

SOUND SALMON SOLUTIONS

SNOHOMISH COUNTY **WASHINGTON**

CATHERINE CREEK/HARTFORD DRIVE 2-D HYDRAULIC MODELING REPORT

**G&O #20473
OCTOBER 2021**



Gray & Osborne, Inc.
CONSULTING ENGINEERS

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INTRODUCTION

The existing crossing that passes Catherine Creek under Hartford Drive in the City of Lake Stevens is a fish passage barrier. The existing crossing is comprised of two side by side 48-in squashed corrugated metal pipes. Sound Salmon Solutions (SSS) has contracted with Gray & Osborne Inc. to design a replacement water crossing structure. The project is funded by the Washington State Recreation and Conservation Office (RCO).

Catherine Creek is a tributary to the Little Pilchuck River. The Catherine Creek watershed is approximately 9,525 acres. The Hartford Drive crossing is approximately 1 mile upstream from the confluence with the Little Pilchuck River. In the existing configuration, the Lake Stevens outlet channel joins Catherine Creek at the outlet of the Hartford Drive water crossing. Upstream of the crossing is a broad wetland that historically was where the Lake Stevens outlet channel joined Catherine Creek. In the time period since the beginning of Euro-American settlement, the Lake Stevens outlet channel was moved, Catherine Creek was straightened, and numerous ditches were built throughout the wetland.

PURPOSE

During the most recent review of the preliminary design of the water crossing replacement, the Technical Review Team (TRT) recommended developing a 2-D hydraulic model in order to confirm the size and the type of the water crossing that would be needed to accommodate Catherine Creek stream flow.

In this report, we present the methods that we used to develop a 2-D hydraulic model of the existing conditions. Additionally, we present the results of the 2-D hydraulic model and discuss the implications of the results in terms of the size and the type of the water crossing that is needed where Hartford Drive crosses Catherine Creek.

METHODS

Gray & Osborne developed a 2-D hydraulic model using the U.S. Army Corps (USACE) Hydraulic Engineering Center River Assessment Software (HEC-RAS) version 6.0.0, which is the most recent version of the software. Developing the model required preprocessing data in GIS software and setting up the model in HEC-RAS. ArcGIS 10.8.1 was used to delineate the modeling domain, process data that was used to create a digital terrain, digitize terrain breaklines, and delineate surface roughness polygons. In HEC-RAS, we created a final digital terrain, constructed a computational mesh, imported the surface roughness polygons, input boundary conditions, and adjusted the model settings including the computation step and simulation time. The procedures that we followed for each step are described below.

MODELING DOMAIN

In our modeling domain, we included the large wetland upstream of the Hartford Drive crossing as well as a portion of the historic Lake Stevens outlet channel wetland and a portion of Catherine Creek downstream of Hartford Drive (Figure 1). The total area of the modeling extent is 9.73 acres.

In total, we included a length of 2,260 feet of Catherine Creek in the modeling domain. We included approximately 880 feet of Catherine Creek downstream of Hartford Drive and approximately 1,380 feet upstream of Hartford Drive. Also, we included approximately 5,150 feet of ditch length and 1,990 feet of the Lake Stevens outlet channel in the modeling domain.

DIGITAL TERRAIN DEVELOPMENT

Gray & Osborne Survey

Gray & Osborne conducted two topographic and bathymetric surveys in the study area. The first survey was conducted in 2020, and the second survey was conducted during the spring of 2021. Both surveys were focused on collecting data within the active channel. In general, the 2021 survey point density was much greater in Catherine Creek than it was in the ditches. Water surface elevations were collected during both the 2020 and the 2021 surveys.

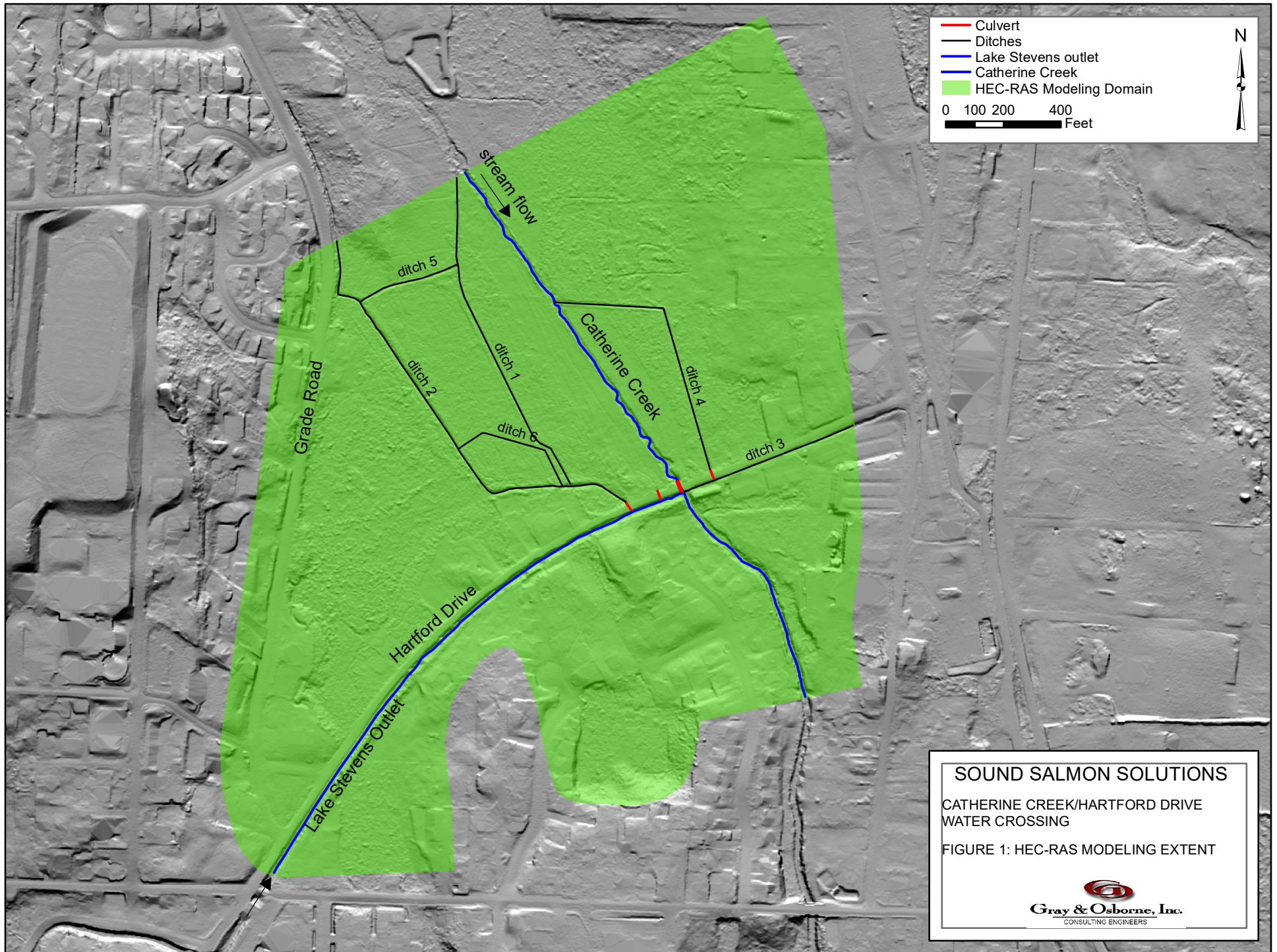
In 2020, Gray & Osborne surveyed the project site on April 20 and June 18. The purpose of the survey was to support the design of the water crossing replacement. The 2020 survey extended approximately 215 feet upstream and 85 feet downstream of the water crossing.

More recently, during the spring of 2021, Gray & Osborne conducted a survey to support the development of a 2-D hydraulic model. The 2021 survey was conducted on June 8, 10, and 14. The 2021 survey covered approximately 1,480 feet of Catherine Creek (including 230 feet downstream and 1,250 feet upstream of the water crossing), approximately 640 feet of the Lake Stevens outlet channel, and approximately 3,490 feet of the ditch network located in the broad wetland upstream of the water crossing.

LiDAR

Three series of red LiDAR data are available for the project site. At the project site, LiDAR was collected in 2005, 2006, and 2017. Because the 2017 LiDAR data is the most recent LiDAR data that has been acquired, we used it in our 2-D hydraulic model.

The 2017 LiDAR data that is available for our study area was collected as part of the 3-D Elevation Program Quality Level 1 Light Detection and Ranging (3DEP QLI LiDAR) project, which was funded by the U.S. Geological Survey and the Washington



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CATHERINE CREEK/HARTFORD DRIVE
WATER CROSSING

FIGURE 1: HEC-RAS MODELING EXTENT


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Department of Natural Resources. For the 3DEP QLI LiDAR project, three different vendors collected LiDAR data across 3.5 million acres spanning 13 counties in western Washington in 2017. The horizontal and vertical resolution of the 2017 data is 3 feet and approximately 0.2 to 0.3 feet, respectively.

In our analysis, we used the hydro-flattened bare earth digital elevation model (DEM) that was generated from the 2017 LiDAR data. The hydro-flattened DEM was created by filtering out all of the higher return points and adding breaklines in order to restrict interpolation in water bodies. The LiDAR vendor added breaklines manually as well as with automated processes in water bodies that are greater than 2 acres in area, tidal areas, and streams and rivers that are greater than 100 feet in width. The water surface elevations from points that were classified as water were then applied in each water body.

In ArcGIS, we resampled the LiDAR DTM from 3-foot to 1-foot pixels.

Terrain Integration

Although LiDAR is an invaluable data source, especially for hydraulic modeling, the red wavelength version of LiDAR does not penetrate water. Furthermore, LiDAR does not represent steep narrow channels, such as dry ditches, well. Therefore, to accurately model the hydraulics of Catherine Creek, it is necessary to integrate the Gray & Osborne survey data with the LiDAR data.

We constructed an integrated digital terrain model (DTM) by combining the bathymetric/topographic surveys (including both of the Gray & Osborne surveys) of the channels and the 2017 LiDAR topographic data. We used both ArcGIS 10.8.1 and RAS Mapper (a geospatial analysis tool available in the HEC-RAS software) to construct the integrated DTM.

First in ArcGIS, we combined the Gray & Osborne survey points from both the 2020 and 2021 surveys. We create a triangulated irregular network (TIN) of the survey points and used the TIN to identify points that were not needed (e.g., culvert inverts and road surface points) or were erroneous points (i.e., tin busts). Then, we created a 1-foot DEM from the TIN.

Because the modeling domain is larger than the area that was covered by the Gray & Osborne survey, it was necessary to create synthetic bathymetry in the channels and ditches that extended beyond the Gray & Osborne survey extent. Specifically, we created synthetic bathymetry and topography in portions of Catherine Creek, the Lake Stevens outlet channel, and five different ditches.

In ArcGIS, we created elevation profiles of the Gray & Osborne DEM and the LiDAR DTM, then in Microsoft Excel we compared the profiles in order to determine the average elevation difference. In ArcGIS, we created new TINs of the channel network

beyond the Gray & Osborne survey extent using the average elevation difference. We merged all of the tins, then created a final channel network DEM.

In addition to creating synthetic topography and bathymetry in portions of the channel network, we modified the LiDAR DTM in a few places. Specifically, we cut through four different high spots along Ditch 3 (Figure 1), and filled a low spot in the levee on the southeast side of the Lake Stevens outlet channel and the historic Lake Stevens outlet wetland.

Using RAS Mapper, we integrated the channel network DEM with the LiDAR DTM. The terrain creation process burned the channel network DEM into the LiDAR DEM, which resulted in a final terrain layer that we used as the geometry for the 2-D hydraulic model.

COMPUTATIONAL MESH

As a required geometry input to a HEC-RAS 2-D hydraulic model, we created a computational mesh. For our model, we created a mesh with grid dimensions of 60 feet x 60 feet. In ArcGIS, we digitized breaklines along linear features that are elevated above the wetland such as levees and roadways and at steep slope breaks beyond the wetland. We also created breaklines along the centerlines of the channel network. After importing the breaklines into HEC-RAS, we enforced the breaklines and recomputed the mesh. We set the near spacing as 20 feet for each breakline. The final computational mesh was an unstructured mesh that includes a mixture of cell sizes including a mixture of cells with different numbers of faces (3 to 8).

SURFACE ROUGHNESS

In ArcGIS, we digitized land cover polygons by interpreting the 2019 National Agriculture Imagery Program (NAIP) aerial imagery. We classified land cover across the modeling domain using the National Land Cover Database (NLCD) land cover classes, then we assigned Manning's N values to each land cover class. We imported our digitized polygons with the land cover class and the Manning's N values into HEC-RAS. Table 1 contains a list of the land cover classes and the associated Manning's N values that were used in the model development.

TABLE 1**Land Cover Classes and Manning's N Values**

Land Cover	Manning's N
Developed, Low Intensity	0.1
Developed, Medium Intensity	0.08
Developed, High Intensity	0.15
Developed, Open Space	0.04
Emergent Herbaceous Wetlands	0.07
Grassland/Herbaceous	0.035
Main Channel	0.05
Open Water	0.04
Woody Wetlands	0.12

BOUNDARY CONDITIONS

We set boundary conditions for five different inflow sites. We set boundary conditions for three different ditches, Catherine Creek, and the Lake Stevens outlet channel. We used daily hydrographs as the boundary conditions for each of the five locations. The length of each of the input hydrograph that we used is 70 days, and extends from October 15, 1990 to December 23, 1991.

To parameterize the inflow boundary conditions of our HEC-RAS 2-D model, we used a variety of streamflow data. We used streamflow data that was measured in three different locations including Catherine Creek, the Lake Stevens outlet channel, and Issaquah Creek near Hobart, WA (USGS gage 12120600). Furthermore, we used the flood frequency predictions for Catherine Creek that are available from the U.S. Geological Survey (USGS) StreamStats web application.

The only empirical streamflow data that is available for Catherine Creek and the Lake Stevens outlet channel was measured in 1996 and 1997 as part of the Lake Stevens/Catherine Creek Watershed Management Plan (Gray & Osborne, 1999). Stream flow was measured in the Lake Stevens outlet channel near 124th Avenue NE from September 1996 to February 1997, and stream flow was measured in Catherine Creek at the 36th Street bridge from December 1996 to February 1997.

In order to extend the short time series of stream flow that is available at Catherine Creek, we conducted a regression analysis using the Catherine Creek streamflow data and the USGS gage 12120600 streamflow data. We chose the Issaquah Creek gage, because it has a relatively long time series (1986 to the present), it is a small creek, and it is located in a similar climatic and topographic zone as Catherine Creek. The methods that we used to select gage 12120600 to include in our regression analysis can be found in Appendix A.

We conducted our regression analysis for the time period between November 30, 1996 and February 27, 1997. The linear relationship is shown in Eq. 1.

$$y = 0.2377x + 2.6371 \quad \text{Eq. 1}$$

where,

y = Catherine Creek at 36th Street bridge stream flow; and
x = Issaquah Creek stream flow

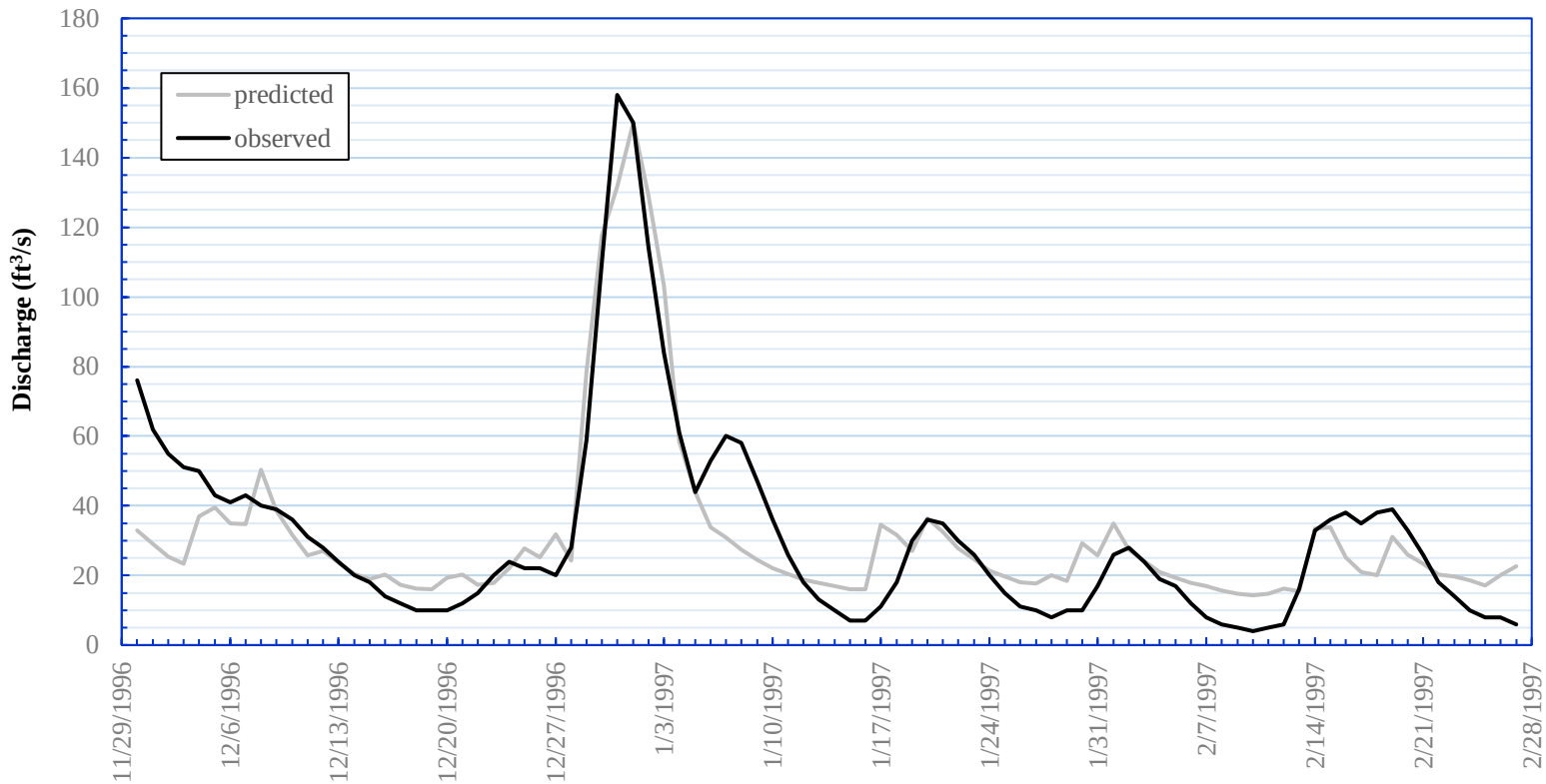
The R² of the linear relationship between Catherine Creek and Issaquah Creek is 0.8045. As shown in Figure 2, the predicted discharge rates are consistently higher than the observed discharge rates during the low streamflow time periods. On the other hand, the predicted discharge rates consistently match the timing and the magnitude of the peak stream flows of the observed discharge record. Because of the reasonable relationship between the two streamflow time series, we decided that the results from our regression analysis would be sufficient for use in our HEC-RAS model.

We altered the predicted Catherine Creek streamflow time series so that the StreamStats flood frequency magnitudes were included. Specifically, we manually adjusted the predicted streamflow time series in order to match the 2-year, 10-year, and the 100-year recurrence interval stream flows that were predicted by StreamStats (Figure 3). In the predicted hydrograph of Catherine Creek between October 15 and December 23, 1990, there are only two floods. We only adjusted the stream flow during these two floods. The first flood includes the 2-year (144 ft³/s) and the 10-year (283 ft³/s) streamflow rate, and the second flood includes the 100-year (474 ft³/s) streamflow rate.

To construct the hydrographs for each of the three ditches that required boundary conditions, we simply multiplied the altered predicted Catherine Creek stream flow by a fraction. We multiplied the altered predicted Catherine Creek stream flow by 0.15 for ditch 1, by 0.1 for ditch 2, by 0.05 by ditch 3 (Figure 4).

For the Lake Stevens outlet channel boundary conditions, we altered the discharge data that was measured in the outlet channel in 1996 and 1997 to better match the adjusted predicted hydrograph in Catherine Creek during the modeling time period (10/15/1990 to 12/23/1991; Figure 5). We did this because the timing and magnitude of the floods during the time period (1996/1997) when streamflow was measured in the outlet channel were different than the timing and magnitude of the floods during the time window that we used as boundary conditions.

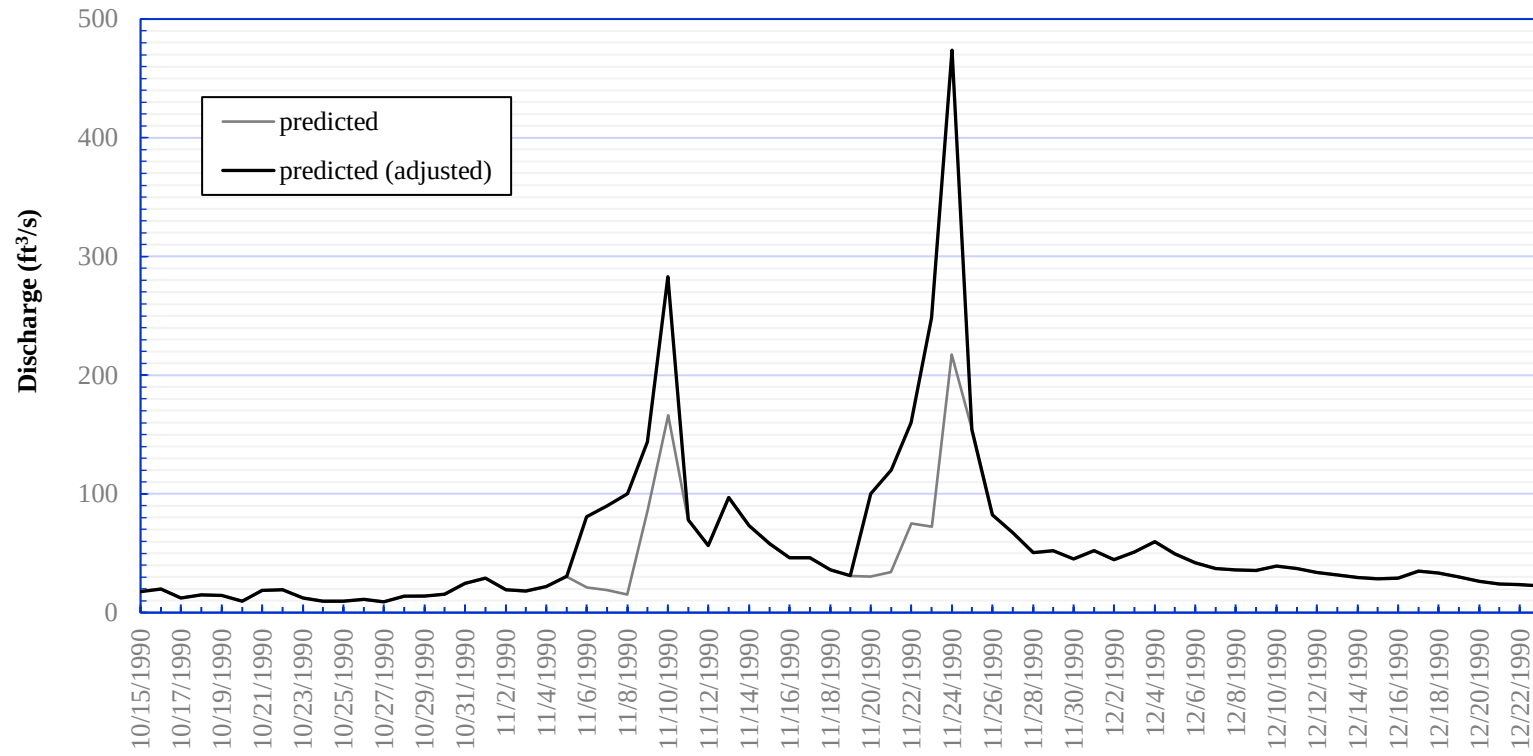
For the downstream boundary condition, we used the normal depth. We set the normal depth similar to the bed elevation slope (0.03) in Catherine Creek near the outflow boundary of the modeling domain.



Both the measured and the predicted discharge data are shown. The predicted discharge time series was calculated using a linear function of the relationship between the observed discharge data at the 36th Street bridge and the discharge data measured at USGS gage 12120600 (Issaquah Creek near Hobart, WA). The R^2 of the linear relationship between the observed discharge data time series and USGS gage 12120600 is 0.8045. Note that during the low streamflow time periods, the predicted discharge rates are consistently higher than the observed discharge rates. On the other hand, during the floods and high flows, the predicted discharge rates consistently match the timing and the magnitude of the observed discharge rates.

FIGURE 2

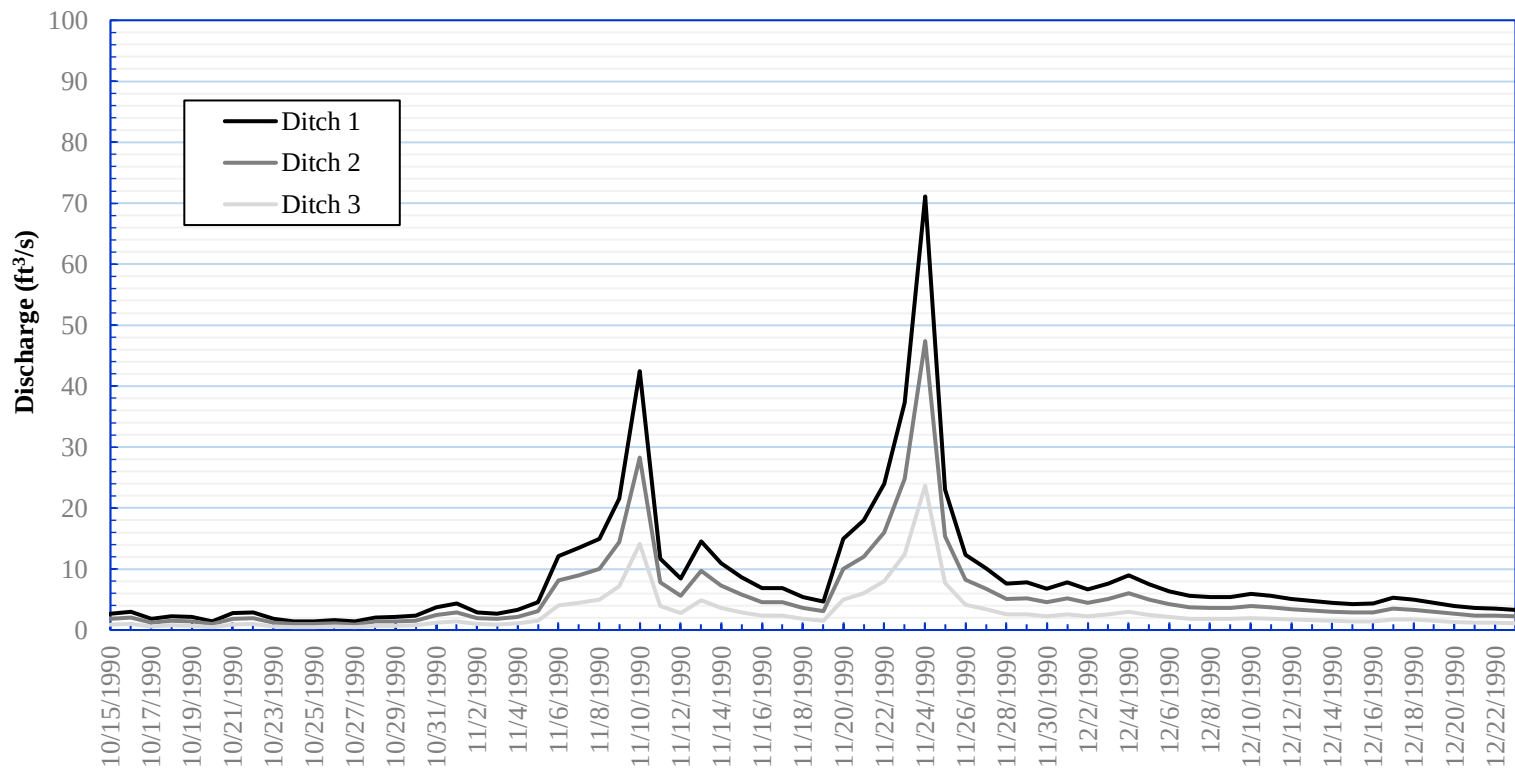
Hydrograph of Catherine Creek at the 36th Street Bridge Measured in 1996/1997



The predicted hydrograph was created using the linear relationship between the measured stream flow in Catherine Creek at the 36th Street bridge and the stream flow that was measured in Issaquah Creek (USGS gage 12120600). The predicted time series was manually adjusted in order to match the 2-year, 10-year, and the 100-year recurrence interval stream flows that were predicted by StreamStats. Note that only the stream flow during the two floods were adjusted.

FIGURE 3

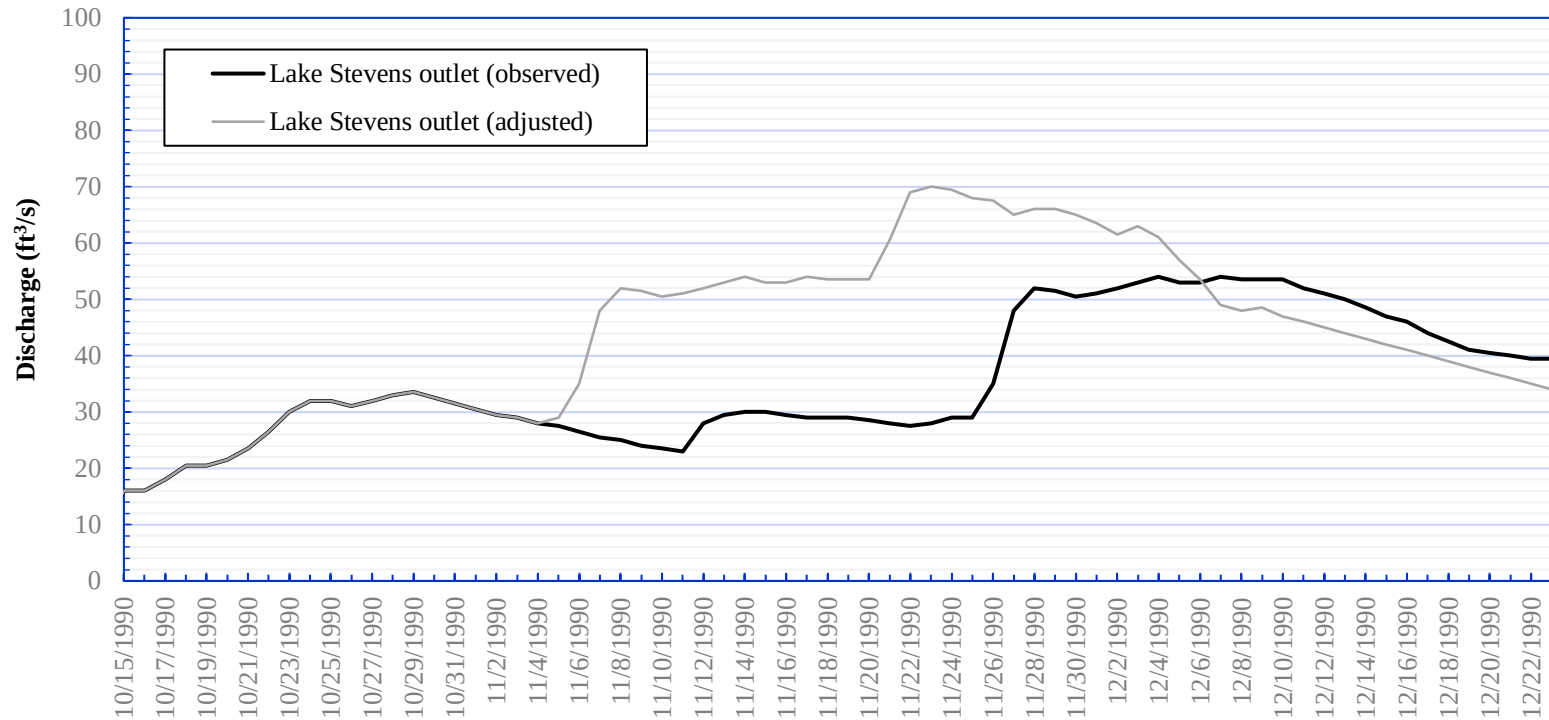
Hydrograph of the Predicted (and Adjusted) Stream Flow in Catherine Creek at the 36th Street Bridge



The upstream extent of ditch 1 is located closest to the upstream extent of Catherine Creek. Ditch 2 is located adjacent to Grade Road at its upstream extent. Ditch 3 is located along the south side of Hartford Drive east of the Catherine Creek water crossing. The adjusted predicted Catherine Creek discharge rate time series was multiplied by factors of 0.15, 0.1, and 0.05 to compute the hydrographs for each of the three ditches, ditch 1, ditch 2, and ditch 3, respectively.

FIGURE 4

Hydrographs of each of the Three Ditches where Boundary Conditions were Needed for the HEC-RAS Model



The hydrograph shown in black contains the discharge rate that were measured in 1996 and 1997. The hydrograph that is shown in gray was altered to better match the altered predicted hydrograph of Catherine Creek during the modeling time period (October 15, 1990 to December 23, 1991). The altered hydrograph was used as the inflow boundary conditions of the Lake Stevens outlet channel.

FIGURE 5
Hydrographs of the Lake Stevens Outlet Channel

CULVERTS

We added five culverts to the geometry model input prior to running our HEC-RAS model. We added two corrugated metal pipes at the Catherine Creek/Hartford Drive water crossing, and three culverts under Hartford Drive that pass water from ditches to the Lake Stevens outlet channel (Figure 1). Table 2 contains a list of the culverts that we added to the model.

TABLE 2

Culvert Information

Culvert Location	Culvert Diameter (in)	Culvert Material	Culvert Length (ft)
Catherine Creek	36	CMP	41
Catherine Creek	36	CMP	40
Ditch 2	36	CMP	38
Ditch 1	24	Concrete	32
Ditch 4	6	PVC	40

COMPUTATION TIME STEP AND SIMULATION TIME

The 2-D version of the HEC-RAS hydraulic modeling software solves along two dimensions the St. Venant equations, which includes both the conservation of mass and the conservation of momentum equations. We selected the conservative version of the Shallow Wave type of the St. Venant equations in each of our simulations. The 2-D model is run in unsteady flow conditions (i.e., water flow changes over time). We set the computation interval to 5 seconds, and the simulation time to 70 days. We set the model to run for 12 hours prior to beginning the simulations in order to establish good initial conditions.

PROPOSED CONDITIONS MODEL SIMULATIONS

To determine the influence of a bridge (as a replacement for the shotgun culverts) on the hydraulics at the project site, we completed two different proposed conditions simulations. We completed a simulation with a 40-foot bridge and one with an 80-foot bridge. Both bridges were designed with a 3-foot-tall bridge deck and a span of 26 feet.

We modified the terrain for each of the bridge simulations. We cut out approximately 30 feet of Hartford Drive to accommodate the 40-foot bridge and approximately 70 feet of Hartford Drive to accommodate the 80-foot bridge. We cut the terrain once for the 40-foot bridge simulation. The dimensions of the 40-foot bridge cut included a bottom width of 6 feet and side slopes of 1.5:1. The top width (30 feet) of the 40-foot bridge cut was a little bit wider than the existing bankfull width. We cut the terrain twice for the

80-foot bridge simulation. The dimensions of the first cut included a bottom width of 22 feet and side slopes of 3.5:1. The dimensions of the second cut (at a lower elevation) included a bottom width of 6 feet and side slopes of 2:1.

To confirm that a replacement bridge can accommodate the potential channel water velocities that may occur, we analyzed the velocities upstream and downstream of the Hartford Drive water crossing and directly underneath the bridge. In channel areas approximately 150 feet upstream and downstream of the Hartford Drive road prism (as well as directly underneath the bridge, we compared the velocity results from the existing conditions model simulation, the 40-foot bridge proposed conditions model simulation, and the 80-foot bridge proposed conditions model simulation at three different stream flows (2-year, 10-year, and 100-year).

SENSITIVITY ANALYSIS

To determine if the assumption about the inflow hydrographs that we used as the boundary conditions for the ditches was appropriate, we conducted a sensitivity analysis. We completed three different model simulations of existing conditions, each with a different set of ditch inflow hydrographs. In each sensitivity run, we held the Catherine Creek, Lake Stevens outlet channel, and the downstream boundary conditions constant. The first set of hydrographs that we used for the original existing conditions simulation are described earlier in the Methods section. For the second scenario, we multiplied the adjusted predicted Catherine Creek hydrograph by 0.1, 0.05, and 0.05 to calculate the hydrographs of ditch 1, ditch 2, and ditch 3, respectively. For the third scenario, we multiplied the adjusted predicted Catherine Creek hydrograph by 0.2, 0.15, and 0.1 to calculate the hydrographs of ditch 1, ditch 2, and ditch 3, respectively.

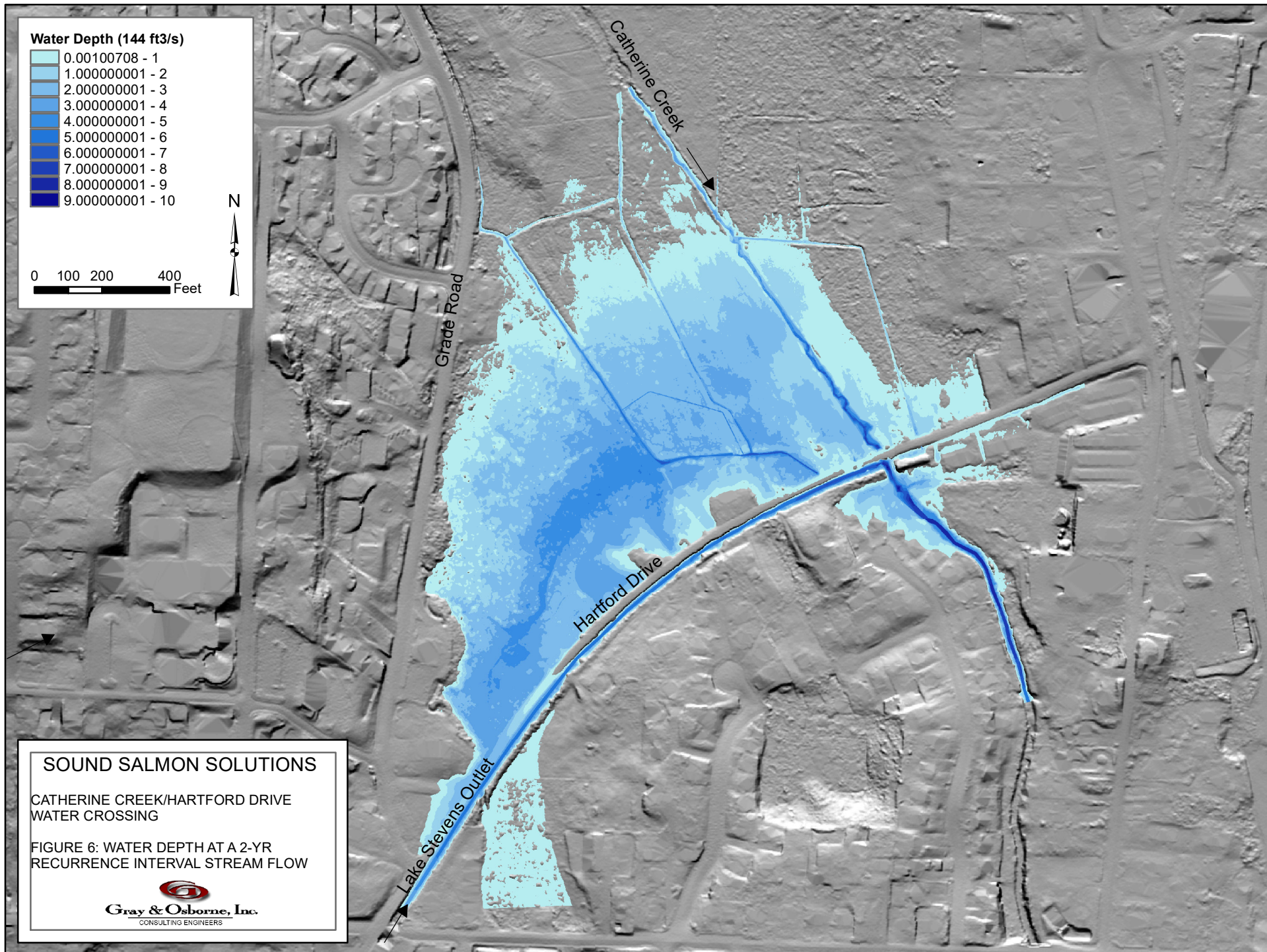
RESULTS

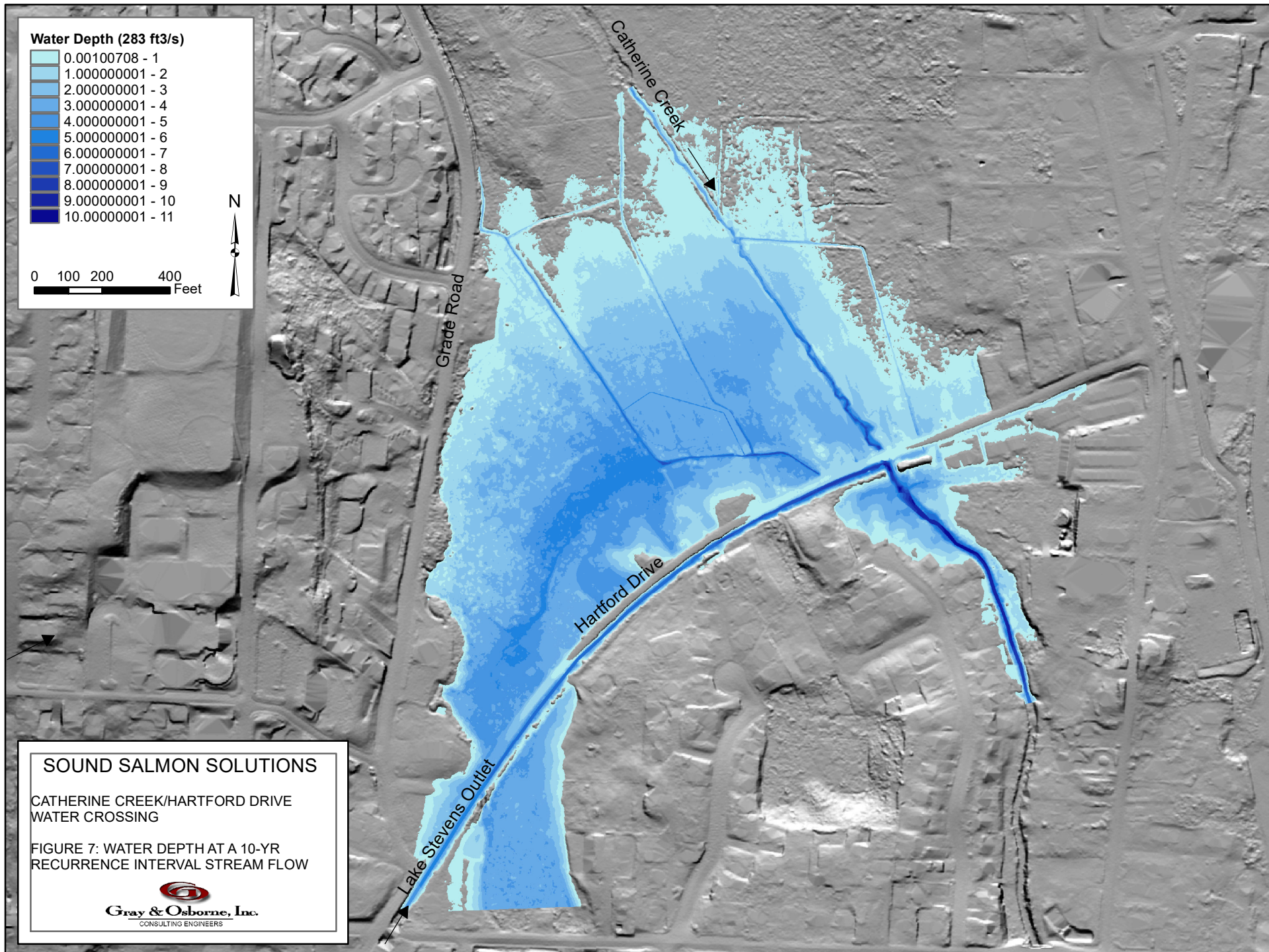
WATER DEPTH AND INUNDATION EXTENT

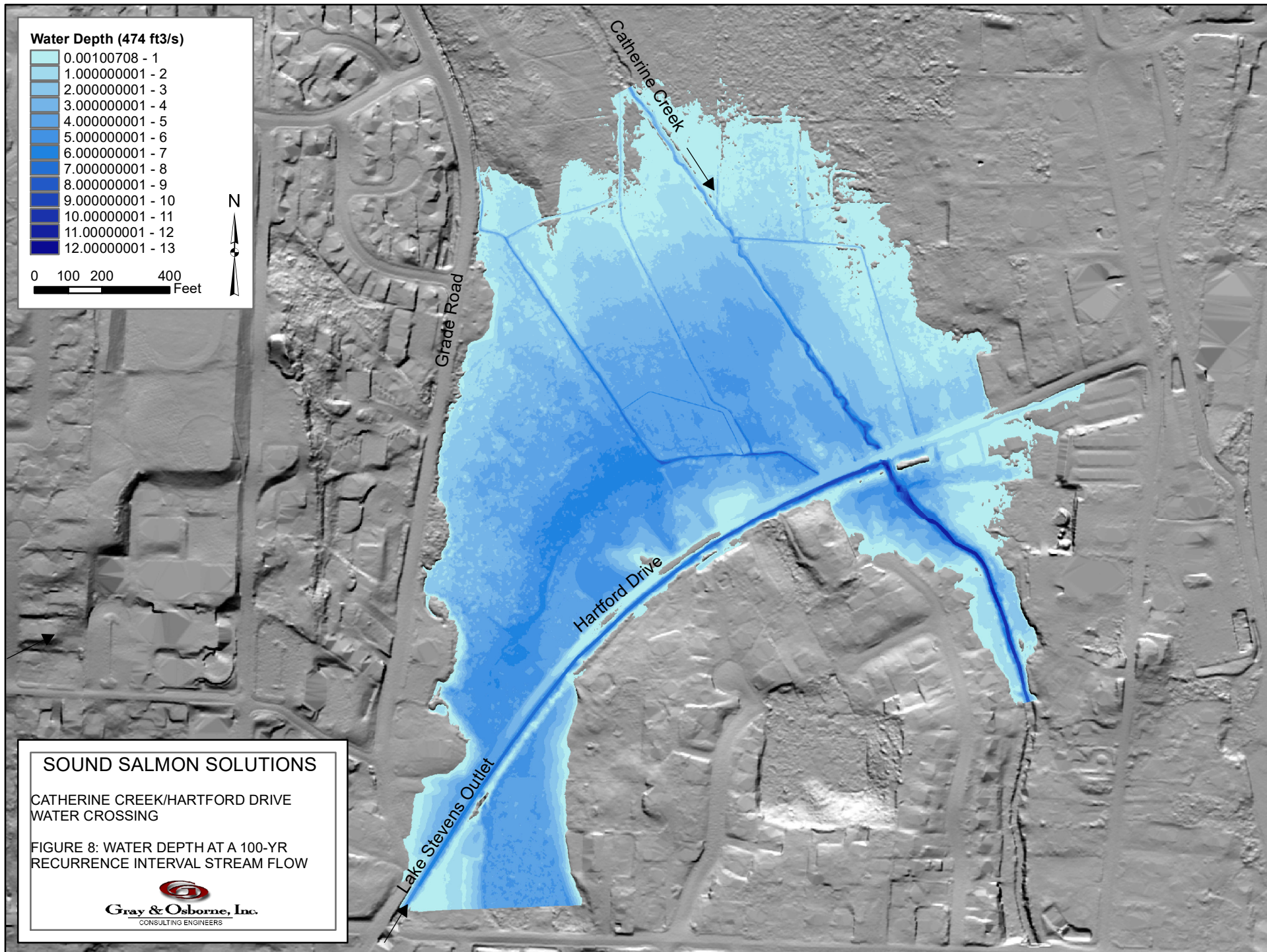
We generated three maps of predicted water depths at the Catherine Creek project site. The maps include water depth predictions at the 2-year (144 ft³/s; Figure 6), 10-year (283 ft³/s; Figure 7), and 100-year (474 ft³/s; Figure 8) recurrence interval stream flows. At each of the modeled stream flows, our HEC-RAS model predicts considerable flooding upstream of Hartford Drive.

The extent of the flooding increases with increasing stream flow. Considerable flooding occurs at the 2-year stream flow, but the greatest amount of flooding occurs at the 100-year stream flow. The overbank flooded areas with the deepest water are located in the wetland north of Hartford Drive, where the remnant lake outlet channel is located.

At the 2-year flow, water overtops Hartford Drive in two different locations. Water overtops Hartford Drive in the vicinity of the historic lake outlet wetland (Figure 6) and







immediately west of the Catherine Creek water crossing. Also, the historic lake outlet wetland south of Hartford Drive experiences standing water due to a high water table.

At the 10-year flow, more of Hartford Drive is overtopped with water than at the 2-year flow. Specifically, the entire length of Hartford Drive that cuts across the historic lake outlet wetland is overtopped (Figure 7). Also, water overtops a significant portion of Hartford Drive in the vicinity of the water crossing. Finally, a considerable amount of the floodplain downstream of the water crossing is flooded during the 10-year flow.

The extent of the flooding is greatest during the 100-year stream flow. Flooding occurs in the historic lake outlet wetland south Hartford Drive, in Catherine Creek south of Hartford Drive, and in the wetland north of Hartford Drive. (Figure 8). At the 100-year flow, nearly the entire length of Hartford Drive is flooded.

The maximum water depth increases with increasing flood magnitudes. For example, the maximum water depth at the 2-year stream flow is 9.3 feet, the maximum water depth at the 10-year stream flow is 10.9 feet, and the maximum water depth at the 100-year stream flow is 12.2 feet. In general, the deepest water (at all three of the modeled stream flows) occurs in the Catherine Creek channel and the Lake Stevens outlet channel. More specifically, water depth is greatest in the portion of Catherine Creek downstream of the confluence with the outlet channel as well as in the outlet channel immediately upstream of the confluence.

In the existing condition, the total area of flooding increases with increasing stream flows. For example, the total area that is flooded during a 2-year stream flow is 1,440,996 ft², during a 10-year stream flow is 1,847,704 ft², and during a 100-year stream flow is 2,227,560 ft² (Figure 9). The percent increase in flooding in the existing condition is greatest between a 2-year stream flow and a 10-year stream flow (28.2 percent increase), whereas between a 10-year stream flow and a 100-year stream flow the percent increase in flooding is 20.6 percent. The percent increase in flooding area between a 2-year and a 100-year stream flow is 54.6 percent. The same is true for the two proposed conditions (the 40-foot bridge and the 80-foot bridge), that is the area of flooding increases with increasing stream flow.

Replacement of the two CMP culverts at the crossing of Catherine Creek and Hartford Drive with either a 40-foot or an 80-foot bridge would reduce the area of flooding at each of the three modeled stream flows. The greatest decrease occurs at a 2-year stream flow, where the inundation extent in the existing condition is 1,440,996 ft², the inundation extent with a 40-foot bridge is 1,121,193 ft² (a 22.2 percent decrease), and the inundation extent with an 80-ft bridge is 1,091,192 ft² (a 24.3 percent decrease, Figure 9). A minimal reduction in flooding extent, however, would be achieved at a 10-year and a 100-year stream flow with either a 40-foot bridge or an 80-foot bridge. For example, at a 10-year stream flow, only a 3.7 percent or a 6.8 percent reduction in flooding extent is achieved with either a 40-foot bridge or an 80-foot bridge, respectively. A much smaller reduction is achieved at a 100-year stream flow; with a 40-foot bridge, the flooding

extent decreases by just 0.01 percent and with an 80-foot bridge the flooding extent decrease by just 0.9 percent.

Less of an area is flooded with an 80-ft bridge than is with a 40-foot bridge. This is true at all three of the modeled stream flows. The largest reduction in flooded area occurs at a 10-year stream flow (3.2 percent decrease). At a 2-year stream flow, an 80-foot bridge would result in a 2.7 percent reduction in flooded area compared to a 40-foot bridge. At a 100-year stream flow, an 80-foot bridge would result in a 0.9% reduction in flooded area compared to a 40-foot bridge.

Adjusting the ditch inflow resulted in minimal changes in the inundation extent. In scenario 2 (least amount of ditch inflow), the flooding extent decreased with each of the three modeled stream flows compared to the original existing conditions model simulation. The largest decrease in flooding extent occurred during a 2-year stream flow (10.1 percent decrease). During a 10-year and a 100-year stream flow, the flooding extent decreased by 6.2 percent and 4.3 percent, respectively. In scenario 3 (most amount of ditch inflow), the flooding extent was less than scenario 2 for two of the modeled stream flows and greater than scenario 2 during a 2-year stream flow. More specifically, during a 10-year and a 100-year stream flow, the flooding extent in scenario 3 decreased by 2.1 percent and 1.1 percent, respectively, but increased by 1.1 percent during a 2-year stream flow.

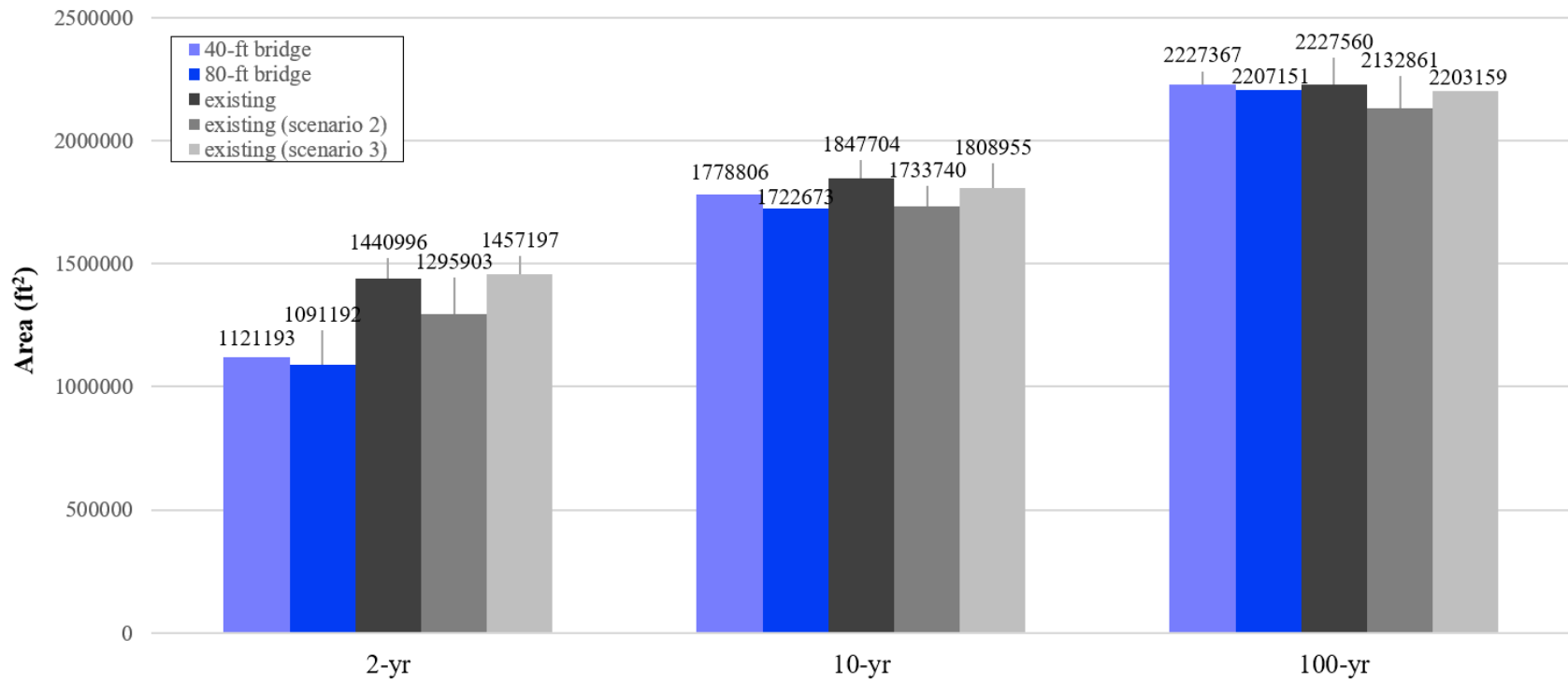


FIGURE 9

Comparison of Inundation Extents in the Existing Conditions and the Proposed Conditions

WATER VELOCITY

In the vicinity of the water crossing, there are differences in water velocity between the upstream and the downstream areas. For example, the median velocity downstream of the water crossing is greater than it is upstream of the water crossing for all of the scenarios (existing condition or proposed conditions at each of the three modeled stream flows) but one, the 80-foot bridge during the 2-year flow (Figure 10). In this scenario, the median downstream velocity is less than the median upstream velocity.

In the vicinity of the water crossing, there are differences in water velocity among the existing and proposed conditions. For example, upstream of the crossing, the median velocity in each of the proposed conditions (40-foot bridge and 80-foot bridge, for all three modeled stream flows) is equal to or greater than the median velocity in the existing condition (Figure 10). On the other hand, downstream of the crossing, the median velocity in each of the proposed conditions (40-foot bridge and 80-foot bridge, for all three modeled stream flows) is similar to or less than the median velocity in the existing condition.

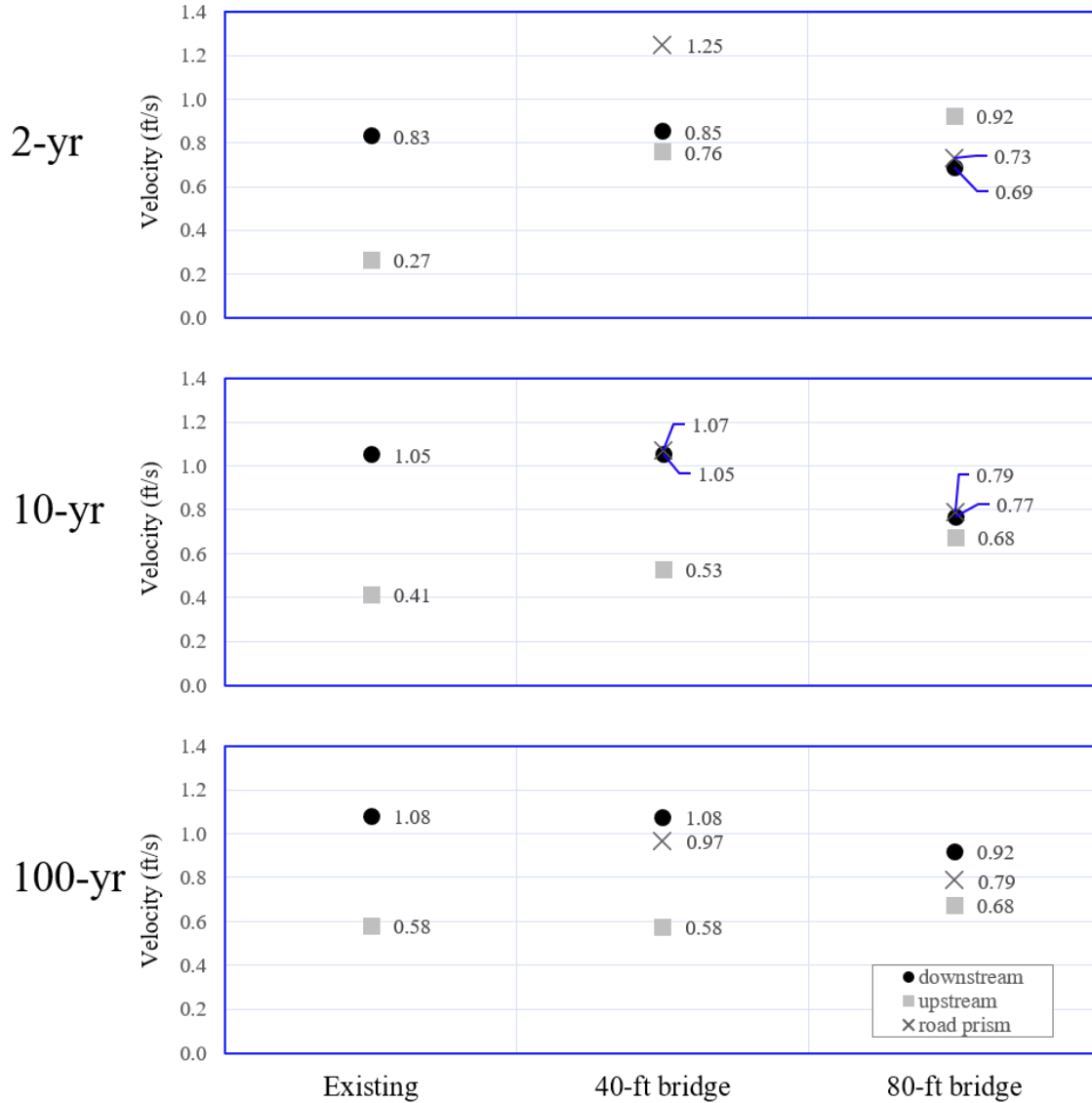
The water velocity directly under the bridge in each of the proposed conditions varies with stream flow. For example, the velocity directly under the 40-foot bridge decreases with increasing stream flow (Figure 10). The water velocity is greatest during a 2-year stream flow (1.25 ft/s) and is the least during a 100-year stream flow (0.97 ft/s). Conversely, the water velocity under the 80-foot bridge increases with increasing stream flow, but not by much. For example, the velocity directly under the 80-foot bridge, slightly increases with each of the three modeled stream flows (the 2-year, 10-year, and 100-year) from 0.73 to 0.77 to 0.79 ft/s.

During each of the three modeled stream flows, the water velocity directly under the 40-foot bridge is greater than the upstream water velocity. On the other hand, in comparison to the downstream velocity, the velocity directly under the 40-foot bridge varies with each of the modeled stream flows. The velocity directly under the 40-foot bridge is greater than the downstream velocity during the 2-year stream flow, is less than the downstream velocity during the 100-year stream flow, and is the same as the downstream velocity during the 10-year stream flow. With an 80-foot bridge, there is less of a pattern in the velocity directly under the bridge compared to the upstream and downstream velocities.

The median velocity downstream of a 40-foot bridge is nearly the same as the existing condition, during each of the three modeled stream flows (Figure 10). On the other hand, the velocity downstream of an 80-foot bridge is significantly less than the velocity downstream of the 40-foot bridge or downstream in the existing condition, during each of the three modeled stream flows.

Shear stress in the vicinity of the water crossing and in the Lake Stevens outlet channel is less with a bridge than it is in the existing condition. Furthermore, under the bridge and

immediately downstream of the bridge, shear stress is less with an 80-foot bridge than it is with a 40-foot bridge.



Plots of the median velocity for each of the three conditions (existing, 40-foot bridge, and 80-foot bridge) are shown here. Median velocities are plotted for three different flood magnitudes (2-year, 10-year, and 100-year). Median velocities are summarized for three areas: the channel upstream of Hartford Drive, the channel area downstream of Hartford Drive, and the area directly underneath the proposed bridge (aka “road prism”).

FIGURE 10
Comparison of Water Velocity in the Existing Condition and the Proposed Conditions

DISCUSSION

MODEL LIMITATIONS AND ASSUMPTIONS

We have not calibrated nor have we validated the model. The stream flow that occurred during the Gray & Osborne topographic surveys is not known because Catherine Creek is not gaged. Furthermore, there is little information about the extent of the flooding at the specific stream flows that we modeled, so we did not validate the model.

Because of the limited amount of streamflow data that is available for the project site, a number of assumptions about the boundary conditions were made in the development of our 2-D hydraulic model. If additional streamflow information becomes available, the model could be updated with this new information.

Because the ground topographic survey did not extend along the length of the entire channel network, we created synthetic topography and bathymetry. The synthetic topography and bathymetry that we created likely has less influence on the model results than the streamflow boundary conditions.

SENSITIVITY ANALYSIS

Changing the amount of inflow to the ditches resulted in slight changes to the inundation extent at each of the three modeled stream flows. The greatest change occurred at the 2-year stream flow between scenario 2 (least amount of ditch inflow) and the original existing condition simulation because the historic wetland was not inundated during scenario 2 but was during the original existing condition model simulation. Because not much change in inundation extent occurred at any of the three modeled stream flows between scenario 3 and the original existing condition simulation, these scenarios are more or less interchangeable. Furthermore, this confirms that the ditch inflow hydrographs that we used in the original existing conditions are suitable.

DESIGN RECOMMENDATIONS

The Catherine Creek/Hartford Drive project site has been highly modified since Euro-American settlement. The area has been impacted by timber harvest, beaver eradication, agriculture, channel straightening, and road building. Specifically, the Lake Stevens outlet has been moved, and now it is essentially an earthen canal. Upstream of Hartford Drive, Catherine Creek has been straightened and a ditch network has been built in the relatively wide wetland area. Prior to channel and wetland modification, it is likely that the wide wetland upstream was ponded during wet periods. Furthermore, historically beavers likely occupied the area and their dams may have created a persistent pond in this area. A beaver dam and pond complex likely contributed to the development of the wetland.

Prior to developing a 2-D hydraulic model, we generated estimates of bankfull width at the Catherine Creek/Hartford Drive water crossing site using two different methods. We measured bankfull width and we computed bankfull width using Barnard et al.'s (2013) multivariate power law equation.

The Barnard et al. (2013) bankfull width equation was developed using measurements of bankfull width, average annual precipitation, and contributing watershed area at 53 sites in high gradient, coarse-bedded streams in western Washington (Eq. 2)

$$Wch = 0.95 * WA^{0.45} * AAP^{0.61} \quad \text{Eq. 2}$$

Where:

Wch = width of the bankfull channel, in feet

WA = watershed area, in mi^2

AAP = average annual precipitation, in in/year

We used StreamStats data as inputs to the Barnard et al (2013) bankfull width equation. Upstream of the water crossing, the measured bankfull width estimates vary between 16 feet and 29 feet, and the average is 22 feet. The average measured bankfull width downstream of the culvert is 28 feet. The modeled bankfull width using the Barnard et al. (2013) equation is 23.9 feet. The modeled and the empirical estimates of bankfull width are in close agreement.

Using the WDFW sizing criteria, which includes bankfull width increases of either 4.4 percent (2040 prediction) or 6.9 percent (2080 prediction) due to climate changes, the size of the water crossing opening with the current Lake Stevens outlet channel configuration should either be either 32 feet or 33 feet (Eq. 3 and Eq. 4; Barnard et al, 2013).

$$W_{culvert\ bed} = (1.2 * 23.9 * 1.044) + 2 = 31.9\ ft \quad \text{Eq. 3}$$

$$W_{culvert\ bed} = (1.2 * 23.9 * 1.069) + 2 = 32.7\ ft \quad \text{Eq. 4}$$

According to Barnard et al. (2013), a bridge is recommended when the bankfull width exceeds 15 feet. Because our estimated bankfull width that accounted for changes in climate is 32 feet to 33 feet, originally, we recommended replacing the CMP culverts with a 35-foot or a 40-foot length precast bridge.

The natural floodplain of Catherine Creek at Hartford Drive is much narrower than it is upstream. In the wetland upstream of Hartford Drive, the maximum width of the 100-year floodplain is approximately 1,750 feet (average width is approximately 1,530 feet). At Hartford Drive, the 100-year floodplain width is approximately 500 to 550 feet. Downstream, the floodplain width narrows. Approximately 600 feet downstream of Hartford Drive, the 100-year floodplain is only 150-feet wide. Although the natural floodplain width at Hartford Drive is approximately 500-feet wide, a levee

restricts the floodplain to a width of approximately 35 feet immediately downstream of the confluence with the Lake Stevens outlet channel and Catherine Creek.

Using the modeled 100-year floodplain widths at the project site and the modeled bankfull width, the average floodplain utilization ratio at the site is approximately 64 ft/ft.

According to Barnard et al. (2013), a bridge design should account for: (1) lateral channel migration; (2) comply with legislation that governs the development within floodplains; and (3) for unconfined channels with floodplain and overbank flow, the velocity in the main channel under the bridge should be similar to the velocity in existing main channel.

Not only would a bridge greatly improve fish passage in Catherine Creek, but it would also improve flooding risk. For example, a bridge (either a 40-foot or an 80-foot bridge) would reduce the total area of flooding at all three of the modeled stream flows (a 2-year, 10-year, and a 100-year stream flow). The largest reduction in flooding extent would occur at a 2-year stream flow, and the smallest reduction in flooding extent would occur at a 100-year stream flow. At a 2-year stream flow, Hartford Drive would experience less flooding, and the inundation would extend in less of the wetland area immediately upstream of Hartford Drive, especially in the vicinity of the water crossing areas. At a 2-year stream flow in the existing condition, water overtops Hartford Drive not only in the vicinity of the historic wetland but also in the vicinity of the Catherine Creek crossing. With a bridge, water does not overtop Hartford Drive in the vicinity of the water crossing.

An 80-foot bridge would provide slightly more reduction in flooding risk than a 40-foot bridge. The total area of flooding is less with an 80-foot bridge than it is with a 40-foot bridge at all three of the modeled stream flows (2-year, 10-year, 100-year). For example, at a 2-year stream flow, an 80-foot bridge would result in a 2.7 percent reduction in flooded area compared to a 40-foot bridge.

An 80-foot bridge would reduce the potential for bed scour downstream of the crossing. For example, the median velocity immediately downstream of the crossing (within 150 feet) decreases with an 80-foot bridge at each of the modeled stream flows (Figure 10). On the other hand, the downstream velocity does not change much with a 40-foot bridge (Figure 10).

During floods, a 40-foot bridge would only slightly improve bed scour potential in the vicinity of the water crossing because of the levee that is perpendicular to the flow that constricts the flow. The levee, whose crest is only approximately 45 feet to the south of the Hartford Drive centerline, is parallel to Hartford Drive and is approximately 160-feet long on the right bank of Catherine Creek and 100-feet long on the left bank of Catherine Creek. No grading of the perpendicular levee was completed in the digital terrain model for the 40-foot bridge. However, a portion of the levee was graded to accommodate the 80-foot bridge. The levee constriction results in high shear stress (and high velocity) in

both the existing condition and with a 40-foot bridge. On the other hand, because of our widening of the levee opening and Hartford Drive opening in the 80-foot bridge scenario, the shear stress (bed scour potential) and velocity directly underneath the bridge and immediately downstream is less than it is in the existing condition and with a 40-foot bridge.

CONCLUSION

Both a 40-foot bridge and an 80-foot bridge would improve fish passage, flooding risk and bed scour potential. However, an 80-foot bridge would provide slightly better conditions than a 40-foot bridge, especially with potential bed scour in the vicinity of the crossing. On the other hand, the 80-foot bridge would cost more than a 40-foot bridge. Therefore, a cost-benefit analysis would assist in deciding which bridge span to use in the future design of the culvert replacement at the crossing of Catherine Creek by Hartford Drive.

REFERENCES

- Barnard, R. J., J. Johnson, P. Brooks, K. M. Bates, B. Heiner, J. P. Klavas, D.C. Ponder, P.D. Smith, and P. D. Powers (2013), Water Crossings Design Guidelines, Washington Department of Fish and Wildlife, Olympia, Washington.
<http://wdfw.wa.gov/hab/ahg/culverts.htm>. 300 pgs.
- Gray & Osborne, 1999. Lake Stevens/Catherine Creek Watershed Management Plan. Prepared for Drainage Improvement District #8 City of Lake Stevens. 392 pgs.

APPENDIX A

USGS STREAMFLOW GAGE SELECTION METHODS

USGS Streamflow Gage Selection Methods

Two undersized corrugated metal culverts are located in Catherine Creek where it is crossed by Hartford Drive in the City of Lake Stevens. Gray & Osborne is designing a replacement crossing that would improve fish passage at the site as well as improve the transport of water, sediment, and debris. The site is located in Snohomish County. The contributing drainage area is approximately 7 mi² (StreamStats).

There is a limited amount of streamflow data available for Catherine Creek. Therefore, in order to create boundary conditions for our HEC-RAS 2-D hydraulic model, it is necessary to supplement the Catherine Creek streamflow data by conducting a regression analysis using Catherine Creek data and data from another nearby similar streamflow gage.

We queried the active USGS gages using three different station characteristics: county, drainage area, and measurement period. We selected gages that met the following criteria:

- Located in one of four Washington counties: Whatcom County, Skagit County, Snohomish County, and King County
- Drainage area less than or equal to 20 mi²
- Discharge measurement period greater than or equal to 30 years (as reported in the “sv_begin_date” field¹)

We chose to filter USGS gages by county, because all four counties listed above have a similar topography and climate. We chose to filter the gages by drainage area, because drainage area has been shown to be a predictor of streamflow. We chose to filter the gages by measurement period in order to provide a better likelihood of capturing the range of possible floods including the 100-yr flood as predicted by StreamStats.

Of the approximately 300 USGS streamflow gages that are active in Washington State, we found fifteen gages that would be suitable for including in our regression analysis (Table 1 and Figure 1). Six of the fifteen streamflow gages that met our criteria drain topography that seems to be similar to Catherine Creek. The other ten gages are located in the foothills to the east of Catherine Creek, a more mountainous topography than that of Catherine Creek. Of the six gages that are located in a landscape similar to that of Catherine Creek, two gages (12201950 and 12202300) are located slightly to the west. Of the remaining four candidate gages, USGS gage 12120600 is closest in latitude to Catherine Creek. Therefore, we chose to use the streamflow data measured at USGS gage 12120600 (Issaquah Creek near Hobart, WA) in our regression analysis.

¹ “sv_begin_date” is the site visit begin date.

Table 1. List of the USGS gages that met our selection criteria for including in our regression analysis.

Station ID	Station Name	County	HUC	Drainage Area (mi ²)	Measurement Period
12099600	Boise Creek At Buckley, WA	King	17110014	15.4	03/11/1977 to present
12115500	Rex River Near Cedar Falls, WA	King	17110012	13.4	10/01/1945 to present
12115700	Boulder Creek Near Cedar Falls, WA	King	17110012	4.64	03/01/1983 to present
12116100	Canyon Creek Near Cedar Falls, WA	King	17110012	0.19	06/01/1945 to present
12117000	Taylor Creek Near Selleck, WA	King	17110012	17.2	07/01/1945 to present
12118400	Rock Creek At Highway 516 Near Ravensdale, WA	King	17110012	11.2	07/01/1956 to present
12118500	Rock Creek Near Maple Valley, WA	King	17110012	12.6	07/01/1945 to present
12120600	Issaquah Creek Near Hobart, WA	King	17110012	17.6	10/01/1986 to present
12137290	South Fork Sultan River Near Sultan, WA	Snohomish	17110009	11.6	10/01/1991 to present
12143700	Boxley Creek Near Cedar Falls, WA	King	17110010	1.57	09/01/1945 to present
12143900	Boxley Creek Near Edgewick, WA	King	17110010	3.64	08/12/1981 to present
12147600	South Fork Tolt River Near Index, WA	King	17110010	5.34	12/01/1959 to present
12148000	South Fork Tolt River Near Carnation, WA	King	17110010	19.7	10/01/1952 to present
12201950	Anderson Creek Near Bellingham, WA	Whatcom	17110002	4.13	10/01/1967 to present
12202300	Olsen Creek Near Bellingham, WA	Whatcom	17110002	3.78	11/01/1967 to present

Candidate USGS Gages to Supplement Catherine Creek Data

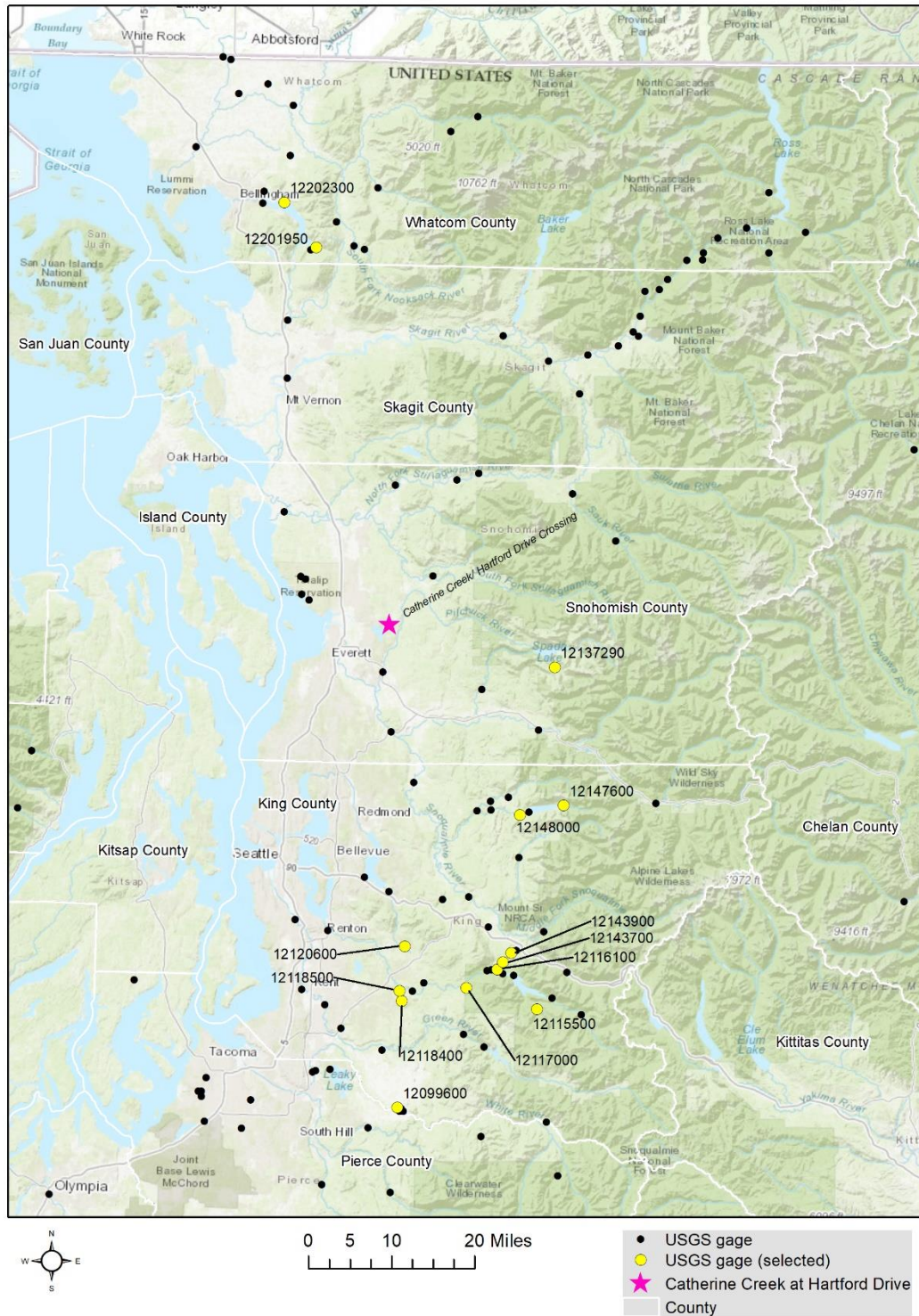


Figure 1. Map of the USGS streamflow gages that are located in the eastern Puget Sound region of western Washington. Also shown are the fifteen USGS gages that met our three selection criteria. USGS gage 12120600 (Issaquah Creek near Hobart, WA) is the gage that we selected to include with the Catherine Creek streamflow data in our regression analysis.