ERDC/CRREL TR-16-3

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Integrating Hydrologic Modeling, Hydraulic Modeling, and Field Data for Ordinary High Water Mark Delineation

John D. Gartner, Robert W. Lichvar, Matthew K. Mersel, and Lindsey E. Lefebvre

February 2016

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Cover image: Santa Ana River in Redlands, CA, showing one thread, about 10 m wide, of a multithreaded river that is about 300 m wide.

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Abstract

This document explores the combined use of hydraulic and hydrologic modeling for ordinary high water mark (OHWM) delineation under the Clean Water Act and for other applications. Delineation of the OHWM is primarily based on identifying and interpreting field indicators. However, field delineation can be challenging and time consuming, especially in arid and semi-arid regions where river flows are highly variable and channels are complex. Therefore, some have turned to mathematical modeling to address these challenges, yet scant information exists on the benefits and limitations of various modeling approaches for OHWM delineation. This document examines and tests the use of hydraulic and hydrologic modeling for these purposes, comparing field-delineated OHWMs with modeled OHWMs and presenting over 40 HEC-RAS and HEC-GeoRAS model runs from six sites in the southwestern U.S. The examples demonstrate that modeling is typically not effective in accurately delineating the OHWM in the absence of extensive field data; however, modeling can be effective at ruling out extreme locations (either too high or too low) that might be misinterpreted as the OHWM. This document has two companion papers on hydraulic modeling and hydrologic modeling, respectively, that help regulators and applicants to properly apply these tools for OHWM delineation purposes.

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Preface

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Acronyms and Abbreviations

CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
CWA	Clean Water Act
DEM	Digital Elevation Model
ERDC	Engineer Research and Development Center
FFA	Flow Frequency Analysis
GIS	Geographic Information System
HEC-RAS	Hydraulic Engineering Center River Analysis System
LiDAR	Light Detection and Ranging
NSF	National Science Foundation
OHWM	Ordinary High Water Mark
RTK GPS	Real-Time Kinetic Global Positioning System
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WRAP	Wetland Regulatory Assistance Program

1 Introduction

1.1 Background

Per Section 404 of the Clean Water Act (CWA), the ordinary high water mark (OHWM) demarcates the lateral extent of federal jurisdiction in non-tidal waters of the United States in the absence of adjacent wetlands. The ability to locate the OHWM is important for determining whether certain activities in and near rivers and streams—such as gravel mining; restoring stream banks; building bridges, houses, and roads; and numerous other human activities—may need to be reviewed and authorized under the CWA. Federal regulations define the OHWM as "that line on the shore established by the fluctuations of water and indicated by physical characteristics such as [a] clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas" (33 CFR 328.3).*

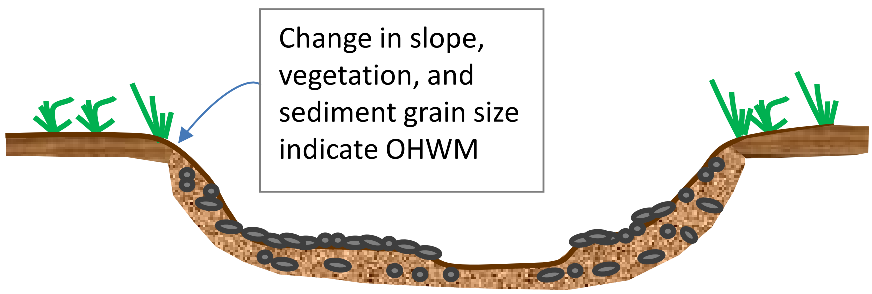
Building on the above definition, a series of manuals and reports by the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) aims to clarify procedures and to reduce some of the difficulties in delineating the OHWM in rivers and streams (Lichvar et al. 2006; Lichvar and McColley 2008; Curtis et al. 2011; Mersel and Lichvar 2014). These documents focus on using field evidence for delineating the OHWM, especially three primary indicators associated with the lateral boundaries of the active channel—topographic breaks in slope, changes in vegetation characteristics, and changes in sediment characteristics—as shown in the archetypal channel in Figure 1. In addition, these documents emphasize that OHWM delineation is principally a field-based exercise and that the OHWM is not associated with a single or universal recurrence interval of flow across different systems.

However, delineating the OHWM can be difficult, especially in arid and semi-arid systems, where channel forms can be complex and flow variability is high (Parsons and Abrahams 1994). Along a single reach, complex channel geometries can create multiple physical features that might be

* U.S. Congress. 1986. *Definition of "Waters of the United States."* Codified at 33 CFR 328.3 (et seq.). Washington, DC: U.S. Government Printing Office.

misinterpreted as indicators of the OHWM. Moreover, highly varied flow histories can make it hard to interpret the hydrology associated with various physical and biological features in the field. Arid regions typically have long intervals between high-flow events and extreme differences in flow magnitude between the lower high-flow events and the higher high-flow events (Leopold and Dunne 1978; Gartner et al. 2016b). In addition, flow histories are usually undocumented because of the lack of stream gages at most sites in the Arid West region of the U.S. (Lanfear and Hirsch 1999; Hirsch and Costa 2004).

Figure 1. A schematic of an archetypal channel that exhibits OHWM primary indicators of changes in slope, sediment texture, and vegetation.



Thus the geomorphic and hydrologic complexities of arid fluvial systems may present challenges to accurate and consistent OHWM delineation. Lichvar et al. (2006) have shown that the presence of organic litter and debris left by floodwaters is not a reliable indicator because they are often found both above and below the OHWM. By contrast, identification of the active channel boundary, as expressed on the landscape by a physical or biological signature typically composed of multiple primary indicators, has been shown to be the most robust and repeatable approach to OHWM delineation in western fluvial systems (Lichvar and McColley 2008; Curtis et al. 2011; Mersel and Lichvar 2014; Mersel et al. 2014). However, in some circumstances, complex channel systems can create in different locations multiple physical features that might be misinterpreted as indicators of the OHWM, such as two or more topographic breaks in slope or changes in vegetation or changes in sediment characteristics at a single cross section. Previous studies have not thoroughly investigated means to address this issue.

Quantitative modeling has the potential to assist with these issues; however, the previous work has not determined the efficacy of modeling for OHWM purposes. Modeling the OHWM is alluring because it could be faster and less expensive than field delineation over very large areas, and the inputs and assumptions of models can be clearly stated. In spite of some efforts to delineate the OHWM through modeling alone by applicants for permits associated with the CWA, no studies have investigated how the OHWM model results depend on model inputs, especially on the choice of discharge value and the resolution and treatment of topographic data. Overall, it has not been established whether or not modeling is even an appropriate method for delineating the OHWM because of the inherent simplifications and assumptions required in models of natural systems.

1.2 Objectives

This report aims to help regulators and applicants understand the potential benefits and limitations of modeling in relation to OHWM delineation. The goal is not to train practitioners in how to perform hydraulic or hydrologic modeling; instead, the goal is to inform practitioners to better interpret and apply modeling results appropriately.

1.3 Approach

This report examines and tests different types of modeling that could be applied to OHWM delineation. It focuses on three of the most important questions:

- First, how do model choices and the resolution of the topographic inputs affect the ability of models to predict the OHWM?
- Second, can hydraulic models be coupled with flow frequency analysis to determine the OHWM in the absence of detailed field reconnaissance?
- Third, can modeling be used to rule out locations that might be misinterpreted as the OHWM?

The primary findings are that modeling is typically not effective in delineating the OHWM in the absence of field data but that modeling can provide further supporting information to rule out extreme locations (high or low) that might be misinterpreted as the OHWM.

2 Summary of Companion Reports

This document is the third of a three-part series on the benefits and limitations of modeling for OHWM delineation purposes. The first focuses on hydraulic modeling (Gartner et al. 2016a), and the second focuses on hydrologic modeling and flow frequency analysis (Gartner et al. 2016b). This third document builds on the detailed analysis and model testing of the other two documents to examine and test how hydraulic and hydrologic modeling used in conjunction can and cannot be applied to OHWM delineation. The first two documents in this three-part series are summarized below.

2.1 The Benefits and Limitations of Hydraulic Modeling for Ordinary High Water Mark Delineation

The first document (Gartner et al. 2016a) defines and examines how hydraulic modeling can assist with OHWM delineation in rivers and streams. Computational hydraulic modeling simulates the water surface elevation for a given discharge. Hydraulic models use a set of algebraic and differential equations based on fundamental physical processes, such as Newton's laws of motion, or well-established empirical relations, such as the Manning equation. The models convert a measured or estimated input (e.g., geometry, discharge rate, and channel roughness) into an output (e.g., water elevation and flow velocity). These models usually make certain assumptions to simplify the calculations, such as assuming that the water flows only directly downstream and that the water surface elevation varies in only the downstream direction, not from one side of a channel to the other (Novak et al. 2010).

Gartner et al. (2016a) also demonstrates that one-dimensional models, such as the Manning equation, the Hydraulic Engineering Center River Analysis System (HEC-RAS), and HEC-GeoRAS, are the most suitable choices if one were to model the OHWM because one-dimensional models have reasonable data requirements and long-standing records of use in simulating water elevations. Two-dimensional and three-dimensional models are too data-intensive and costly to merit modeling OHWM over delineating OHWM in the field. In all cases, model results must be field verified. Model uncertainty can arise from choosing incorrect roughness values and downstream boundary conditions. However, the extents of modeled water surfaces (that is, the results or model output) are more dependent on the topographic input and the chosen edge of the model, such as which areas of a multi-threaded channel are included or not.

2.2 Hydrologic Modeling and Flood Frequency Analysis for Ordinary High Water Mark Delineation

The second document (Gartner et al. 2016b) tests modeling techniques for estimating flow frequencies (also known as recurrence intervals) and assesses their utility for OHWM delineation. The goal of flow frequency analysis is to determine how often flows of various magnitudes occur, for example, the peak flow that occurs once every 5 years on average. There are three primary ways to determine flood flow frequencies, each with its benefits and limitations: (1) stream-gage analysis, (2) regression equations, and (3) rainfall-runoff modeling. Under a broad view, these are all hydrologic models in that they use a set of inputs (such as stream- or rain-gage records or watershed characteristics) to mathematically compute a desired hydrologic result (in this case, recurrence-interval estimates of high flows).

In general, flow frequency analysis is suitable for order-of-magnitude estimates of flood flows; and recurrence intervals are one of the primary ways with which hydrologists, planners, and engineers characterize high-flow events. For example, it is often helpful to know whether the 5-year recurrence-interval flood event is 10 or 1000 m^3/s.

It is well established that the OHWM is not associated with a specific flood recurrence interval; however, a study of 14 sites across the western U.S. shows that recurrence intervals corresponding with the OHWM range from approximately 1.1- to 10-year recurrence-interval peak flow with a potential 15.5-year recurrence-interval flow at one site (Curtis et al. 2011). This is a wide range, and the findings do not account for the high uncertainty in flow frequency analysis. Accordingly, it is unreasonable to associate the OHWM with a single characteristic discharge recurrence interval. It is even less reasonable to use this discharge as the input to a hydraulic model to compute the OHWM location.

Nevertheless, this range of observed recurrence intervals offers a preliminary estimate for the bounds on what is considered reasonable for the OHWM. For example, the 50-year recurrence-interval flow is likely too high to reasonably be associated with the OHWM. Likewise a flow below the lower confidence limit of the 1.1-year recurrence-interval flow is generally too low to be associated with the OHWM.

The overarching conclusions of Gartner et al. (2016b) are the following:

- There are multiple ways to estimate recurrence intervals. Each technique will give slightly different answers, and each technique has its own benefits and limitations.
- In most cases, regional regression equations are the first choice for estimating flood recurrence intervals for OHWM purposes, unless there is a gage at the site, in which case Log-Pearson Type III analysis may be preferred because of the narrower confidence intervals.
- The limited utility of flow frequency analysis in OHWM delineation is due partly to the inherent uncertainty in determining flow recurrence intervals.
- Despite this uncertainty, flow frequency analysis can assist with OHWM delineation in some circumstances.

3 Site Description and Methods Overview

This study focuses on six sites across southern California, Arizona, and New Mexico (Table 1) that are typical of streams in the Arid West environment. The sites also have nearby U.S. Geological Survey (USGS) stream gages and a recent history of OHWM measurements (Lichvar et al. 2006; Curtis et al. 2011). Similar to other Arid West rivers, the studied rivers have (a) highly variable flow, (b) riparian vegetation that is clearly distinct from upland species, and (c) complex channel systems. The studied rivers exhibit low-flow channels, active channels, and floodplains. Most exhibit a multi-threaded channel form with subsidiary channels. These subsidiary channels may occasionally contain flows in current or recent time periods, or they may be relict channels that no longer contain flows even in extreme events. These complex channel patterns are common in rivers with high sediment loads, especially when they drain from mountainous topography to broader valleys.

Table 1. Site locations.

Site Name	Location	USGS Gage ID	Drainage Area (km^2)	OHWM Discharge* (m^3/s)	Topographic Data		
					10 m DEM	Cross Section	LiDAR†
Cristianitos	San Clemente, CA	11046360	82	46	x	x	
Mission	Desert Hot Springs, CA	10257600	92	18	x	x	x
New River	Rock Springs, AZ	9513780	177	43	x	x	
Dry Beaver	Rimrock, AZ	9505350	368	223	x	x	
Mojave	Afton, CA	10263000	5493	340	x		x
Rio Puerco	Bernardo, NM	8353000	19036	176	x		

* The discharge associated with the OHWM at these particular sites as determined by Curtis et al. (2011)

† Light detection and ranging

Throughout, this study compares modeled OHWM locations with field-delineated OHWM locations and considers the field-delineated OHWM to be the true location of the OHWM at the time of the field visit. Standard methods defined by Lichvar and McColley (2008) were used to determine the field-delineated OHWM based on the three primary indicators associated with the lateral limits of the active channel—topographic breaks in slope, changes in vegetation characteristics, and changes in sediment characteristics. The field delineations were reinforced through examination of current and historical satellite imagery. Field visits occurred in summer 2012, and study reaches were 100 to 500 m long. Note that the OHWM delineations presented here were performed solely for the purposes of this study; furthermore, determining whether any stream is a jurisdictional water of the United States is beyond the scope of this study and involves further assessment in accordance with regulations, case law, and clarifying guidance.

The assessment used two types of hydraulic models to determine the modeled OHWM: HEC-RAS and HEC-GeoRAS. These two models use the same computations to determine water surface elevations and extents. They differ only in how the data are entered and displayed. HEC-RAS uses topography from cross sections, and the output is limited to the cross-section locations. Thus, the result of the modeled water boundary is displayed as points on the cross sections with no explicit information between cross sections.

In contrast, HEC-GeoRAS is a HEC-RAS model that interfaces with ESRI ArcGIS. HEC-GeoRAS can be used to extract cross-section topography from digital elevation models (DEMs) in the ESRI ArcGIS program. After the hydraulic computations are completed, the program can merge the modeled water surface with the DEM to display the water boundary in the terrain between cross sections. Thus, the result of the modeled water boundary is a polygon or group of polygons. Both HEC-RAS and HEC-GeoRAS are one-dimensional models in that they simulate changes in flow hydraulics in only one direction—downstream. However, HEC-GeoRAS results can be viewed in three-dimensional space when the output is draped over a DEM.

To compare different types and resolutions of input data, the topography required for the models was obtained in three ways. First, 1/3 arc-second DEMs were downloaded from the National Elevation Dataset (USGS 2014). These have a grid size of approximately 10 m and are referred to here as the 10 m DEMs. Second, during the summer 2012 field visits, high-resolution topography was measured at cross sections by using a real-time kinetic global positioning system (RTK GPS) with sub-10-cm precision in the horizontal and vertical dimensions. Third, this study used 2005 LiDAR data that produced a 1 m gridded DEM with sub-10-cm precision in the vertical and horizontal dimensions available for the Mission Creek and

Mojave Creek sites (Lichvar et al. 2006). The Manning's roughness coefficient, *n*, was also estimated in the field.

The discharge value is another key variable tested in these model runs. One set of model runs used the discharge corresponding with the OHWM at these particular locations as determined by Curtis et al. (2011), who measured the OHWM elevation adjacent to gages at these sites and determined the discharge based on the gages' stage-discharge relationship, also known as the rating curve. An exception was Mojave Creek, where the field-delineated OHWM was not reported. Instead, at this location an alternate discharge reported by Curtis et al. (2011) based on the discharge of the last high-flow event measured at the gage was used. At the other sites in their study, the discharge of the last high-flow event was typically the same order of magnitude as the field-determined discharge. While the OHWM elevation may have changed since the Curtis et al. (2011) fieldwork, which was conducted in 2010, the discharge associated with the OHWM (in terms of m^3/s) was likely unchanged at the time of the additional 2012 fieldwork.

Another set of model runs varied the discharge in the model to examine how flow frequency analysis might be used to delineate the OHWM. Because data from Curtis et al. (2011) suggest the discharges associated with the OHWM could be between the 1.1-year and 15-year recurrence intervals, these runs modeled the lower 90% confidence limit of the 1.1-year flow and the upper 90% confidence of the 15-year flow. They produced the flow frequency analysis narrow and wide simulations.

A final set of model runs examined whether modeling can help to rule out questionable OHWM locations. These runs used topography derived from the field-surveyed cross sections and varied the flow amount iteratively until the flow levels matched the elevations of the points of interest. Then Log-Pearson Type III analysis of the gage data determined the recurrence intervals of these flows.

Initially, model parameters were set at standard values as is typically done in a model that is not fine-tuned to a location and where all other model inputs are known. Steady flow analysis was used, and the contraction and expansion coefficients were set at 0.1 and 0.3, respectively. The downstream boundary condition was set as critical depth, though this boundary has little effect on upstream locations in these rivers (Gartner et al., 2016a). Manning roughness coefficient, n, was set at 0.04 and 0.08 for the vegetation-free and slightly vegetated areas, respectively, following tabulated values in Brunner (2010). These are average values for these types of locations. In one set of model runs, Manning's n was adjusted in an attempt to best match the model output with the field-delineated OHWM.

The following sections include additional details on the methods where pertinent.

4 Model Choices and Topographic Inputs

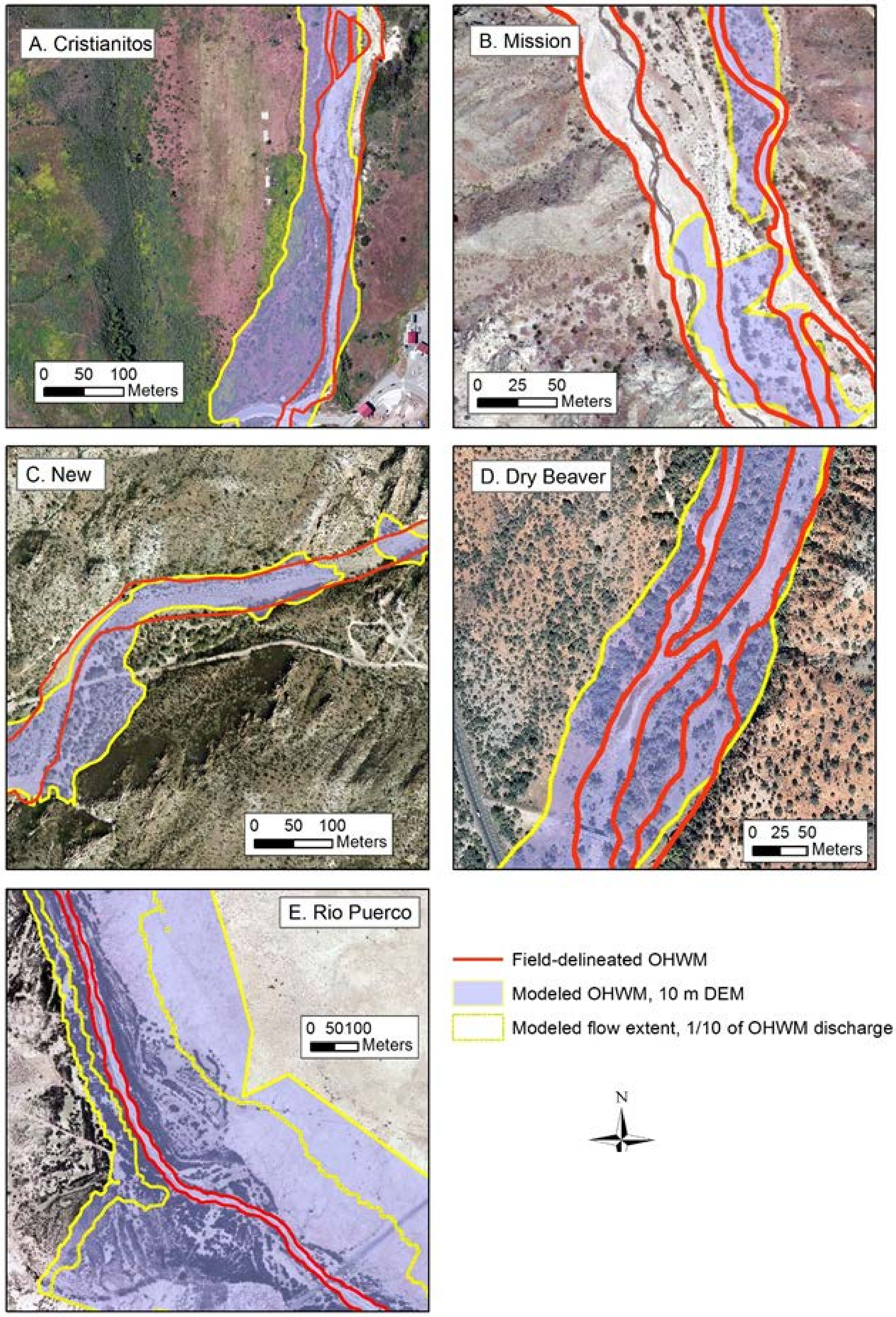
This section reviews tests of whether the OHWM location can be predicted through hydraulic modeling if the discharge associated with the OHWM is known at nearby locations on the river. The OHWM discharge was determined by Curtis et al. (2011) at USGS stream gages located at or within a few hundred meters of the study sites. This flow is the input flow for the hydraulic models. The ERDC team compared the modeled locations of the OHWM with field-delineated locations of the OWHM; examined choices in model type, comparing HEC-RAS and HEC-GeoRAS; and evaluated choices in model inputs, especially topography and model boundaries. The study used three types of topographic input: 10 m DEMs, high-precision cross-section surveys, and 1 m LiDAR DEMs. This tests how well modeling simulates the OHWM boundary at the gage and how well modeling predicts the OHWM boundary when extrapolating this flow to different locations.

4.1 10 m DEMs

These model runs compute water surface extent and elevation using HEC-GeoRAS with 10 m DEMs as the topographic input. These topographic data were tested because they are freely available throughout the U.S. (USGS 2014), and one may be tempted to use them for a broad-brush delineation or to determine locations to focus field investigations. Given the resolution of the topographic data, it is a foregone conclusion that these models are unable to delineate the OHWM at a resolution better than 10 m. Yet the difference between modeled and field-delineated OHWM can be greater than 100 m.

Figure 2 shows the field-delineated (red line) and modeled OHWM (yellow line and light blue shading). In the field-delineation, at some locations, high ground existed mid-channel with primary indicators (changes in slope, vegetation, or sediment) around this higher ground. These were “islands” above the OHWM but set within the broader field-delineated OHWM.

Figure 2. Field-delineated (*red line*) OHWM vs. a model-predicted (*yellow line and light blue shading*) OHWM that uses 10 m DEM topography in HEC-GeoRAS.



The modeling results show that the 10 m DEM topographic data are unsuitable for modeling the OHWM. In some locations, the model-predicted OHWM is only a few meters from the field-delineated OHWM. However, in other locations the results show discrepancies of up to 100 m (Figure 2). For example, Figure 2B shows modeled OHWM boundaries that are up to

75 m from the field-delineated OHWM, and in places there is no overlap between the modeled and field-delineated OHWM.

The Rio Puerco site exemplifies how inaccurate this type of modeling can be compared to field delineati0n (Figure 2E). Prior to the modeling, this site appeared likely to produce the best results because it has a single-thread channel with steep banks at the OHWM location. In a steep sided channel, slight changes in modeled water elevation should not change the modeled water width greatly. However, the overbank areas and adjacent uplands are relatively flat surfaces, and the water elevation computed by the model spilled far out onto these surfaces. Because the model results matched the field-delineated OHWM so poorly, another model was run at 1/10 of the discharge Curtis et al. (2011) associated with the OWHM. Even this produced a modeled boundary 100 m or more from the field-delineated boundary.

In some locations, the model results indicate disconnected water bodies with no apparent way for water to flow to or from the separate polygons (see Figure 2B and C). This is an artifact of how the flow levels are incorporated with the DEM topography in HEC-GeoRAS. The model computes a water elevation at several cross sections along the stream and then interpolates a water-surface plane between cross sections. This plane is then compared with the DEM. Areas of land that are lower than this plane are shown as inundated, and areas that are above this plane are dry. The model does not compute how water gets from one location to another. It computes only how deep the water would need to be at each cross section to convey the flow. This is further evidence that the 10 m DEMs are unsuitable inputs for OHWM modeling and also that HEC-GeoRAS can produce physically unsound results between cross sections.

If one were to use this type of modeling even as just a rough estimation of the OHWM, some areas would be missed. Table 2 summarizes the areas of field-delineated and modeled OHWM. The modeled areas are generally greater than the field-delineated areas. However, the modeled areas never fully encompass the field-delineated areas.

Table 2. Areas of field-delineated and modeled OHWM at study reaches.

Site	Reach Length (m)	Area (m^2)		
		Field Delineation	Modeled (10 m DEM)	Overlap (Field and 10 m DEM Modeling)
Cristianitos	550	19,140	49,585	15,258
Mission	290	12,053	11,283	3,895
New	675	35,768	53,667	28,439
Dry Beaver	450	22,884	52,089	21,676
Rio Puerco	1150	23,708	68,828	23,708

4.2 High-resolution cross-section data

This set of model runs investigates HEC-RAS modeling of the OHWM by using topography input from the cross sections measured in the field. The first set of model runs uses the entire width of the measured cross sections. The next run incorporates field evidence such as high water marks and natural levees to improve the models by adjusting the model boundaries—omitting or including subsidiary channels in these complex channel systems. This is the level of calibration that would be expected if the OHWM were not known. Then, the models were further calibrated by adjusting Manning's *n* to attempt to best simulate the field-delineated OHWM and to examine if it is possible to model the OHWM at all.

Using the entire width of the field-surveyed cross sections, the modeled OHWM locations average 5.7 m lateral distance from field-delineated OHWM location (Figure 3; Table 3). However, there are some locations where this distance is up to 60 m. For consistency, the calculations include the distances on the outermost OHWM location, even if there are "islands" that are above the OHWM in the field delineation or model prediction.

Models using cross-section topography far outperform models using 10 m DEM topography, but there are two main disadvantages. First, the improvement in modeling accuracy comes at the expense of several days of work for each site, including surveying in the field and modeling in the office. Another downside of these models is that they simulate the OHWM at the cross sections only, without explicit information on how to interpolate between cross sections. For this reason, the OHWM boundaries are marked as dots along the cross sections in Figure 3. Accurately interpolating model results between cross sections would require analysis of aerial photographs and topography on the ground, which largely defeats the purpose of trying to model the OHWM remotely.

The locations with the greatest difference between the modeled and field-delineated OHWM occur where the topography is relatively flat or there are complex channels. A slight difference in the modeled water elevation can induce a relatively large increase in the modeled inundated area, as is the case for the middle cross sections at Cristianitos Creek (Figure 3A). Note the large difference in the width of the OHWM at two adjacent cross sections.

Figure 3. Field-delineated OHWM vs. a model-predicted OHWM that uses high-precision cross-section topography in HEC-RAS.

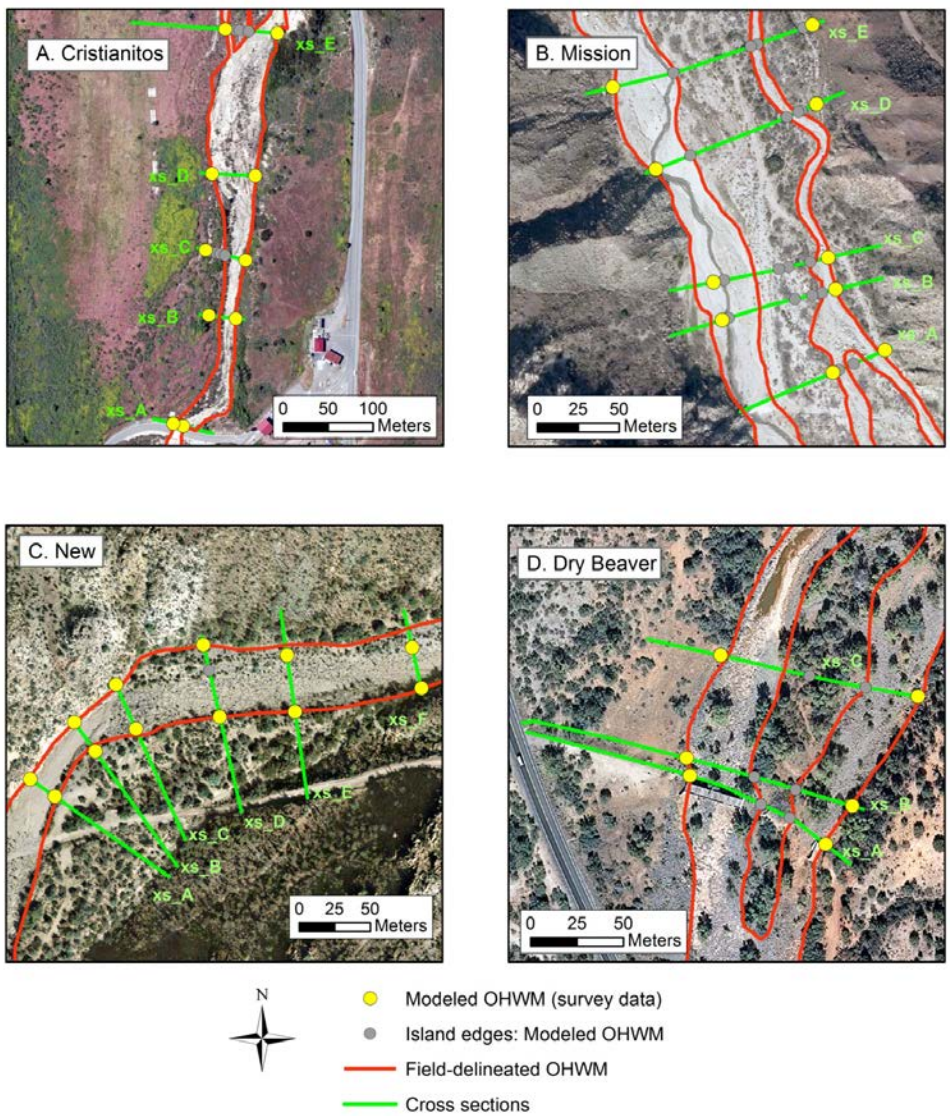


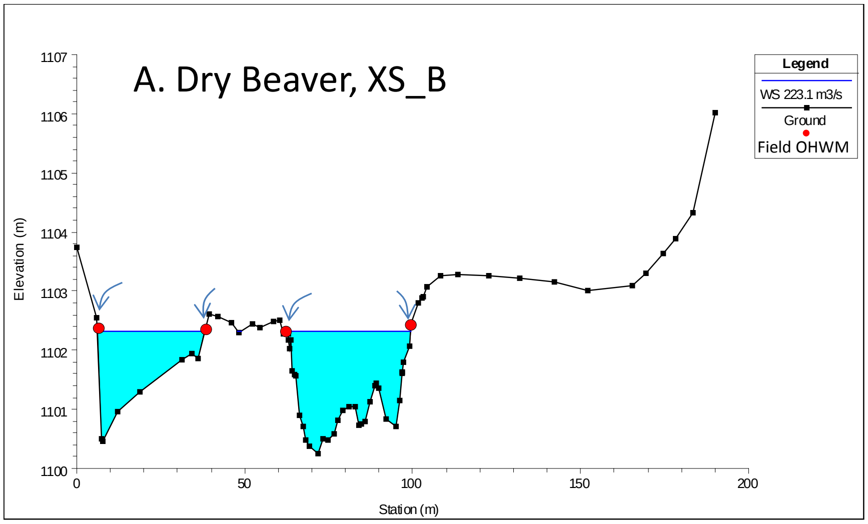
Table 3. Distances between field-delineated OHWM and modeled OHWM based on high-precision cross-section topography in HEC-RAS.

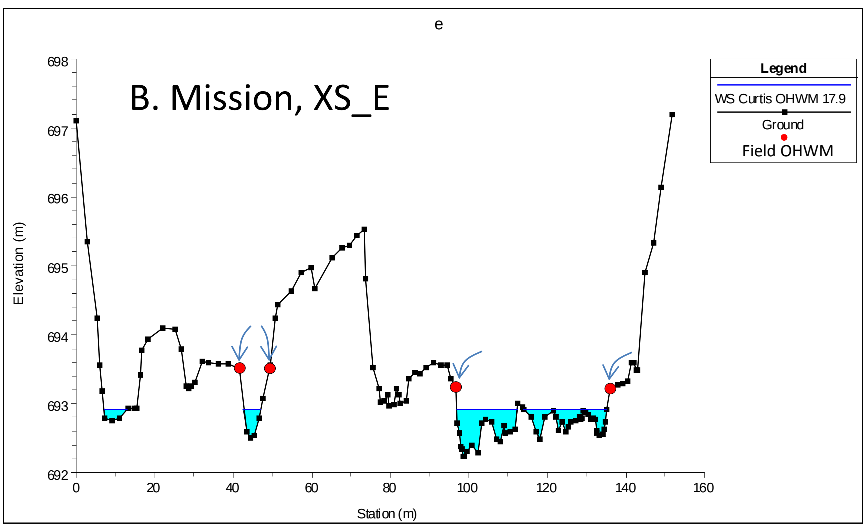
Site	Cross Section	West Bank (m)	East Bank (m)
Cristianitos	xs_A	0.0	0.0
	xs_B	11.9	0.8
	xs_C	22.7	1.1
	xs_D	0.5	0.0
	xs_E	1.0	1.3
Mission	xs_A	60.0	3.0
	xs_B	7.1	0.2
	xs_C	11.6	0.4
	xs_D	2.4	12.2
	xs_E	1.5	32.7
New	xs_A	0.1	2.2
	xs_B	0.1	4.5
	xs_C	2.4	5.3
	xs_D	0.3	0.2
	xs_E	7.5	0.4
	xs_F	14.0	0.2
Dry Beaver	xs_A	0.3	0.6
	xs_B	1.8	0.9
	xs_C	3.6	1.5
Average		5.7	
Minimum		0.0	
Maximum		60.0	

These model runs use the field-surveyed cross-section topography and flow values from Curtis et al. (2011). For consistency, islands were not considered. The values represent the distance between the outermost boundaries of the field-delineated and modeled OHWMs.

At other locations with subtle topography, such as at Cristianitos and elsewhere, there are mid-river islands, slightly higher than the OHWM. In some cases the model predicts the island locations within a few meters of the field delineation, as at Dry Beaver (Figure 4A). In other locations, the modeled island locations do not match the field delineation, as at Mission Creek (Figure 4B). Here, the field delineation indicates one island approximately between stations 55 and 95 m, but the modeled flow shows two islands approximately between stations 15 and 43 m and between stations 48 and 95 m. The islands create two issues. First, the flow hydraulics around these features are complex, perhaps better simulated by two-dimensional models, which are typically much more time and labor intensive than one-dimensional models (Gartner et al. 2016a). Second, interpolating the OHWM between modeled cross sections is especially difficult because of subtle but important changes in topography.

Figure 4. A cross-sectional view of field-delineated OHWMs vs. OHWMs modeled using cross-section topography and HEC-RAS. The edges of the field-delineated OHWM are marked by *arrows*, and the *black line* shows the cross-section topography. The modeled OHWM level is shown by the *blue line*, and the edges of the modeled OHWM are located where the *blue lines* meet the *black lines.*





When using the entire width of the cross section at Mission Creek, a subsidiary channel on the eastern side of the valley creates a large error in the modeled OHWM (Figures 3B and 4B). During field reconnaissance, it was observed that the subsidiary channel would be occupied only during high flows. The upstream entrance to this channel is higher than the low-flow channel within the main channel; and further downstream, there is high ground separating the subsidiary flow path from the main channel along the study reach. This creates an island that is above the OHWM between the main channel and the subsidiary channel. However, the subsidiary high-flow path to the east is actually lower than the main channel along the lower end of the study reach. Thus, the model shows this channel filling before the main channel in some cross sections, causing complications in the model. An additional complication is that the USGS stream gage measures flows from only the main channel (west side) because of this berm; and therefore, the discharge associated with the OHWM by Curtis et al. (2011) characterizes the flows only in the main channel on the west side of the valley.

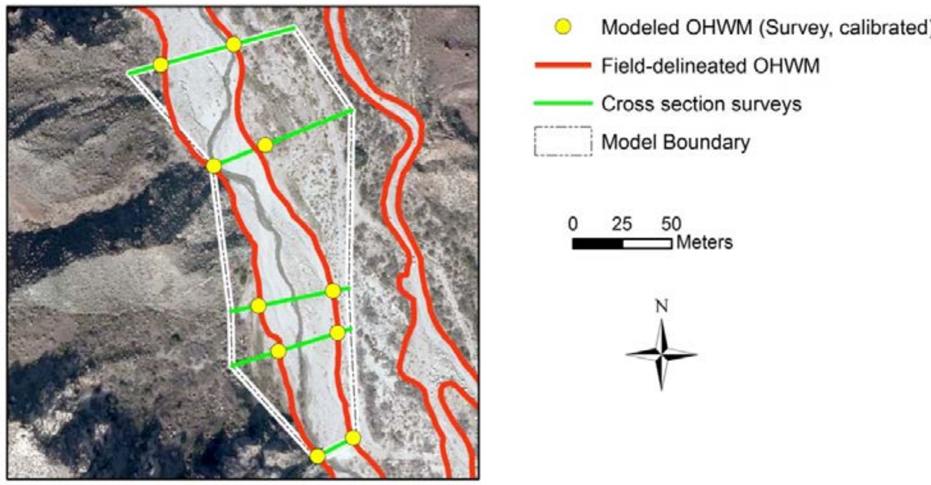
Using this field evidence dramatically improves the Mission Creek HEC-RAS model of just the main channel by adjusting the model boundary. This comes at the expense of modeling the OWHM in the subsidiary model—it is excluded from this deeper analysis. When the model boundary is set along the island separating the main channel from the subsidiary channel, the distance between the modeled and field-delineated OHWMs averages 1.3 m (Table 4; Figure 5) as opposed to averaging 13.1 m when the entire valley bottom was modeled (based on data in Table 3 for Mission Creek). Furthermore, when the model was run with the relatively low discharge at the time of the field visit, 0.03 m^3/s, the modeled flow and the observed flow match within 10 cm in the vertical dimensions and within 0.5 m in the horizontal dimension. This shows that a critical aspect of these models is the decision about which areas to include or not include in the model. Moreover, it stresses the importance of field reconnaissance, in this case to assess model results and to support decisions about the model boundaries.

Table 4. For Mission Creek, distances between field-delineated OHWM and modeled OHWM based on high-precision cross-section topography in HEC-RAS and a revised model.

Site	Cross Section	West Bank (m)	East Bank (m)
Mission (revised model boundary)	xs_A	0.3	0.4
	xs_B	0.8	0.7
	xs_C	1.0	0.4
	xs_D	1.8	5.3
	xs_E	1.8	0.7
Average		1.3	
Minimum		0.3	
Maximum		5.3	

The values represent the distance between the outermost boundaries of the field-delineated and modeled OHWMs. For consistency, islands boundaries were not considered. These model runs use the field-surveyed cross-section topography from this study and flow values from Curtis et al. (2011).

Figure 5. Field-delineated OHWMs vs. modeled OHWMs using cross-section topography and a calibrated HEC-RAS model focusing on the main channel to the west.



All the previous model runs tested how well modeling predicts the OHWM if the OHWM is not known a priori, as one would do in a real-world application of modeling the OHWM; but model runs are also able to test how much the models need to be calibrated to make the model-predicted and field-delineated OHWMs match. Of course, these fine-tuning adjustments would not be possible if the field-delineated OHWMs were not already surveyed in the field. There are many ways to adjust the models and a vast number of solutions given the number of cross sections and variables that can be adjusted at each cross section, such as discharge, contraction and expansion coefficients, model boundary, etc. The calibration process was restricted solely to adjusting only Manning's *n* for each cross section. Table 5 shows the initial and adjusted *n* values to make the modeled water elevation match the field-delineated OHWM elevation on each bank. In several cases, the *n* values are within the expected range of 0.02 to 0.08 for channels of these types; however, there are many locations where changing the *n* value alone was insufficient.

Table 5. Adjusted *n* values and field-delineated OHWM for east and west sides of the channel.

Location	Cross Section	Initial *n* Value*	Adjusted *n* value		Field OHWM Elevation		
			East OHWM	West OHWM	East Side	West Side	Difference
Cristianitos	xs_A	0.04	†	†	‡	‡	
	xs_B	0.04	0.022	0.042	31.44	31.10	0.34
	xs_C	0.04	†	0.059	§	31.74	
	xs_D	0.04	0.022	†	32.08	§	
	xs_E	0.04	†	0.040	§	33.22	
Mission	xs_A	0.04	†	†	‡	§	
	xs_B	0.04	†	> 0.1	§	687.08	
	xs_C	0.04	0.041	†	687.75	§	
	xs_D	0.04	> 0.1	†	691.05	§	
	xs_E	0.04	> 0.1	>0.1	693.26	693.23	0.03
New	xs_A	0.04	> 0.1	†	674.72	§	
	xs_B	0.04	> 0.1	†	674.91	§	
	xs_C	0.04	> 0.1	†	675.17	§	
	xs_D	0.04	†	>0.1	§	675.57	
	xs_E	0.04	0.080	0.076	675.98	675.96	0.02
	xs_F	0.04	†	0.061	§	676.52	
Dry Beaver	xs_A	0.04	†	†	§	§	
	xs_B	0.04	0.040	†	1102.32	§	
	xs_C	0.04	0.051	0.054	1103.44	1103.48	0.04

* Manning's roughness coefficient, *n*, is unitless.

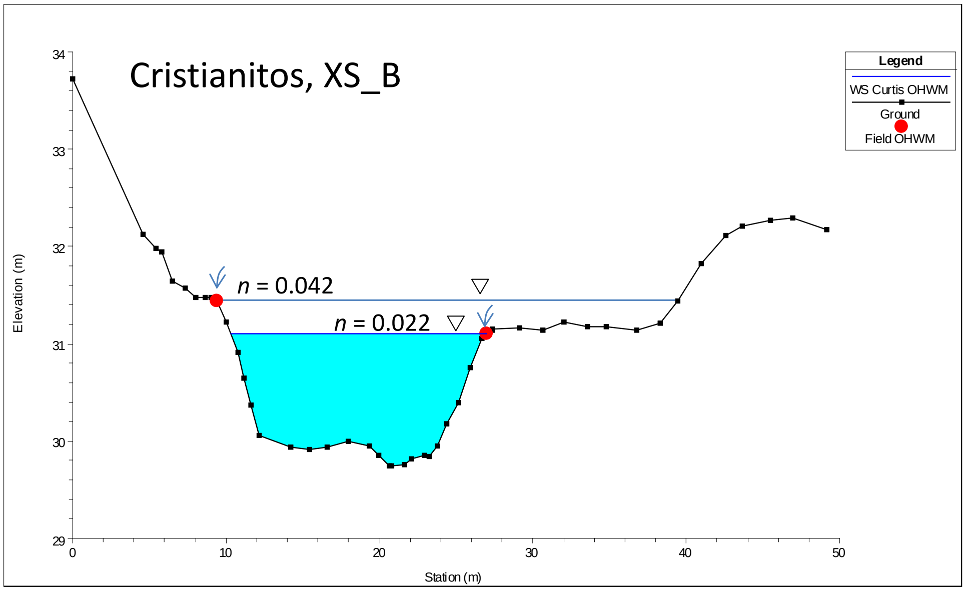
† Fine-tuned *n* value not computed because OHWM exact elevation unclear.

‡ Concrete weir or bridge abutment, OHWM exact elevation unclear.

§ Near vertical bank, OHWM exact elevation unclear.

Two characteristics are evident in these data. First, the field data indicate that when the elevation of the OHWM mark is clear on both sides of the channel, the OHWM elevation is between 0.04 and 0.34 m higher on one side of the channel than on the other. Figure 6 depicts an example from Cristianitos Creek that requires an *n* value of 0.022 to simulate the OHWM on the right side and an *n* value of 0.042 to simulate the OHWM on the left side. This elevation difference may be because fast-moving waters are often uneven and higher on one side of the channel than on the other. It may also be because the OHWM is not established by a single flow event but by recurring high flows.

Figure 6. Adjusting *n* values to calibrate a HEC-RAS model to field-delineated OHWMs at different elevations across a channel.



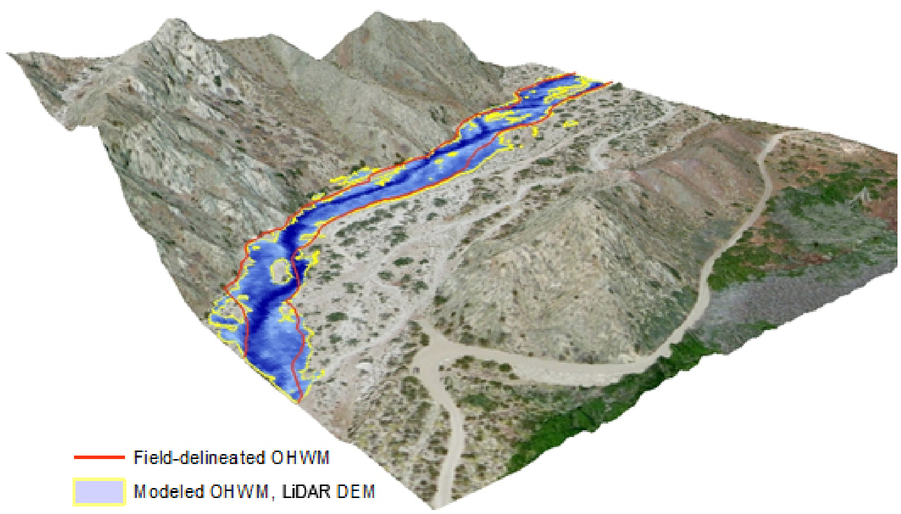
Second, in many locations, the models could not simulate the OHWM elevations by increasing the *n* value alone, as noted where the adjusted *n* value is greater than 0.1 (Table 5), above the range for channels of these types. It may be that the modeled discharge was too small or that other adjustments to the model would need to be made, such as surveying more cross sections. It could also be that the channel bed had eroded before the field visit and that the expressions of the OHWM lag some channel changes. In any case, this points to the inherent challenges in modeling the OHWM; and it also highlights the sensitivity of model outputs to the chosen inputs. It appears that the models accurately predicted the lateral location of the OHWM only when the vertical elevation was not crucial, such as on steep banks.

In sum, these model runs begin with high-resolution cross-section topography and, based on field evidence, are successively calibrated by adjusting model boundaries and then adjusting Manning's *n*. Using high-resolution topography data greatly increases the accuracy of the model results compared to using the 10 m DEMs. However, even in a best-case scenario, there are still deficiencies in how accurately the models simulated the OHWM at the cross sections. Furthermore, the models do not simulate the OHWM between cross sections, and interpolating between cross sections can be difficult.

4.3 LiDAR data and the importance of field reconnaissance

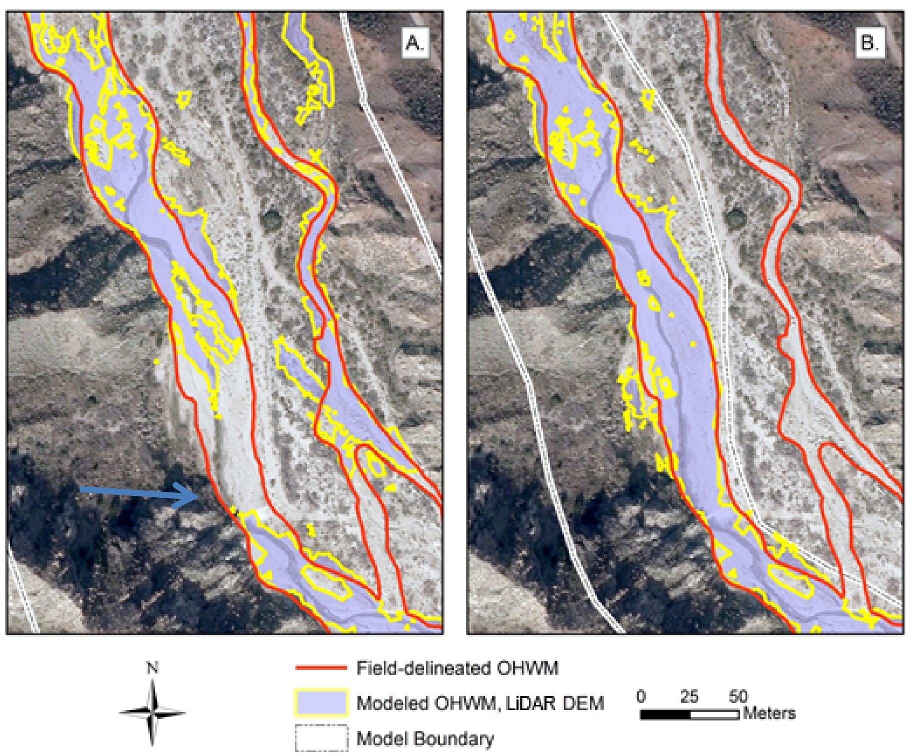
This section uses topography input from LiDAR to investigate how HEC-GeoRAS models perform in the complicated, multi-thread channel system at the Mission Creek site. Currently, LiDAR data provide some of the highest-resolution topographic data that is available in gridded format. Cross-section measurements can sometimes provide more precise topographic data along the line of the cross section, but it is usually impractical to survey multiple points in every square meter of a study area, as airborne LiDAR does. The gridded data allow the model to simulate the OHWM boundary between cross sections, even though flow hydraulics are computed only at the cross sections. A fly-by perspective of the modeled OHWM boundary on the landscape can be created in ArcGIS (Figure 7). The advent of LiDAR has transformed the study of rivers. Unfortunately it is costly and only rarely available. Its use will increase as more datasets become publicly available and as states, counties, and the National Science Foundation (NSF) collect LiDAR data (NSF 2014).

Figure 7. Created using LiDAR topography in HEC-GeoRAS, an oblique perspective of the modeled OHWM in the main channel at Mission Creek.



The first model run with LiDAR at Mission Creek allows the model to run across the entire valley bottom. This does not incorporate information from the detailed field reconnaissance performed in summer 2013. This model run uses only remotely sensed topography collected in 2005, a known discharge associated with the OHWM from previous work (Curtis et al. 2011), and standard values for other model parameters. There were no extreme flows between these dates that would dramatically alter the channel morphology. The model result is clearly incorrect (Figure 8A). In the areas where the subsidiary flow path is lower than the main channel as described above, the modeled OHWM is up to 90 m from the field-delineated OHWM in the main channel (marked by blue arrow). Furthermore, the modeled water path jumps from the main channel to the subsidiary channel with no apparent connection. Of course this is not physically possible, but the calculations of the model do not consider how water gets from one location to the next. Instead, the model calculates water filling from the lowest point at each cross section up to the elevation required to convey the flow at that cross section. This model run exemplifies the importance of field validation of model results and shows that modeling using only remotely sensed data can be very misleading.

Figure 8. For Mission Creek, field-delineated OHWMs vs. modeled OHWMs using LiDAR topography and a HEC-GeoRAS model: (A) using the entire valley width and (B) focusing the model on the main channel on the west.



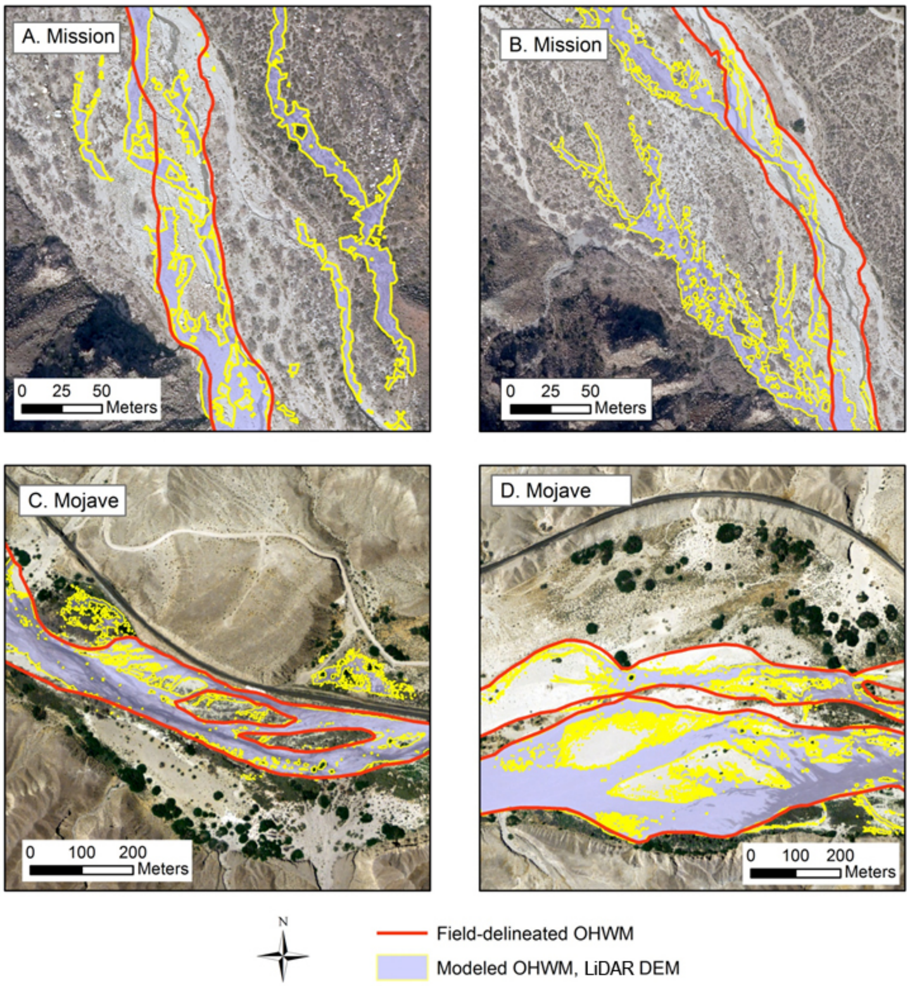
The second model run with LiDAR incorporates the field reconnaissance from summer 2013 and sets the model boundary to exclude the subsidiary channel on the eastern side of the valley in an attempt to better model the OHWM in just the main channel (Figure 8B). Here, the modeled OHWM was typically less than 10 m laterally from the field-delineated OHWM location, a vast improvement over the previous model run, which did not incorporate the field reconnaissance. However, it is less accurate than the

HEC-RAS model of this channel based on cross-section data, where the average predicted OHWM was 1.3 m from the field-delineated OHWM. In addition, the OHWM boundary is not perfect with isolated ponds and jagged boundaries due to slight errors in the LiDAR data. Yet, the LiDAR-based model simulates the OHWM between cross sections, so it provides vastly more information about the site than modeling OHWM at just the cross sections.

The next four model runs examine other reaches in the Mission Creek and Mojave Creek watersheds without incorporating field reconnaissance in the model. These test how frequently the modeled OHWM was grossly incorrect, even when the topography input is from aerial LiDAR, the most accurate topographic data short of field surveys. Flow inputs are the Curtis et al. (2011) OHWM flows. Figure 9A and B show different model runs on reaches centered 500 and 700 m upstream of the gage on Mission Creek, respectively, with different cross sections extracted from the LiDAR data as input to the HEC-GeoRAS models. Figure 9C and D show reaches centered 500 and 2100 m upstream of the gage on Mojave Creek, respectively. In each case, the modeled OHWM flow creates “ponds” with no clear connection between the water bodies. An egregious error can be seen on the right side of Figure 9A. Here the modeled OHWM occurs in channels that are fully vegetated, indicating flow paths with substantial terrestrial vegetation, similar to the upland interfluves. It is likely that these flow paths have not had substantial flow in several decades or more. They may even be paleochannels, unoccupied for thousands of years. Abandoned channels like these are common in arid and semi-arid regions, especially in alluvial fans and other locations where steep channels from the mountains debauch sediment into less rugged terrain (Parsons and Abrahams 1994). Figure 9B used a different set of cross sections for the model, and here the modeled OHWM was primarily on the west side of the valley. The main flow channel showed little to no flow.

At the Mojave sites (Figure 9C and D), the models are better at predicting the OHWM than the models at the Mission sites. At Mojave, the modeled OHWM roughly simulates some islands and boundaries of the field-delineated OHWM. However, the models also indicate islands that do not exist in the field-delineated OHWM channel, and the difference between the modeled and field-delineated OHWM is greater than 100 m laterally. Although these models based on LiDAR data may shed light on the conditions at these immensely wide and complicated channels, the model results cannot be a surrogate for the field-delineated OHWM.

Figure 9. Mission and Mojave Creeks field-delineated OHWMs vs. modeled OHWMs using LiDAR topography.



These tests of modeled OHWMs confirm that multi-threaded channels are very difficult to model and that it is best to use field work to delineate the OWHM. Typically, it is far more effective and efficient to delineate the OHWM based on the standard methods of physical indicators observed in the field and corroborated by satellite imagery. Two-dimensional models might outperform the one-dimensional models, but any model attempting to delineate the OHWM in multi-threaded channels requires extensive field reconnaissance, detailed topography inputs, and careful model calibrations. These added costs of two-dimensional modeling outweigh the benefits, which are marginal or questionable compared to a field-based OHWM delineation.

5 Combining Hydraulic Modeling with Flow Frequency Analysis

This section explores how one would model the OHWM without prior knowledge of the discharge associated with the OHWM and relies on flow frequency analysis to determine the discharge to model. As stated previously, Curtis et al. (2011) found that discharges associated with the OHWM in the Arid West region have recurrence intervals that range from approximately 1.1 to 15 years across several sites. Here the study models the discharge of the lower 90% confidence limit of the 1.1-year event (termed “FFA narrow simulation” in Figure 10) and the upper 90% confidence limit of the 15-year event (termed “FFA wide simulation” in Figure 10), determined through Log-Pearson Type III gage analysis. Table 6 presents the discharge values and 90% confidence limits. This by no means implies that the OHWM is strictly between the 1.1- and 15-year recurrence interval—the OHWM-associated flow may be less or greater at any given site. However, using the initial findings from Curtis et al. (2011) as a starting point allowed an examination of how wide the differences are between these two limits and a comparison of these results with the field-delineated OHWM. For topography input, the models used cross-section data from field surveys.

Table 6. Selected flows and recurrence intervals based on gage analysis.

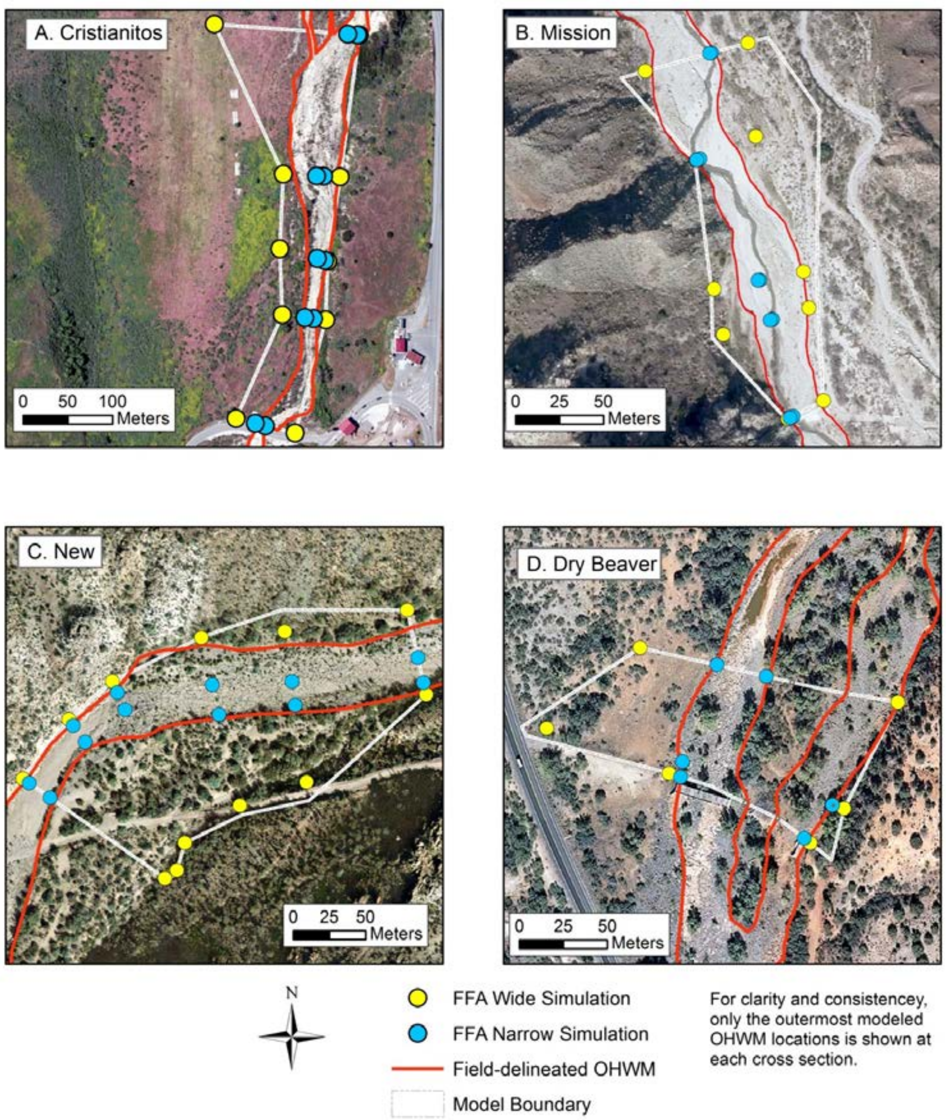
Site	Recurrence Interval (years)	Flow (m^3/s)	90% Confidence Limits (m^3/s)	
Mission	15	27	15	55*
	1.1	0.04	0.02*	0.07
New River	15	437	297	691*
	1.1	4.8	3.1*	7.0
Cristianitos	15	118	58	308*
	1.1	0.5	0.2*	1.0
Dry Beaver	15	483	365	676*
	1.1	17.7	12.9*	23.1

* These flows were simulated in flow frequency analysis model runs.

Figure 10 shows the vast differences between the two modeled OHWM locations and the differences between the modeled and field-delineated OHWMs. The differences between the narrow and wide simulations are up to 50 m or more. These results and the findings in the previous section make it clear that this technique cannot be used to accurately delineate the

OHWM. This technique contains not only the sources of error from hydraulic modeling but also the sources of errors from flow frequency analysis, which can be substantial (Gartner et al. 2016b). And, as stressed throughout the OHWM literature, the OHWM is not associated with a single recurrence interval. Using this technique based on flow frequency analysis with remotely sensed data, such as the 10 m DEMs or the LiDAR data, and without field reconnaissance would produce even more questionable results. At best, this technique could estimate a range of possible boundaries of the OHWM; but it may not cover even the entire range.

Figure 10. Combining flow frequency analysis with hydraulic modeling to delineate the OHWM. "FFA Wide Simulation" refers to the OHWM modeled using the discharge of the upper 90% confidence limit of the 15-year event, and "FFA Narrow Simulation" refers to the model of the discharge of the lower 90% confidence limit of the 1.1-year flood event.



It is not surprising that the OHWM is associated with different recurrence intervals for different sites because the OHWM is the cumulative expression of several natural processes. Every river is subject to these factors, and many of these factors have a characteristic frequency. However, each of these factors contributes to a differing degree and with a different frequency in every river.

Consider, for example, topographic breaks in slope, which are one of the three primary indicators of the OHWM. These breaks in slope have an analog in the bankfull channel, which has been studied extensively in the field of geomorphology (Williams 1978). The bankfull channel is often defined as the top of the channel just where water spills onto the floodplain. The bankfull location is a break in slope at the channel top, and this change in slope could be one of the primary indicators of the OHWM at some sites. The bankfull channel is the cumulative expression of several natural processes, including a series of high and low flows, sediment inputs from tributaries and hill slopes, erosion and deposition on the bed and banks, and other processes that affect channel form (Knighton 1998). Every river has these processes but to varying degrees. Thus, nearly every river has the broadly similar expression of a channel, but this expression varies from location to location. It is not reasonable to conclude that a single recurrence interval of flow should be the channel-filling flow at all locations. Not only does every river have a slightly different flow history, but also, more importantly, the history of flows is not the only factor that dictates the channel size. Field data are consistent with this interpretation. Williams (1978) found that the bankfull discharges range from 1.01- to 32-year recurrence-interval peak floods in rivers across the U.S., with no clear regional patterns. This highlights the highly variable relationship between streamflow recurrence intervals and physical features observed in the field.

It follows logically that the OHWM should not be defined by recurrence intervals and that modeling the OHWM based on the flow of a certain recurrence interval is untenable. The field indicators of the OHWM integrate a multitude of factors affecting a river and in a sense simplify the incredibly complex nature of these factors into a single expression of the OHWM. In contrast, models simplify the river system by ignoring most of these factors. Models focus on just the dominant parameters and use these in computations to simulate one aspect of the river, such as the water elevation for a given discharge. There is an inherent disconnect between modeling and the OHWM observed in the field. As a result, models can only approximate the OHWM, and field indicators are better than models at identifying the OWHM.

6 Testing Extreme Low and High Locations

The results in the previous sections clearly show that the exact location of the OHWM cannot be determined easily by hydraulic modeling and that using modeling in the absence of field verification is indefensible. Because of all the field data that must be collected and analyzed to ensure that the models produce the best possible results, it is typically easier and faster to delineate the OHWM directly in the field rather than through modeling.

This section asks the inverse question—can hydraulic modeling determine where the OHWM is *not* located? As explained in the introduction, some locations may have physical features that could erroneously be interpreted as physical indicators of the OHWM. Arid West streams often have a low-flow channel that exhibits a break in slope and potentially a change in sediment texture or vegetation characteristics. Sandy material within the low-flow channel is transported in the low-flow events, and the low-flow channel can be bounded by coarser bed material that is transported in larger events. Some may mistake this low-flow channel boundary as the OHWM. At the opposite end of the spectrum, the outer edge of a floodplain or the remnants of an extreme flood event could be misinterpreted as the OHWM where changes in vegetation, sediment, or topography are present.

Therefore, here the study combines hydraulic modeling with flow frequency analysis to provide quantitative insight on whether some high or low locations could be considered the OHWM. HEC-RAS was used to model the discharges required to fill a cross section to the elevation of (a) the lowest break in slope, often associated with the low-flow channel, and (b) the highest break in slope, sometimes associated with the edges of flood deposits, potentially from extreme flood events. This allows determining the flow recurrence interval of those discharges and comparing them with the range of recurrence intervals from Curtis et al. (2011).

Figure 11 shows the modeled water surface of a low-flow channel at Cristianitos Creek. Table 7 summarizes the results for Cristianitos and for four other sites. In four of the five cases, the recurrence intervals are far below the range of recurrence intervals in Curtis et al. (2011). For example, at New River, the low-flow channel is modeled to contain a flow of 0.02 m^3/s, which is far below the lower limit of the 1.1-year recurrence-interval peak flow of 3.1 m^3/s. This provides quantitative evidence that these low-flow channels are not justifiable locations for the OHWM, even when one consider the uncertainty in the hydraulic modeling and the flood frequency analysis.

Figure 11. A model combining hydraulic modeling with flow frequency analysis of water surfaces of a low-flow channel (0.02 m^3/s) and a high break in slope (95 m^3/s) at Cristianitos Creek.

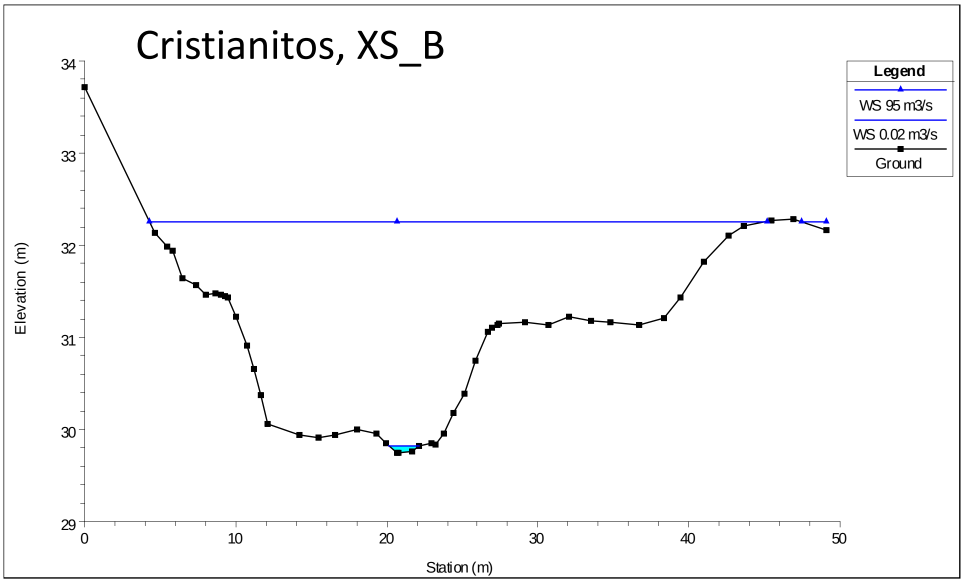


Table 7. Flows, recurrence intervals, and modeled discharge for five sites.

Site	Recurrence Interval (years)	Flow (m^3/s)	90 % Confidence Limits (m^3/s)		Modeled Discharge (m^3/s)			
					High-Flow Surface		Low-Flow Surface	
Cristianitos	15	118	58	308	95			
	1.1	0.5	0.2	1.0			0.02	†
Mission	15	27	15	55	354	*		
	1.1	0.04	0.02	0.07			0.05	
New River	15	437	297	691	325			
	1.1	4.8	3.1	7.0			0.2	†
Dry Beaver	15	483	365	676	600			
	1.1	17.7	12.9	23.1			0.4	†
Mojave	15	193	111	372	5000	*		
	1.1	0.2	0.1	0.3			0.08	†

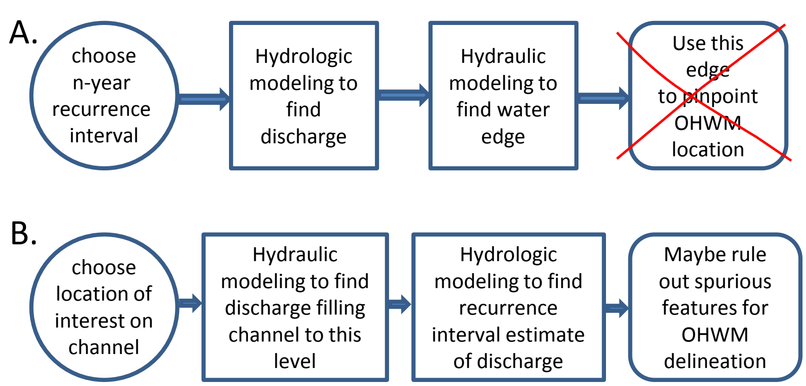
* The modeled discharge of the high-water surface is significantly greater than the 15-year recurrence-interval discharge.

† The modeled discharge of the low-water surface is significantly less than the 1.1-year recurrence-interval discharge.

Figure 11 also shows the water surface of a flow modeled to match a break in slope high on the channel at Cristianitos Creek. The discharges associated with breaks in slope high on the channels are modeled in a similar fashion at four other sites, also (Table 7). In two of five cases, the recurrence intervals are above the range of recurrence intervals in Curtis et al. (2011). For example, at Mission Creek, the flow of 354 m^3/s fills the channel to the break in slope high on the left bank, a discharge that is substantially higher than the upper limit of the 15-year recurrence-interval event of 55 m^3/s. Thus, one might reasonably conclude that the OHWM is likely at a lower elevation that exhibits primary indicators. In contrast, there are three locations that this modeling approach does not rule out as possible locations for the OHWM. For example, a flood deposit high on the right bank of the New River corresponds to a modeled flow of 325 m^3/s. This is the approximately 10- to 15-year flood event according to Log-Pearson Type III gage analysis. In cases like this, the preponderance of field evidence would prevail in the delineation of the OHWM.

These data suggest that modeling can sometimes determine where the OHWM is *not* located and thus potentially help narrow down the OHWM location. However, as is a consistent theme throughout this document and in companion documents (Gartner et al. 2016a, 2016b), hydraulic modeling and flow frequency analysis have several sources of error and uncertainty. They cannot be used to determine the OHWM location in the absence of field evidence. Figure 12 illustrates these concepts.

Figure 12. Different applications of OHWM in modeling: (A) invalid and (B) sometimes appropriate.



7 Conclusions

This document sets out to answer three of the most important questions about the efficacy of modeling the OHWM. First, how do model choices and the resolution of the topographic inputs affect the ability of models to predict the OHWM? Second, can hydraulic models be coupled with flow frequency analysis to delineate the OHWM in the absence of detailed field reconnaissance? Third, can modeling be used to rule out locations that might be misinterpreted as the OHWM?

The two major findings are that (1) modeling is not effective in delineating the OHWM in the absence of field data; however, (2) modeling can be effective at ruling out extreme low or high locations that might be misinterpreted as the OHWM.

Regarding the first of these major findings, field validation and the resolution of topographic data are two critical concerns in hydraulic modeling of the OHWM. Yet, even when the best available topographic data are used as model inputs and models are calibrated to field observations, the models can grossly misplace the location of the OHWM by tens of meters or more. This issue is particularly relevant in complex channel systems in arid regions and elsewhere where alluvial fans, multi-threaded channels, and other dynamic channels with high sediment yields relative to discharge are common. In these locations, careful field surveys are needed to determine not only where the OHWM is located for a given channel but also which channels in a multi-threaded system are presently active under the current hydrologic regime. Generally, by the time all this field work is completed, it is more efficient to delineate the OHWM in the field. Moreover, field evidence from physical indicators is the current standard in OHWM delineation.

Regarding the second of these major findings, this study shows that even though modeling is typically ineffective and inefficient in determining the location of the OHWM, modeling can, in some situations, help determine where the OHWM is *not* located. This is sometimes useful at sites that have a physical feature that could be misinterpreted as the OHWM, such as a low-flow channel or the markings from an extreme flood. In some of these situations, the modeled discharges associated with these extreme low or high features have recurrence intervals that are far beyond the bounds of what would be considered reasonable for an ordinary high-flow event.

It is not acceptable to delineate the OHWM by simply choosing a recurrence interval, say the 5- or 15-year flood event, and modeling the extent of this discharge using available topographic data. On one level, this is indefensible because the uncertainties in flow frequency analysis combined with the uncertainties in hydraulic modeling produce a modeled OHWM with even greater uncertainty. On another level, there is an inherent disconnect between the physical indicators of the OHWM observed in the field and the modeling that attempts to replicate the OHWM. The field indicators of the OHWM integrate a multitude of factors affecting a river and in effect simplify the incredibly complex nature of these factors into a single expression of the OHWM. In contrast, models simplify the river system by ignoring most of these factors. Models focus on just the dominant factors and use these in computations to simulate one aspect of the river, such as the flow frequency or water elevation for a given discharge. As a result, models can at best only approximate the OHWM, and physical features are better than models at identifying the OHWM.

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14. ABSTRACT
This document explores the combined use of hydraulic and hydrologic modeling for ordinary high water mark (OHWM) delineation under the Clean Water Act and for other applications. Delineation of the OHWM is primarily based on identifying and interpreting field indicators. However, field delineation can be challenging and time consuming, especially in arid and semi-arid regions where river flows are highly variable and channels are complex. Therefore, some have turned to mathematical modeling to address these challenges, yet scant information exists on the benefits and limitations of various modeling approaches for OHWM delineation. This document examines and tests the use of hydraulic and hydrologic modeling for these purposes, comparing field-delineated OHWMs with modeled OHWMs and presenting over 40 HEC-RAS and HEC-GeoRAS model runs from six sites in the southwestern U.S. The examples demonstrate that modeling is typically not effective in accurately delineating the OHWM in the absence of extensive field data; however, modeling can be effective at ruling out extreme locations (either too high or too low) that might be misinterpreted as the OHWM. This document has two companion papers on hydraulic modeling and hydrologic modeling, respectively, that help regulators and applicants to properly apply these tools for OHWM delineation purposes.

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