The optical river bathymetry toolkit

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Abstract
Spatially distributed information on water depth is essential for many applications in river research and management and, under certain circumstances, can be inferred from remotely sensed data. Although fluvial remote sensing has emerged as a rapidly developing subdiscipline of the riverine sciences, more widespread adoption of these techniques has been hindered by a lack of accessible software. The Optical River Bathymetry Toolkit (ORByT) fills this void by providing a standalone package for mapping water depth from passive optical image data. The ORByT interface enables end users to import images and field-based depth measurements, create and refine water masks, and perform spectrally based depth retrieval via an Optimal Band Ratio Analysis algorithm. The resulting bathymetric map can be exported as an image file, point cloud, and/or cross section; a thorough accuracy assessment also is incorporated into the workflow. In addition, image-derived depth estimates can be subtracted from water surface elevations to obtain bed elevations suitable for input to a hydrodynamic model. Potential users of ORByT must bear in mind the inherent limitations of passive optical remote sensing: reliable bathymetry can only be inferred in clear-flowing, shallow streams; this approach is not appropriate for more turbid, deeper rivers.

KEYWORDS
bathymetry, depth, remote sensing, rivers, software, spectra

1 | INTRODUCTION
Information on river bathymetry is essential for studies in ecology and geomorphology and for various river management applications such as habitat assessment. Obtaining this information via field methods can be laborious, however, and surveys typically are limited in spatial extent. Remote sensing provides an alternative, more efficient means of mapping depth over broader areas and thus plays an increasing role in river-oriented data collection. Fluvial remote sensing has advanced considerably as new sensors, platforms, and algorithms have become available; for reviews, refer to Marcus and Fonstad (2010), Entwistle, Heritage, and Milan (2018), and Tomsett and Leyland (2019). A persistent obstacle to wider adoption of these techniques is the lack of software intended for application to river systems. The toolkit described herein takes a step toward filling this void.

The Optical River Bathymetry Toolkit (ORByT) is a standalone software package for mapping depth from passive optical image data. The program allows users to import and explore red–green–blue (RGB), multi- or hyperspectral images, and field measurements of depth. More specialized tools are provided for generating water masks, extracting spectra, retrieving water depth, and incorporating observations of water surface elevation (WSE) to obtain bed elevation data suitable for hydrodynamic modeling. ORByT is a Windows application developed in MATLAB® and freely available from the U.S. Geological Survey code repository at https://code.usgs.gov/cjl/orbyt-optical-river-bathymetry-toolkit/. Documentation includes a tutorial for using ORByT and a lecture that
provides background on the spectrally based approach implemented within the software.

The objective of this paper is to introduce ORByT and illustrate its application using an example data set consisting of a satellite image and field-based depth measurements. The following sections: (1) summarize the theory behind Optimal Band Ratio Analysis (OBRA), the core spectrally based depth retrieval algorithm; (2) describe the various functions available within the graphical user interface; and (3) discuss the limitations, as well as the future, of ORByT.

2 | METHODS

2.1 | Spectrally based depth retrieval: Theoretical basis for ORByT

Mapping water depth is one of the most mature applications of remote sensing to rivers and builds upon a foundation established in coastal settings. Early work by Lyzenga (1978) set the stage for efforts to retrieve river depths from airborne multispectral images using regression-based methods (e.g., Winterbottom & Gilvear, 1997). Hugue, Lapointe, Eaton, and Lepoutre (2016) demonstrated how these techniques can be applied to satellite data to characterize instream habitat across entire watersheds. For smaller-scale investigations, unmanned aircraft systems (UAS) have become a viable tool for mapping depth, often using photogrammetric structure from motion algorithms (e.g., Dietrich, 2017). In addition, bathymetric light detection and ranging (lidar) has emerged as an alternative remote sensing technology for measuring bed elevations via water-penetrating, green wavelength lasers (e.g., Mandlburger, Pfennigbauer, Schwarz, Flöry, & Nussbaumer, 2020). Most recently, Niroumand-Jadidi, Bovolo, and Bruzzone (2020) built upon the spectrally based approach emphasized herein by incorporating multiple band ratio predictors that vary as a function of depth.

The physical basis for inferring depth from passive optical images is the interaction of light and water (Mobley, 1994). The attenuation of solar radiation by water varies spectrally as a function of wavelength and thus leads to a relationship between depth and reflectance. Although the total radiance depends not only on depth but also bottom reflectance, water column optical properties, sun glint from the water surface, and atmospheric effects, a ratio-based algorithm can help isolate the effect of depth. More specifically, Optimal Band Ratio Analysis (OBRA) identifies the numerator and denominator bands centered at \( \lambda_1 \) and \( \lambda_2 \). The inputs to OBRA are paired observations of \( d \) and \( R(\lambda) \) and the algorithm involves calculating \( X \) values for all possible band combinations and performing a regression of \( X \) against \( d \) for each pair of wavelengths. The optimal band ratio is that which produces the highest \( R^2 \) (Legleiter et al., 2009).

However, Legleiter et al. (2009) cautioned that linear \( X \) versus \( d \) regressions can yield negative depth estimates in shallow areas. Similarly, adding an \( X^2 \) term can help to avoid underestimates of depth in pools (Legleiter & Overstreet, 2012) but also lead to overestimates of depth along channel margins (Legleiter et al., 2018). To mitigate these shortcomings, Legleiter and Harrison (2019b) generalized OBRA by considering four types of \( X \) versus \( d \) relation:

\[
\text{Linear: } d = b_0 + b_1 X, \\
\text{Quadratic: } d = b_0 + b_1 X + b_2 X^2, \\
\text{Exponential: } d = b_0 e^{b_1 X}, \\
\text{Power: } d = b_0 X^{b_1},
\]

where \( b_0, b_1, \) and \( b_2 \) are fitted coefficients; Legleiter and Harrison (2019b) describe how Equations (4) and (5) can be linearized for regression analysis. This generalized OBRA framework enables greater flexibility in curve-fitting and model selection, with the goal of providing more reliable depth estimates across the full range of depths.
3 | RESULTS

3.1 | Components of the ORByT workflow

The ORByT interface leads the user through the workflow illustrated in Figure 1, beginning with input of an image and field measurements, followed by image processing tasks, depth retrieval analysis, and an optional module for computing bed elevations. Each stage corresponds to a tab on the left side of the ORByT interface (Figure 2). The right panel displays various images and derived products, but some ORByT tools generate separate figures for interacting with images and visualizing results. The following subsections describe the features available within ORByT’s four main tabs, each of which includes buttons to perform the functions shown in Figure 1. A case study from the upper Sacramento River in northern California, USA, is used to illustrate the software (Legleiter & Harrison, 2019a, 2019b).

3.1.1 | Inputs and exploration

The first tab in ORByT, Inputs, prompts the user to specify a working directory that contains image data and field measurements of depth. Alternatively, a MATLAB \*.mat data file containing the output from a previous ORByT session can be loaded to resume a prior analysis. The basic input to ORByT is an image file consisting of three or more spectral bands; the toolkit accepts images in GeoTIFF or ENVI format (.dat binary file with associated .hdr header text file). Spatial referencing information is extracted from the GeoTIFF or ENVI header and the first band is displayed in the ORByT interface. Although a GeoTIFF includes all of the bands in a multispectral image, the file does not specify their wavelengths. To provide this information, the user can load a text file listing the center wavelength of each band or enter them directly into a table within ORByT.

Once the image is loaded and the wavelengths specified, the user can select a specific band to display in grayscale. ORByT displays images with a 98% linear contrast stretch such that the largest 1% and smallest 1% of the non-zero pixels in the image are omitted and the middle 98% are stretched across the monitor’s range of brightness. The image display in the ORByT interface includes tools for panning, zooming, returning to the full extent, copying to the clipboard, and saving a screenshot. Alternatively, the user can launch a separate image viewer tool by clicking Explore Grayscale Image. The currently selected band is displayed in a primary window with scroll bars for panning and an overview window showing the entire extent. To visualize spectral characteristics, ORByT allows the image to be displayed in color by specifying the band numbers to be displayed in red, green, and blue. For example, Figure 2 shows a false color composite representation of the Sacramento River image in which the near-infrared (NIR) band is displayed as red, the red band as green, and the green band as blue. Vegetation along the banks appears red due to its high reflectance in the NIR, whereas the river is dark due to strong absorption of NIR radiation by water.

In addition to image data, depth retrieval via OBRA requires field measurements, ideally made as close as possible to when the image is acquired, to calibrate the image-derived quantity X to depth. The field data must be in the same coordinate system as the image and stored in a text file with X (easting) and Y (northing) coordinates and depths. ORByT displays a map of the field measurements in a new figure along with a histogram and summary statistics. To visualize the depth measurements in the context of the image, ORByT can overlay color-coded point symbols representing the field data on a grayscale display of the current band (Figure 3). These graphical outputs provide a
means of visualizing the spatial distribution of field data and summarizing the range of depths represented.

3.1.2 | Image processing

The second ORByT tab, Image Processing, features tools to prepare an image for depth retrieval. This workflow involves creating and refining a water mask, converting it to a vector polygon, importing an edited mask, spatially smoothing a water-only image, and clipping field data to the mask. Although numerous methods for identifying water bodies in remotely sensed data are available (Huang, Chen, Zhang, & Wu, 2018), ORByT implements a basic masking approach that does not require specific bands, as would be needed to calculate indices such as the Normalized Difference Water Index. Instead, a threshold-based mask is produced from a single band, typically the longest wavelength available because absorption by pure water increases with wavelength throughout the visible and near-infrared portions of the spectrum (Legleiter, Roberts, Marcus, & Fonstad, 2004). ORByT provides an interactive contrast adjustment tool that allows the user to identify minimum and maximum pixel values that isolate the water within the channel (Figure 4). By manipulating the histogram shown in Figure 4c, the user can select threshold values that result in pixels higher than the maximum being displayed as white, pixels less than the minimum as black, and pixels with intermediate values in shades of gray. The objective is to manipulate the contrast stretch so that areas outside the channel are white and the river appears gray. Once the user enters minimum and maximum threshold values, the initial mask is created and displayed. The resulting mask is binary, consisting of white pixels (ones) within the channel and black pixels (zeros) on dry land. The initial mask might appear pixelated, incomplete, or too extensive, but ORByT includes tools to refine the mask by performing morphological opening to remove isolated pixels, image segmentation to select features of interest, and morphological closing to fuse gaps. The segmentation phase is interactive. The result of the opening operation is displayed in a new window and the user is prompted to select one or more segments to be included in the mask by clicking on white areas that represent the channel (Figure 4d). After these segments are identified, the segmentation and closing are applied and the final mask is displayed.

At this point, the water mask is a binary, raster representation of the river, but for some types of analysis, vector data are more
appropriate. In addition, if further refinement of the mask is needed, manual editing is easier for vector polygons. ORByT thus includes a function for converting the raster mask to a shapefile. Even if additional editing is not required, this step is mandatory because the polygon derived from the mask is used to clip the field data. The shapefile can be opened in separate geographic information system (GIS) software and edited manually. If such changes are made to the mask, another ORByT tool allows a shapefile to be imported and converted to a binary raster. Importantly, this functionality allows a water mask generated via some other more sophisticated or convenient means to be incorporated into ORByT.

Once the mask is finalized, the next step involves applying the mask to the image. Multiplying the binary mask by each band of the original image converts all terrestrial pixels to zeros and maintains the aquatic features of interest. The masking operation emphasizes variations in reflectance within the river that would be obscured by the much broader range that would be observed if both wet and dry areas were included. Upon applying the mask, ORByT displays the new water-only image for the selected band in grayscale using a 98% contrast stretch based on pixel values within the channel. In addition to creating a water-only image, the vector mask is used to clip the field measurements to a polygon that represents the channel area of interest. This procedure ensures that only the field data within the final mask are retained for depth retrieval.

Images of rivers often appear pixelated due to small-scale variations in water surface texture, and thus surface reflectance, that make the scene noisy (Overstreet & Legleiter, 2017). To mitigate these effects, ORByT applies a spatial smoothing filter. Image texture is
smoothed by taking the median of the values within an \( n \times n \)-pixel moving window and replacing the central pixel with the median; \( n \) is a user-specified window size. The selection of a window size will depend on the spatial resolution of the image and the degree of smoothing required to reduce noise within a particular scene; some trial and error might be necessary to optimize the choice of \( n \). The results of this operation are visualized in a new figure containing both the original, unfiltered image and the smoothed, spatially filtered image. The two panels are linked so that zooming or panning in one panel produces the same effect in the other panel.

Once the image has been masked and spatially filtered, the user can examine spatial variations in reflectance (i.e., water color) within the channel by displaying a water-only RGB image. The bands designated to be displayed as red, green, and blue on the Inputs tab are used to produce a color composite analogous to Figure 2 but now focused on the channel. In many cases, the water-only image will appear washed out due to the small range of pixel values present within the river. This representation makes the important point that spectrally based depth retrieval often is based on very subtle variations in reflectance.

### 3.1.3 | Depth retrieval

Having imported and processed the image, the user can proceed to the most important phase of the ORByT workflow. The Depth Retrieval tab provides functions for computing pixel-scale mean depths, partitioning observations into calibration and validation subsets, extracting spectra, performing generalized OBRA, assessing accuracy, generating a bathymetric map, defining channel cross sections, and exporting results as images and point clouds.

The first step toward depth retrieval involves identifying pixels co-located with field measurements that can be used to calibrate the image-derived quantity \( X \) to depth \( d \). In addition, the difference between the field data, which represent points, and the larger area encompassed by each pixel must be taken into account. For example, if a pixel contains multiple field measurements, those measurements should not be treated as independent observations. To address this issue, ORByT links each field measurement to the closest pixel center, compiles a list of unique field data-containing pixels, and averages all of the points located within each of these pixels to obtain a pixel-scale mean depth for each of the unique pixels. This process is computationally intensive for large field data sets and/or small pixel sizes.

In addition to being used for calibration, a portion of the field data is withheld and used to assess the accuracy of image-derived depth estimates. Validation is central to a thorough depth retrieval analysis and is incorporated directly into the ORByT workflow. The user specifies the proportion of field data to be used for calibration and the pixel-scale mean depths are sampled at random to form a calibration subset. All remaining observations are withheld as a separate validation subset. The choice of a calibration proportion depends on the number of measurements available, but must be large enough to...
ensure robust calibration and accuracy assessment. Legleiter et al. (2018) describe a stratified approach to sampling field measurements to be used for calibration so as to ensure even coverage across the full range of depths present in the river of interest; this technique could be incorporated into a future release. ORByT produces a new figure with maps, histograms, and summary statistics for both subsets (Figure 5).

At this point, spectral information is incorporated into the depth retrieval workflow by extracting values in each spectral band from all of the unique image pixels with co-located depth measurements (Figure 6a,b). In this example, the data do not represent reflectance but rather raw digital numbers (DN) from the satellite image, which was not radiometrically calibrated or atmospherically corrected. The resulting paired observations of depth and reflectance serve as input to OBRA, but first outliers must be removed. The most common cause of anomalous spectra is the inclusion of higher reflectance terrestrial areas where the mask encompasses mixed pixels along the bank. ORByT provides a tool for removing spectra via a threshold operation.

The user first selects a band in which the outlying spectra are distinct from the majority of the data. For the Sacramento image, the 824 nm band has unusually high reflectance for a few pixels, most notably in the validation subset shown in Figure 6b. The user can interact with the plot to identify appropriate threshold values. Clicking Remove Spectral Outliers deletes any spectra with reflectances greater than the maximum threshold or less than the minimum threshold from both subsets and plots the updated spectra; pixels with anomalously high NIR reflectance are not present in Figure 6c,d.

For large data sets like that from the Sacramento River, the number of spectra can obscure potential correlations between depth and reflectance, but ORByT provides a tool for summarizing the spectra and visualizing their relationship with water depth. The user can press a button to calculate deciles of the depth distribution and plot the corresponding spectra for both the calibration and validation subsets. The lines representing each decile in Figure 6e,f are colored based on depth, with red tones indicating shallow depths and darker blue colors representing deeper water. The similarity of these spectra indicates...
FIGURE 6  Spectra extracted from the Sacramento River image at the locations of pixel-scale mean depths, for both the (a) calibration and (b) validation subsets of the data. Outliers are removed from the spectral data sets based on user-specified band thresholds; the resulting spectra are shown in panels (c) and (d). Spectra corresponding to deciles of the distribution of pixel-scale mean depths for the (e) calibration and (f) validation subsets [Color figure can be viewed at wileyonlinelibrary.com]
that differences in depth are associated with subtle differences in reflectance.

To quantify relationships between depth and reflectance and thus enable depth to be estimated for each pixel, ORByT performs generalized OBRA. This algorithm allows the user to derive empirical relationships between depth and reflectance for the four different model types given by Equations (2)–(5). Figure 7 provides an example of OBRA output for an exponential model derived from the Sacramento image. Figure 7a shows the calibration relationship between X and d, with each point on the plot representing a pixel from the calibration subset. The ratio of the green (547 nm) to the NIR (723 nm) band yielded the highest regression R² value for that (λ₁, λ₂) combination. For this example, the optimal band ratio yields a much stronger relationship than any other wavelength pair. Similar plots for other model types can help select which X versus d relation is best for depth retrieval.

Once the user chooses an OBRA model type, the next step involves applying the corresponding X versus d relation to produce a bathymetric map from the image. For the Sacramento River, the exponential model (Figure 7a) was appropriate because this functional form avoided the negative depth estimates in shallow areas that often occur for linear models, the overpredictions of depth in shallow areas that can result from quadratic models, and the numerical instability that can plague power models (Legleiter & Harrison, 2019b). The resulting map of water depth is displayed within ORByT along with a color bar. In addition, clicking Extract Channel Cross-Section plots the depth map in a new window and prompts the user to digitize a transect along which depth estimates will be extracted, along with any field-based depth measurements within a user-specified distance of the transect line. An example of the output from this process is shown in Figure 8 for a cross section downstream of the bend apex with deeper water toward the outer (west) bank. In this case, the field data indicate that depths were underpredicted in the deepest part of the channel, as commonly occurs for spectrally based depth retrieval. ORByT also creates a text file with columns for the x and y spatial coordinates, distances from the cross-section start point, and field-measured and image-derived depths.

In addition to the bathymetric map, ORByT produces a figure summarizing depth retrieval accuracy assessment based on the validation subset of pixel-scale mean depths. The three panels in Figure 9 include: (a) a histogram and summary statistics for depth retrieval errors, defined as field-measured minus image-derived depth; (b) a map of errors showing where depths were underpredicted (positive values) or overpredicted (negative values); and (c) an observed (field-measured) versus predicted (image-derived) (OP) regression in which an R² of 1 and a line with a slope of 1 and an intercept of 0 would indicate perfect agreement. ORByT also produces text files with accuracy assessment results.

Because depth information is crucial to many applications in river research and management, ORByT allows the user to export remotely sensed bathymetry for use in subsequent analyses, such as habitat assessment. The OBRA-based depth map can be exported as both a GeoTIFF image and a point cloud. Before exporting the depth map as an image, the user is prompted to specify a coordinate system
reference code to be embedded in the GeoTIFF header. The interface includes a button that opens a website that lists codes for various projections. In addition, the ORByT export tool generates a point cloud in a text file consisting of three columns (x, y, and depth). ORByT also provides a function to save results to a *.mat MATLAB data file that contains all of the intermediate and final outputs that are stored internally within the software during an ORByT session. A *.mat file saved by the user can be loaded into ORByT to resume an analysis or review previously generated results.

3.1.4 | Bed elevation

Although the primary purpose of ORByT is to infer depth from passive optical images, the program also can be used to combine depth estimates with information on WSE to calculate bed elevations. This kind of data is crucial for many applications, including hydrodynamic modeling of flow and sediment transport. The Bed Elevation tab guides the user through a workflow that involves importing and displaying a LiDAR DEM, extracting WSEs from the DEM, subtracting image-derived depths from WSEs to obtain bed elevations, and exporting a topobathymetric point cloud. To facilitate this type of analysis, ORByT allows the user to specify the range of elevations used to display the DEM, extending from the minimum elevation in the DEM to the minimum plus the specified value. Setting an appropriate display range thus requires knowledge of the topography within the study area. For example, because the Sacramento River is flanked by high bluffs, the display range was selected to focus on lower elevations for visualizing topography along the channel. Another button prompts the user to select a LiDAR DEM to import. The DEM must be a raster ENVI file with any “no data” values represented by negative elevations.

![Image-derived bathymetric map: Depth in m](image1)

![Channel cross-section extracted from image-derived bathymetric map](image2)

**FIGURE 8** (a) Bathymetric map and (b) channel cross section derived from a satellite image of the Sacramento River using an exponential OBRA model [Color figure can be viewed at wileyonlinelibrary.com]
The selected DEM is displayed in grayscale with tones extending from the minimum elevation in the DEM to the minimum plus the specified range value, which emphasizes the subtle topography along the river shown in Figure 10a.

The next step involves fusing the image-derived depth map and the DEM with WSEs to produce a hybrid DEM with bed elevations. Clicking a button labeled “Process LiDAR and ORByT-derived Depths” carves out the terrestrial topography, extracts WSEs within the channel, and produces a figure that shows the dry terrain, WSEs, and ORByT-derived depths (Figure 10). The three panels of this figure are linked so that when the user pans or zooms in one panel, the view also changes in the other panels. The user can customize the WSE display by entering an elevation range value, as described above for the initial DEM display. ORByT then combines the three data sets shown in Figure 10a–c to produce a fused DEM with bed elevations within the wetted channel. The fused DEM is displayed in a new figure with a color scale extending from the minimum bed elevation in the fused DEM to that minimum plus the DEM display range specified previously, as shown in Figure 10d. Note that the data are represented as points, not a raster grid, and the spacing of these points is dictated by the spatial resolution of the LiDAR DEM used as input. The resulting fused DEM can be exported as a topobathymetric point cloud for use in other applications. Two buttons allow the user to export the point cloud to a generic *.csv text file and/or a *.tpo file. The latter file type is intended for use as input topography for the International River Interface Cooperative (iRIC) hydrodynamic modeling package (Nelson et al., 2016). Finally, the user can save the ORByT session to a *.mat file that includes the fused DEM.

4 | DISCUSSION

4.1 | Limitations and applicability

ORByT is a standalone software package for mapping depth from passive optical image data, a powerful approach that could facilitate applications in river research and management. However, potential users of ORByT must bear in mind the limitations of the toolkit. For example, the OBRA depth retrieval algorithm implemented in ORByT is empirical and thus requires field measurements for calibration. Ideally, field data would be collected at the time the image is acquired, but this level of coordination is difficult. More importantly, although the interaction of light and water provides a sound physical basis for inferring depth from passive optical image data under appropriate circumstances, absorption and scattering of solar radiation within the water column also restrict this approach to clear, relatively shallow water. For this reason, ORByT comes with the critical caveat that the toolkit is only applicable to streams satisfying these conditions and not to more turbid and/or deeper rivers. Familiarity with the river of interest and knowledge of the flow conditions and water column optical properties during image acquisition are essential to effective use of ORByT.

4.2 | Future research directions

This paper describes the initial version of ORByT, but the toolkit is expected to expand and improve. For example, a subsequent release will enable users to address a key question: what is the maximum
detectable depth? A plausible estimate of this important parameter, \( d_{\text{max}} \), can be obtained via OBRA of Progressively Truncated Input Depths (OPTID) (Legleiter et al., 2018). This method involves creating subsets of the original field data by applying a series of depth thresholds, discarding observations that exceed each of these cutoff depths, and repeating OBRA at each iteration. If the data set includes depths in excess of \( d_{\text{max}} \), the OBRA \( R^2 \) value will be reduced due to saturation of the radiance signal in deeper water. By examining a plot of cutoff depth versus OBRA \( R^2 \), the user can infer \( d_{\text{max}} \) as an inflection point where \( R^2 \) ceases to increase or begins to decrease as deeper observations are included in the calibration data set. Similarly, Legleiter and Fosness (2019) probed the limits of spectrally based depth retrieval by using OPTID to infer \( d_{\text{max}} \) and then a logistic regression model to estimate the probability of optically deep water, where \( d > d_{\text{max}} \), for each pixel in an image. This approach provides a means of identifying portions of the channel where depth estimates are unreliable and should be left as voids in depth maps and topobathymetric DEMs. Incorporating these techniques into ORByT will explicitly inform users of the inherent limitations of spectrally based depth retrieval and help to avoid misguided applications of the approach.

Another important shortcoming of ORByT is its reliance upon field-based depth measurements for calibrating an \( X \) versus \( d \) relation via OBRA. However, alternative depth retrieval algorithms that do not require field data at the time of image acquisition are available and could be incorporated into ORByT. For example, a method called Flow Resistance Equation-Based Imaging of River Depths (FREEBIRD) uses hydraulic relations along with a known discharge or estimate of the channel aspect (width/depth) ratio to infer the coefficients of a linear relation between an image-derived quantity and depth that can then be applied throughout an image to produce a bathymetric map (Legleiter, 2015). Similarly, if some prior field data from the river of interest are available, even if they are not geo-referenced, and the probability distribution of depths can be assumed not to have changed between the field survey and the image acquisition, Image-to-

![FIGURE 10](https://example.com/figure10.png)

(a) Terrestrial topography from a LiDAR DEM; (b) water surface elevations (WSEs) extracted from the DEM within the channel; (c) depth estimates produced in ORByT; and (d) final fused DEM of the Sacramento River produced by combining LiDAR WSEs with image-derived depths to obtain bed elevations within the wetted channel. [Color figure can be viewed at wileyonlinelibrary.com]
Depth Quantile Transformation (IDQT) provides a means of mapping river bathymetry when field measurements cannot be made when the river is imaged (Legleiter, 2016). Incorporating these techniques into ORByT would enable greater flexibility by relaxing the need for simultaneous field-based depth measurements.

5 | CONCLUSIONS

Depth is an important attribute of interest to ecologists, geomorphologists, and river managers that is amenable to remote sensing under some circumstances. Although the use of image-based techniques for characterizing fluvial systems has expanded over the past decade, the lack of software tools designed for this purpose remains an impediment to wider application. This paper introduced the Optical River Bathymetry Toolkit (ORByT), a standalone program for mapping depth from passive optical image data. ORByT’s graphical user interface is organized into a series of tabs that provide access to functions for importing images and field-based depth measurements, creating and refining water masks, estimating water depths via a spectrally based algorithm (Optimal Band Ratio Analysis), and combining image-derived depth estimates with information on water surface elevations to obtain bed elevations throughout the wetted channel. The case study presented as an example herein, described in greater detail by Legleiter and Harrison (2019b), demonstrated the potential to use images acquired from various sensors and platforms to derive reliable bathymetric information via the techniques available within this software package. However, potential users of ORByT are cautioned that this approach is only suitable under certain conditions, primarily clear-flowing streams with relatively shallow depths; the toolkit should not be applied to more turbid, deeper rivers. Future extensions to ORByT will focus on inferring the maximum detectable depth, identifying areas that exceed this depth, and incorporating additional algorithms that do not require field data from the time of image acquisition to calibrate an image-derived quantity to depth.

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DATA AVAILABILITY STATEMENT

The field measurements and satellite image data from the Sacramento River used as an example application of the ORByT software are available through a data release hosted by the USGS ScienceBase catalog: Legleiter, C.J., and Harrison, L.R., 2019, Remotely sensed data and field measurements used for bathymetric mapping of the upper Sacramento River in northern California, U.S. Geological Survey data release, https://doi.org/10.5066/F7Q52NZ1.

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