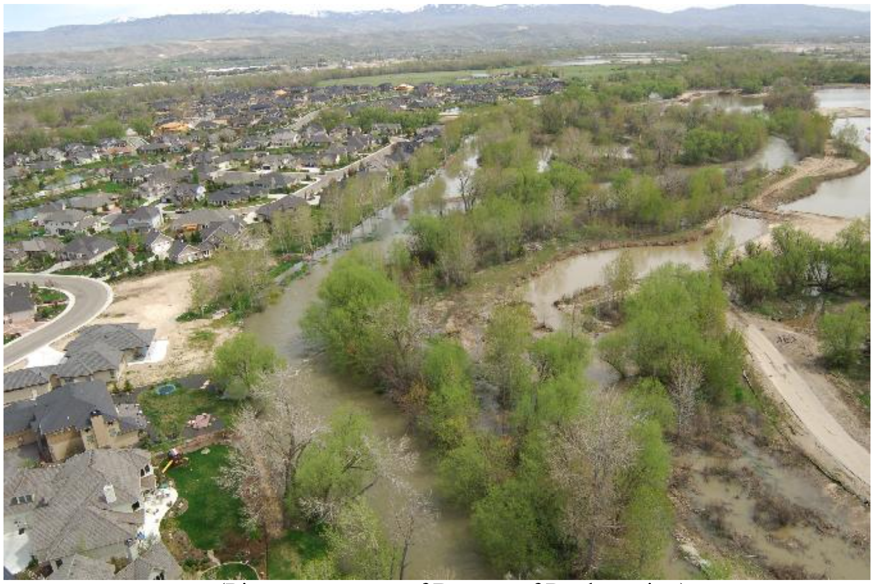
Impact of channel vegetation on the water surface elevation and floodplain inundation extent in the Lower Boise River System



(Picture courtesy of Bureau of Reclamation)

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- DISCLAIMER -

This report presents preliminary results from hydrodynamic model to study impact of channel vegetation on water surface elevation and floodplain inundation extent. The study is part of the class CE 504: Effects of Vegetation in Channels of Spring 2011. This report does not recommend any action alternative nor does it represent the official view of the University of Idaho.

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Conversion Factors (Barton et al., 2005)

Multiply	By	To obtain
centimeter (cm)	0.394	inch (in.)
kilometer (km)	0.621	mile (mi)
meter (m)	3.281	foot (ft)
square kilometer (km^2)	247.100	acre
square kilometer (km^2)	0.386	square mile (mi^2)
cubic meter per second (m^3/s)	70.070	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.310	cubic foot per second (cfs)

EXECUTIVE SUMMARY

A floodplain hydraulic model was developed to simulate the effects of channel vegetation on river water surface elevations and the extent of floodplain inundation along the Eagle Island section of the Boise River. This analysis investigated the impact of channel vegetation on both channel and the adjacent floodplain.

One of the main objectives of the study was to give managers initial guidance on a variety of possible future vegetation scenarios in the river channel. Seven scenarios were selected: Current, Concrete, Hiveg (high vegetation), Medveg (medium vegetation), Noveg (no vegetation), Xmodi (partially occluded) and 100-year flood.

1. Current scenario: existing vegetation condition in the channel.
2. Concrete scenario: the channel being replaced with a concrete channel.
3. Hiveg scenario: the extreme case where the channel was entirely covered by thick shrubs of willows and cottonwoods.
4. Medveg scenario: more than 10-year old trees and bushes in the channel,
5. Noveg scenario: removal of all in-channel vegetation,
6. Xmodi scenario: 35% reduction in cross-sectional area due to woody debris obstructing the North and South Channel bridges of Eagle Road.
7. 100-yr scenario: the occurrence of a 100-year return period flood event of 470 m^3/s (16,600 cfs) based on Glenwood gage station.

The first six scenarios were simulated with bankfull discharge of 198 m^3/s (7000 cfs).

Model results showed that removal of existing vegetation including woody debris piles in the channel would result in negligible changes in both water surface elevation and floodplain inundation extent for the bankfull discharge. Woody debris obstructing 35% of the cross-sectional area under both Eagle Road bridges had no significant effects on floodplain inundation extent for the bankfull discharge. However, the effects of woody debris clustering and accumulating under the bridges and increase in channel vegetation may have a key effect on river water surface elevation and floodplain inundation extent for larger than bankfull return interval flood events (e.g., 50-, or 100-year).

The main conclusions of the study are:

- Removal or increase of in-channel vegetation results in relatively minor changes on water surface elevation and flood inundation extent for bankfull discharge.
- Effects of vegetation management on water surface elevations vary with different reaches.
    - Effects in the Upper and North Reach of the Boise River have the most significant impact.
- Flow resistance added by the woody debris piles has negligible effect on water surface elevation and floodplain inundation extent.

    - Obstructed areas in the channel created by accumulation of woody debris and trash could affect flood conveyance. This process was not investigated in this report.
- The accumulation of woody debris under bridges has minor impact on water surface elevations and flood inundation extent at bankfull discharge.
    - However, woody debris may have a significant effect at flows larger than bankfull.

1. GENERAL INTRODUCTION

Estimation of flooding extent and water surface elevation (WSE) along the Boise River has traditionally been simulated using one-dimensional (1D) hydraulic models. One-dimensional models are effective tools for rivers with confined rivers with limited floodplains such as the Boise River near Lucky Peak (Canyon section). However, as floodplains become less confined, predictions of overland flow paths become increasing difficult to model with a 1D approach. Therefore, two-dimensional (2D) hydrodynamic models are the most effective approach in these landscapes. Two-dimensional models require detailed and accurate submerged and terrestrial topographies. Most of the floodplain of the Lower Boise River is unconfined and relatively flat and high-resolution topography surveyed by Experimental Advanced Airborne Research Lidar (EAARL) technology is available. The EAARL is specifically designed to survey submerged topography.

Therefore, a 2D hydraulic model was used to predict flow paths and flood inundation extent using EAARL data. For the current study, the MIKEFLOOD hydrodynamic (HD) model developed in 2009, jointly by Idaho Department of Water Resources (IDWR), University of Idaho, and DHI Water and Environment (DHI) was used to simulate water surface elevation (WSE) along the river and flood inundation extent on the floodplain.

MIKE FLOOD links MIKE 11, a 1D model in the channel, and MIKE 21, a 2D model on the floodplain, models dynamically using lateral links. A lateral link allows a string of MIKE 21 cells to exchange flow information to a given reach in MIKE 11. The coupling of the 1D and 2D models allow water to flow back and forth from channel to floodplain.

MIKE 11 is a professional engineering package intended for the simulation of flows in rivers and channels using an implicit finite-difference scheme for the computation of unsteady flows in rivers and estuaries. MIKE 11 solves the cross-sectional averaged equations for the conservation of continuity and momentum (i.e., the Saint Venant equations).

MIKE 21 is a 2D free-surface flow modeling software used to simulate hydraulics and hydraulics-related phenomena in estuaries, coastal area and floodplain. MIKE 21 simulates the water level variations and flows in response to bathymetry and various parameter values (bed resistance, turbulent eddy coefficients) using a finite difference algorithm. It solves the time-dependent vertically averaged equations of continuity and conservation of momentum in the two horizontal dimensions. The water levels and flows are calculated on a rectangular grid based on topography, bed resistance and hydrographic boundary conditions.

This project's major objective was to study the effect of channel vegetation on the water surface elevation (WSE) and inundation extent in the Lower Boise River System using a coupled 1D and 2D hydrodynamic model. Manning's roughness of the riverbed (Top-of-bank to top-of-bank) was changed to account for different in-channel vegetation treatments. The Manning's roughness on the floodplain (Beyond top-of-bank) remained similar in all the scenarios. This research was conducted with the co-operation of Idaho Department of Water Resources (IDWR), Boise River

Flood Control District (FCD) 10 including Center for Ecohydraulic Research (CER), University of Idaho.

The Danish Hydraulic Institute (DHI) software package MIKE FLOOD was used to link 1D River and 2D floodplain models. Mass and momentum exchange processes between the river channel and the adjacent floodplain were numerically simulated with the MIKEFLOOD model. In the river channel, a 1D model was used and linked dynamically with a 2D model (floodplain).

This report presents summaries of model development and simulation results (maps and table), which show simulated WSE and floodplain inundation extent. The results presented here should be interpreted carefully according to the methodology adopted in this part of the study.

1.1 Hydrodynamic models

One-dimensional (1D) and two-dimensional (2D) models are used and have proven to have the ability to simulate inundation patterns, water depth, and velocity for rivers and floodplain (Bates and Roo, 2000; Horritt and Bates, 2002; Hunter et al., 2005; Mason et al., 2003).

One-dimensional models are capable of simulating real flooding phenomena in channels, but they are incapable of representing spatially complex flow patterns and topography where over-bank flows occur (Mason et al., 2003).

More recently, 2D finite difference and finite element models are developed to simulate floodplain inundation patterns and the floodplain physical processes. Studies demonstrate that the 2D modeling approach is capable of simulating river floodplain physical processes in complex topographies (Horritt, 2000; Horritt and Bates, 2002; MacWilliams et al., 2004). The 2D model is also able to simulate local velocities, floodplain inundation depths, durations, and shear stresses, which are all important parameters that drive riverine ecological processes and are an indicator of flood hazard in urban settings.

1.2 Lower Boise River

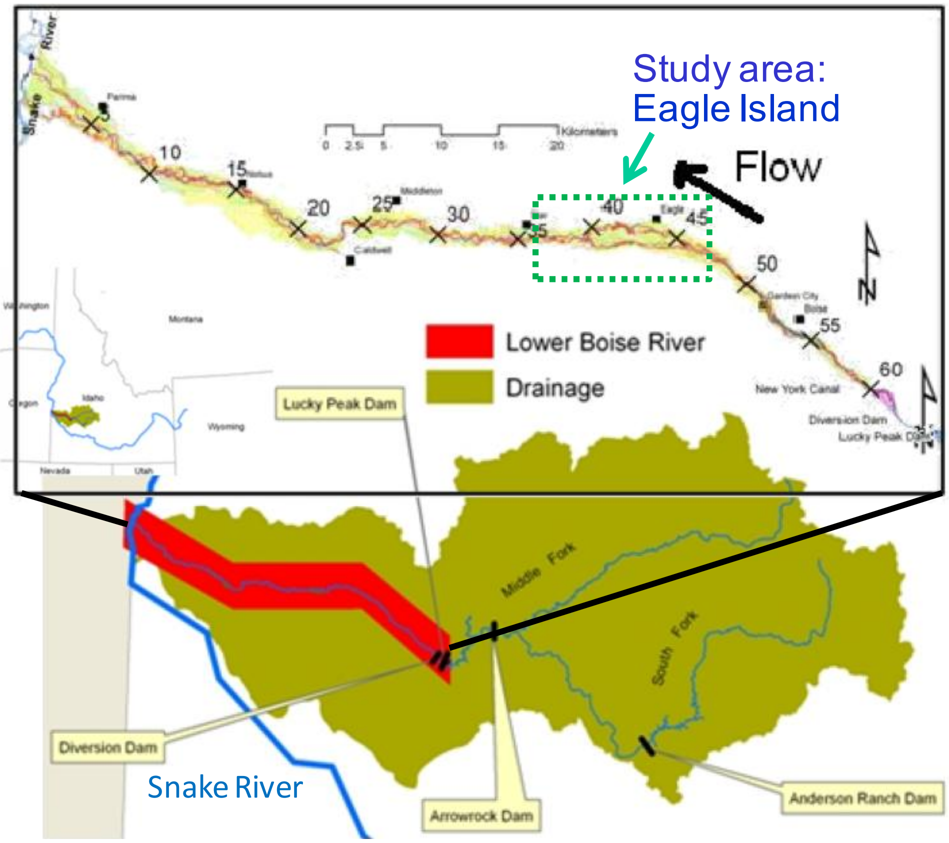

Figure 1: Boise River watershed and Lower Boise River

Lower Boise River is approximately a 100 km (62.1 mi) long reach extending from the Army Corps operated Lucky Peak Dam (Figure 1) to the confluence with the Snake River (MacCoy and Blew, 2005). The Boise River provides irrigation water to 1,300 km^2 (321,200 acres) of agricultural land. The Boise River below Lucky Peak Dam flows through urban areas and agricultural land. The three large dams (Anderson Ranch, Arrowrock, and Lucky Peak completed in 1915, 1950, and 1954, respectively) in the upper basin significantly alter the flow and sediment regime of the lower river. The dams are primarily managed for irrigation, recreation, and flood control.

2. METHODOLOGY

2.1 Functional Scenarios

In this study, the MIKEFLOOD model (see Figure 2) calibrated for the current channel vegetation conditions was modified to simulate the effect of four different channel vegetation scenarios, of 35% bridge blockage due to woody debris and of a 100-year recurrence interval (RI) flood event (Table 1) on the water surface elevation and floodplain inundation extent. The 100-year RI event is a hypothetical 1% chance annual occurrence event. The Current scenario represented existing vegetation condition in the channel; therefore Manning's roughness (Table 1) was optimized to match observed WSE as close as possible. The Concrete, Noveg, Medveg and Hiveg scenarios represented hypothetical channel vegetation. The Concrete and Hiveg scenarios corresponded to the two end- member cases of very low flow resistance and very high flow resistance. The Concrete scenario represented the channel being replaced with a concrete channel, whereas Hiveg corresponded to the extreme case where the channel was entirely covered by thick shrubs of willows and cottonwoods. These two scenarios represented extreme boundaries of Manning's roughness that may apply in the river system modeling. Medveg and Noveg represent the cases for which the riverbed had more than 10 year old trees and bushes and the vegetation was entirely removed, respectively.

Table 1: Different scenarios based on channel vegetation, discharge and modified cross-section and corresponding Manning's roughness

SN	Scenarios	Discharge		Channel roughness (n)	Remark
		m^3/s	cfs		
S1	Current	198	~7000 (~10-year RI)	0.035	Existing condition
S2	Concrete	198	~7000 (~10-year RI)	0.012	Hypothetical concrete channel
S3	Noveg	198	~7000 (~10-year RI)	0.030	No vegetation
S4	Medveg	198	~7000 (~10-year RI)	0.050	Medium vegetation (Trees of more than 10 year old)
S5	Hiveg	198	~7000 (~10-year RI)	0.120	High vegetation (Thick shrubs of willow and cottonwood
S6	100-yr	470	~16600 (100-year RI)	0.035	Existing condition
S7	Xmodi	198	~7000 (~10-year RI)	0.035	Existing condition (Woody debris stuck under bridge by reducing section by ~35%

The Manning's roughness for these hypothetical vegetation conditions were estimated based on professional judgment and from the descriptions in the work of Acrement and Schneider (1989). One of the shortcomings of this methodology was the conservative assumption of same vegetation conditions over the entire channel section. In reality, vegetation cannot completely establish in the channel within the minimum flow level.

The 100-yr scenario represented the occurrence of a 100-year flow condition based on Glenwood gage station, just upstream of the study area.

The Xmodi scenario represented the condition of a reduction in flow area due to woody debris accumulating under an existing bridge. The cross-sections just upstream of the North and South Channel Bridges were reduced by 35% for this scenario (Figure 3). Real time 24-hour hydrograph from 12-13 May, 2006 (discharge varies from 193-201 m^3/s (6,800-7,100 cfs) was used to simulate all the scenarios expect for the 100-yr. 100-yr scenario was simulated with 16-hour hypothetical hydrograph (Figure 3) with peak discharge of 470 m^3/s (16,600 cfs).

2.2 Model Setup

During the model setup, the 1D MIKE 11 model for the channel and the 2D MIKE 21 model for the floodplain models were set separately. Later, the MIKE FLOOD was used to dynamically link MIKE 11 and MIKE 21 models using lateral links (Figure 2).

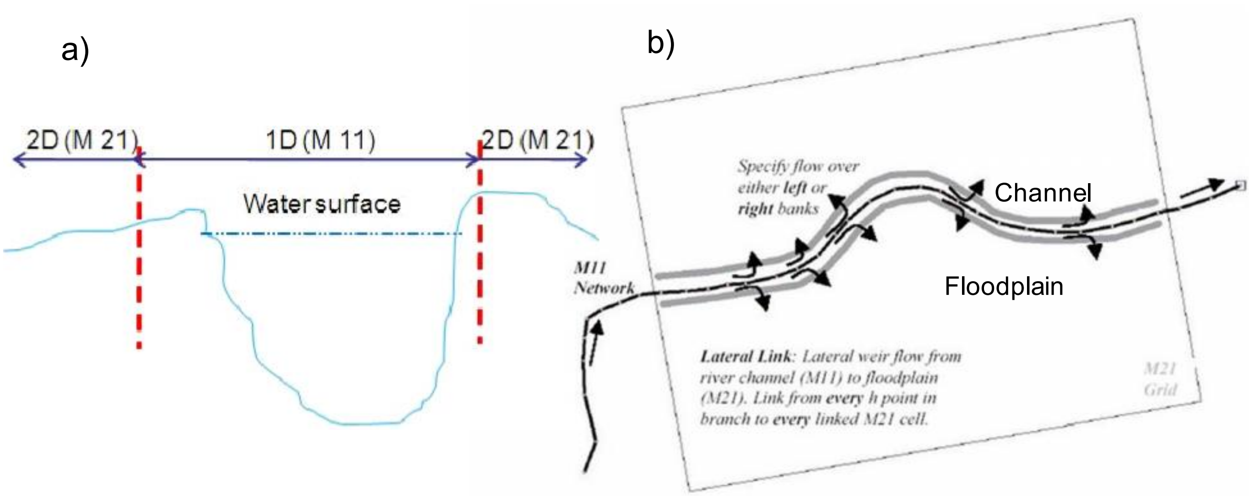

Figure 2: Schematic showing the link between MIKE11 and MIKE21 models using MIKEFLOOD model in a) cross-section and in b) plan views

2.2.1 1D HD model

The MIKE 11 model was setup to simulate in-channel flows of the Boise River. The Eagle Island channel network was represented by branches. The network for this model consisted two branches, i.e., Boise River, and Boise River-South. The Boise River branch started at Glenwood Bridge and ended at Star Rd Bridge. The Boise River-South branch started at the river divide (Head of Eagle Island); followed the channel along the south of Eagle Island, and ended where the north and south Channels rejoined at the downstream end of Eagle Island. Total of six bridges were input in the model as structures (DHI, 2009).

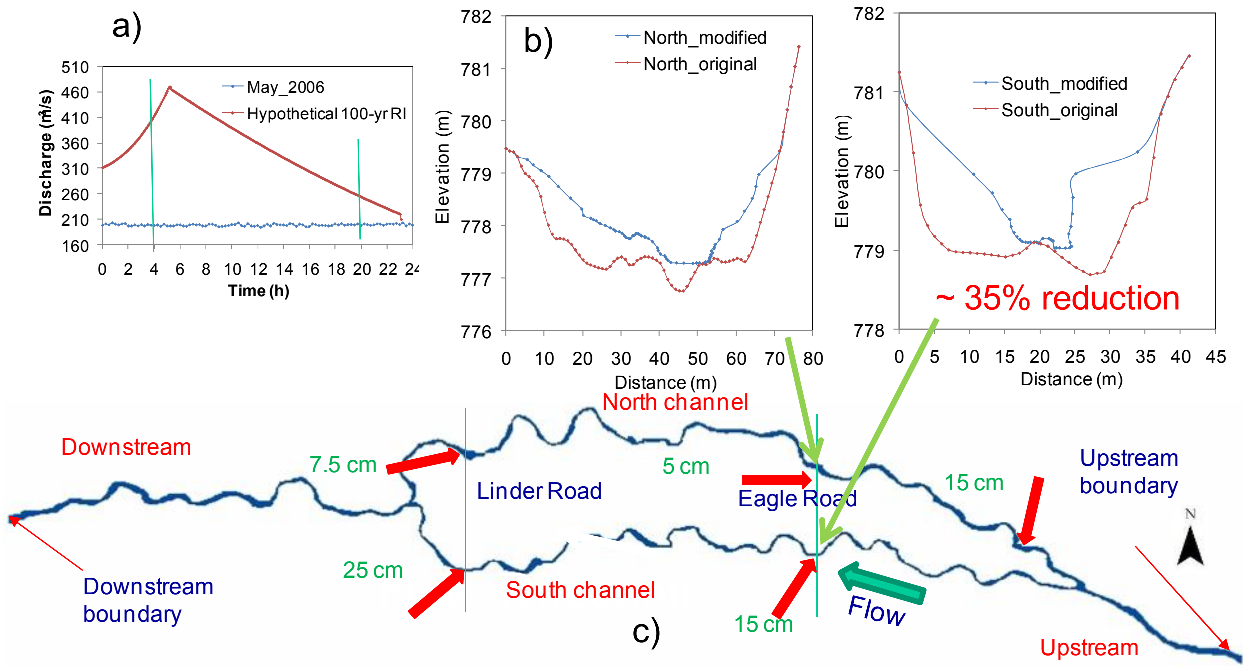

Figure 3: a) hydrographs used in the simulation, b) change and cross-sectional area at the brides on Eagle Road and c) location of the bridges where measured and simulated Water Surface Elevations (WSEs) were compared and cross-sections are modified. The numerical value (e.g., 15 cm or 6 inches) indicated differences between measured and simulated WSE at that location

The river bathymetry for the MIKE 11 model consisted of a series of cross-sections along the river. The elevations at the cross-sections were extracted from the EAARL derived Digital Elevation Model (DEM) that had a 1-m horizontal resolution. Generally, the locations of the cross-sections coincided with USGS surveyed cross-sections in 1997-1998 (Hortness and Werner, 1999). Upstream boundary conditions for the model consisted of time series of different discharges at the Glenwood Bridge. The downstream boundary was defined by a discharge (Q) and stage (H) relationship, which was adopted from the HEC-RAS model (DHI, 2009).

2.2.2 2D HD model

A MIKE 21 software package was used to setup the 2D model for the floodplain in this study. The floodplain bathymetry was developed by resampling 1-m resolution DEM to a 7m grid size for the MIKE21 model (DHI, 2009).

For the 2D model, the Manning's roughness was varied spatially based on land cover types (Figure 4). The land cover types were based on a digital land cover map developed prior to 2004. Four different land cover types were considered and corresponding Manning's roughness values were: Riparian/Wetland (0.100), Agricultural (0.033), Water body (0.029) and Development/Residential (0.025).

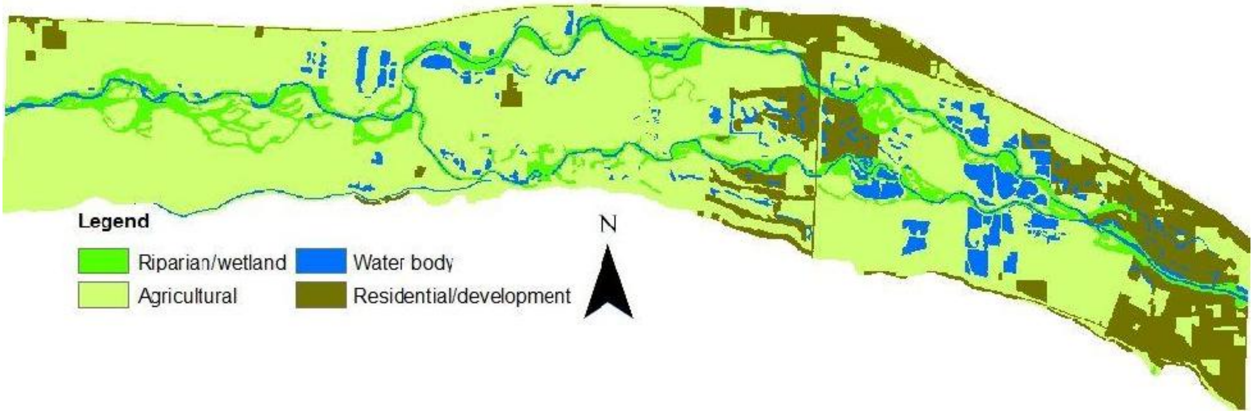

Figure 4: Spatially distributed land cover types

2.3 Calibration and validation

Generally, parameters such as channel and floodplain roughness were optimized in hydraulic models during the calibration process. The Boise River MIKE FLOOD model was calibrated by adjusting the channel resistance in the MIKE 11 model so that simulated inundated areas and simulated water surface elevations (WSEs) in the river were consistent with observations made during the flood event (DHI, 2009). The time period of 24 hours from May 12, 2006, 8:00 am to May 13, 2006, 8:00 am was used for the calibration period. In addition, adjustments were made to the 1D and 2D models during the calibration period to reflect the actual hydrodynamics such as channel WSE and inundation extent. For example, a levee breach on the south channel was introduced into the model to mimic the actual breach that occurred during the 2006 flood event (DHI, 2009).

2.4 Analysis

Water surface elevations for all the scenarios were compared with current scenarios for the Upstream, North, South and Downstream reaches (Figure 3) to analyze the impact of Channel vegetation. Mean, standard deviation (SD), and 95 percentile of difference between the Current condition and the other scenarios were calculated. Therefore, positive mean depth indicates higher value in the Current scenario than any other scenario. Floodplain inundation extent was delineated with five depth classes (i.e., ≤0.2 m, 0.2-0.5 m, 0.5-0.8 m, 0.8 m-1.2, >1.2 m). The area associated with each depth class and total inundated area for different scenarios were calculated in order to study the impact of channel roughness to the floodplain inundation extent.

3. RESULTS AND DISCUSSION

Water surface elevations and floodplain inundation extent were estimated for all the scenarios to study the impact of channel vegetation. The results of the calibration simulations, in terms of water level differences between observations and simulations, were summarized in Figure 3 and DHI (2009). The differences in measured and simulated WSE were from 5 (2 inches) to 25 cm

(10 inches) (Figure 3). The lowest difference (5 cm or 2 inches) was estimated at the Eagle Road Bridge in the North Channel, while highest (25 cm or 10 inches) at the Linder Road Bridge in the South Channel.

3.1 Water Surface Elevation

Table 2: Difference in water surface elevation (m) between Current and the other specific scenarios for the different reaches

	n*	South-Channel			Upstream			North-Channel			Downstream		
		Mean	SD	95%	Mean	SD	95%	Mean	SD	95%	Mean	SD	95%
Hiveg	**0.120**	0.28	0.18	0.57	0.79	0.39	1.37	0.32	0.22	0.77	0.22	0.13	0.47
Medveg	**0.050**	0.08	0.07	0.17	0.31	0.13	0.50	0.20	0.09	0.37	0.07	0.03	0.13
Noveg	**0.030**	-0.01	0.01	0.00	-0.12	0.04	-0.07	-0.02	0.03	0.03	-0.04	0.02	-0.02
Concrete	**0.012**	-0.61	0.14	-0.42	-0.90	0.18	-0.63	-0.53	0.19	-0.19	-0.57	0.15	-0.35
Xmodi	**0.035**	0.04	0.05	0.10				0.03	0.04	0.08			
100-YR	**0.035**	0.22	0.11	0.40	0.73	0.17	0.94	0.33	0.13	0.57	0.17	0.05	0.25

n*= Manning's Roughness 0.95%= 95 percentile

The model simulated highest mean WSE differences (0.22 - 0.79 m) between Hiveg and Current scenarios in all the reaches (i.e., upstream, downstream, South and North Channel). As expected, the WSE were decreased with less vegetation density (Table 2).

Mean WSE differences were highest in the Upstream reach (0.79 m) compared to all other reaches for Hiveg, Medveg, Noveg, and Concrete scenarios, while lowest occurred in the Downstream reach.

The Noveg scenario had a negligible impact on WSE with reference to the Current scenario in South (0.01 m), North (0.02 m), and Downstream (0.04 m), when compared to Upper reach (0.12 m).

The cross-section modification (Xmodi) altered the WSEs at few cross-sections of the North and South Channels. Mean WSEs of 0.04 m and 0.03 m were increased in Xmodi from the Current scenario in the South and the North Channel, respectively.

The 100-yr RI flood simulated higher WSE than the current scenario, but lesser than hypothetical Hiveg.

3.2 Floodplain inundation extent

The floodplain inundation extent was summarized in Figures 5, 6, 7 and Table 3 for five depth classes (i.e., ≤0.2 m, 0.2-0.5 m, 0.5-0.8 m, 0.8 m-1.2, >1.2 m) and for different scenarios. Higher channel roughness resulted in larger flooded areas than lower channel roughness. That was expected because higher channel roughness simulated greater WSE in the channel, which in turn caused larger floodplain inundation extent.

The Current scenario inundated 8.3 km^2 (2,016 acres) of floodplain, while 16.3 km^2 (4,027 acres) with Hiveg.

The hypothetical Concrete scenario inundated the smallest (1.9 km2) (470 acres) area compared to all the other scenarios. The floodplain inundation areas of the Concrete scenario not the results of channel overflow but rather of permanent water bodies (constructed wetlands and ponds).

However, WSEs increased slightly with Xmodi scenario in the South and North Channels, the Xmodi did not contribute additional floodplain inundation.

Table 3: Summary of the floodplain inundation extent

Depth class	**100_yr 0.035***		**Hiveg 0.120***		**Medveg 0.050***		**Xmodi 0.035***		**Current 0.035***		**Noveg 0.030***		**Concrete 0.012***	
(m)	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**	**(Km^2)**	**(%)**
< 0.2	5.0	33	5.4	33	4.2	38	3.2	39	3.2	39	2.6	39	0.4	21
0.2-0.5	4.1	28	4.7	29	2.8	25	1.9	23	1.9	23	1.4	22	0.2	12
0.5-0.8	1.9	13	2.1	13	1.3	12	0.9	11	0.9	11	0.7	11	0.2	13
0.8-1.2	1.2	8	1.3	8	0.8	7	0.6	8	0.6	8	0.5	8	0.3	14
>1.2	2.5	17	2.8	17	2.0	18	1.6	20	1.6	20	1.4	21	0.8	40
Total	**14.8**		**16.3**		**11.1**		**8.3**		**8.3**		**6.6**		**1.9**	

* Manning's roughness

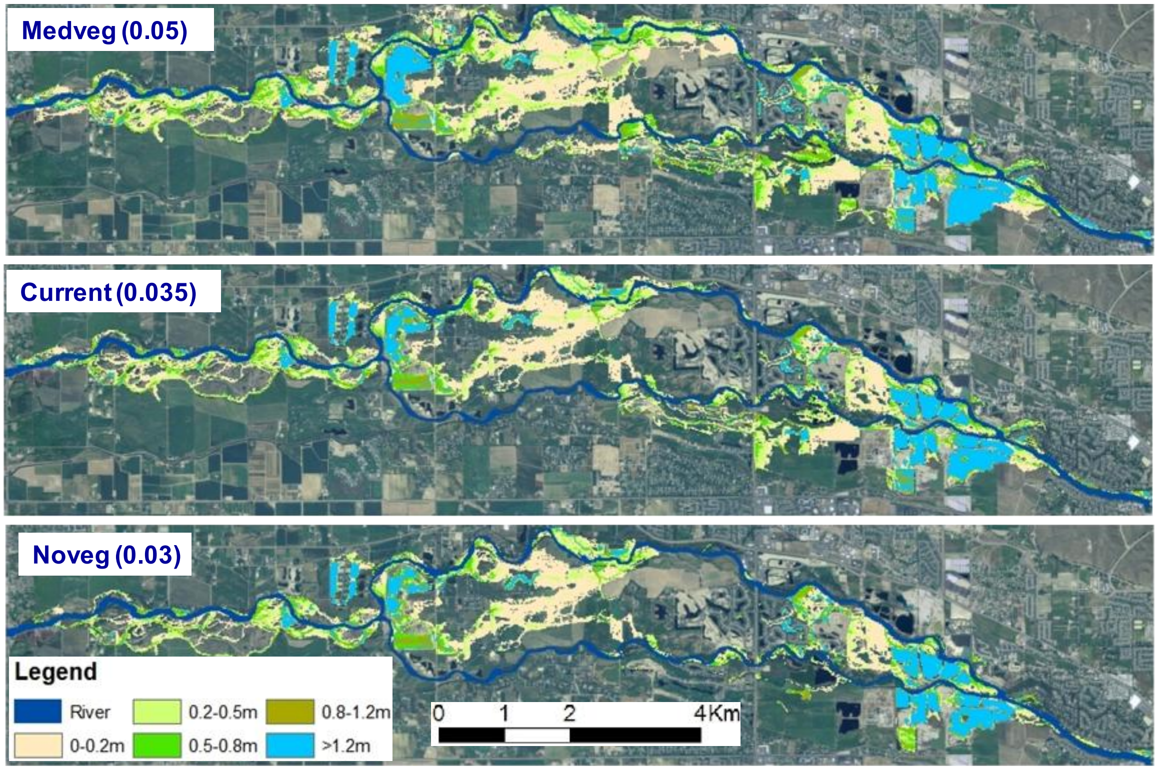

Figure 5: Spatial distributed floodplain inundation extent on the floodplain for the Current, Medveg and Noveg scenarios

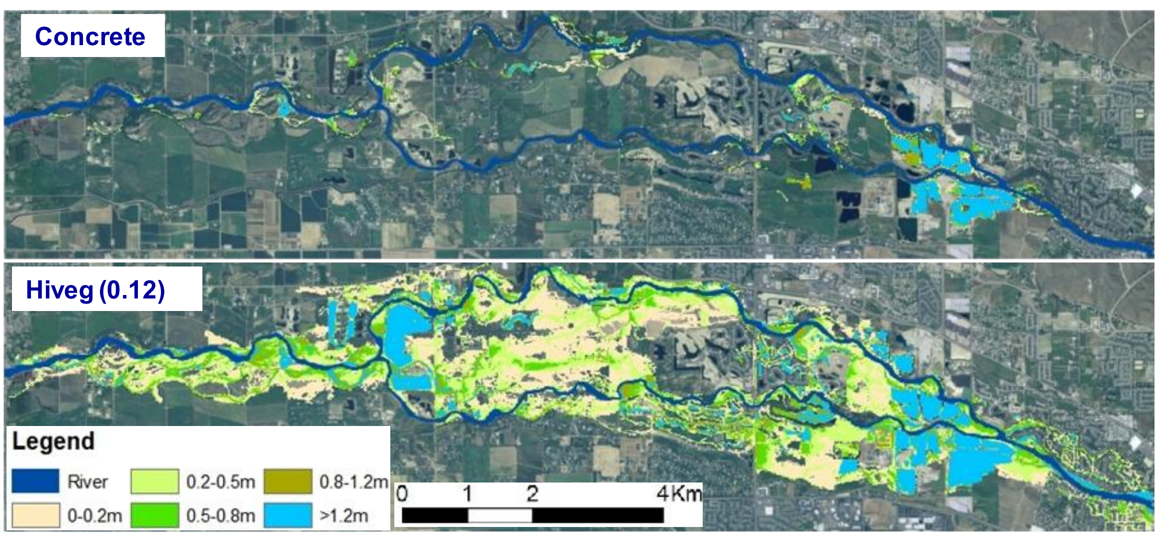

Figure 6: Spatial distributed inundation extent on the floodplain for the hypothetical Concrete and Hiveg scenarios

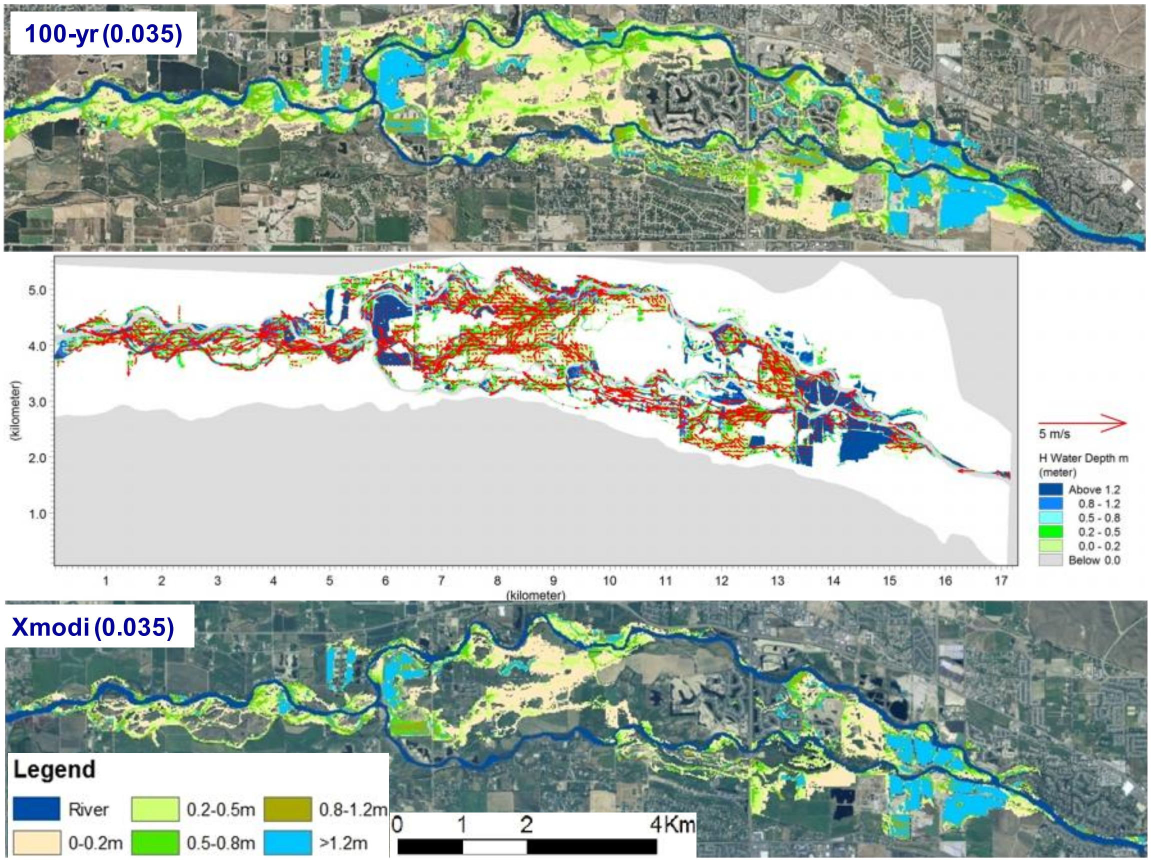

Figure 7: Spatial distributed inundation extent on the floodplain for the 100-yr RI with velocity vectors and Xmodi scenarios

This study was designed assuming a consistent vegetation density across the entire channel section. This was a conservative assumption because it is unlikely that tree or brush vegetations develop in the entire channel within the minimum flow level. Therefore, separation of a minimum flow channel, while assigning Manning's roughness in the channel, would result in more realistic scenarios. Channel roughness coefficients were selected based on published values on other river systems because very limited high flow data to calibrate or validate the model were available for the Boise River. Model predictions can be refined when more detailed management alternatives are available, but the intent of the study was to give managers initial guidance on possible future scenarios. Furthermore, large woody debris in the channel may cause local issues by directing flows against bends causing local scour. Another important issue is the spatial resolution of the model grid size, which was 7 by 7 m (23 feet by 23 feet) cell. The current grid size may have not represent some important floodplain features such as irrigation channel and narrow levees including other topographic features that serve as levees whose dimension is 7 m (23 feet) or smaller. Finer grid size model (e.g., 5 m or 16 feet) may be able to address some of the uncertainties related with spatial resolution of the existing model.

4. CONCLUSION AND FUTURE STUDIES

The findings of this study represent preliminary results intended to provide river managers with scientific knowledge about the relative importance of vegetation on flood elevations. This study does not evaluate future morphological conditions in the channel. For example, 100% vegetation removal would destabilize the channel, resulting in erosion and deposition patterns that could worsen flood risk in many reaches. The connection between vegetation management practices, channel stability and deposition patterns should be considered in the future management of the Boise River.

Results revealed that the largest and smallest changes in water surface elevations due to different vegetation management approaches occurred in the Upper and Lower reaches, respectively. The changes were larger in the North Channel than in the South Channel.

Removing existing vegetation including woody debris piles in the channel would reduce the water surface elevation at the most 12 cm (4 inches) in the Upper reach and less than 4 cm (1-½inches) in other reaches. This change in water surface elevation due to channel vegetation removal would result to the potential reduction of about 1.7 km^2 (420 acres) of inundation on the floodplain.

The Medveg scenario, which corresponds to 10-year old trees and bushes within the river channel, would result in an additional 2.8 km^2 (692 acres) extent of floodplain inundation of which 1 km^2 (247 acres) would have flood depths less than 0.2 m (8 inches). The increase in vegetation (Medveg) from current conditions would contribute an increase of the mean and maximum water surface elevations of 0.3 m and 0.5 m (12 and 20 inches), respectively in the Upper reach. Thus, these simulation results suggest that reduction of channel vegetation would not play a major role on decreasing inundation extents for the bankfull discharge.

Effects of channel vegetations on water surface elevations vary in the different reaches and the most affected are the North Channel and Upper reaches.

Woody debris obstructing 35% of the cross-sectional area under both Eagle Road bridges would have no significant effects on floodplain inundation extent for the bankfull discharge of 198 m^3/s (7,000 cfs). However, maximum water surface elevations increased by 10 cm (4 inches) in the South Channel and 8 cm (3 inches) in the North Channel for a short section upstream the bridges. These increases in water surface elevations would not contribute to any additional floodplain inundation areas.

However, the effects of woody debris clustering and accumulating under the bridges and increases in channel vegetation including existing woody debris piles, may have a significant effect on river water surface elevation and floodplain inundation extent for larger return interval flood events (e.g., 50- or 100-year). These events were not simulated in this study.

Floodplain inundation extent and differences in water surface elevations might change, if a longer duration flood (> 24 hours) was considered for larger return interval flood events.

The main conclusions of the study are summarized as follows:

The main conclusions of the study are:

- Removal or increase of in-channel vegetation results in relatively minor changes on water surface elevation and flood inundation extent for bankfull discharge.
- Effects of vegetation management on water surface elevations vary with different reaches.
    - Effects in the Upper and North Reach of the Boise River have the most significant impact.
- Flow resistance added by the woody debris pile has negligible effect on water surface elevation and floodplain inundation extent.
    - Obstructed areas in the channel created by accumulation of woody debris and trash could affect flood conveyance. This process was not investigated in this report.
- The accumulation of woody debris under bridges has minor impact on water surface elevations and flood inundation extent at bankfull discharge.
    - However, woody debris may have a significant effect at flows larger than bankfull.

Future study should focus on the important areas that are vulnerable to flooding, such as low-lying subdivisions. This future study could be performed by using a full 2D model utilizing water surface elevation boundary conditions and discharges provided from the 1D model.

Future investigations should consider hydrographs longer than 24 hours for estimating floodplain inundation extents (investigate a flood period similar to a natural hydrograph). Future investigations should consider large floods where bridges may become constrictions and therefore more influenced by debris accumulations. A 100-year flood event scenario (470 m^3/s or 16,600 cfs) could be used to study the impact of woody debris accumulation at the bridges on water surface elevations and floodplain inundation extent due to the backwater effect induced by woody debris accumulating at the bridges.

Finally, the differences between measured and simulated water surface elevations obtained in the calibration process appear to be high for the objective of the present study. Future studies should verify the potential differences through the use of additional field measurements at a range of flows.

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