

# SYNTHETIC BATHYMETRY METHOD DEVELOPMENT, VALIDATION AND APPLICATION TO FIVE PACIFIC NORTHWEST RIVERS

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**Abstract:** This paper presents a simple, robust, and relatively efficient workflow to create and "burn in" high resolution synthetic river bathymetry data into existing LiDAR datasets. The Synthetic Bathymetry (SB) method uses widely available GIS and hydraulic modeling techniques to create physically-based synthetic bed elevation data without introducing significant error in computed water surface elevations and average channel velocities, under conditions where discharge at time of DEM data acquisition is known. The SB method was applied and validated on a small, steep, braided cobble bed river, large and small cobble bed wandering rivers with wide floodplains, and a small, entrenched, low gradient river with tidal influence all in Washington State – as well as a very large, flat gradient reservoir reach in Montana. As a test of the validity of the approach the results of models based on SB data were compared against models based on traditional survey methods, and against models based on LiDAR alone. For low (base) flows, bankfull (2-year) and 100-year flood flows the differences in computed water surface elevations, inundation area, and velocity were small (MAE in water surface elevation of less than 1 foot for all 5 study reaches under low flow, and less than 1 foot for all but the reservoir reach under 2 year and 100-year flood flows). At lesser flood flows to bankfull flows, the MAE in stage is modestly higher, as compared with the baseline models. For the reservoir reach, the model results were generally poor during 100-year flood flows as compared with the other rivers, however the error reduction in water surface elevation (from use of an unadjusted DEM alone) was nearly 30 feet. The good to excellent agreement of the SB models to the baseline in four of the five study reaches is attributed to the ability of the SB method to create the flow area needed to convey flood flows at comparable stages and velocities as survey based models. The SB method holds promise for speeding up and reducing the cost of 1-D and 2-D hydraulic modeling efforts where multiple decimal place accuracy is not required. The SB method can significantly reduce error in cases where only a DEM is available, and reduce the need for tedious, subjective terrain data manipulation commonly associated with interpolation between widely spaced cross sections. The SB method could improve the quality of models in cases where site conditions (unstable channel, remoteness, turbidity, safety) prevent bathymetric data collection but otherwise allow for above-water aerial survey techniques (photogrammetry, satellite, LiDAR, Structure from Motion). Other potential uses include estimation of bed elevations to track sediment movement under rapidly changing conditions, such as below a dam removal.

## INTRODUCTION

This paper presents a relatively simple technique for creating physically based riverine bathymetric data from digital elevation models (DEMs) and discharge data using GIS and the US Army Corps of Engineers software HEC-RAS (USACE 2014). For the purposes of this paper DEM pertains to topographic datasets derived from photogrammetry or Light Detection And Ranging (LiDAR) techniques. The method described in this paper results in a "burned in" or "eroded" (synthetic) river bottom within a digital terrain model that otherwise lacks bathymetric data. In shallow rivers the method has shown promise at preserving riffle crest elevations, side channels, and large in-channel roughness elements. The technique can be used for any case where flow is nominally unidirectional, confined within banks, and is either known or can be estimated at time of topographic survey. Virtually any 1-D or 2-D modeling package that allows for computation of inundation maps can use this method.

The method, termed herein as the synthetic bathymetry (SB) method, has several potential applications in the fields of hydrology, hydraulics and fluvial geomorphology and is best suited for determining reasonably accurate water surface elevations in situations where data is scarce and/or where projects do not require stringent accuracy. The method also allows for filling in gaps between surveyed cross sections without interpolation, which helps preserve the near bank, and mid channel topography (large roughness elements) that may be important for 2-dimensional model studies. It also allows for a physically based estimate of riverbed elevations below the water surface which can be valuable for estimating long term geomorphic change over large areas.

This paper investigates the relative accuracy of one dimensional hydraulic models constructed from surveyed cross sections, from DEM data alone, and from DEM data blended with SB data. Published flood insurance study data or recently calibrated survey-grade hydraulic models are used as benchmarks to test the validity of the results using SB data.

## BACKGROUND

LiDAR data sets are becoming widespread and have quickly become some of the most valuable data for hydrologic, hydraulic and geomorphic studies. The LiDAR data is usually extracted and processed for inclusion in a numerical model of hydrologic processes. Due to technical limitations many LiDAR datasets lack elevation information below the water surface (bathymetry), requiring collection of channel data with other methods. Alternately, models are used without this data due to cost constraints, reducing the quality of the results. As survey and post processing technologies improve, terrestrial floodplain topography can be acquired for large study areas in the time it takes to fly along the river in a helicopter or airplane. Despite their high resolution, most available LiDAR data sets used to create DEMs do not include bathymetric LiDAR data (now possible with certain sensors and shallow, clear water conditions – see River Bathymetry Tool Kit (McKean et al, 2009)). Other recent innovative methods to remotely survey the channel bottom, which also require clear water conditions, include correlation of aerial imagery based DEMs to physical measurements of depth (Javernick et al, 2014). Currently, several technologies are available to acquire high resolution topographic and bathymetric data to support floodplain studies (Bangen et al, 2014). Many of these technologies are complex and costly to use. Considerable effort and skill are necessary to check, verify, and blend available data to create a seamless riverine terrain model. Also, due to the high equipment costs associated with some technologies and large data sets created by modern equipment, considerable effort and expense are necessary to acquire, maintain, and post-process these data. But as two dimensional modeling moves to the forefront of hydraulic engineering practice, the demands for bathymetric data will continue to increase.

Thus, the current state of the practice is one where engineers and scientists have a plethora of terrestrial data sets to choose from, from which any number of cross sections can be created. Below-water bathymetric data, however, remain sparse and difficult to acquire in many settings. Use of interpolated or “best guess” bathymetry in hydraulic models introduces unknown errors that add uncertainty and risk to project findings and decisions resulting from the modeling. Fortunately, many of the issues resulting from missing bathymetry can be partly overcome by applying first principles and combining off-the-shelf GIS and hydraulic modeling software. This paper presents and validates one such method, termed the Synthetic Bathymetry (SB) method that allows for automatic manipulation of terrain data to “burn in” SB data under the LiDAR water surface to address circumstances where underwater survey data is lacking but improved model accuracy is desired.

## SYNTHETIC BATHYMETRY METHODOLOGY

Commonly used open channel flow numerical models allow for computation of fluid depth based on first principles of open channel flow (conservation of energy, continuity of flow, conservation of momentum). If a numerical backwater model is used, such as HEC-RAS (USACE 2014), to perform a standard step backwater calculation, the energy losses due to cumulative expansion, contraction, and roughness losses can be accounted for in estimating the local variation in hydraulic conditions, such as velocity, depth, and stage. As with most open channel flow models, the quality of the hydraulic output depends on the quality of the input, namely survey data and how well the modeler captures the characteristics of the terrain.

For purposes of floodplain modeling and mapping, the goal is typically to first compute the losses in energy (expressed as fluid head) using standard step backwater computations, then to map the resulting water surface elevations across the terrain data used to construct the model. All major changes in cross section, planform, slope, and roughness need to be represented in the model to yield good estimates of local and cumulative energy losses. If a river model is constructed accounting for local changes in slope, width and roughness, then the depths and velocities can still be computed even if the bed elevations are not known with high accuracy. In this situation the accuracy of the results will be biased by the initial error in the bed elevations. Recognizing that LiDAR provides an extensive and detailed record of the water elevation at time of survey (calibration data), we can write the following equation for the LiDAR surveyed water surface elevation ( $WSE_{Survey}$ ) resulting from a hydraulic simulation of the flow elevation at time of the LiDAR flight:

$$\mathbf{WSE}_{\text{Survey}} = \mathbf{WSE}_{\text{initial}} - \mathbf{E}_{\text{initial}} \quad (1)$$

Where E represents error, the difference between the computed elevation ( $\mathbf{WSE}_{\text{initial}}$ ), and the “true” elevation and If the water level in the LiDAR is treated as terra firma in the model cross sections (as a false river bottom), all flow will then occur above the “correct” elevation. Thus the depth of flow above the initial “false bed” is the error in equation 1.

$$\mathbf{E}_{\text{initial}} = \mathbf{WSE}_{\text{initial}} - \mathbf{Z}_{\text{false bed}} = \mathbf{Y}_{\text{initial}} \quad (2)$$

Where:

$$\mathbf{Z}_{\text{false bed}} = \text{Bare earth LiDAR elev} = \mathbf{WSE}_{\text{Survey}}$$

$$\mathbf{Y}_{\text{initial}} = \text{initially computed flow depth (above raw DEM)}$$

Expressed spatially, across a raster grid, at all locations within a raster cell,

$$\mathbf{E}_{\text{initial}(ij)} = \mathbf{Y}_{\text{initial}(ij)} \quad (3)$$

Where i and j denotes the spatial location of a given raster cell of a given dimension. It is then proposed that,

$$\mathbf{Z}_{\text{SB}(ij)} = \mathbf{Z}_{\text{false bed}(ij)} - \mathbf{Y}_{\text{initial}(ij)} \quad (4)$$

Where  $\mathbf{Z}_{\text{SB}(ij)}$  represents a synthetic river bottom elevation at a given raster cell. By subtracting the initially computed flow depth ( $\mathbf{Y}_{\text{initial}(ij)}$ ) from the false bed ( $\mathbf{Z}_{\text{false bed}(ij)}$ ) at every raster cell, the synthetic river bottom is “burned” or “eroded” into the DEM, creating the SB data set ( $\mathbf{Z}_{\text{SB}(ij)}$ ). Note that the error is specific to each location in the modeled space, and that modern versions of both open channel flow and GIS software are needed to perform the above calculations. In this paper, Arc GIS version 10.1 and HEC-RAS version 5.0 were used. This version of HEC-RAS allows for simulation of 1- or 2-dimensional flows and rapid computation of inundation depth rasters (Geotiff format) at all points in the model domain. SB data creation requires low flow inundation depth rasters to be created at the same resolution as the underlying terrain raster (Figure 1).

Figure 1 below illustrates a short a portion of two Dungeness River low flow hydraulic models created to test the effects of the different bathymetric data sources on model accuracy (see low flow calibration and high flow calibration sections of this paper for more discussion). Figure 1 shows how the raw, LiDAR Only (LO) DEM compares with a SB based DEM, and how the approach uses GIS raster math to calculate the elevation of the SB raster data at the grid cell scale. Note the greater area of inundation present in the LO low flow model results – which is due to the effects of the artificially high false bed in the DEM. Also note the planar contours of the channel bed present in the LO DEM as compared with the SB DEM.

Once the “burned” or “eroded” DEM is created the quality of the resulting data needs to be checked by running the low flow hydraulic model extracted from the SB data. The low flow model should include reasonable flow resistance parameters and the best estimate for discharge available throughout the model domain. Using the water surface profile plot options and comparing the initial DEM-based plan to the SB-based plan in HEC-RAS allows for verification that the results are reasonable (Figure 2). Our experience is that minimal tuning of n-values is necessary to provide good fit between the computed and surveyed low flow water surface elevations. Figure 2 is representative of the quality of fit that results when low flow data is known with confidence and high quality LiDAR is used.

In application of the SB workflow (described during talk) we found that there are common difficulties when calibrating to low flow surveyed water elevations extracted from the DEM. These typically occur at the downstream end of the model (if the starting water surface is assumed to equal the surveyed water surface). Our initial experiences suggest that starting the model at normal depth will overcome most downstream boundary problems. Increasing n values locally can be used to force the river to deeper depths where pools are known to be present. If calibration difficulties are encountered throughout the model, this is most likely an indication of poor discharge estimates in the model. Even if available survey data is outdated, it should be used as a check of the SB DEM. If the SB data is suspect, it should be replaced with traditional survey data.

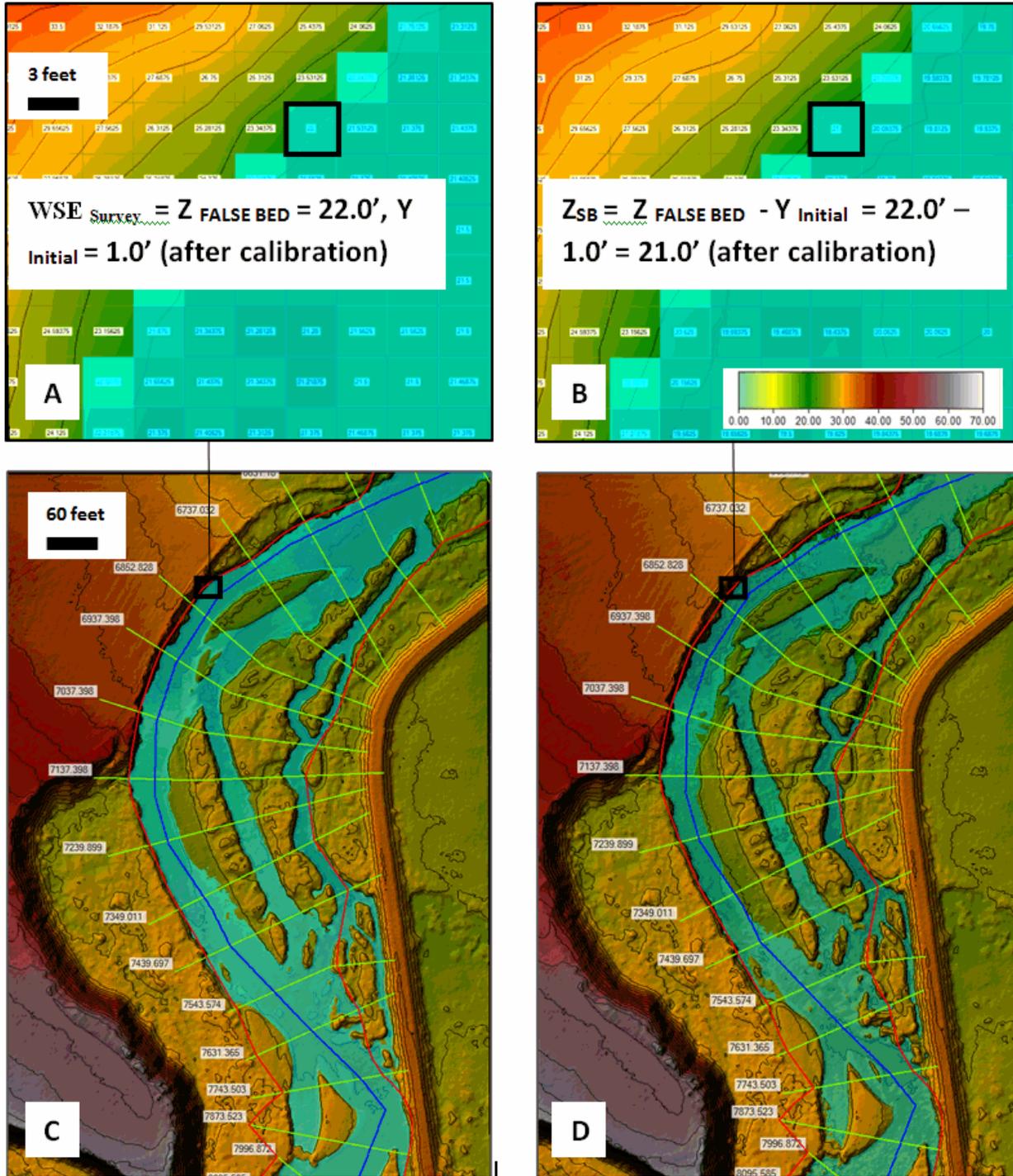
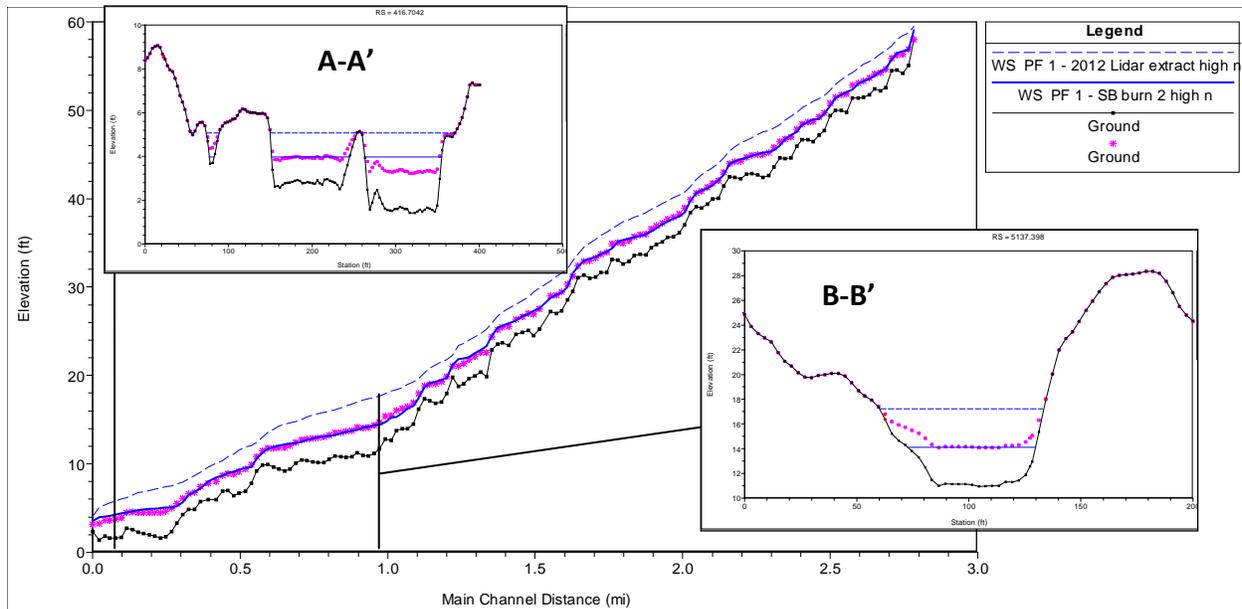


Figure 1: Dungeness River, WA (RM 1.3 to RM 1.6). (A) Close up showing initial LiDAR terrain grid cell center elevations ( $Z_{FALSE\ BED}$ ). Each grid cell is 3 feet x 3 feet. Blue shaded numbers are cells that are wetted. Discharge at time of survey is 340 cfs. (B) Close up showing SB terrain computed grid cell center elevations ( $Z_{SB}$ ), and how  $Z_{SB}$  is computed. (C) LiDAR terrain data overlaid with low flow hydraulic model cross sections, river centerline, banks, and resulting initial estimate of inundation area for flow at time of the LiDAR flight. Contour interval is 2 feet. Flow direction is south to north. (D) Synthetic bathymetry terrain data overlaid with low flow hydraulic model and computed inundation area. Note that all major geomorphic landforms with exception of deep pools are captured.



**Figure 2 –Dungeness River, WA. Low flow hydraulic model verification against LiDAR surveyed water surface. In the water surface profile and cross sections the dashed blue line is initial estimate of water surface profile using LiDAR false bed elevation. Blue solid line is water surface computed after burning the initial depths into the LiDAR to create synthetic bathymetry (SB) data. Pink \* is initial LiDAR surveyed water surface elevation (assumed to equal lowest point on cross section extracted from bare earth LiDAR) used to validate SB low flow model. Cross section A-A’ shows how the method is able to burn side channels and main channels simultaneously while preserving large scale geomorphic features. The error in the depth is partly attributable to uncertainties about how much flow was in the main channel vs. the side channel. If the side channel was assumed dry, the main channel would have been stamped to a deeper elevation, which may have resulted in a better match. These errors are unavoidable without aerial photos to aid decisions on where to set limits of the channel in the model. Cross section B-B’ is representative of how the method works in an ideal setting. The water surface matches the LiDAR survey, with minimal alteration of the cross section shape.**

Note that the SB DEM is created after one or more calibration attempts to match low flow water elevations. This ensures that the low flow model and DEM have adequate conveyance to match low flow water surface elevations. In real rivers, as well as in numerical models, it is widely known that riffles are a primary control on flood elevations and that at high flows water surface elevations tend to follow a smoother longitudinal profile that drowns out bed elevation undulations more prominent at low flows. A fundamental assumption embedded in this approach is that as long as the SB DEM is the result of a well calibrated numerical model that captures riffle elevations (as shown in Figure 2 above), error in thalweg elevations between riffles will not significantly impact estimates of flood elevations. A primary goal of the high flow validation section of this paper is to test the validity of this assumption.

## STUDY REACH DATA

Hydraulic models developed by others were acquired to establish baseline conditions for investigating the effects on the results of hydraulic models derived from ground survey based methods, from LiDAR alone, and from LiDAR blended with SB data. All baseline models used for validation purposes were developed by others. The Green River models were acquired from King County, prepared as part of a Preliminary Revised Flood Insurance Study (2007). The Skykomish River model was obtained from Snohomish County and was developed as part of a Revised Flood Insurance Study (2010). The Dungeness River model was developed by USACE Seattle District as part of a Feasibility Study (2014). The Clark Fork model was developed by USACE Northwest Division as part of the Columbia River Treaty Flood Risk Assessment (2012). All baseline models were used as-is, reflect real-world conditions and are based on modern modeling and mapping standards.

The Dungeness, Skykomish, and Green River in western Washington State, and the Clark Fork River, a tributary to the Columbia in Idaho and Montana were used for this study (Figure 3). For ease of comparison the Green River model was subdivided into the Middle and Lower Green Rivers based on a geologic reach break near river mile (RM) 32. All study reaches in Washington State are glacially modified alluvial floodplains, draining heavily forested mountains that have hydrology typical of the Puget Sound lowlands (high intensity fall and winter rains, spring snowmelt runoff). A flood control dam on the Green River caps flood flows at the pre-dam 2-year recurrence interval discharge, while the Skykomish and Dungeness are free flowing. In contrast, the Clark Fork River study reach is wholly contained by a bedrock gorge and is heavily influenced by hydroelectric dams located at both ends of the study reach, which causes the river to behave like a reservoir under all but the highest discharges.

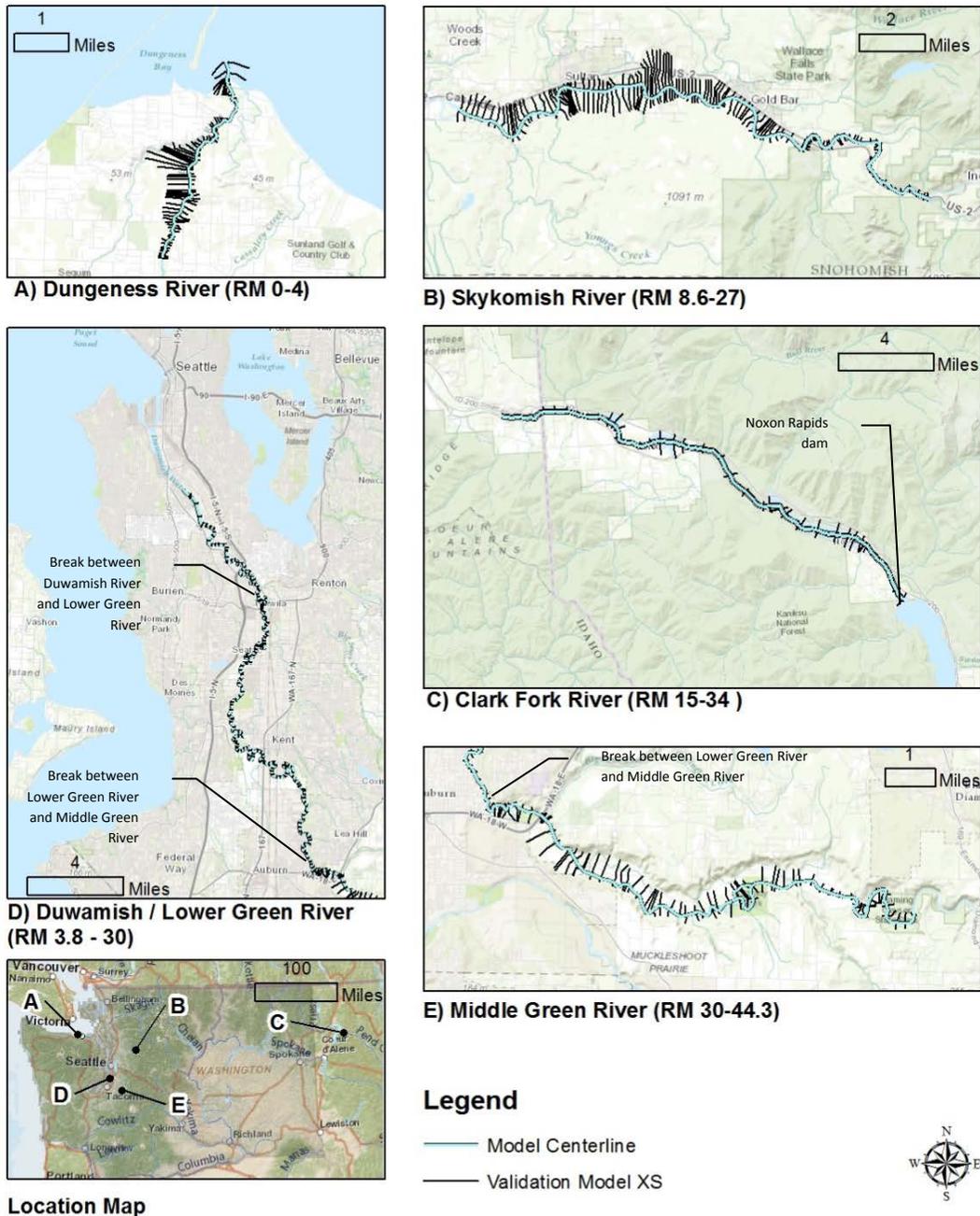


Figure 3: Location and vicinity maps of SB low flow and validation model reaches

The Dungeness River is the shortest and steepest of the study reaches, with the lowest 100-year discharge, while the Lower Green River is the longest and narrowest of the study reaches (Table 1). The flattest and most confined reach is the Clark Fork River – however the flat gradient is the result of a downstream dam. The natural valley gradient is much steeper given the canyon setting. The Dungeness, Skykomish, and Middle Green River are gravel/cobble bedded with boulders in places. The Skykomish River is the largest of the alluvial rivers studied, with large amplitude migrating meanders and wide floodplain. All alluvial rivers studied are artificially confined by road embankments, revetments and levees near developed areas, the lower half of the Dungeness River and Lower Green River being the most confined. Hydrologic data available is of relatively high quality, with more than 80% of the study reaches gauged for all but the lower half of the Skykomish River. Flows at time of survey were about 10% of the 2 year discharge for the Dungeness and Green River, about 4% for the Skykomish, and about 22% for the Clark Fork, indicating that the discharge at time of survey was well below bankfull conditions.

**Table 1: Study Reach Low Flow and Baseline Model Data**

Study Reach	Length (miles)	Minimum % gaged in reach	Drainage Area (square miles)	Reach Average (Std Dev)		Discharge Estimates (cfs)		
				EGL Slope & (EGL Stdev) (ft/ft) (1)	BFW/ BFD & (BFW/BFD Stdev) (ft/ft) (2)	@ time of survey	50% AEP (2-yr)	1% AEP (100-yr)
A. Dungeness River, WA	2.8	95%	198	0.0044 (0.0024)	67 (95)	340	3,000	9,100
B. Skykomish River, WA	20.1	60%	563	0.0034 (0.0027)	42 (28)	1,040 to 2,400	37,800 to 51,700	118,000 to 156,900
C. Clark Fork River (ID, MT)	18.6	99%	22,067	0.000045 (0.0001)	23 (21)	17,000 to 19,400	78,000	140,000
D. Lower Green River, WA	26.1	91%	462	0.0004 (0.0002)	7 (4)	1,090 to 1,210	9,200	12,810 to 13,410
E. Middle Green River, WA	14.3	81%	390	0.0025 (0.0016)	18 (9)	660 to 1,090	9,200	12,250 to 12,810

(1) From 2-year discharge energy grade line computed from baseline (ground surveyed) model

(2) Bankfull Width (BFW) and Depth (BFD) computed from 2-yr discharge max depth and width (survey model)

### SB LOW FLOW MODEL CALIBRATION

The key issues affecting the quality of the results of the SB method are determining the extent of low flow model cross sections, estimating the amount of flow present within the model at time of survey, and deciding how much to refine the model to achieve good match to the surveyed water surface elevations.

Table 2 below summarizes the error in the SB and LiDAR Only (LO) computed water surface elevations – in low flow conditions – for the five study reaches with respect to surveyed water surface elevations at each transect location in the model, after one or two calibration attempts. Calibration consisted of adjusting Manning’s n values in the channel for the low flow model to better match the LiDAR surveyed water surface. In cases where significant amounts of flow was diverted at different elevations into side channels we either isolated all the flow into the dominant channel by limiting the cross section width, or constructed a connected side channel reach. The results were compared with the surveyed water elevations, which are extracted from the low point on each model cross section. Alternatively one could have used a 2-D model to estimate water elevations in the main and side channels at low flow.

The results for all five study reaches provide excellent-to-good matches of the surveyed water elevations during low flow conditions (average difference in computed low flow elevation is less than 0.1 to 0.5 feet from surveyed

elevation). In contrast the average error using only the LiDAR data ranges from 1.8 to 5.6 feet (and more than 25 feet in the Clark Fork reservoir reach). Note that in all cases additional refinements of the SB data to better match surveyed elevations were possible, however we viewed the low flow results as favorable enough to proceed to high flow validation.

**Table 2: Low flow SB derived hydraulic model results after calibration vs. LO hydraulic model results as compared with low-flow surveyed water surface elevations**

Study Reach	A. Dungeness, WA		B. Skykomish, WA		C. Clark Fork ID, MT		D. Lower Green, WA		E. Middle Green, WA	
	SB	LO	SB	LO	SB	LO	SB	LO	SB	LO
<b>Absolute Error in Computed WSE vs. Surveyed WSE</b>	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
Median	0.03	1.81	0.46	3.12	0.66	25.84	0.07	5.61	0.22	2.12
Average	0.03	1.86	0.43	3.21	0.30	25.56	0.07	5.52	0.18	2.20
Stdev	0.29	0.48	0.47	0.91	0.62	1.63	0.41	2.05	0.36	0.79
Min	-0.7	0.9	-0.7	1.3	-0.9	17.2	-1.0	0.7	-1.5	0.6
Max	1.0	3.4	2.2	6.9	0.8	26.7	1.1	9.0	1.0	6.1
N=	145		222		42		292		185	
Reach length (mi)	2.8		20.1		18.9		26.1		14.3	

The excellent results on the 26-mile long Lower Green River reach were surprising given the tidal influence, however the survey at low tide and trapezoidal channel shape helped ensure that much of the channel conveyance area was captured in the initial terrain data. The higher-than-average errors in the Skykomish model are attributed to large uncertainties in flow at time of survey, effects of split flows around gravel bars, and errors and artifacts in the older vintage LiDAR data (trees, etc.). The excellent results for the Dungeness are partly attributed to the modern techniques used to acquire and post process the LiDAR data and the presence of a stream gage within the reach. The Clark Fork River reach – which is a backwatered canyon upstream of a dam – actually fairs better in the low flow than high flow model run (discussed in next section) because the known water surface at the downstream pool drives the water surface profile throughout the reach.

The good to excellent results over a wide range of channel sizes, slopes, and geomorphic types suggests that the SB method is capable of creating low flow hydraulic models that closely match surveyed water elevations, while preserving major geomorphic features of the channel (Figure 1D, Figure 2). Additionally, use of LiDAR data without adjustment may result in errors (under low flows) that exceed tolerances for most types of engineering studies. The effects of using unadjusted bare earth LiDAR data or SB terrain data without further parameter adjustment for flood conditions are presented in the next section.

### SB HIGH FLOW MODEL VALIDATION

To validate the SB (and LO) DEMs, baseline hydraulic models developed by others to estimate floodplain depths and elevations were modified by re-cutting all cross sections from the original LO DEM and from the SB DEM. The steady flow step backwater models were then run with the new cross section data but without any further parameter or boundary condition adjustments to determine how the errors in the underlying terrain data affected the model results for the “bankfull” 2-year (50% annual exceedance probability) and “base” 100-year (1% annual exceedance probability) flood events.

Table 3 below summarizes the error in computed water surface elevation, flow area, average channel velocity, and average channel shear stress for the five study reaches from SB-based model and LO-based model with respect to results computed from the baseline models. The error statistics shown in Table 4 represent reach averages of the cross sectional difference between the results for the SB model or LO model and the baseline model. The percent change in error in Table 3 represents the reduction in error resulting from use of the SB model vs. the LiDAR only model.

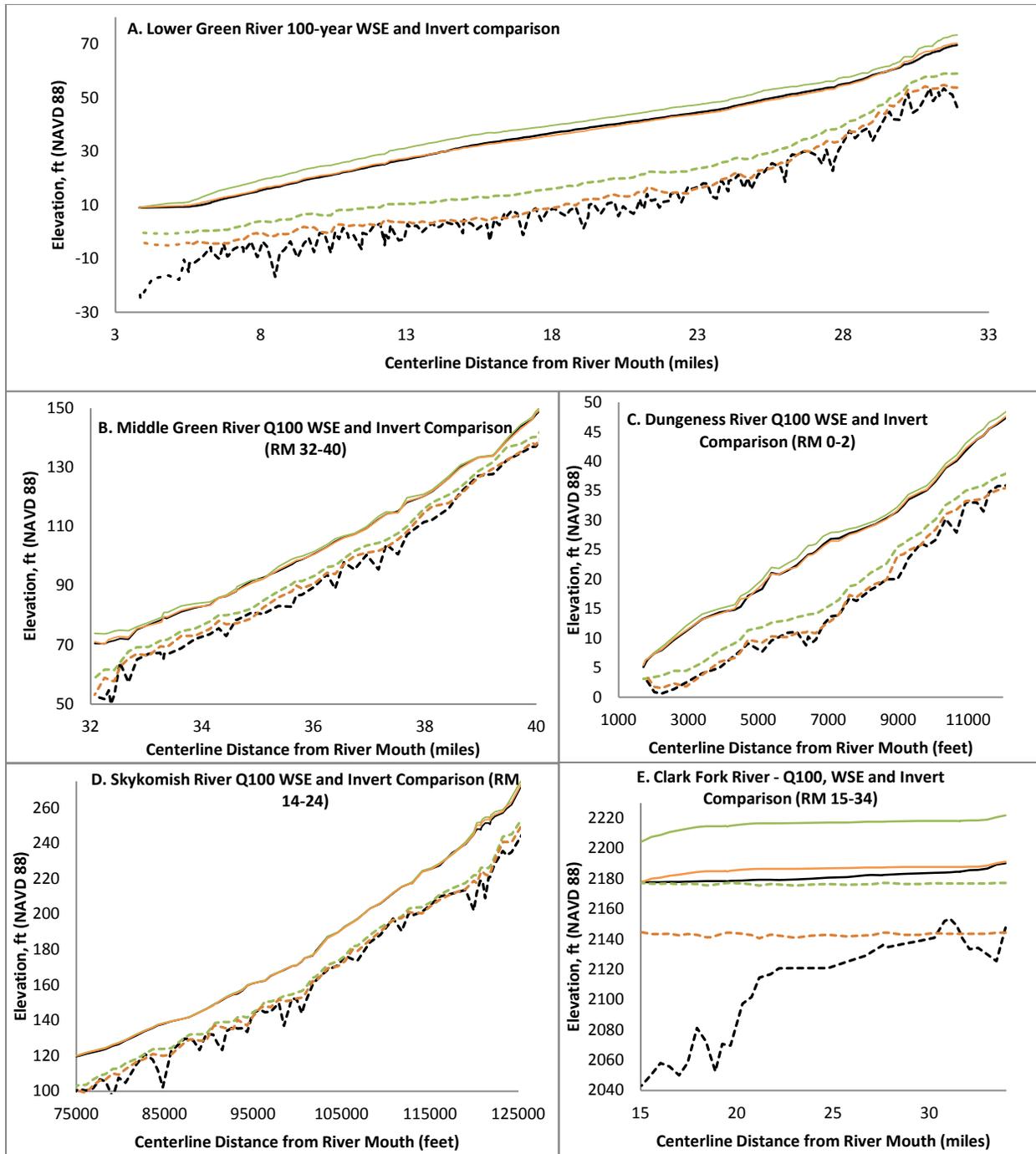
**Table 3: Study Reach Average Absolute Error Residuals in Computed WSE, flow area, velocity, and shear stress for SB and LiDAR Models with respect to Baseline Model**

Study reach	A. Dungeness		B. Skykomish		C. Clark Fork		D. Lower Green		E. Middle Green		Study Average % Change		
	SB	LO	SB	LO	SB	LO	SB	LO	SB	LO	Note 1	Note 2	
$\Delta$ 2-Yr WSE (ft)	Med	-0.2	1.2	0.4	1.1	0.7	25.8	-0.4	3.6	0.1	1.1	95%	96%
	Avg	-0.1	1.2	0.6	1.5	0.3	25.6	-0.2	3.5	0.1	1.3	92%	93%
	SD	0.3	0.5	1.0	1.2	0.6	1.6	0.6	0.8	0.5	0.9	29%	35%
	Min	-0.9	0.1	-1.4	-0.2	-0.9	17.2	-1.2	0.1	-0.9	0.1	1182%	967%
	Max	0.7	2.0	4.2	5.6	0.8	26.7	1.8	4.7	1.4	3.8	53%	62%
$\Delta$ 100-Yr WSE (ft)	Med	0.0	0.9	0.3	0.7	4.9	30.2	-0.3	3.2	0.1	1.0	90%	89%
	Avg	0.0	0.9	0.5	1.2	4.7	29.9	-0.1	3.2	0.1	1.2	87%	87%
	SD	0.3	0.4	0.9	1.2	2.0	0.8	0.6	0.7	0.4	0.9	25%	-12%
	Min	-0.6	0.1	-1.2	-0.5	0.0	26.9	-1.0	0.1	-0.8	-0.6	332%	286%
	Max	1.3	1.8	5.8	7.0	7.3	30.6	1.7	4.3	1.3	3.4	42%	49%
$\Delta$ 2-Yr Flow Area (ft <sup>2</sup> )	Med	8	74	97	480	1617	-3465	13	64	46	551	85%	97%
	Avg	0	78	210	684	-333	-6521	-31	-15	75	863	39%	50%
	SD	77	121	879	1113	20411	19031	399	708	470	1183	40%	31%
$\Delta$ 100-Yr Area (ft <sup>2</sup> )	Med	21	122	92	535	6240	-2988	12	225	33	647	89%	133%
	Avg	8	421	145	762	8950	-3256	-36	334	134	1057	94%	150%
	SD	147	2124	1174	1205	25690	7542	411	960	543	1453	54%	-5%
$\Delta$ 2-Yr Velocity (ft/s)	Med	-0.1	-0.3	-0.1	-0.3	-0.1	0.2	0.0	0.1	-0.1	-0.4	80%	90%
	Avg	0.0	-0.2	-0.2	-0.4	-0.1	0.6	0.0	0.2	0.0	-0.2	90%	95%
	SD	0.7	0.7	1.2	1.1	0.9	1.9	0.4	0.6	0.9	1.1	11%	19%
$\Delta$ 100-Yr Velocity (ft/s)	Med	-0.1	-0.4	-0.1	-0.3	-0.7	0.3	-0.1	0.0	-0.2	-0.5	224%	243%
	Avg	-0.1	-0.3	-0.2	-0.4	-0.2	0.4	0.0	0.1	-0.1	-0.3	81%	95%
	SD	0.8	0.7	1.1	1.0	2.4	0.4	0.4	0.7	0.9	1.3	13%	-94%
$\Delta$ 2-Yr Shear (lb/ft <sup>2</sup> )	Med	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50%	60%
	Avg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	6%	35%
	SD	0.3	0.3	0.7	0.7	0.1	0.1	0.1	0.1	0.4	0.4	4%	9%
$\Delta$ 100-Yr Shear (lb/ft <sup>2</sup> )	Med	0.0	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.1	73%	121%
	Avg	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	8%	32%
	SD	0.4	0.4	0.8	0.6	0.4	0.1	0.1	0.1	0.4	0.5	2%	-73%

Note 1 – Study average % change is the difference in the LO reach average error statistic and SB reach average error statistic divided by the reach average LO error statistic, then averaged for all reaches (excluding Clark Fork).

Note 2 – Study average % change includes Clark Fork.

From Table 3 we can see that the study reach median error in SB model computed water surface elevation (WSE) ranged from -0.4 feet (Lower Green River) to 0.7 feet (Clark Fork) for the 2-year event, and ranged from -0.3 feet to 4.9 feet for the 100-year event (same reaches). The Dungeness and Middle Green models have the best overall match of the baseline WSEs, with 0.2 feet or less error on average for both the 2 year and 100-year events. Figure 5 provides a representative comparison of computed water surface profiles for all study reaches. The improvement in results from use of the SB method is most pronounced for the Lower Green, Clark Fork and Dungeness, which are all highly channelized or confined. The unconfined Middle Green and Skykomish have overbank floodplains that convey much of the flood flow, causing the results to be less sensitive to use of SB data.



**Figure 5. Computed 100-year flood water surface profiles and invert elevations for A) Lower Green (RM 3-32), B) Middle Green (RM 32-40), C) Dungeness (RM 0-2), D) Skykomish (RM 14-24), E) Clark Fork (RM 15-34). Green lines reflect initial bed elevation and computed WSE from original LO data, orange lines reflect SB bed elevation and computed WSE from SB data, black lines reflect surveyed bed elevation and computed WSE from baseline RAS model. Solid lines are computed WSEs, dashed lines are invert elevations.**

The limitations and benefits of the SB method are seen from inspection of the Clark Fork results. Clearly the method cannot reproduce the river invert elevations submerged under the dam backwater, however the model still reduces average error in stage by more than 25 feet if one had used the LiDAR alone. For all but the Clark Fork the SB channel invert tracks the elevation of existing riffles quite closely, and results in hydraulic models that closely match

those of the baseline model in terms of WSE, flow area, velocity, and shear stress. Compared with models based on use of LiDAR alone, results are significantly improved for all study reaches.

The slight upward bias in flood stage resulting from the SB approach (under normal conditions) and more pronounced upward bias from use of LiDAR data without adjustment is when comparing total inundation area. Inundation area error is 0-5% in all reaches using the SB method, compared to 2-50% using the LO model. The error for the 2-year event is higher than that of the 100-year event for all but the channelized (trapezoidal) Lower Green. At higher stages the other reaches use more floodplain conveyance – which is not affected by the bathymetric data collection method.

## SUMMARY

The SB method allows for creation of reasonable synthetic channel bathymetry data from LiDAR data, flow information, and widely available GIS and hydraulic software. The quality of the results can be easily demonstrated by comparing computed water elevations and velocities to the DEM water surface elevation at time of survey and to baseline model results or to high water marks. For this study the SB method results (comparison of computed flood stage to baseline) were excellent for a short steep sediment laden river with recent LiDAR and a gage within the reach, and poor for a reach upstream of a dam where true channel depths were many times that estimated using the SB approach. For a low gradient tidal river and medium gradient gravel bed river the results were very good. On a medium gradient wandering gravel bedded river with older LiDAR and higher uncertainty over low flow discharge the data were generally good to poor in isolated areas near bridges.

For all five study reaches the SB method significantly reduces the errors resulting from use of cross sectional data derived from LiDAR alone but does not eliminate the errors. This trend of reduced error is observed for all the flows analyzed and all the hydraulic parameters analyzed, other than depth. The median and average error when compared to baseline hydraulic models was typically less than 1 foot at bankfull stages, and under ideal conditions was less than 0.5 ft at 100-year flood stages. A river reach that is significantly affected by downstream backwater caused by a dam was used to check the quality of the method under non-ideal conditions. While the stage errors at low flow were less than 1 foot, the SB method was not able to create enough conveyance to pass 100-year flood flows with less than 4.7 feet of error (reach average). While this result at first glance is poor compared with the other reaches studied, the relative reduction in error compared with using a DEM without bathymetry is about six-fold. The location within a bedrock canyon suggests the error may not be significant with respect to adjacent development.

## DISCUSSION

Under low and 2-year flood conditions we observed good to excellent matches of baseline and SB water surface elevations for all five study reaches, with the MAE of less than 1 foot for all but the Clark Fork reservoir reach. (Note that the results presented in this paper are not being compared to observed conditions at high flows which means that while the SB model results may provide a good match to the baseline model, the quality of the SB model with respect to real world conditions has only been evaluated for low flows and not under flood conditions). For nearly all flows and reaches, the results of the validation effort were surprisingly good (for the parameters that are typically meaningful for analysis and design, with the exception of maximum depth) considering that the SB based models lacked below-water survey data. This suggests that in similar conditions we would expect to have similar results, provided the quality of datasets and approach used to derive the SB data are similar.

To understand why the SB data results in a model that agrees well with the baseline, consider the significant error in maximum depth associated with models that still provided good to excellent estimates of flood stages (Figure 5) and inundation area. Concurrently, the good results of flow area, velocity, and stage shown in Table 3 (resulting from a 1-D step backwater model) suggest only reasonable estimates of cross sectional area, slope, and roughness are required. Because we are simulating physics of flow in one dimension, using open channel flow equations, all flow is assumed to be down valley, contained within banks, steady and uniform. During low flows, when LiDAR is typically acquired, these conditions are satisfied more often than not. We are simply using physical equations in the SB method (hydraulic model) to tell us how much space (area or volume) flow “takes up” at a given location. Then we are using GIS to create that space below the surface of a DEM for the river so it can pass the surveyed flow at the surveyed elevation. These results appear to confirm our primary assumption that as long as riffles are captured in the SB DEM that errors in flood stage will be small.

The quality of the results in this study are likely related to the setting and quality of the underlying data used to create the SB data. Reaches where the river was confined (Dungeness, Lower Green) with a trapezoidal cross section had the best agreement with the baseline models. The effort to create and apply SB data is significantly less than that needed to perform channel surveys. In less than one day we were able to use the technique to create a 40 mile long model that matched the baseline model computed 100-year flood elevations by less than 0.5 ft on average. While reach average hydraulic conditions computed from 1-D SB based models tracked closely with the baseline models, errors were higher at bankfull stages than at flood flows when the floodplain is active. Other difficulties were encountered where significant backwater was present, at hydraulic constrictions, and abrupt changes in grade or bed elevation. While no effort was made to calibrate the SB models to historical high water marks, we are confident that the close agreement with the baseline model results (with the exception of the Clark Fork) would allow for good calibration with reasonable parameters.

While the SB method will typically result in a DEM that includes a wider and shallower river than exists, it avoids the creation of artifacts common with using educated guesses or automated techniques to “burn” channels into DEMs from sparse survey data. For example all features above the water surface are preserved rather than “averaged out” as occurs when topography is created from widely spaced cross sections. This preserves side channels and bars that may be important for capturing flow paths or effects of macro roughness elements, however it will not capture deep pools or submerged features that may be important for habitat studies. This implies that a potential benefit of the SB approach is to improve the accuracy of a DEM (and model) between surveyed sections.

### **THE NEED FOR DUE DILIGENCE AND REFINEMENT**

This paper presents the promising results of a validation study of a method to create synthetic bathymetry for five rivers in the Pacific Northwest of varying size and geomorphic character. Until such time that the method has been validated for a wider range of channel types and rivers by other practitioners, we must recommend against applying it in cases where higher resolution survey grade data is warranted (i.e. life safety is of concern). In cases where flow data at time of DEM survey is lacking or uncertain, the SB approach will not provide reliable results, and could result in under-estimation of flood risk. Field data (discharge-elevation rating curves) may be needed to ensure the results are reasonable or to improve results. The potential cost savings of this method, while attractive, implore practitioners to collect detailed calibration and verification datasets to demonstrate the quality of the underlying SB data and model results. Models developed with this approach should be flagged as such, and a calibration and verification write-up should be included with model documentation. Before applying the SB method to a reach lacking a baseline model it is strongly recommended that one first independently validate the approach on a reach with a survey grade calibrated model to ensure that the approach is providing reasonable results. Further validation studies of the SB method with 1-D and 2-D unsteady state models are also recommended.

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