shape of the increase in urbanization presented in **Figure 7** suggests that the added urbanization consists of isolated islands across the main landscape, leading to the added impervious areas behaving more like indirectly connected impervious areas. This means that the impervious surfaces are not directly connected to the stormwater drainage system and may allow runoff to infiltrate into the soil before it reaches the drainage system. As a result, the added impervious areas did not directly contribute to the generated volume and rate of runoff. A watershed that has less pasture and crop cover and increased urban development over the past few decades may see more of an impact in changes to land use due to urbanization. For these reasons, the relative contribution of land use changes to the water surface elevation and flow rate within Coulee Ile des Cannes is small. Another explanation for the results can be attributed to the time difference between the release dates of the two impervious data sets used in the hydrologic model is eighteen years. While the area studied has several new urban developments and land use changes over the past two decades, more differences may have been reflected if land use/impervious data from further in the past was available.

The assessment of channel modifications made over the past few decades in Coulee Ile des Cannes are concluded to have more of an impact on water surface elevations and flow rates compared to land use changes. Channel modifications in the watershed consist of drainage improvement projects completed by LCG that cleared the channel path while at the same time deepened and widened the bottom and sides of the main channel of the coulee. These projects were completed to increase channel capacity and lower water surface elevation. The current channel, due to the modifications, now has a much deeper and wider channel bottom compared to the pre-modified bathymetry. After conducting simulations using both design storms and historical storms, the results indicate that modifications to the coulee have led to a reduction in water surface elevation throughout the entire length of the main channel. Additionally, there is now an increased flow rate at the outlet. The hydrographs for the current channel flow at the outlet of the coulee for each storm exhibit steeper rise and recession limbs, indicating that water moves quickly out of the channel into the Vermilion River. Although this reduction in water surface elevation in Coulee Ile des Cannes may be beneficial, it could potentially result in problems for the Vermilion River. This is because the channel dredging has led to an increase in flow rate of water drained into the Vermilion River. Therefore, while there has been a reduction in water surface elevation, there is a tradeoff in the form of increased flow rate, which can have implications for downstream river management. This is an impending issue because it is causing stages in the Vermilion River to rise due to the increased flow coming into it. While the increase to the Vermilion River is not large, it raises awareness of what channel modifications can do. While the modifications benefit the local coulee, there are implications downstream. If further channel modifications are considered, this may cause more of an increase in stages in the Vermilion.

The analysis using past and current precipitation depths for the 10, 50, and 100-year design storms was beneficial for showing the impact of precipitation to Coulee Ile des Cannes. The model outputs using the past precipitation produced systematically reduced water surface profiles compared to the outputs of land use changes and channel modifications. More than a foot difference between past and current water surface elevations were observed in some locations. This analysis gave way to understand the impact of storm precipitation on the water surface elevation of the coulee. Using hypothetical design storms is common industry practice for structure and drainage design, which makes it important to understand what a difference of one inch of rain can do to the water surface elevation within a channel. The difference between the past and current design storm precipitation depths were ~1.7 inches for the 10-year design storm and ~3 inches for the 100-year design storm. These differences in the precipitation then translated to over a foot difference in water surface elevation nearly uniform along the channel's length. A change in water surface elevation by one foot can have significant implications, such as flooding of a house, overtopping of a bridge, or making a road impassable. The analysis of the precipitation data from Lafayette airport gives evidence of how design storm magnitudes can constantly be changing based on the frequency and intensity of storms that occur in the area. The likelihood and depth of any design storm can change with each year of record due to its nonstationarity. Producing the plot of the average annual precipitation for an increasing sample size, **Figure 27**, is an example on how there is an upward trend in the depth of the maximum annual precipitation. With these results it can be said that changes in precipitation have a more significant contribution to changes in water surface elevation and flow rates and it predominates the impact of changes in land use and modifications to channel bathymetry. Engineers need to acknowledge that the nonstationarity of precipitation patterns may lead to an increase in the depth associated with design storms over time. This implies that a structure designed to withstand a 100-year flood event at present may not be able to withstand a similar event in the future, during its design life.

The final scenario of this analysis examines past land use, channel modifications, and design storm precipitation in an all-past scenario to compare to the current baseline scenario. Combining each past condition in one simulation allows for examination into how they react together and their impact on water surface elevation and flow rates within Coulee Ile des Cannes. With past land use not having a significant impact on the water surface elevation and flow rate, the driver which impacts the results of this scenario the most is the past precipitation. The pre-modified channel in this scenario causes the impact of the past precipitation to not be as uniform as when it was isolated for its individual impact due to the current channel bathymetry having a much flatter bottom profile than the pre-modified channel. This not only increases the channel volume capacity but increases the flow rate. The pre-modified channel and past precipitation together is a representation of how the past channel reacts to less rain compared to the increased intensity that the current channel may be experiencing now.

All scenarios were completed to determine the relative contribution of changes to land use, channel bathymetry, and precipitation in Coulee Ile des Cannes. While there are many factors that affect changes in water surface elevation and flow rates within a river reach, these three factors could be considered as major morphologic drivers of changes in river hydraulics. Based on the results produced by the hydrologic and hydraulic model outputs, it can be concluded that changes in precipitation have the most significant impact on differences in water surface elevations. While channel modifications, such as dredging, can contribute to efforts to reduce flood risk locally, it may not be sustainable or can have negative impacts to downstream hydraulics. The upward trend in the precipitation data suggests that the annual maximum precipitation is increasing and an increase in precipitation can lead to increased water surface elevations. Flood mitigation efforts should concentrate on sustainable infrastructure design and solutions that benefit local areas without causing problems for places downstream. Structures that were designed to withstand a 10-year storm in the past may not be able to withstand a 10-year design storm in the future. Future flood mitigation has the potential to be sustainable and resilient. Therefore, making decisions that address current flooding problems while accounting for future changes and increases in precipitation are necessary.

Reversing impacts of past changes with new flood mitigation measures

Flood Detention Ponds

In this analysis, storage areas were implemented into the hydraulic model of Coulee Ile des Cannes as a flood mitigation measure with the objective to quantify their impact to the current condition of the coulee. The hydraulic model was updated with the inclusion of four additional storage areas. These storage areas were placed with two located along the main channel and the other two positioned along Coulee Granges. The scenarios with the detention ponds are simulated in the hydraulic model for the two historical storms of May 2014 and August 2016. Similar to the results shown in the previous section, the outcomes of this flood mitigation measure will be presented in a manner that allows for comparison. Specifically, the focus will be on how the implementation of detention impacts the flood dynamics along the main channel of Coulee Ile des Cannes. The maximum water surface profile of the two storms may be seen in **Figure 32** below. Looking at both water surface profiles, there is a reduction in the water surface elevation for both storms due to the existence of the detention ponds. The values for these reductions in the water surface elevation can be found in **Table 12** below. A positive difference in the table represents a reduction in the water surface elevation from the current conditions. The largest reduction in water surface elevation is ~0.78 feet for the 2014 storm and ~0.60 feet for the 2016 storm. The reductions for both storms mainly occur at Coulee Ile des Cannes' most downstream end. The flow hydrographs taken from the outlet of the coulee, in **Figure 33**, reveal a reduction in maximum flow rate due to the presence of the detention ponds. Specifically, as mentioned in **Table 13**, a ~900 cfs and ~846 cfs reduction for the May 2014 and August 2016 storms. The double peaks of the August 2016 storm have a reduction in the flow rate at the peaks for the scenario with detention.

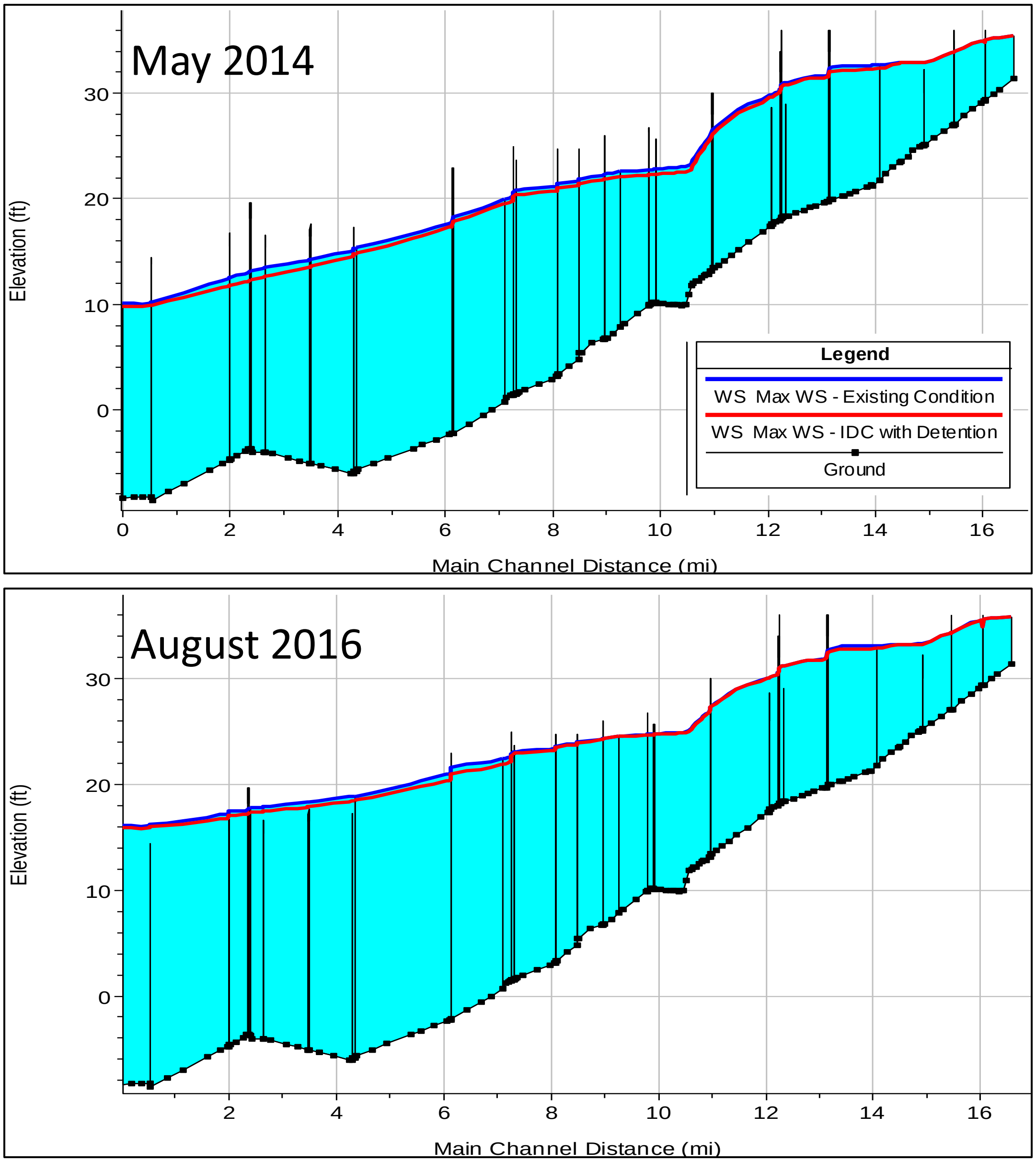


Figure 32. Maximum water surface profiles comparing the baseline condition in Coulee Ile des Cannes to a scenario with detention ponds placed within the watershed for the May 2014 and August 2016 storms.

Table 12. Difference in maximum water surface elevation along main channel in Coulee Ile des Cannes for examination of detention reservoir impacts for the May 2014 and August 2016 storms.

Miles from IDC Outlet	Difference in water surface elevation (ft)	
	May 2014	August 2016
Outlet	0.26	0.22
2	0.78	0.39
4	0.61	0.44
6	0.4	0.6
8	0.44	0.14
10	0.48	0.06
12	0.4	0.03
14	0.4	0.25
16	0	0.01

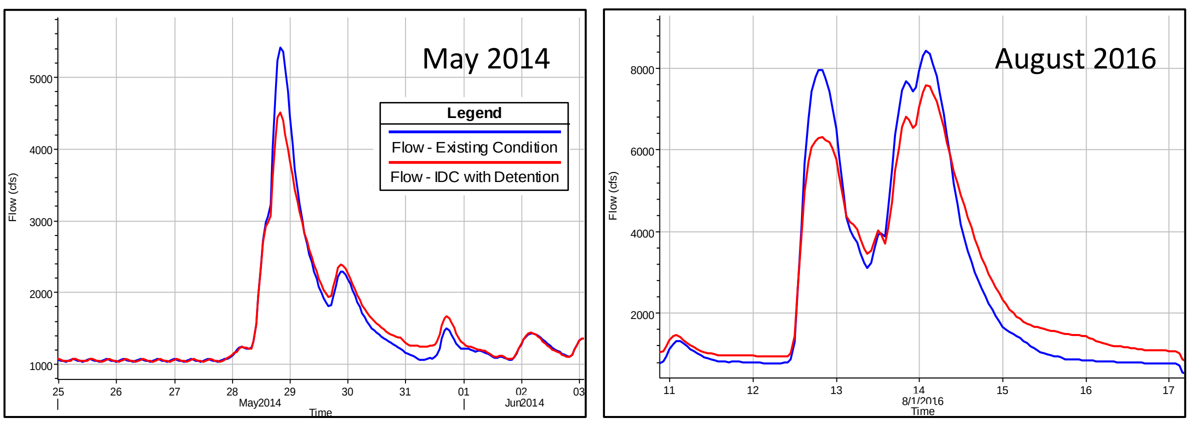


Figure 33. Flow hydrographs at outlet of Coulee Ile des Cannes of baseline conditions and scenarios with detention ponds implemented for the May 2014 and August 2016 storms.

Table 13. Reduction in flow rate due to implementation of detention ponds at outlet of Coulee Ile des Cannes.

Precipitation Event	Reduction in Flow Rate at Outlet (cfs)	Percent Difference
May 2014	899.62	19.97%
August 2016	846.05	11.16%

Implemented as a flood mitigation measure for Coulee Ile des Cannes, the implementation of the four detention ponds has resulted in notable decreases in both the water surface elevation and flow rate within the coulee. Analysis of historical storms May2014, and August 2016 storms, which roughly corresponds to the 10-year and 100-year design storms, indicate that the reductions are generally less than one foot at most locations along the coulee. However, the downstream section near the outlet exhibits the most significant impact. The implementation of the detention ponds has resulted in a deceleration of the maximum flow rate within Coulee Ile des Cannes, which has mitigated the increase in flow rate caused by the channel modifications. This is due to the fact that the detention ponds act as temporary storage reservoirs, retaining excess water during high flow period of the storm and gradually releasing it downstream over time. As a result, the peak flow rate is reduced, and the flow rate hydrograph is flattened, resulting in a longer and slower discharge of water downstream.

Incorporating the detention ponds into the complete hydraulic model of Vermilion River has allowed for a more comprehensive evaluation of their impact on both Coulee Ile des Cannes and the Vermilion River. The results show that, during the May 2014 storm event, the Vermilion River experienced a reduction of 0.20 ft in the maximum water surface elevation at the outlet of Coulee Ile des Cannes, while during the August 2016 storm, the reduction was 0.22 ft. These reductions are significant as they demonstrate the effectiveness of the detention ponds in mitigating the effects of high-flow events not only in Coulee Ile des Cannes but also in the broader Vermilion River system. By reducing the peak flow rate and flattening the flow rate hydrograph, the detention ponds have reduced the potential for downstream flooding and related damages. These reductions due to the detention ponds nearly reverse the impact of the channel modifications. As was seen with the impact of the modified channel bathymetry above, the channel modifications increased flow rates in Ile des Cannes which increases the stage in the Vermilion River. With these detention ponds though, the increase due to the channel modifications has now been reduced.

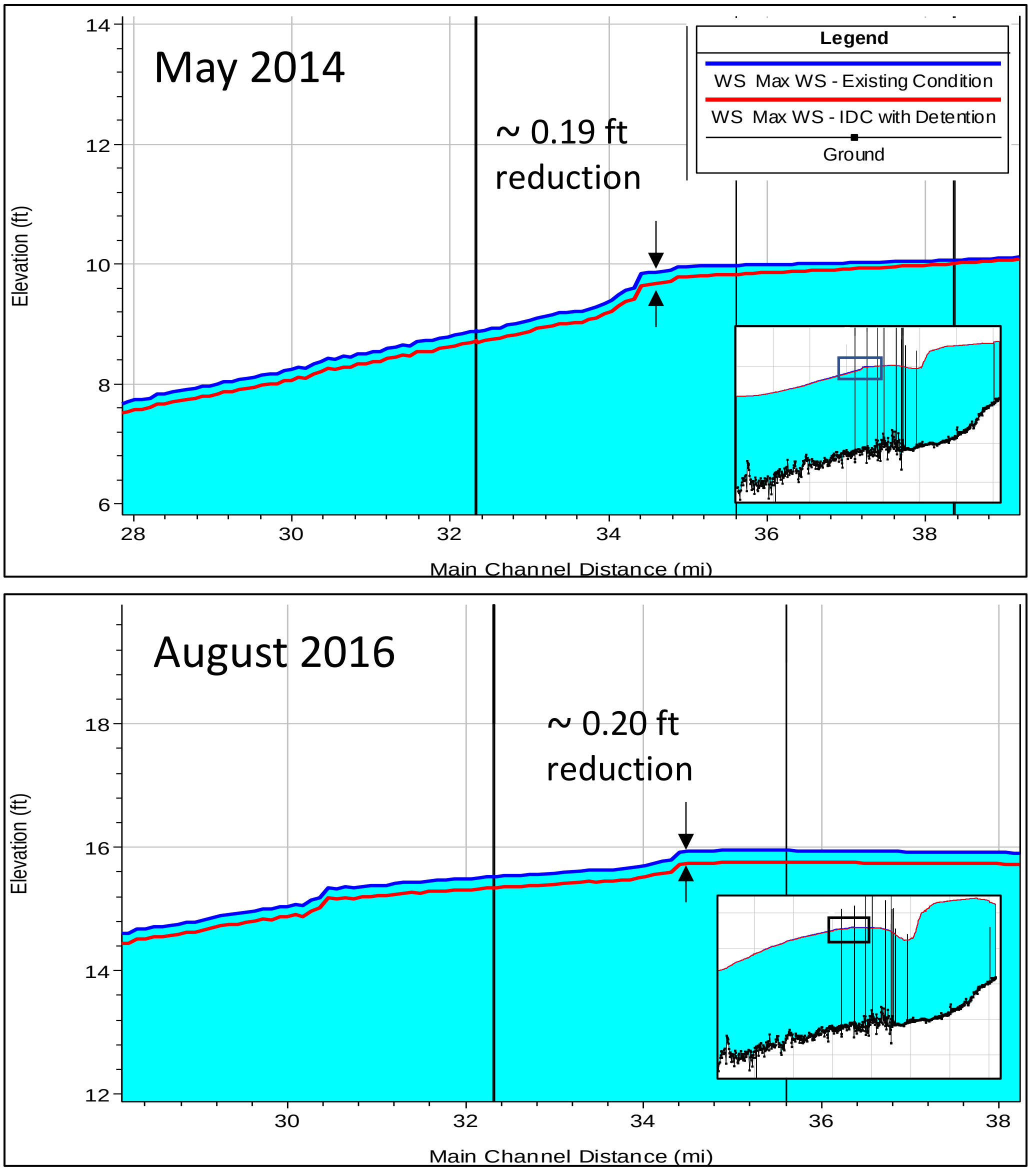


Figure 34. The impact of the detention ponds in Coulee Ile des Cannes on the water surface elevation in the Vermilion River at the outlet of Coulee Ile des Cannes.

Flood Control Structures

Using a hydraulic model of the Vermilion River and its tributaries, simulations were performed for Hurricane Barry of 2019 and Hurricane Laura of 2020. The existing condition (i.e., without the structure) for each storm was simulated first to provide a baseline scenario. The water surface profiles for the existing condition are shown in **Figure 36**. The intensity of Hurricane Barry is comparable to a 2-year design storm and Hurricane Laura is comparable to a 5-year design storm. Using the same hydrologic inputs and model boundary conditions for all model simulations, simulations were performed for each of the proposed structure's scenarios. The impact of the proposed structure was evaluated by plotting and examining the maximum water surface profile of the main river reach for the existing condition and the scenarios with the structure. Results for this analysis are reported as differences in water surface elevations at four key locations along the river: Surrey at mile 46.42, the outlet of Coulee Ile Des Cannes at mile 34.41, Perry at mile 17.13, and Palmetto Island at mile 5.89. These locations are pointed out on the map in **Figure 35** below. Results will also be examined along the main reach of Coulee Ile Des Cannes to gain insight to the structures impacts to upstream tributaries. The existing conditions of Hurricane Barry have a moderate storm surge in Vermilion Bay measured at 6 ft. Hurricane Laura existing conditions had a higher storm surge at 9.5 ft.

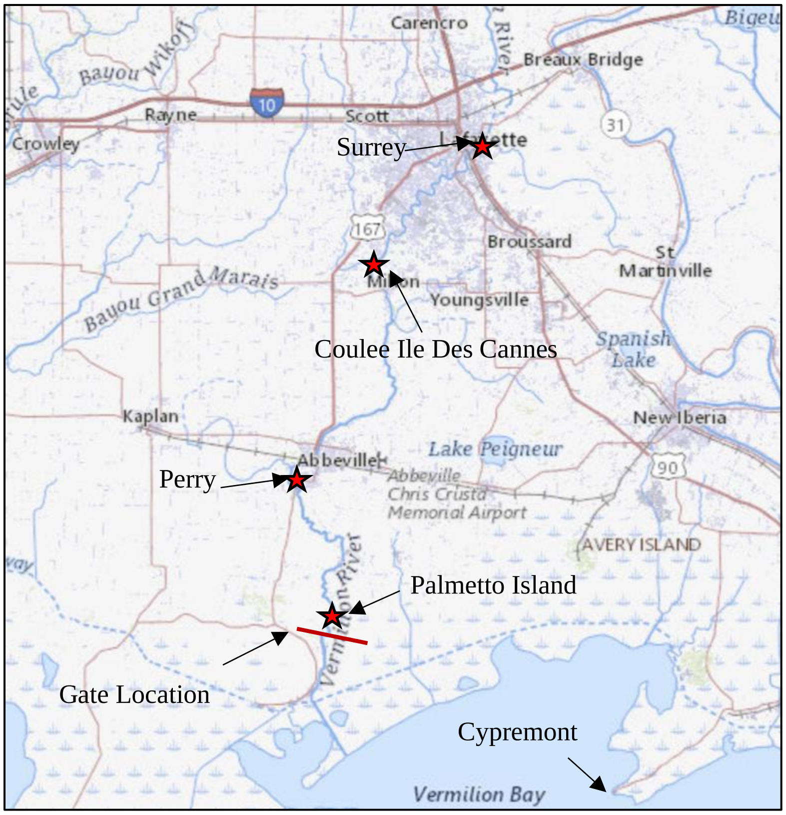


Figure 35. A map of Vermilion River pointing out representative locations where impact of flood control structure was examined. The gate's location is represented with the red line.

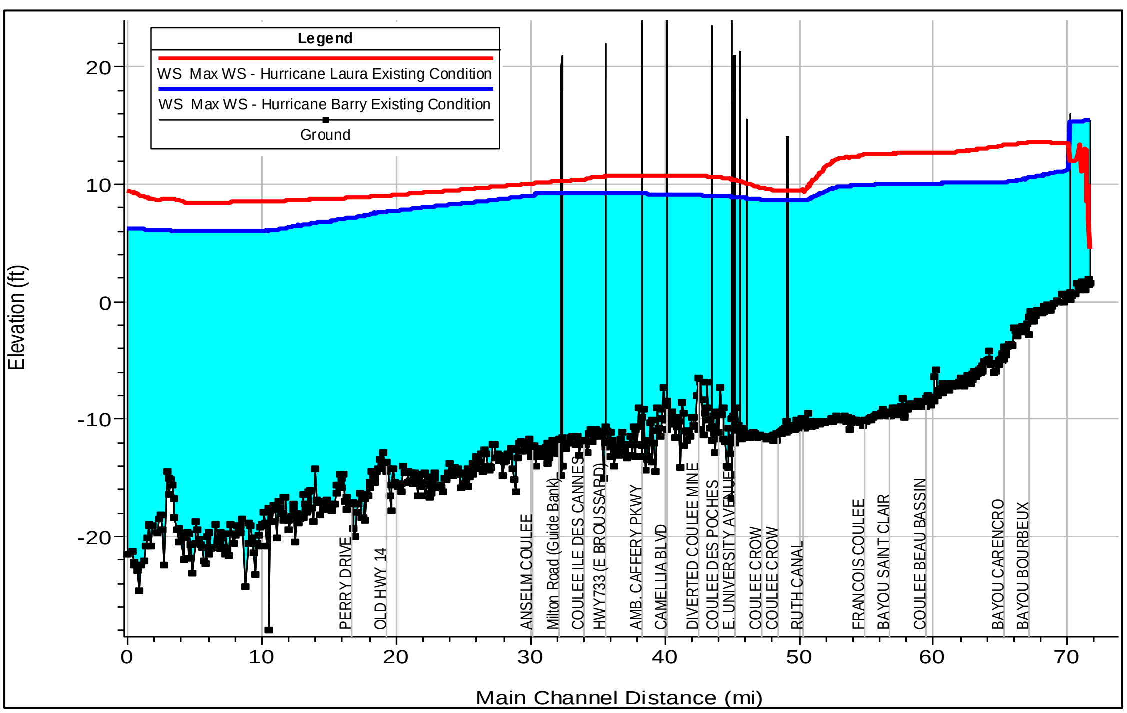


Figure 36. Maximum water surface profile in Vermilion River of the existing condition without the flood control structure for Hurricane Barry and Hurricane Laura.

The results summarizing the differences in maximum water surface elevations at the selected locations are shown in **Table 14**. For the two storms considered in the simulations of the flood gate, both scenarios resulted in a reduction in the maximum water surface elevations. These reductions can be viewed in the maximum water surface profiles for the two storms in **Figure 37** below. The magnitudes and locations of reductions varied between the two storms and scenarios considered. During gate operation, river stages reduce as upstream flows are diverted around the gate with the pumping system. Once the gate is opened after the storm surge has subsided, flows upstream of the gate can start to move downstream. The river stage then rises again but can maintain considerable reductions in the maximum stage of the river due to the operation of the pump during gate closure. For the simulated scenarios of Hurricane Barry, Test 4 included a 3000 cfs pumping rate for the duration of gate closure, which was 42 hours total. This scenario shows favorable reductions in the maximum water surface elevation in Vermilion Parish and all the way upstream in Lafayette Parish. In this scenario, reductions of 0.68 ft were obtained at Surrey in Lafayette and the largest at Palmetto Island at 1.59 ft below the existing condition. For the simulations of Hurricane Laura, Test 5 included pumping at varied rates throughout the 39-hour gate closure duration. Pumping started at 2700 cfs, increased to 4500 cfs, and finally increased to 6000 cfs before the gate re-opened. Reduction in this scenario's water surface elevation ranged from 0.73 ft at Surrey to 3.67 ft upstream of the Palmetto Island gate.

Table 14. Reduction in water surface profile for Hurricane Barry and Hurricane Laura at representative locations along the Vermilion River.

Location	Barry (Test 4)	Laura (Test 5)
Palmetto Island	-1.59	-3.67
Perry	-0.94	-3.27
Coulee Ile des Cannes	-0.98	-2.12
Surrey	-0.68	-0.73

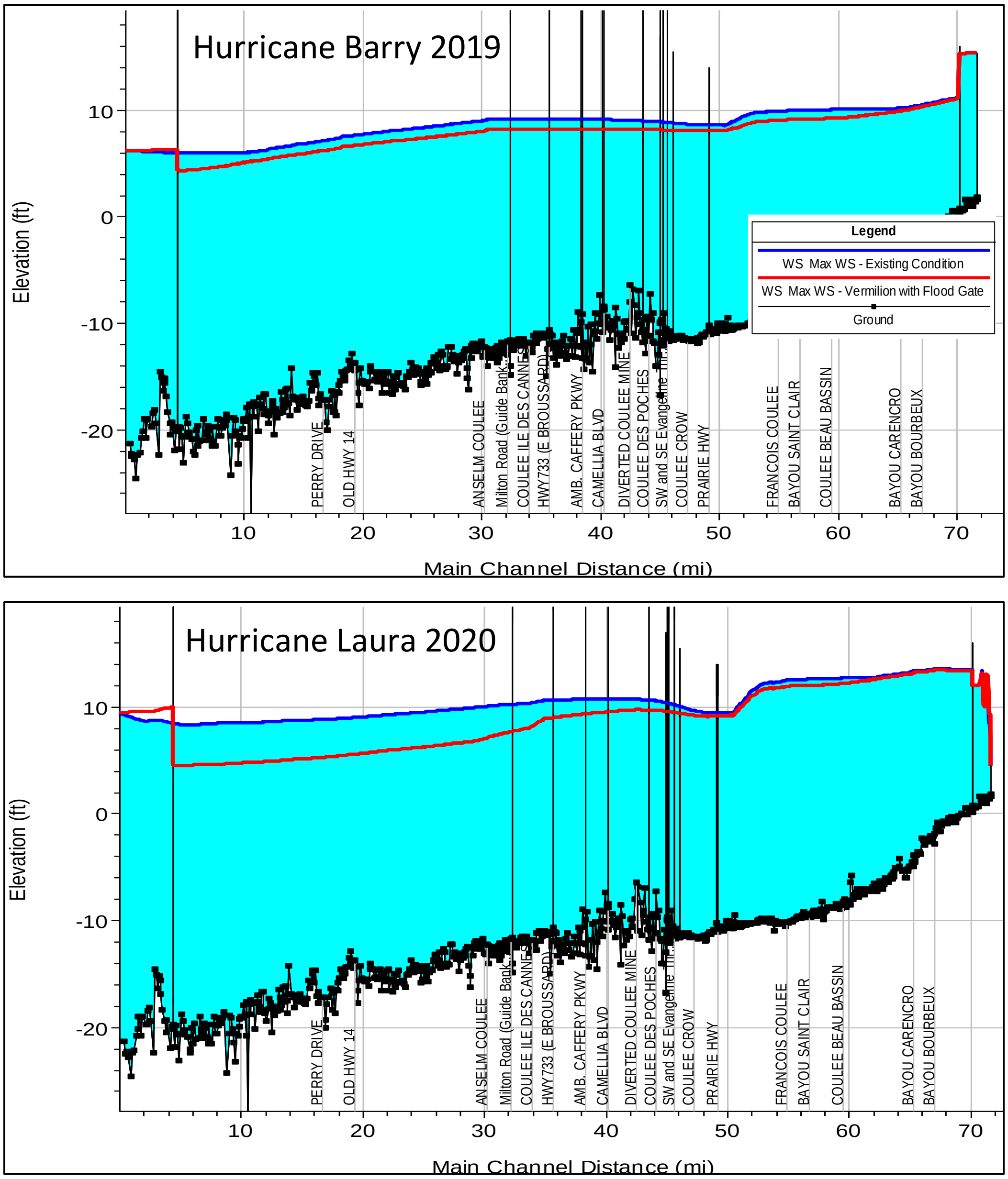


Figure 37. Maximum water surface profile in the Vermilion River of Hurricane Barry and Hurricane Laura comparing the existing condition to the scenarios with flood gate and pump.

The stage and flow hydrographs of the two storms were examined at Perry and Coulee Ile des Cannes along the Vermilion River. **Figure 38** below shows the hydrographs for Hurricane Barry and **Figure 39** shows the hydrographs for Hurricane Laura. For Hurricane Barry, at Perry, due to the operation of the gate the state reduces the stage ~10 ft during gate closure for a reduction of 0.94 ft at the peak of the hydrograph. At Coulee Ile des

Cannes, the reduction during gate closure reached ~7 ft for a maximum reduction of ~0.98 ft during the peak of the hydrograph. The flow hydrographs show that with the structure there are no longer reverse flows from the upstream movement of the storms surge in Vermilion Parish at Perry and all the way upstream in Lafayette Parish at Coulee Ile des Cannes outlet.

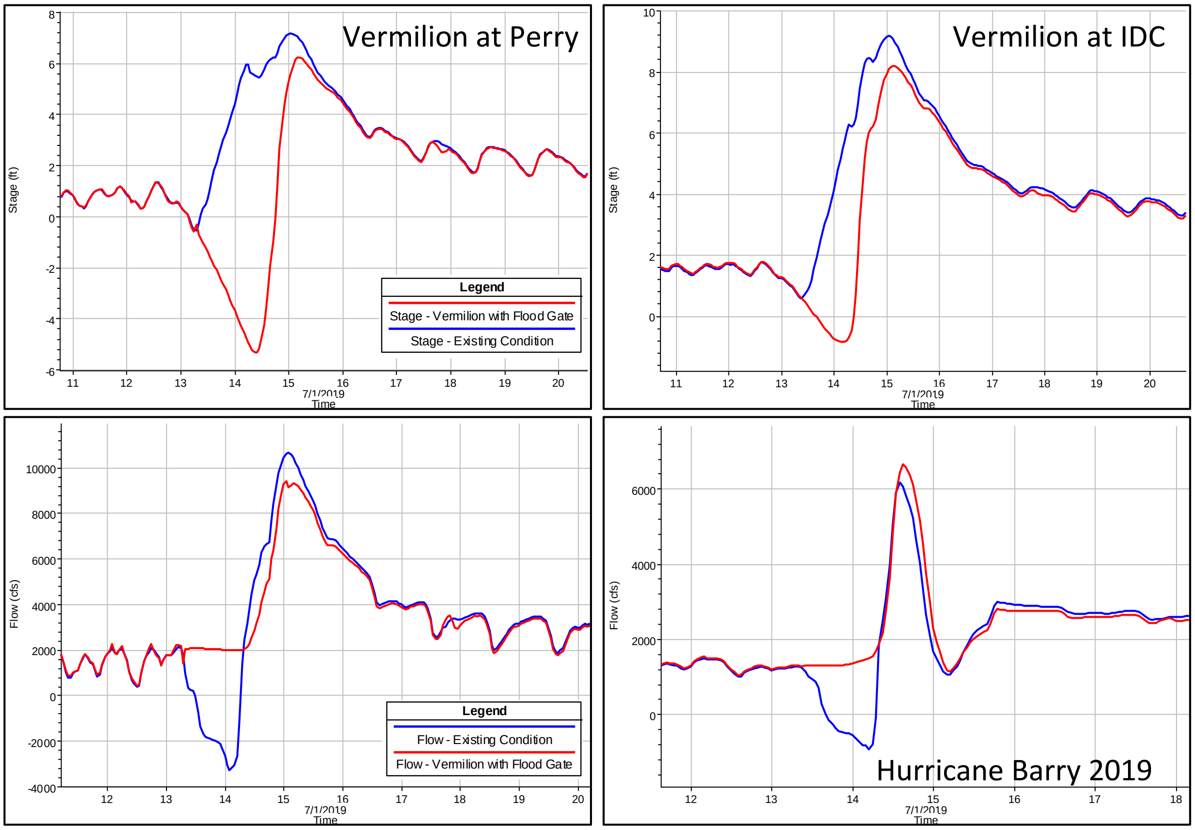


Figure 38. Stage (top) and flow (bottom) hydrographs for Hurricane Barry at Perry (left) and the Vermilion near the outlet of Coulee Ile des Cannes (right) of the existing condition and the scenario with the operation of the flood gate and pump.

For Hurricane Laura, the stage hydrograph at Perry shows a ~7 ft reduction due to the operation of the gate with a maximum reduction of 3.27 ft at the peak of the hydrograph. At Coulee Ile des Cannes, a ~4 ft reduction was achieved during gate closure for a maximum reduction at the peak of the hydrograph is 2.12 ft. Similar to the result of Hurricane Barry, the flow hydrographs at both locations reveal the reverse flows due to the upstream movement of the storm surge have nearly been eliminated in Vermilion Parish and upstream in Lafayette Parish at Coulee Ile des Cannes. These reductions in the water surface elevation for Hurricane Laura are prominently greater than those of Hurricane Barry largely because of how much larger the storm surge of Hurricane Laura was.

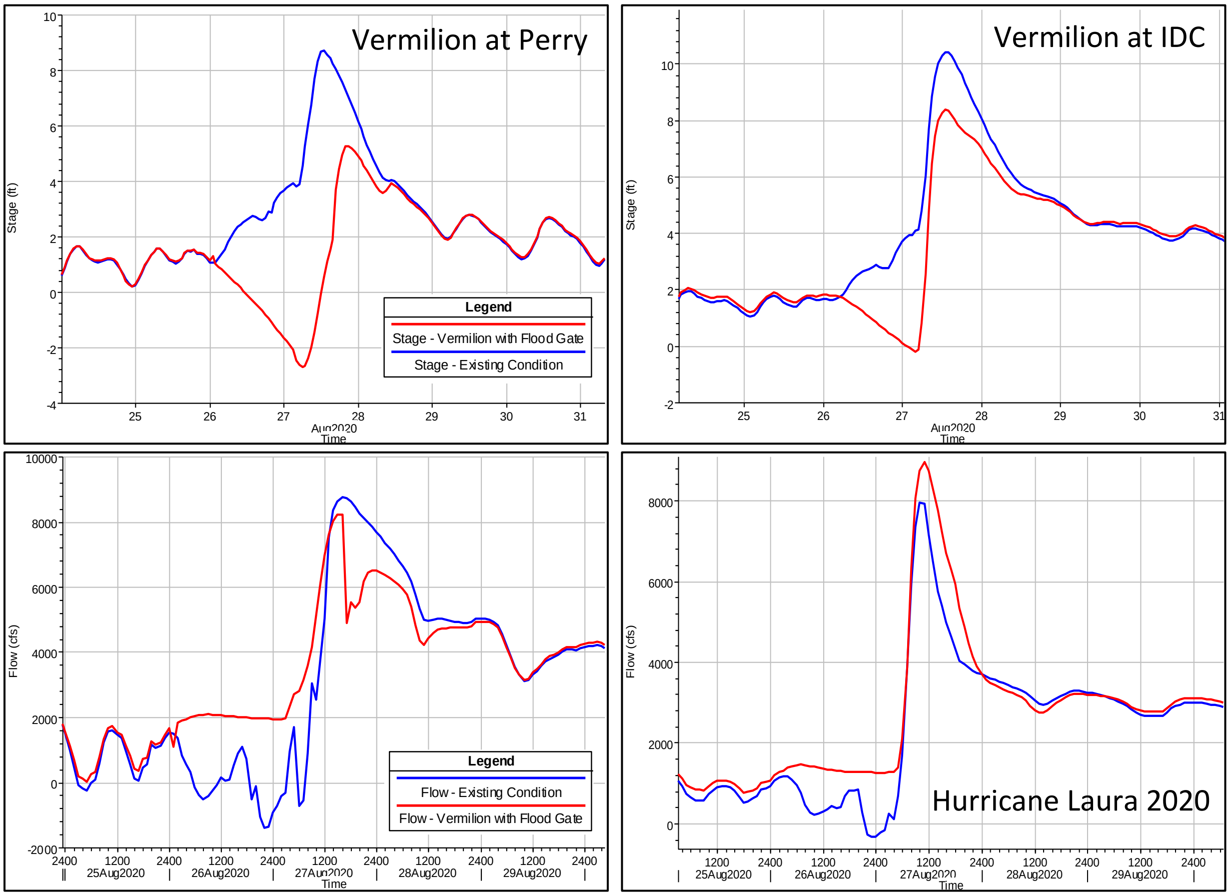


Figure 39. Stage and flow hydrograph for Hurricane Laura at Perry (left) and the Vermilion near the outlet of Coulee Ile des Cannes (right) for the existing condition and the scenario with the operation of the flood gate and pump.

To analyze what impact the gate has on the Vermilion River tributaries, the water surface profile of Coulee Ile des Cannes' main channel was examined. These water surface profiles can be seen in **Figure 40** below. The calculated differences between the two water surface elevations are included in **Table 15**. For Hurricane Barry, higher reductions in water surface elevation were evident from the outlet of coulee to approximately 7 miles upstream. Between the coulee outlet and 4 miles upstream, there is a ~0.99 ft reduction in the water surface elevation. For Hurricane Laura, similar results were observed. There is also an evident reduction in the water surface elevation from the outlet of the coulee to about 7 miles upstream of the main channel. At Mile 2 and Mile 4, the water surface elevation was ~1.79 ft and ~1.32 ft below the existing condition.

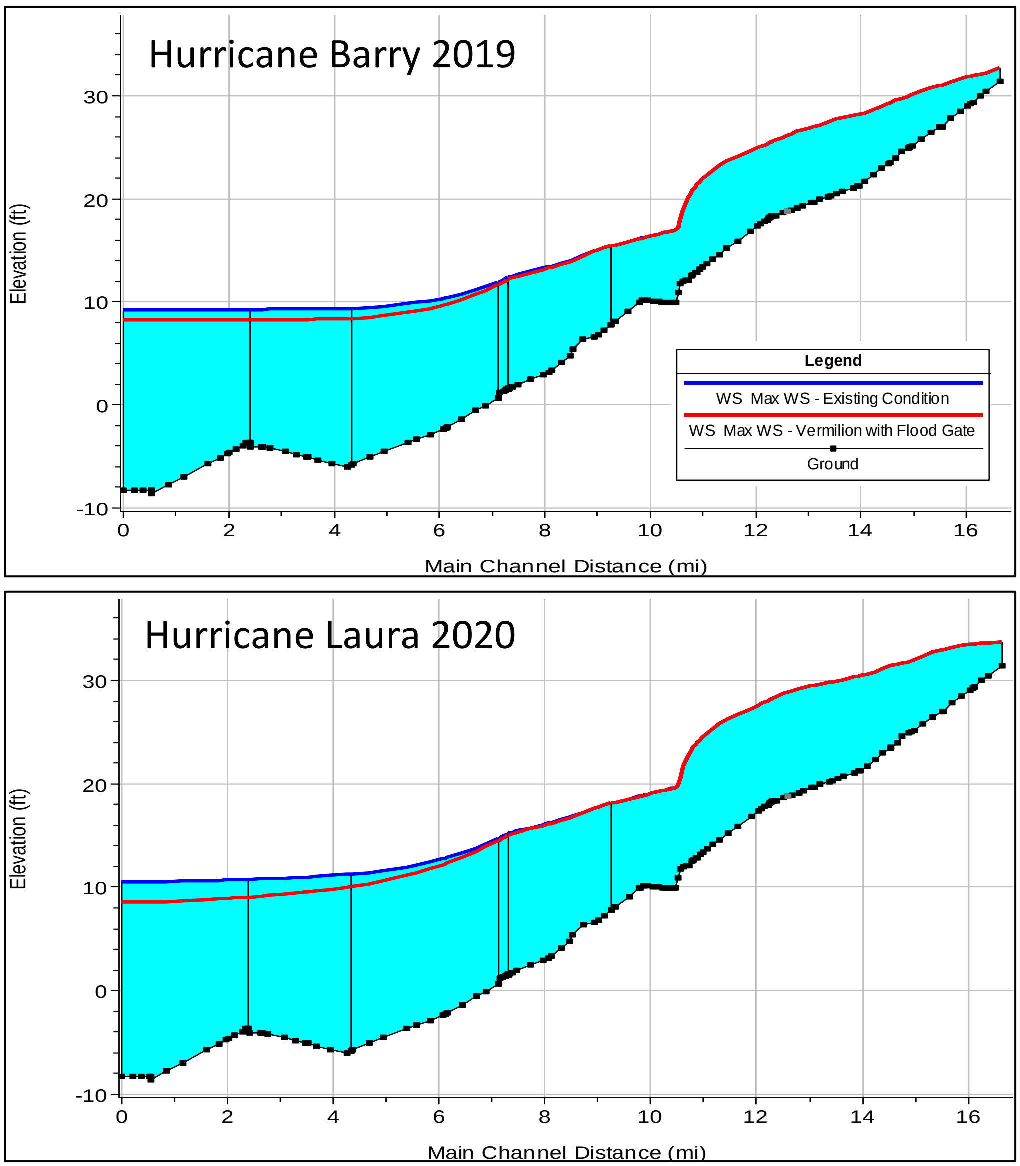


Figure 40. Maximum water surface profile of Coulee Ile des Cannes for Hurricane Barry and Hurricane Laura of the existing conditions and scenarios with the operation of the flood gate and pump.

Table 15. Reduction in water surface elevation along Coulee Ile des Cannes due to operation of flood control structure for Hurricane Barry and Hurricane Laura.

Miles from IDC Outlet	Reduction in water surface elevation (ft)	
	Barry Scenario	Laura Scenario
Outlet	0.99	1.98
2	0.99	1.79
4	0.99	1.32
6	0.73	0.67
8	0.15	0.1

Finally, to connect the flood mitigation measures within Coulee Ile des Cannes with the flood control structure on the downstream end of the Vermilion River, the detention ponds were placed in the Vermilion River hydraulic model. The detention ponds do not additionally impact the water surface elevation within Coulee Ile des Cannes. These results may be attributed to the two simulations being with tropical storms as the precipitation input, and the storms being comparable to a 2-year and a 5-year storm. In the scenarios with the detention ponds in Coulee Ile des Cannes with the inland storms of August 2016 and May 2014, there are reductions in the water surface elevation, but not significantly. Along the main channel, the water surface elevation was reduced by less than one foot. With those results, it is understandable why a reduction was not seen with the smaller storms.

These results from the flood control structure suggest that adding a flood control structure in the downstream section of the Vermilion River has a potential to reduce water surface elevations during tropical storm events, not only in Vermilion Parish but also upstream in Lafayette. These results suggest that the operation of a flood control structure during tropical storm events has the potential to prevent flooding for coastal communities in Vermilion Parish and for residents in Lafayette Parish. However, the operation of a structure like this would require much further investigation into how the gate would perform under different inland rainfall conditions, storm surge conditions, and other variables such as wind magnitude and direction. The operation of a structure like this would also require a real-time monitoring system that includes gauges monitoring the water level conditions in the Vermilion Bay and Gulf of Mexico along with river stages at locations upstream and downstream. A structure like this could have negative impacts on the river and surrounding communities if erroneous decisions (e.g., closing the gate too early, or opening it back up too late) were made. The operation of the structure should also be supported with a real-time modeling-based forecasting system that would provide operators with short-term forecasts of the expected river stages, rainfall predictions, and gulf conditions.

Chapter 4 Summary and Conclusions

The primary objective of this research investigation is to evaluate the extent to which anthropogenic factors and natural factors contribute to increased flooding in low-gradient watersheds. The study focuses on Coulee Ile des Cannes, a major tributary of the Vermilion River in south-central Louisiana, and assesses the potential for flood mitigation measures to counteract the impact of these factors. Anthropogenic factors examined in this study include land use changes due to urbanization and channel modifications within the local sub-watershed. The natural factor studied is precipitation, specifically analyzed through design storm precipitation depth.

To assess the impact of changes in land use, channel modifications, and precipitation on Coulee Ile des Cannes, the study uses hydrologic and hydraulic models of the watershed. Historical conditions for each variable are input into the models and compared to current conditions. For land use changes, two impervious grid maps are ingested into the hydrologic model representing past and current land use/imperviousness. Channel modifications are examined by comparing the previous bathymetry of the coulee to the current version after recent modifications, including dredging and drainage improvement projects. Precipitation changes are analyzed by computing current and past design storm point precipitation estimates using data from a precipitation gauge in Lafayette, LA.

Each of these past conditions is individually compared to a baseline scenario representing current conditions, and a combined scenario is created to assess the impact of all past conditions compared to current conditions. The precipitation input for these scenarios includes 10, 50, and 100-year design storms, as well as two historical storms from May 2014 and August 2016. Data for the historical storms are obtained from the National Centers for Environmental Prediction (NCEP) Stage-IV and input into the hydrologic model.

After assessing the impact of past changes to the watershed, simulations are conducted to evaluate the potential for flood mitigation measures to offset their effects. The first measure involves placing four detention pond reservoirs in Coulee Ile des Cannes watershed, selected based on recent projects by Lafayette Consolidated Government. This measure is simulated for the May 2014 and August 2016 storms. The second measure involves placing a flood control structure on the Vermilion River to operate during tropical storm events and prevent storm surge from flooding coastal communities. The impact of the structure is examined downstream in Vermilion Parish and upstream in Lafayette Parish and Coulee Ile des Cannes for Hurricanes Barry of 2019 and Laura of 2020. The operation of the flood control structure involves closing the gate as a tropical storm approaches and river stages rise. While the gate is closed, a pumping system diverts flows around the gate to reduce the river stage upstream. When the storm surge subsides, the gate re-opens and flows upstream of the gate can start to move downstream again. The final analysis evaluates the impact of the detention ponds in conjunction with the flood control structure during the two tropical storm events.

In summary, this study employs hydrologic and hydraulic models to assess the impact of anthropogenic and natural factors on increased flooding in Coulee Ile des Cannes, a major tributary of the Vermilion River in south-central Louisiana. The study also evaluates the potential for flood mitigation measures, such as detention ponds and a flood control structure, to counteract the effects of these factors. The simulations conducted in this study provide insights into the effectiveness of these measures in reducing flood risk and inform future management strategies for low-gradient watersheds. From these analyses and simulations, the main conclusions from this study are as follows:

- Changes in land use, such as urbanization, can affect the amount of water that infiltrates into the soil, and can increase the amount of runoff. This can lead to changes in flow rates and water levels, which can impact downstream communities and ecosystems.
- The degree to which land use changes affect water surface elevation and flow hydrographs in a coulee is strongly influenced by the scale of the changes relative to the catchment's size. Additionally, the nature of the urbanization pattern, including whether it is directly or indirectly connected, also plays a crucial role in determining the significance of the impact.
- Low return period storms, frequent storms, tend to amplify the impact of changes in a watershed's land use or channel modification on the maximum water surface elevation and flow hydrographs in channels, whereas high return period storms can mask such significance due to the large amount of precipitation. However, it is crucial to acknowledge that even during high return period storms, changes in the watershed can still have a notable impact depending on several factors, such as the extent and type of changes, storm characteristics especially its spatial distribution.
- In the case of coulee Ile des Cannes, the watershed comprises urban developments, pasture/hay, and cultivated crops as main land uses. Despite the increased urban development over two decades, the majority of land cover remains pasture and crops. This caused the differences in maximum water surface elevation and flow rate to be

minimal because of the new urban developments. The results indicate an increase in water surface elevation of less than inches, and flow rates increase by a maximum of 200 cfs for simulated storms.

- Analysis of Coulee Ile des Cannes channel bathymetry reveals that the current channel is wider, deeper, and flatter compared to the past conditions of the coulee. The study finds that the current channel dimensions results in higher flow rates at the outlet, with an overall reduction in maximum water surface profile for all studied storms. Additionally, the flow hydrographs at the outlet have a steeper rise and recession limb than the pre-modified channel, indicating faster water drainage into the Vermilion River.
- Although the channel modifications for the coulee Ile Des Cannes succeeded in locally reducing water surface elevation, the resulting increase in flow rate at the outlet caused an increase in stages downstream in the Vermilion River. As such, the positive contribution of channel modifications in Coulee Ile des Cannes may be offset by their negative impact on the Vermilion River
- The study performed frequency analysis on the annual maximum precipitation data obtained from Lafayette airport to evaluate the significance of the variability of design storm rainfall rates and its impact on water surface profiles in the coulees resulting from the storm. The results indicate that the precipitation depths can significantly influence the water surface elevations, and even small differences of one or two inches of rain can lead to a substantial variation up to a foot in the maximum water surface elevation obtained along the coulee. These results suggest that changes in precipitation contribute more to water surface elevations than land use changes and

channel modifications especially when considering high return period storms (severe storms).

- The study's findings underscore the criticality of incorporating nonstationary factors into the input data used for hydrologic modeling and design. The analysis of the precipitation data time series reveals a substantial shift, increasing trend, in the data over time. This observation emphasizes the importance of considering the nonstationary nature of precipitation data when designing structures that can withstand both current and future storm events.
- Analyzing the contribution of design storm precipitation showed how two different point precipitation estimates impacts water surface elevations and flow rates within Coulee Ile des Cannes. This analysis looked at past point precipitation estimates for the 10, 50, and 100-year design storms. The past precipitation scenarios produced a more uniform reduction in water surface elevation along the length of the main channel. Amongst all the design storms, the past precipitation was more than a foot below the current condition in some locations on the main channel. The analysis of the annual maximum precipitation from the data from Lafayette airport shows how design storm rainfall rates can constantly be changing and how a difference in one to three inches of rain can translate to a foot difference in water surface elevation. These results suggest that changes in precipitation contribute more to water surface elevations than land use changes and channel modifications. Accounting for changes in precipitation is necessary for future flood mitigation and designing sustainable and resilient infrastructure. Methods for determining design storm precipitation depths

should account for nonstationary factors which influence hydrologic data so that structures will be designed to withstand current and future storm events.

- The detention ponds implemented along Coulee Ile des Cannes and Coulee Granges provides a benefit to water surface elevations along the main channel of the coulee. The four ponds placed in the watershed resulted in less than a foot reduction in most locations along the coulee for the May 2014 and August 2016 storms. The detention ponds were placed in the complete Vermilion River hydraulic model to see if there was any impact to the main river. The May 2014 storm resulted in a 0.19-foot reduction in stage in the Vermilion River and the August 2016 storm in a 0.20-ft reduction. These results indicate that the detention ponds can reverse the impact of the increased flow rate that the channel modifications created which will reduce the stage in the Vermilion River.

- The flood control structure on the downstream end of the Vermilion River can reduce the maximum water surface elevation in the river and reduce flooding for communities in Vermilion Parish and upstream in Lafayette Parish. During Hurricane Barry, at a pumping of 3000 cfs for a total of 42 hours of gate closure, the maximum water surface elevation was reduced by 1.59, 0.94, 0.98, and 0.68 ft at Palmetto Island, Perry, the outlet of Coulee Ile des Cannes, and Surrey Street. During Hurricane Laura, with pumping varying at rates between 2,700 and 6,000 cfs, maximum water surface elevation was reduced by 3.67, 3.27, 2.12, and 0.73 ft at the same locations. These storms were also examined within Coulee Ile des Cannes and resulted in up to a foot and over a foot reduction for about 6 miles for Hurricane Barry and Hurricane Laura. This indicated the flood control structure can also benefit upstream tributaries. However, a flood control structure such as this requires much more extensive research to evaluate the performance under different inland rainfall conditions, storm surge conditions, and other tropical storms and scenarios. It would also require real-time monitoring systems and modeling forecasting systems so that proper decisions could be made. The detention ponds were also simulated with the flood control structure for Hurricane Barry and Hurricane Laura. These scenarios did not see any impact within Coulee Ile des Cannes due to the detention ponds. Hurricane Barry and Hurricane Laura are comparable to a 2 and 5-year design storms while the May 2014 and August 2016 storms are comparable to a 10 and 100-year design storms. These results concluded that the detention ponds simulated may not impact smaller storms.

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Biographical Sketch

Carly Phillips was born in Alexandria, LA on March 19, 1999. She graduated from the University of Louisiana at Lafayette in May of 2021 with a Bachelor of Science degree in civil engineering with a minor in mathematics. She then entered the master's degree program in civil engineering at UL Lafayette in the fall of 2021. Between Carly's completion of her undergraduate degree and the start of her master's program, she received her Louisiana E.I.T. certification in the summer of 2021. Her research in the master's program is focused on riverine hydrologic and hydraulic modeling in a low-gradient watershed. Carly graduated in the spring of 2023 with a Master of Science degree with a concentration in civil engineering.

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