Standard Operating Procedure for the Wetted Perimeter Method in California

CDFW-IFP-004

Version 3

July 2020

California Department of Fish and Wildlife
Instream Flow Program
West Sacramento, California

**Standard Operating Procedure for the
Wetted Perimeter Method in California**

CDFW-IFP-004

Version 3

Approved by:

Robert Holmes, California Department of Fish and Wildlife, Statewide Water Planning
Program Manager, July 2, 2020

Will Hagan, Quality Assurance Program Manager, July 2, 2020

Prepared by:

Originally prepared by Candice Heinz, California Department of Fish and Wildlife
Instream Flow Program, August 27, 2013. Revised by Danielle Elledge, California
Department of Fish and Wildlife Instream Flow Program, July 2, 2020.

Suggested Citation:

CDFW (2020). Standard operating procedure for the wetted perimeter method in
California. California Department of Fish and Wildlife, Instream Flow Program (CDFW),
West Sacramento, CA. CDFW-IFP-004. Version 3.

Available: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

Table of Contents

List of Tables

List of Figures

Abbreviations and Acronyms

Term	Definition
BMI	Benthic macroinvertebrate
cfs	Cubic feet per second
cm	Centimeter
Department	California Department of Fish and Wildlife
ft	Feet/foot
GPS	Global positioning system
HP	Headpin
IFP	Instream Flow Program
in.	Inch
LBWE	Left bank wetted edge
m	Meter
RBWE	Right bank wetted edge
s	Second
SOP	Standard operating procedure
TP	Tailpin
USGS	United States Geological Survey
VBM	Vertical benchmark
WPM	Wetted perimeter method
WSEL	Water surface elevation

Conversions

1 cfs $\approx$ 2.83 × 10^{-2} m^3/s
1 in. = 2.54 cm
1 ft = 0.3048 m

Acknowledgements

Introduction

This standard operating procedure (SOP) represents the protocol used in the wetted perimeter method (WPM) studies conducted by the California Department of Fish and Wildlife (Department) Instream Flow Program (IFP). This updated version of the WPM SOP adds clarification to the method overview and results interpretation content of the previous SOP. It may be used in conjunction with other IFP SOPs. Instructions are provided for:

- Preparation and considerations for field work:
    - WPM limitations and constraints
    - Method application
    - Site selection

- Data collection:
    - Equipment list
    - Field procedures

- Data analysis:
    - Wetted perimeter rating curve development
    - Wetted perimeter discharge curve development
    - Results interpretation and low-flow threshold identification

Scope of Application

This SOP provides procedural reference for Department staff conducting WPM, when site conditions and research objectives indicate WPM is an appropriate method. For example, the WPM may be used to evaluate dry-season baseflows at riffle sites that contain hydraulic bed controls. This SOP is intended as an informational resource for staff from other state and federal agencies, nongovernmental organizations, private contractors, and other organizations throughout California.

The WPM is used to identify the low-flow component of the hydrologic regime for ecological function and benthic macroinvertebrate (BMI) production (Annear et al. 2004). Use of the WPM for fish and wildlife includes the following considerations:

- Transect locations must be at hydraulic control points of representative riffles.

- The method is applicable in streams with well-defined pool and riffle sequences.

- The method may be used to identify a low-flow threshold.

- The method is not suitable for complex channels.

- Other methods and/or models are needed to assess flow requirements for other riverine elements such as channel geomorphology, connectivity, or water quality.

There are two main approaches to conducting hydraulic-control-based habitat methods such as the WPM. Both approaches require data to be collected along the hydraulic control of a representative alluvial riffle. The field-based approach requires a minimum of 10 site visits at prescribed flow events to generate hydraulic habitat relationships. The modelling approach uses a surveyed bed profile paired with a discharge measurement and a computer program based on Manning's equation to develop hydraulic habitat relationships.

This SOP focuses on describing WPM data collection and analysis using the modeling approach. It provides an overview of rating curve development but does not describe hydraulic modelling in depth to account for user discretion in selecting a computer program based on Manning's equation. The Department encourages SOP users to contact the IFP with any questions or for assistance with project planning. The Department is not responsible for inappropriate application or inaccurate interpretation of the WPM SOP. The Department recommends that an experienced instream flow practitioner conduct all field work and data analysis.

What is the Wetted Perimeter Method?

The WPM is a site-specific method used to identify low-flow thresholds. These thresholds are identified by evaluating the percent of bankfull channel perimeter that is wetted at a series of flows and the relationship between wetted perimeter and flow. For the purposes of this SOP, the term "wetted perimeter" refers to the perimeter of a cross-sectional area of a streambed from wetted edge to wetted edge (Figure 1). The WPM can be used to identify dry-season low flows that protect productive riffle habitats. This

flow is intended to support BMI production in riffle habitats at a level sufficient to maintain fish populations during the dry season (Jowett 1997; Annear et al. 2004). The WPM is often combined with other instream flow methodologies to develop a comprehensive understanding of instream flow needs (Annear et al. 2004).
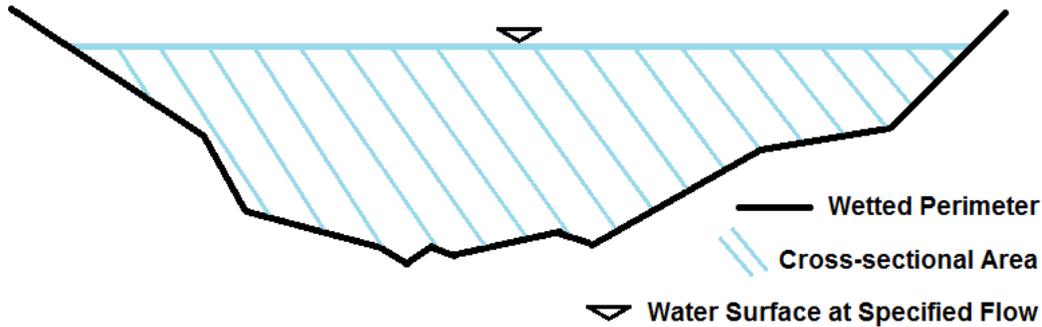
Figure 1. Visual representation of wetted perimeter.

Riffles are characterized by a hydraulic control (Figure 2) and shallow habitats with relatively fast velocities compared to pools or glides. As such, riffles tend to generate high concentrations of dissolved oxygen, and consist of substrates (i.e., gravel and cobble) that are well-suited for BMI production and the spawning of many species of salmonids. As a result of their shallow depths, riffles (and their hydraulic parameters) are more sensitive to changes in stream flow than other habitat types (e.g., pools, runs, and glides). Dewatering of riffles decreases BMI productivity during the summer.
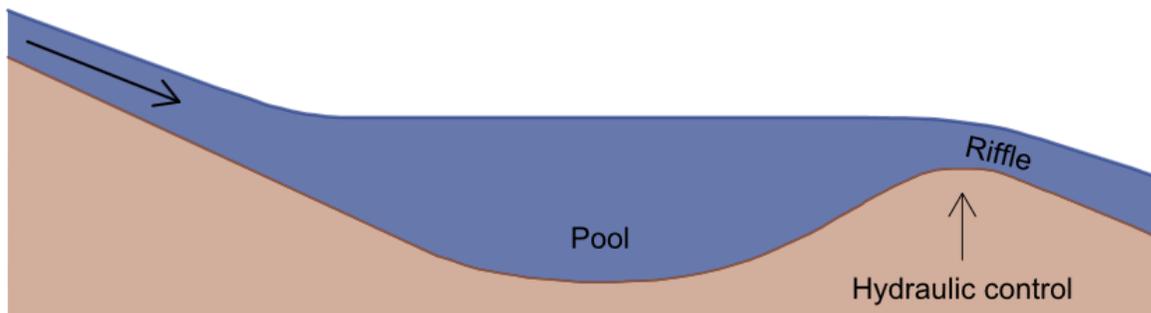
Figure 2. Conceptualized longitudinal profile of a pool-riffle sequence showing the location of the hydraulic control.

Method Overview

Cross-sectional transects are established at the hydraulic control point of riffles. The transect is typically placed on the apex (highest point) of the controlling bed element. This method assumes that the stream channel is stable and unchanging over time (Annear et al. 2004).

Bed elevation readings are obtained along the stream channel cross section using standard survey levels, such as an auto level or total station (see *Standard Operating Procedure for Streambed and Water Surface Elevation Data Collection in California* (CDFW 2013a)). Hydraulic slope is also estimated by measuring the riffle length and taking water surface elevations (WSELs) at the upstream and downstream extent of each riffle mesohabitat unit. A discharge measurement must be recorded for each WPM transect. A single discharge may be used for all transects located in the same reach if it is free of physical obstructions, tributaries, or diversions between each WPM transect, and discharge remains consistent across sites (see *Standard Operating Procedure for Discharge Measurements in Wadeable Streams in California* (CDFW 2020)). Discharge may also be obtained from a nearby representative stream gage, if a field measurement is not feasible (see *Section 1.3 Additional Considerations*).

Determination of the bankfull stage elevation is an integral component of the WPM. The bankfull width of the stream (which is necessary for determining the percent of wetted perimeter) is measured along the transect at bankfull elevation using a fiberglass measuring tape (see *Section 1.3 Additional Considerations*). All WPM data, including transect lengths, channel cross section elevations, WSELs at the upstream and downstream boundaries of the riffle, and discharge data should be collected near the anticipated low-flow threshold flow (see *Section 1.1 Method Limitations and Constraints*).

Bed elevation and WSEL data are used to calculate the flow area (*A*), wetted perimeter, and hydraulic radius (*R*) at each transect. Hydraulic radius is defined as the ratio of flow area to the wetted perimeter (i.e., the portion of the cross section's perimeter that is "wet" (Gupta 2008)). WSEL and riffle length are used to compute hydraulic slope (*S*),

and a discharge measurement (Q) is collected in the field or obtained from a representative gage. These values are then used to calculate Manning's roughness coefficient (n) using the Manning's equation for open channel flow (Gupta 2008):

$$Equation\ 1: \qquad n = \left(\frac{1.486}{Q}\right) AR^{\frac{2}{3}}S^{\frac{1}{2}} \qquad \textit{(English units)}$$

The calculated values for hydraulic slope and Manning's roughness coefficient, along with the bed elevation data collected in the field and discharge, are used as inputs to create rating curves between discharge and average hydraulic depth, average flow velocity, and wetted perimeter.

The hydraulic parameters described above are modeled over a range of flows based on a single field flow measurement and the estimated Manning's roughness coefficient. The Department IFP employs a computer program based on Manning's equation to model open channel flow. There are many programs available for this analysis, therefore it is important to keep in mind that data collection requirements may differ depending on the computer program selected. The Manning's roughness coefficient varies over the sampled range of flow (USGS 2001). Calibration of the hydraulic model may require multiple measurements of discharge paired with WSEL to represent the hydraulic conditions over the modeled range of flow. Additional site visits at different discharges may be useful to calibrate the predictive hydraulic model (Annear et al. 2004).

Using these modeled parameters, a wetted perimeter-discharge curve is developed for each transect (Figure 3). Two points of marked change in slope, also referred to as points of maximum curvature or inflection points, can be identified on the curve (Gippel and Stewardson 1998; Annear et al. 2004). The breakpoint is found at the curve's first (lower) point of marked change in slope, where the slope of the curve exhibits a rapid decrease (Kim and Choi 2019). The breakpoint defines the threshold below which aquatic habitat conditions for BMI rapidly decline (Leathe and Nelson 1989). The incipient asymptote is identified at a second (upper) point of marked change in slope where the slope of the curve is approaching zero, indicative of the upper threshold for

riffle productivity (Kim and Choi 2019). Flows at the incipient asymptote are assumed to provide near-optimum food production for riffle habitats (Leathe and Nelson 1989).
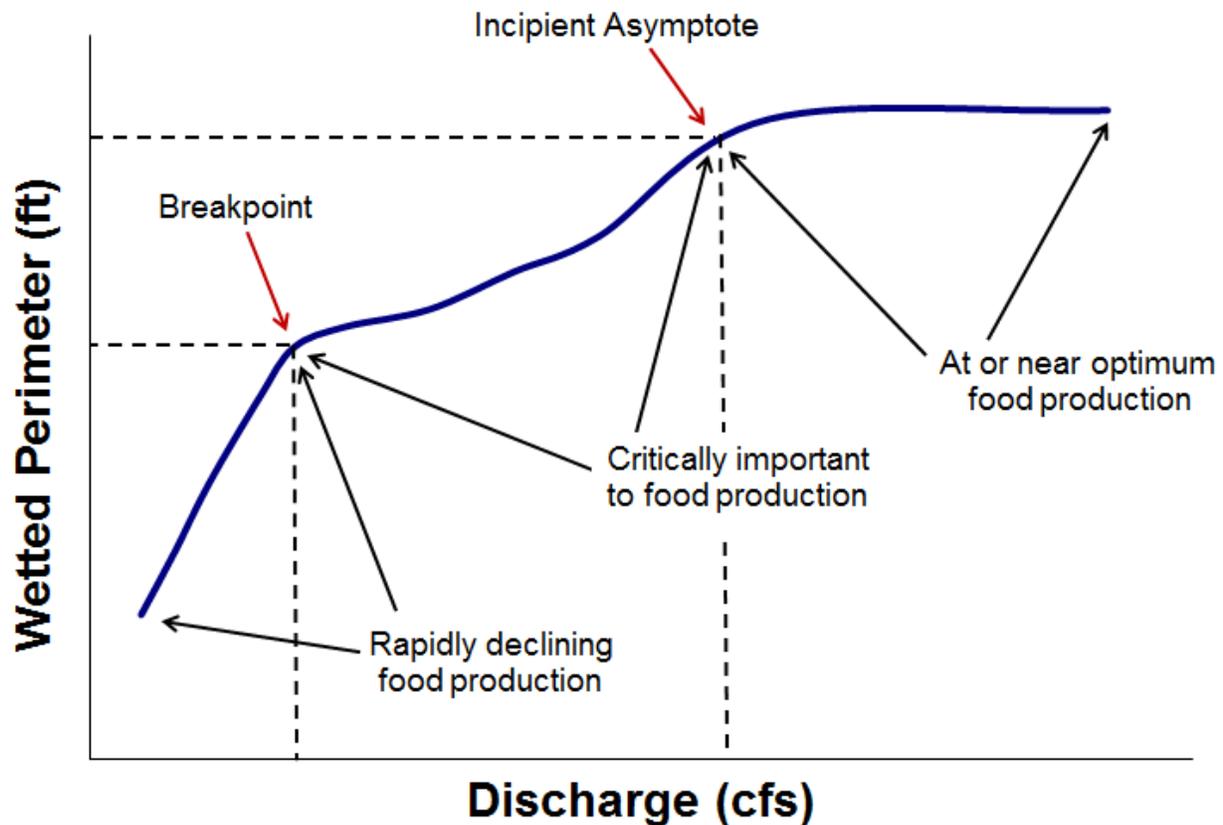
Figure 3. An example wetted perimeter-discharge curve showing the relationship between the breakpoint and incipient asymptote, and BMI production. Figure adopted from (Leathe and Nelson 1989).

Section 1: Field Work Preparation and Considerations

1.1 Method Limitations and Constraints

The WPM should be limited to use in riffles with rectangular streambed profiles. Distinct and identifiable breakpoints on the wetted perimeter-discharge curve are a function of channel geomorphology (Figure 4); rectangular streambeds will generate a sharp breakpoint whereas triangular or V-shaped channels will be less defined (Gippel and Stewardson 1998). This method is not applicable for use in determining life-stage-specific rearing flows or identifying trade-offs between flow levels and specific biological

12

functions, water quality, connectivity, or geomorphic processes. The method only provides information to establish a low-flow threshold; it does not provide the all-necessary flow regime components that are critical to riverine ecology (Annear et al. 2004).

Streambed Cross Section Profile   **Wetted Perimeter vs Discharge Relationship**
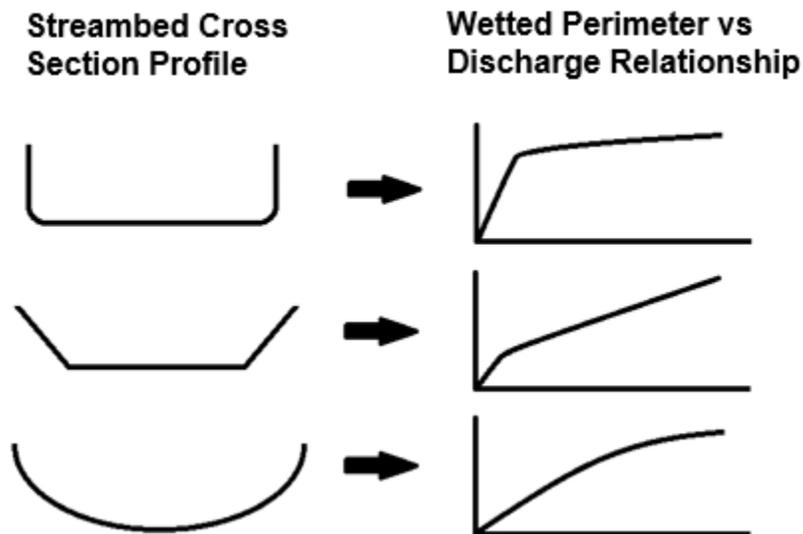
Figure 4. Streambed cross-sectional bed profiles and the corresponding wetted perimeter-discharge relationships.

To identify WPM flows using Manning's equation, an experienced practitioner should survey sites when flow is near the anticipated low-flow threshold flow. Determining the approximate low-flow threshold flow at the time of survey may be difficult. Flow duration analysis may be used to help guide the timing of field surveys (see *Standard Operating Procedure for Flow Duration Analysis in California* (CDFW 2013b)). In some cases, it may take multiple surveys to capture field data at the approximate low-flow threshold. If field surveys are taken at the same WPM transect at multiple flows, each survey event will require collection of corresponding slope measurements.

The Manning's equation best predicts the target hydraulic parameters when the channel is surveyed close to the target flow stage. In alluvial channels, the Manning's roughness coefficient is particularly sensitive to changes in WSEL and is generally much higher during low flow conditions when compared to high flow conditions (Limerinos 1970;

Arcement and Schneider 1989). As such, the streambed should be watered at the toe of each bank to avoid transects containing dry portions of streambed.

1.2 Site Selection

For best results, select a site with characteristics that support accurate WPM measurements. Within a river reach, target a minimum of three representative riffles with roughly rectangular beds (as opposed to V-shaped channels) for the WPM. A sample size of at least three provides a robust representation of the variety of riffles in a reach. Select riffle sites that are representative of the overall geomorphic structure and shape of the river reach. For each riffle surveyed, the transect must be located at the hydraulic control, which is typically located at the riffle crest (see Figures 2 and 5). Streamflow should be uniform across the transect to maximize the reliability of Manning's equation (Grant et al. 1992). The transect location should have natural banks, not eroding or undercut banks, and be free from braiding (CWCB 2006).

Figure 5. Example of a transect across the hydraulic control at the top of a riffle. Stream is flowing from right to left.

Note: While selecting riffles, beware of redds (e.g., salmonid, lamprey) that may be present. If transect placement intersects with the presence of redds, the riffle is not suitable for survey at that time.

1.3 Additional Considerations

Discharge may be obtained from a nearby representative stream gage if it cannot be measured in the field. The stream gage must be located near enough to the transect to negate stream gains and losses and be representative of conditions during the time of the WPM survey. The downloaded gage data would be paired with the bed profile and WSEL survey data and used in place of a field discharge measurement for the transect WPM analysis. Practitioners must understand and identify the limitations and accuracy of the stream gage selected for use with the WPM. For example, the United States Geological Survey (USGS) operates stream gages that are accurate to the nearest 0.01 feet (ft) or 0.2 percent of stage, whichever is greater (Olson and Norris 2007). Although it is acceptable to use gage discharge data for WPM analysis, the IFP recommends that a field discharge measurement be taken, if feasible, to increase confidence in the modeled relationship between the surveyed WSELs and flow.

The bankfull elevation and width are used to identify the associated maximum available wetted perimeter. The IFP follows bankfull identification processes outlined by Leopold et al. (1964), Rosgen (1994), and the Colorado Water Conservation Board (CWCB 2006). For the purposes of this SOP, bankfull elevation is determined using the following indicators:

- Top of point bars
- The lower limit of perennial vegetation
- Change in slope from gradual to abrupt or vice versa
- Change in substrate particle size
- Bank undercuts
- Stain lines (Harrelson et al. 1994)

All indicators need not be present. The bankfull elevation, as depicted in Figure 6, can be recognized by physical indicators along the stream bank. Special considerations may be necessary when working in intermittent and ephemeral streams where bankfull stage indicators may be less defined (USACE 2012).

Note: Bankfull conditions commonly occur at elevations where there are visible changes in channel slope, vegetation, and/or substrate.
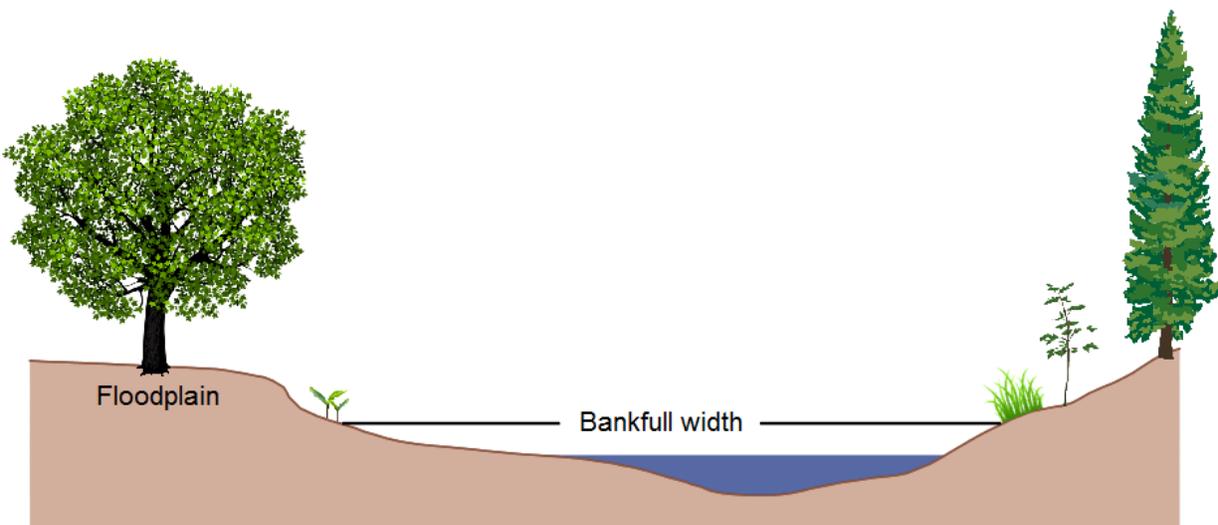
Figure 6. Conceptualized cross section of a stream channel highlighting the bankfull elevation for use with the WPM.

WPM surveys should be conducted or overseen by at least two practitioners who have experience with standard surveying equipment for collecting streambed and WSEL data as well as discharge measurements. Contact Department IFP staff for project planning and method assistance.

Section 2: Field Procedures

2.1 Equipment List [1]

Auto level

Bucket (for velocity flow meter calibration; non-metallic)

Camera

Clipboard

Fiberglass measuring tapes (two)

Field datasheets or notebook (Rite in the Rain® or other water-resistant brand)

Flagging tape

Gloves

Global positioning system (GPS) unit

Hammer (for staff gage and rebar)

Lag bolt (for vertical benchmark (VBM))

Loppers or pruning shears (if needed to remove vegetation)

Pencils

Permanent marker

Portable velocity flow meter

Rebar (two per transect) and safety caps

Stadia rod (engineering grade rod capable of measuring 1/10 ft and 1/100 ft)

Staff gage (to monitor change in flow conditions)

Tripod

USGS top-setting wading rod

---

[1] Calibrate the velocity flow meter and auto level according to manufacturer's instructions prior to use. Confirm that the completed calibration is recorded on appropriate field documents.

2.2 Data Collection

Step 1: Insert the staff gage into the substrate near the stream's edge, near the transect, and out of the foot traffic path (see Figure 7). Record gage height to the nearest 0.01 ft. immediately before and after data collection to account for any fluctuations in water surface height that may occur during data collection. If the stage is changing during data collection, wait for conditions to stabilize before retaking discharge (see *Changes in Stage* on page 21).

Step 2: During the field survey, establish each transect identified during the site selection process (outlined in *Section 1.2 Site Selection*):

- Establish the transect headpin (HP) and tailpin (TP) on the stream banks so that the measuring tape is level and is located across the apex of the riffle's hydraulic control. Install the HP and TP by hammering in rebar on the left and the right banks, respectively. The HP and TP must be installed above bankfull to ensure that the left and right bankfull locations can be identified and recorded along the transect tape.
- Install the VBM on a permanent, unmovable point (see CDFW 2013a).
- Mark GPS waypoints at the HP, TP, and VBM, and record the corresponding waypoints.

Step 3: String the fiberglass measuring tape across the transect from HP to TP creating a taut, level, and straight line with the measuring tape. Starting at 0 ft, record the total distance from HP to TP. Record the distances on the measuring tape to the nearest 0.1 ft where the left bank wetted edge (LBWE) and right bank wetted edge (RBWE) occur. Additionally, record the distances on the measuring tape where bankfull conditions occur on the left bank and right bank to the nearest 0.1 ft. Take photos, notes, sketches, and mark with flagging to identify changes in slope, substrate, and vegetation to support the identification of the bankfull elevation in the field.

Step 4: Photograph the transect facing upstream and downstream and ensure that the left bank and right bank are visible in each photo. Take additional photos of the left and right bank capturing the bankfull indicators (see *Method Overview*). Photos taken in the

field can be used to help confirm bankfull stage prior to data analysis. Ensure that the photos are clear and record photo identification numbers.

Step 5: Set up the auto level in a location where the entire transect is within the line of sight of the instrument, if possible. Otherwise, a turning point must be established to collect streambed elevation data for the entire transect (see Harrelson et al. 1994). Ensure that there is a clear line of sight between the auto level and the VBM, HP, and TP locations. After recording the VBM elevation, collect and record streambed elevation data at 1-ft increments from HP to TP, with additional measurements taken at the lowest point at the thalweg and at any changes in slope, as needed. Take additional elevation points along the transect to identify marked changes in slope, substrate, and vegetation to support the identification of the bankfull elevation. Smaller or larger increments may be allowed to accurately capture higher levels of bed complexity and to adhere to the goal of representing all topographical change[2]. For detailed guidance on collecting streambed elevation data see CDFW 2013a.

Step 6: At the transect, measure and record representative WSELs near the LBWE, RBWE, and at the mid-channel. At the downstream extent of the riffle, preceding changes in hydraulic slope, measure and record representative WSELs at the midchannel and near the LBWE and RBWE as needed. Measure and record the riffle length from the transect (i.e., upstream extent) to the downstream extent of unit where the WSELs were measured. These measurements will be used to calculate hydraulic slope[3]. Once all bed and WSEL data are collected, resurvey the VBM using the auto level and stadia rod. To ensure the auto level was stationary for the survey duration,

---

[2] Increments greater than 1 ft may be appropriate in engineered channels, such as concrete-lined channels, with a relatively uniform cross section.

[3] An experienced practitioner may use professional judgment to determine the level of detail needed to accurately measure the change in hydraulic slope. For example, if the transect is located on a river bend and it is determined that WSELs on the left bank are more representative than measurements on the right bank, it may be acceptable to only take measurements in the representative areas.

resurvey the VBM to confirm the error of closure is +/- 0.02 ft. For detailed guidance on collecting WSEL data, see CDFW 2013a.

Note: The upstream extent is located at the hydraulic control (i.e., on the transect) and the downstream extent occurs at the bottom of the riffle mesohabitat unit, just upstream of the next habitat unit and preceding changes in hydraulic slope.

Step 7: WPM transects within the river reach must be accompanied by a representative discharge measurement to develop discharge rating curves. Ideally, discharge is measured in the field. Find a suitable location to measure discharge in the reach near the WPM transect and establish a discharge cross section. For detailed guidance on measuring discharge, see CDFW 2020. If field measurement is not feasible, and an operational stream gage is located near enough to the transect to negate stream gains and losses, discharge may be obtained from the stream gage as opposed to measuring discharge directly (see *Section 1.3 Additional Considerations*).

Step 8: After data collection is complete, check the staff gage to ensure that flow conditions remained stable during the survey (see *Changes in Stage* on page 21). Review that data sheets are complete prior to removal of survey equipment.

Note: Crew safety is of paramount importance when conducting instream flow studies; only perform fieldwork when field conditions are safe.

Figure 7. Example of staff gage used to monitor change in flow conditions.

Changes in Stage

Flow magnitude can rise or fall during the time discharge measurements are collected. The degree of variation in staff gage height is indicative of whether the stream flow was in equilibrium during data collection. When the change in stage is 0.1 ft or less between the beginning and end of data collection, this indicates the mean gage height has no significant error (Turnipseed and Sauer 2010). We therefore consider flow conditions to be stable if the variance in gage height is less than 0.1 ft. If stage height has changed by 0.1 ft or more, resurveying may be warranted.

Section 3: Data Analysis

3.1 Developing the Wetted Perimeter Rating Curve

Data may be entered and stored in a spreadsheet program such as Microsoft Excel in preparation for analysis. Once all field data are entered and checked according to quality assurance procedures identified in the project study plan, development of rating curves and data analysis can commence. Department IFP quality assurance documents are available at https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP.

The Department IFP uses the commercially available software NHC Hydraulic Calculator (HydroCalc (Molls 2008)), a computer program based on Manning's equation, to model hydraulic parameters and the stage-discharge relationship for cross-sectional transects. However, several programs based on Manning's equation are available and any can be used. For more guidance on hydraulic modelling, please contact the Department IFP.

Step 1: Calculate the discharge measurement associated with the WPM transect (see CDFW 2020). A practitioner may also choose to use discharge data from an operational stream gage in place of a field discharge measurement (see *Section 1.3 Additional Considerations*). The gage data must be representative of conditions during the time of the WPM survey. Ensure that gage data selected for pairing is based off time and date of survey data of interest. Although it is acceptable to use gage discharge data for WPM analysis, the IFP recommends that a field discharge measurement be taken, if feasible, to increase confidence in the modeled relationship between the surveyed WSELs and flow.

Step 2: Convert surveyed streambed and WSEL data from foresight measurements to elevations. This is done by subtracting the foresight height from the height of the instrument. For purposes of WPM data collection, the height of the instrument or instrument height is the VBM elevation, assumed to be 100 ft, plus the VBM foresight height measured in the field.

Step 3: The hydraulic slope of the WPM riffle mesohabitat unit is calculated as the average WSEL elevation measured at the hydraulic control minus the average WSEL elevation measured at the downstream extent of the mesohabitat unit, divided by the average length of the mesohabitat unit.

Step 4: Manning's *n* is calculated using Equation 1 (see *Method Overview*). Area is calculated as the wetted area of the WPM transect, using the bed elevation data. Hydraulic radius is calculated as the area divided by wetted perimeter.

Step 5: Flow, Manning's *n*, slope, and the associated bed elevations for the WPM transect are uploaded into HydroCalc (Figure 8). HydroCalc is then used to compute the WPM transect parameters of flow area, wetted perimeter, hydraulic radius, and average WSEL. The closer the predicted transect parameters are to the field-surveyed data, the stronger the relationship is between the HydroCalc rating curve and the surveyed data. Calibration is considered achieved when the predicted WSEL is within 0.1 ft of the field-surveyed WSEL at the corresponding discharge measurement (USFWS 2011).
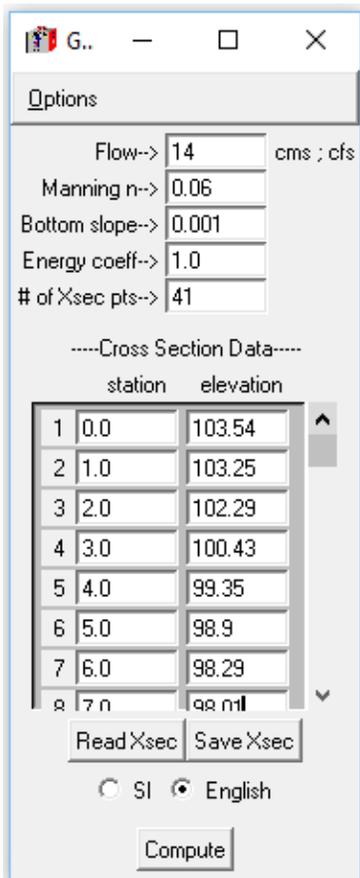
Figure 8. Example WPM transect data uploaded into HydroCalc (Molls 2008) for rating curve generation.

Step 6: Plot the validated HydroCalc cross section parameters (Figure 9). The plot can be used to approximate the bankfull stage elevation identified in the field. Manually adjust the flow value in HydroCalc until the water surface (blue line) is positioned where bankfull conditions are met. Using the HydroCalc bankfull stage elevation, record locations along the transect to determine the bankfull width in ft. The bankfull width and associated flow are used later in the WPM analysis.
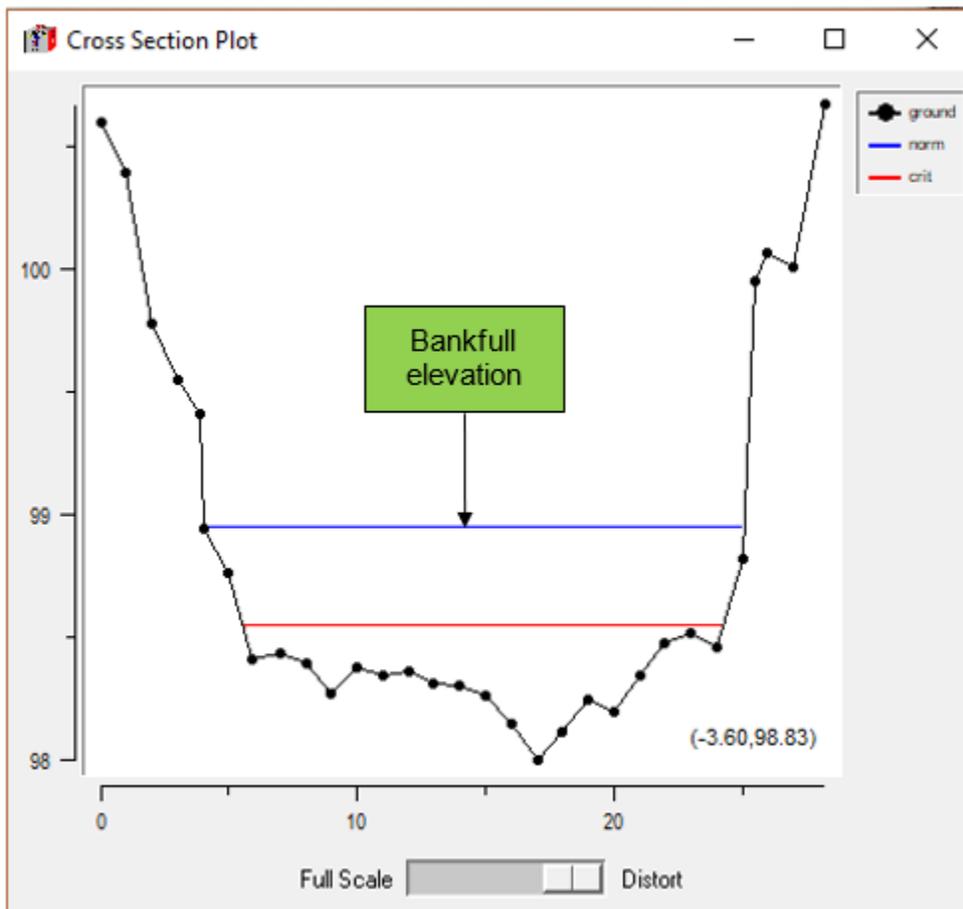
Figure 9. Example HydroCalc (Molls 2008) WPM cross section plot and bankfull stage elevation.

Step 7: The rating curve is generated in HydroCalc by selecting *Rating Curve*. The practitioner then selects a flow range and number of data points. The previously identified bankfull flow must be entered so that bankfull wetted perimeter can be calculated (Figure 10).
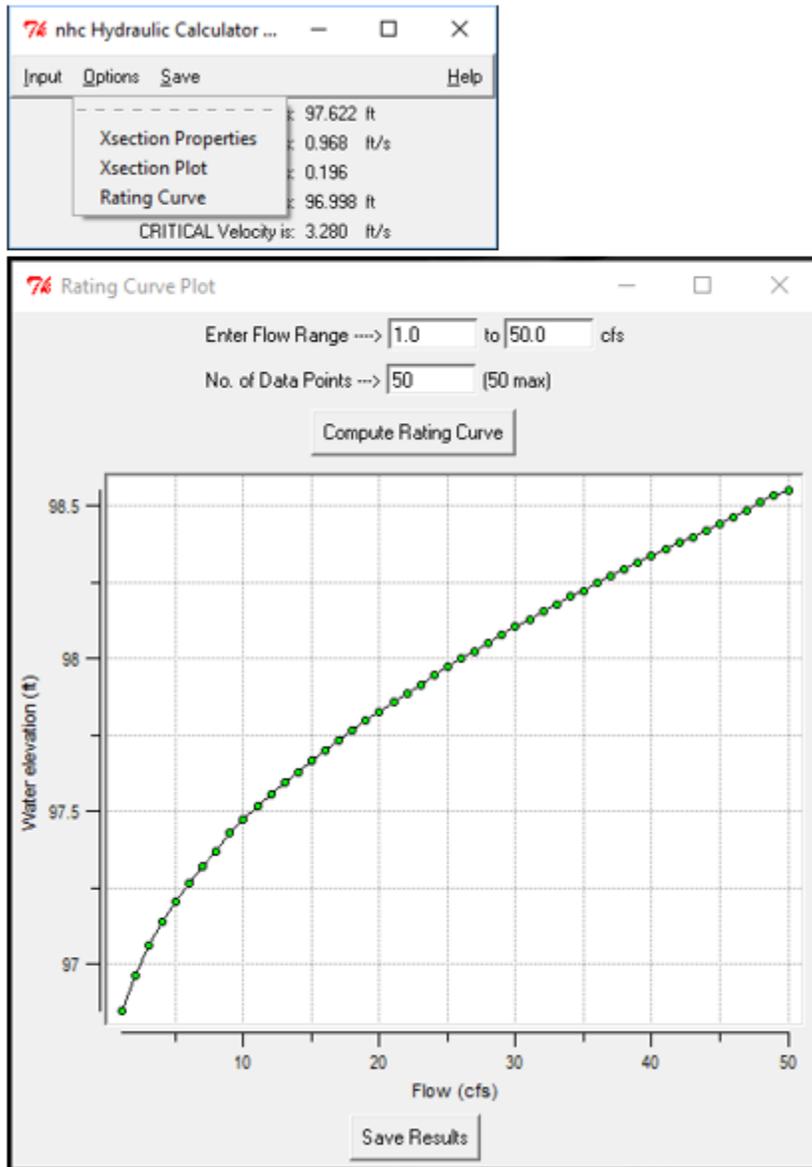

Figure 10. Example rating curve computation using HydroCalc (Molls 2008).

3.2 Developing the Wetted Perimeter-Discharge Curve

Using the hydraulic parameters for flow (i.e., cubic feet per second (cfs)) and wetted perimeter (i.e., ft) from the rating curve output, plot the wetted perimeter-discharge curve (Figure 11). Record the HydroCalc rating curve hydraulic parameters in a spreadsheet program or notebook. List flow and wetted perimeter, then calculate percent wetted perimeter at each flow increment by dividing the predicted incremental wetted perimeter by the maximum wetted perimeter determined at bankfull stage.
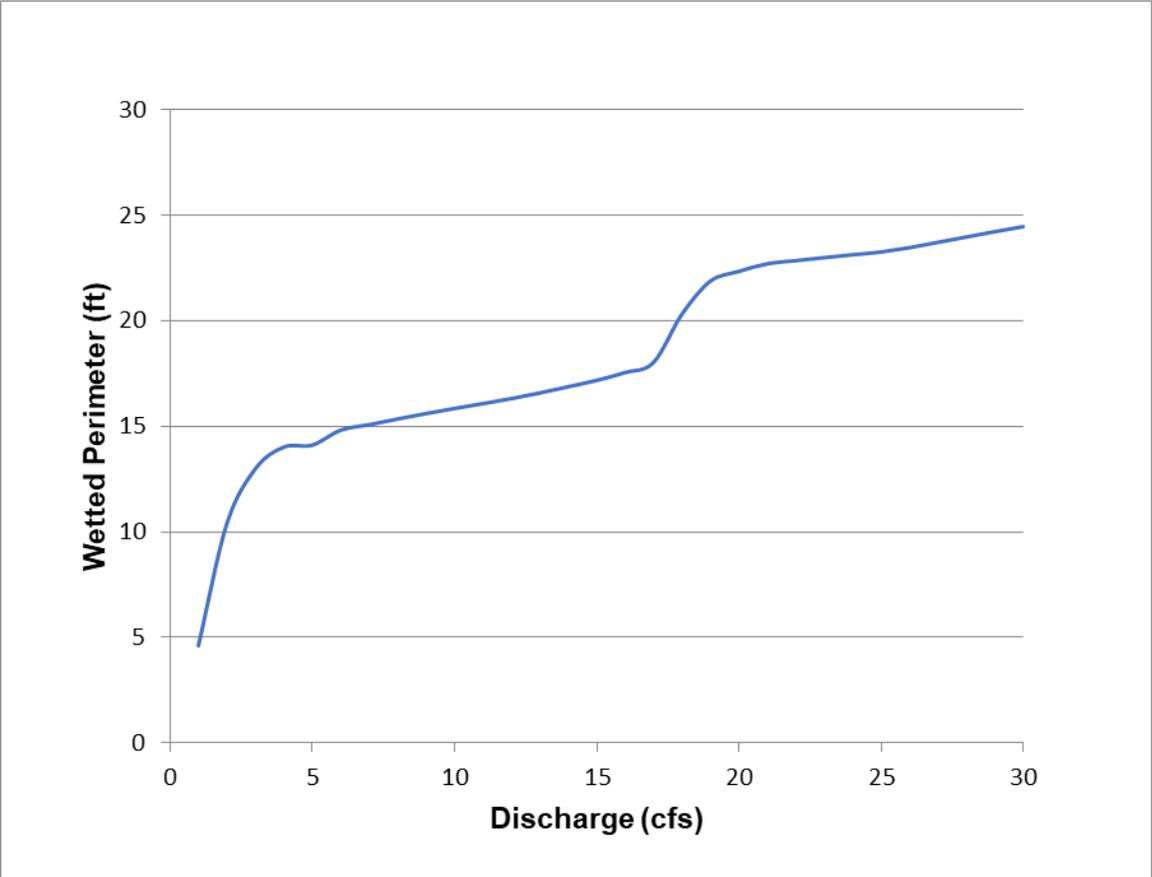

Figure 11. An example of a wetted perimeter-discharge curve.

3.3 Interpreting Results and Identifying the Low-Flow Threshold

To identify the low-flow threshold, the breakpoint flow is compared to the flow meeting the percent wetted perimeter requirement. The greater of these two numbers is selected as the low-flow threshold (Annear et al. 2004). In other words, the low-flow threshold is identified at the flow that:

- meets the breakpoint, and
- will wet a minimum percentage of the bankfull channel perimeter (Nehring 1979; Annear et al. 2004) as follows:

  - 50% wetted perimeter for streams with a bankfull width up to 50 ft, or
  - 60% wetted perimeter for stream with a bankfull width greater than 50 ft and up to 60 ft, or
  - 70% wetted perimeter for streams with a bankfull width greater than 60 ft and up to 100 ft.

The following two scenarios provide guidance on how to apply the WPM when identifying the low-flow threshold. Scenario 1 (Figure 12) is a stream with a bankfull width that is less than 50 ft, and Scenario 2 (Figure 13) is an example of a stream with a bankfull width that is greater than 50 ft. For the purposes of illustration, assume that these two streams are otherwise identical, and the wetted perimeter results are provided in Table 1. In each scenario, the low-flow threshold is identified either at the breakpoint or the flow that meets the percent wetted perimeter requirement dependent on bankfull width, whichever is greater.

Note: The breakpoint and incipient asymptote can be difficult to identify and may require professional judgment. The Department recommends that an experienced instream flow practitioner conduct the data analysis.

Scenario 1: The surveyed stream has a bankfull width of 20 ft.

- The stream has a bankfull width less than 50 ft, therefore the low-flow threshold must produce a wetted perimeter that is at least 50% of the bankfull channel perimeter. Fifty percent wetted perimeter is achieved at 2 cfs (Table 1; Figure 12).

- The breakpoint is identified at the curve's first point of marked change in slope at 3 cfs (Figure 12).

- Based on the comparison of these two values, the low-flow threshold is identified at the breakpoint of 3 cfs because this flow is the greater of the two flows on the wetted perimeter discharge curve.
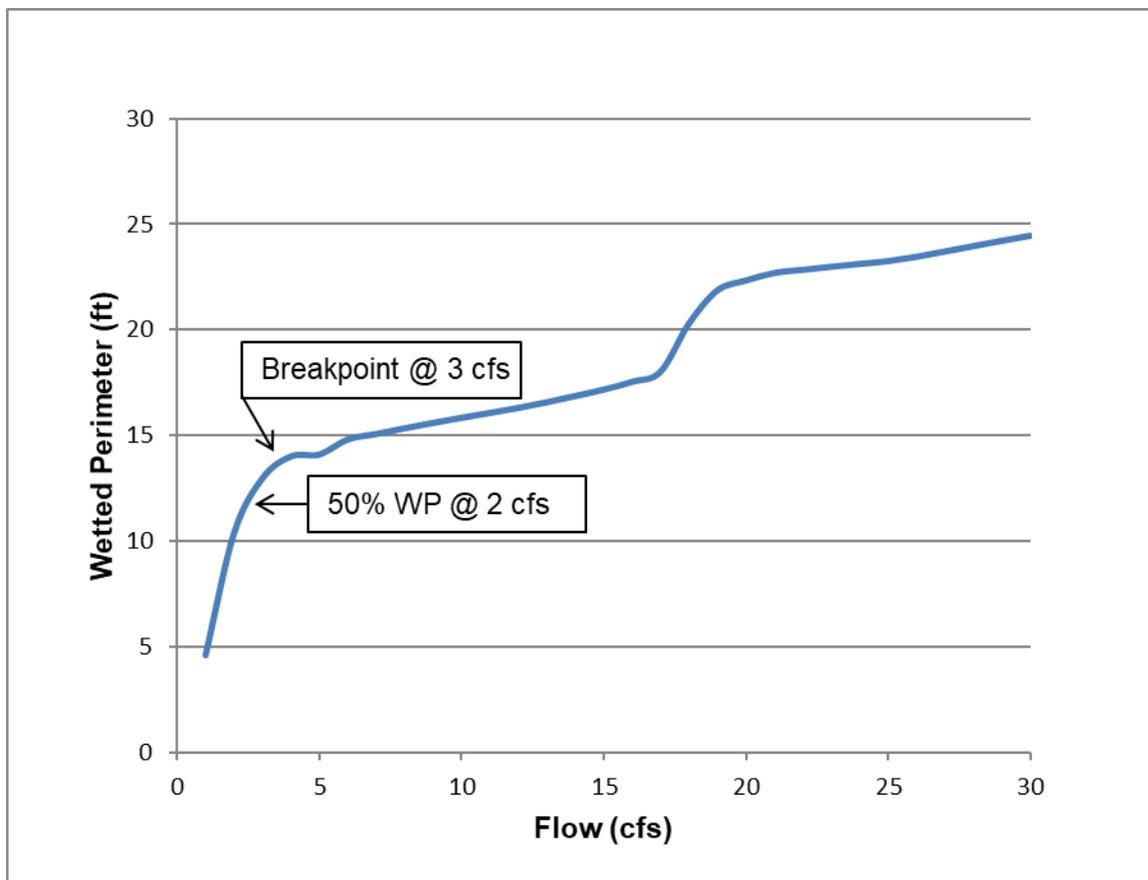
Figure 12. Example wetted perimeter-discharge curve for a riffle site displaying Scenario 1.

Scenario 2: The surveyed stream has a bankfull width of 55 ft.

- The stream has a bankfull width greater than 50 ft, therefore the low-flow threshold must produce a wetted perimeter that is 60% of bankfull. Sixty percent wetted perimeter is achieved at 6 cfs (Table 1; Figure 13).

- The breakpoint is identified at the curve's first point of marked change in slope at 3 cfs (Figure 13).

- Based on the comparison of these two values, the low-flow threshold is identified at the 60% wetted perimeter requirement of 6 cfs because this flow is the greater of the two flows on the wetted perimeter discharge curve.
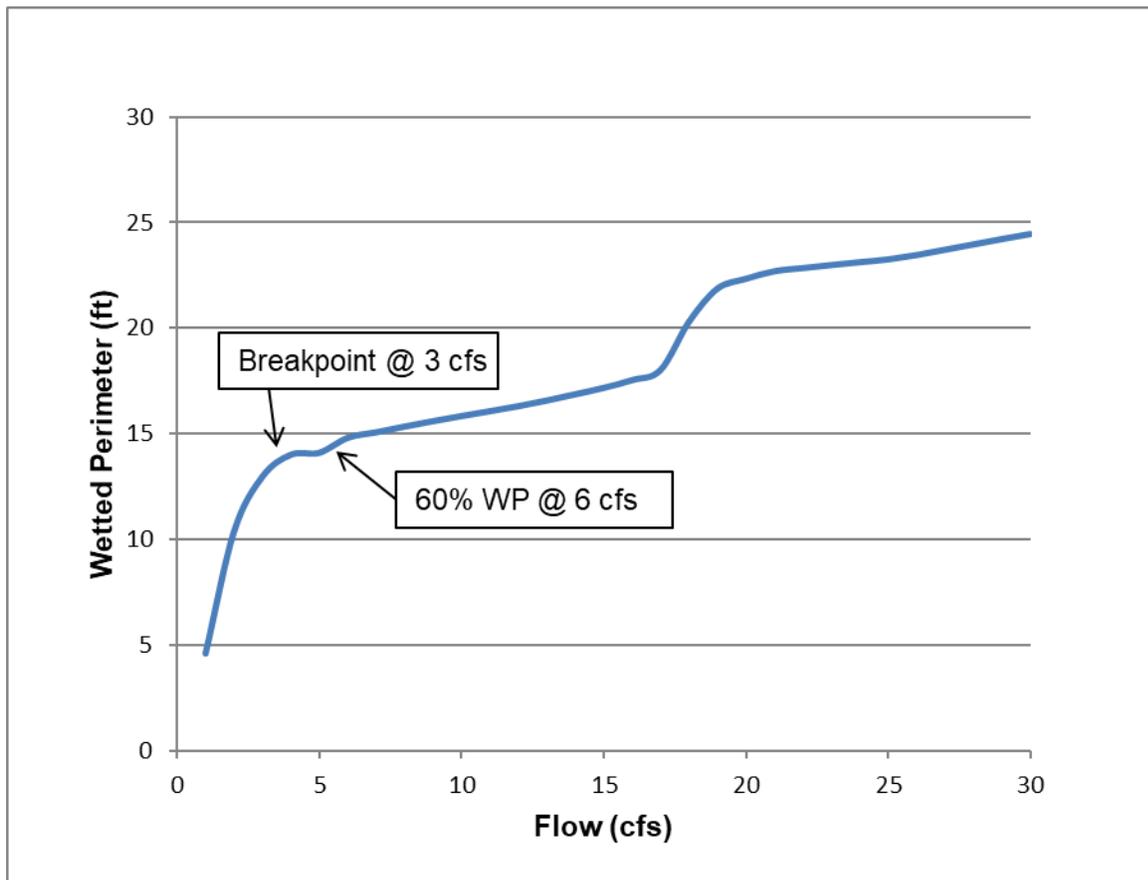
Figure 13. Example wetted perimeter-discharge curve for a riffle site displaying Scenario 2.

Table 1. Example WPM transect flows and hydraulic parameters for Scenarios 1 and 2, which represent different bankfull channel widths. Green boxes point to the identified low-flow threshold flow for each scenario.

Flow (cfs)	Wetted Perimeter (ft)	Wetted Perimeter (%)
1	4.576	35.02
2	10.361	50.56
3	12.968	53.00
4	14.007	57.25
5	14.097	57.62
6	14.808	60.52
7	15.067	61.58
8	15.339	62.70
9	15.595	63.74

Scenario 1 ← (points to row 3)

Scenario 2 ← (points to row 6)

Glossary

Term	Definition
Bankfull	The observed and identifiable location on each bank where change in slope, change in substrate, and/or lower limit of perennial vegetation occurs. Additional indicators include the top of point bars, bank undercuts, and stain lines (Leopold et al. 1964; Rosgen 1994; CWCB 2006).
Breakpoint	The breakpoint of a wetted perimeter-discharge curve defines the lower threshold below which aquatic riffle habitat conditions for BMI's rapidly decline. The breakpoint represents the transition from "critically important food production" to "rapidly declining food production." The breakpoint is identified at the curve's first (lower) point of marked change in slope.
Discharge	The volume of water passing through a given cross-sectional area per unit time, typically expressed in cfs.
Hydraulic control	A horizontal or vertical constriction in the channel, such as the crest of a riffle (Annear et al. 2004).
Incipient asymptote	The incipient asymptote of a wetted perimeter-discharge curve defines the upper threshold at or above which aquatic riffle habitat conditions are at optimum food production. The incipient asymptote represents the transition between "critically important food production" and "optimum food production." The incipient asymptote is identified at the curve's second (upper) point of marked change in slope.
Low-flow threshold	The low-flow component of the hydrologic regime for ecological function and BMI production (Annear et al. 2004). Using the WPM, the low-flow threshold is determined by the breakpoint on the wetted perimeter-discharge curve or the percent wetted perimeter requirement, whichever is greater.
Toe of bank	The break in slope at the foot of a streambank where the bank meets the streambed.

Term	Definition
Wetted perimeter-discharge curve	A wetted perimeter-discharge curve is developed by plotting wetted perimeter values of a cross section of a stream (i.e., y-axis) against associated discharge values (i.e., x-axis). The curve reflects the amount of wetted streambed at various flows with the assumption that flow levels influence food productivity in riffles. If the surveyed channel is rectangular in shape, the curve should display two distinct points of marked change in slope: the breakpoint and the incipient asymptote. The wetted perimeter-discharge curve is useful for determining low-flow thresholds and can be used as a component of a larger instream flow needs assessment.

References

Annear, T., I. Chrisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jobsis, J. Kauffman, J. Marshall, K. Mayes, G. Smith, R. Wentworth and C. Stalnaker (2004). Instream flows for riverine resource stewardship. Revised edition. Instream Flow Council, Cheyenne, WY.

Arcement, G. J. and V. R. Schneider (1989). Guide for selecting Manning's roughness coefficients for natural channels and flood plains. United States Geological Survey (USGS). USGS Water-supply Paper 2339.

CDFW (2013a). Standard operating procedure for streambed and water surface elevation data collection in California. California Department of Fish and Wildlife, Instream Flow Program (CDFW), Sacramento, CA. CDFW-IFP-003. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=74173.

CDFW (2013b). Standard operating procedure for flow duration analysis in California. California Department of Fish and Wildlife, Instream Flow Program (CDFW), Sacramento, CA. CDFW-IFP-005. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=74183.

CDFW (2020). Standard operating procedure for discharge measurements in wadeable streams in California. California Department of Fish and Wildlife, Instream Flow Program (CDFW), West Sacramento, CA. CDFW-IFP-002, Version 2.

CWCB (2006). Development of instream flow recommendations in Colorado using R2CROSS for Microsoft Excel. Colorado Water Conservation Board, Department of Natural Resources, Stream and Lake Protection Section (CWCB), Denver, CO.

Gippel, C. J. and M. J. Stewardson (1998). Use of wetted perimeter in defining minimum environmental flows. Regulated Rivers: Research & Management **14**: 53-67.

Grant, G. E., J. E. Duval, G. J. Koerper and J. L. Fogg (1992). XSPRO: A channel cross-section analyzer. Bureau of Land Management (BLM), Denver, CO. Technical note 387.

Gupta, R. S. (2008). Hydrology and hydraulic systems. 3rd edition. Waveland Press, Long Grove, IL.

Harrelson, C., C. Rawlins and J. Potyondy (1994). Stream channel reference sites: An illustrated guide to field technique. United States Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO. General Technical Report RM-245**:** 61. Available: https://www.fs.fed.us/biology/nsaec/fishxing/fplibrary/Harrelson_1994_Stream_Channel_Reference_Sites_An_Illustrated.pdf.

Jowett, I. G. (1997). Instream flow methods: A comparison of approaches. Regulated Rivers: Research & Management **13**: 115-127.

Kim, S. K. and S. U. Choi (2019). Comparison of environmental flows from a habitat suitability perspective: A case study in the Naeseong-cheon Stream in Korea. Ecohydrology **12**(6): 1-10.

Leathe, S. and F. Nelson (1989). A literature evaluation of Montana's wetted perimeter inflection point method for deriving instream flow recommendations. Montana Department of Fish, Wildlife, and Parks, Helena, MT.

Leopold, L. B., M. G. Wolman and J. P. Miller (1964). Fluvial processes in geomorphology. Dover Publications, New York, NY.

Limerinos, J. T. (1970). Determination of the Manning coefficient from measured bed roughness in natural channels, studies of flow in alluvial channels. United States Government Printing Office, Washington, DC. Geological Survey Water-Supply Paper 1898-B.

Molls, T. (2008). HydroCalc. Version 3.0c (build 105) [computer software].

Nehring, R. B. (1979). Evaluation of instream flow methods and determination of water quantity needs for streams in the state of Colorado.

Olson, S. A. and J. M. Norris (2007). U.S. Geological Survey streamgaging from the National Streamflow Information Program. United States Geological Survey, National Streamflow Information Program (USGS), Pembroke, NH. Available: https://pubs.usgs.gov/fs/2005/3131/FS2005-3131.pdf.

Rosgen, D. L. (1994). A classification of natural rivers. Catena **22**: 169-199.

Turnipseed, D. P. and V. B. Sauer (2010). Discharge measurements at gaging stations: techniques and methods 3–A8. U.S. Geological Survey, Reston, VA. Available: https://pubs.usgs.gov/tm/tm3-a8/.

USACE (2012). Field identification of Ordinary High Water Mark in relationship to the field identification of bankfull stage for the Galveston District's Tiered Stream Condition Assessment Standard Operating Procedure. United States Army Corps of Engineers (USACE), Galveston, TX. Available: https://www.swg.usace.army.mil/Portals/26/docs/regulatory/Streams/BFvOHWM.pdf.

USFWS (2011). Sacramento Fish and Wildlfie office standards for Physical Habitat Simulation studies. U.S. Fish and Wildlife Service, Sacramento Fish and Wildlife Office (USFWS), Sacramento, CA.

USGS (2001). PHABSIM for Windows, user's manual and exercises. U.S. Geological Survey, Midcontinent Ecological Science Center (USGS), Fort Collins, CO. Open File Report 01-340.