| **Technical Supplement 5** | **Developing Regional Relationships for Bankfull Discharge Using Bankfull Indices** |

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Cover photo: Bankfull or channel-forming flow can be determined by field measurements, using indicators. Systematic measurement of bankfull conditions in a region can result in the development of regional curves that relate bankfull stream discharge and other geomorphic characteristics to watershed drainage area.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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Purpose

This technical supplement presents a basic approach for the development of regional relationships for bankfull discharge using bankfull indices. This technical supplement provides guidelines to identifying bankfull stages along riparian stream corridors and procedures to determine the bankfull discharge associated with the bankfull stage. The bankfull discharge is used as a surrogate for the channel-forming discharge. While this technical supplement is primarily focused on the development of curves that are used in the Rosgen geomorphic channel design approach (NEH654.11), they are applicable to other assessment and design tools, as well.

Regional curves

Regional curves are constructed from observations and measurements of stable riffle cross sections on gaged rivers and streams. They are empirical by nature. The measured bankfull data are plotted versus the contributing drainage area flowing through the measured cross section(s). The regression equations express mathematical relationships between the bankfull channel dimensions: cross-sectional area, top width, mean depth, and the contributing drainage area.

Regional curves are a useful planning tool for natural stream design, stream restoration/stream enhancement, and fish habitat improvement or enhancement projects. They may provide estimations of the bankfull channel dimensions and bankfull discharge for any ungaged river or stream within the same physiographic area, given its drainage area.

However, discharge, not drainage area, is the driving force that moves, shapes, and maintains channels. Watershed shape, drainage pattern, slope, vegetal cover, land use, and management practices all affect the timing and magnitudes of runoff and, therefore, affect the size of the bankfull channels. Mathematically, better correlations exist between the bankfull hydraulic geometry and bankfull discharge. In watersheds with similar drainage areas, magnitude and duration of bankfull discharges can vary and, hence, hydraulic geometries at bankfull stage will vary due to the shape and cover of the watershed. Regime curves (hydraulic geometry vs. effective discharge) improve correlation over regional curves. Hydraulic geometry is described in further detail in NEH654.07 and NEH654.09.

USGS gage station selection criteria

Regional curves are constructed from stream survey measurements at U.S. Geological Survey (USGS) gaging stations. The period of record should accurately reflect the expected land uses and reported drainage size of the watershed. Gage data should be collected to represent a wide array of drainage areas with similar selection criteria.

Selection criteria for USGS gages to be used for regional curves are based on several factors: length of record, channel and drainage network stability, land use (rural vs. urban), drainage area size and shape, and the degree of (flood) control within the watershed. These criteria should match for the gages used to develop the regional curves. A combination of factors must be avoided. In addition, the criteria for the gages used to develop the curve should also match the intended project or evaluation area. Additional issues are described.

Stability of channel and drainage area network

The period of record should accurately reflect the expected land uses and reported drainage size of the watershed for the entire period of record. It may be difficult to recognize a natural drainage system that has undergone some degree of land use change or instability in its past. When researching gages, look for clues which may indicate that the watershed's hydrology and sediment production has changed over the length of record. Such clues may be obtained from a series of historic aerial photos, land use maps, mining records, road development, grazing or farm practices, development patterns, or fire records. These practices can affect the timing and volume of runoff, as well as the sediment production in a given watershed.

Gages on streams with flood control or diversions

Bankfull channel dimensions normally correspond to the uncontrolled drainage area. The assumption behind taking measurements of streams at known drainage areas and discharges is that a link can be made between the stream's geometric parameters and peak rates of discharge with uncontrolled drainage areas. Dams, detention basins, and diversions affect the watershed hydrology by storing part or all of the peak discharges and releasing an attenuated flow regime. This will also affect sediment transport, which is critical to channel formation and maintenance. Dams and storage basins may store all incoming bed-material load and only a small portion of the finer wash load. Flood control affects the timing of peak discharges and may prevent the normal bankfull event from occurring downstream of the impoundment. Therefore, it is generally recommended to avoid gaging stations in watersheds that have flood control and water diversions.

Urban versus rural land use drainage areas

Urbanization generally increases the amount of impervious surface in a watershed. Additionally, stormwater and sewer conveyance systems combine to increase the volume of runoff and magnitude of runoff for a given storm event. Urbanization of a drainage area tends to reduce the recurrence interval for the bankfull event; from say, a 1.5-year recurrence interval to a 1.2-year recurrence interval. Urbanization may also increase flow velocities, increasing the forces and stresses imposed on the beds and banks of the channels. This is brought about in a number of ways such as changes in alignment (meander patterns, cutoffs, and increased stream gradient), encroachment on the flood plain, reduction in the boundary roughness, and changes in the median bed-material particle sizes. Urban areas are unique and should be separated from natural drainage areas to account for these changes in hydrology and sediment transport regimes. For example, regional curves may be constructed separately to represent natural forested and/or rangeland areas, rural farmed areas, or urban areas.

Equipment and human resources

Creating regional curves requires a team for collecting, analyzing, extracting, and transforming data into information. The size of the survey crew varies, depending on the site and intended use of the curves.

Surveys can be conducted with any standard survey instruments including a theodolite, total station, automatic level, or a laser level. The following equipment is usually needed to conduct these surveys:

- stable tripod
- telescoping rods, prisms
- two-way radios
- field notebook(s)
- compass
- measuring tape
- camera
- waders
- flagging
- station pins and nails
- orange vests
- personal flotation devices
- ruler (in millimeters, for rocks)
- data collection sheets

Other items may include a Global Positioning System (GPS) unit for precise locations, range finder to expedite the surveying process, buckets and shovel for sampling bed and bank materials, set of sieves for determining grain size, and scale for weighing samples.

In-office data collection

Gage data

The USGS Web site (*http://waterdata.usgs.gov/nwis/rt*) contains information such as station name and number, latitude and longitude of the gage site, drainage area, period of record, number of years of record,

and peak annual discharges and corresponding peak gage heights for each year in the period of record (n years). An estimate of the 1.5-year discharge is derived using techniques described in NEH654.05 and is used as a surrogate for bankfull discharge recurrence interval.

For the gages of interest, the practitioner should contact the local USGS data chief and request station descriptions, current rating tables, and summaries of discharge measurement notes. However, it is important to note that while each gage station may have a unique rating curve, the relationship between gage height and discharge is not necessarily unique. The rating curve may shift over the long term, as the cross-sectional shape and/or elevation changes, and it may shift over the course of a hydrograph due to the unsteady loop effect or due to changing bedforms.

The user should collect an existing gage analysis, or information sufficient to conduct such an analysis, following the procedures described in NEH654.05. By cross-referencing the estimated flows with the rating table, the user can define specific gage heights as the elevations for specific return intervals or specific chances of exceedance.

Discharge measurement notes are useful in that they provide specific cross-sectional flow areas, top widths of flow, and velocities for specific gage heights and discharge measurements. Plotting measurements below and above the bankfull discharge allows the user to estimate flow area, top width, and velocity at the bankfull or channel-forming flow.

Aerial photographs, topographic maps, and geology maps of the watershed of interest should be examined. These maps and photos can reveal details of the watershed and land use patterns that indicate the conditions that help shape the drainage network.

The topographic maps will also provide information required for stream characterization that is not easily obtained from the ground survey. Reach slope, sinuosity, and meander belt width can be estimated from these maps. Average reach slope can be estimated from the topographic maps by measuring the planimetric distance between contour intervals. It is recommended that the practitioner identify two to four consecutive contour intervals both downstream and

upstream from the gage and measure the streamwise distance between the contour intervals.

A cross-reference to the USGS rating curve will provide the gage height for the 1.5-year discharge. When at the site, the user should locate the staff gage and identify a relatively flat depositional feature above or below this gage height corresponding to the bankfull discharge. If the staff gage has been removed, the user should locate an existing reference mark (from the station description) that refers back to a gage elevation. With a measuring tape, measure up or down to the gage height corresponding to the 1.5-year discharge, and again, look for the first flat depositional feature around this elevation. The practitioner should study this feature and the corresponding material size. Of particular interest are moss lines, debris lines, changes in slope and other distinguishing features. The elevation of these features relative to the water surface may be useful in identifying bankfull stages away from the gage site.

Note that the bankfull discharge elevation may vary significantly from the 1.5-year recurrence interval that is a normal surrogate for bankfull discharge in natural streams. As stated previously, the recurrence interval for the bankfull flow may be more frequent in developed watersheds.

Use of discharge notes

Discharge measurement notes can also provide insight into the hydraulic characteristics of the stream. Discharge measurement notes are a summary of discharge measurements taken throughout the period of record. They include date of measurement, gage height, discharge, top width of water in the cross section, cross-sectional area of flow, and mean velocity in the measurement cross section. The location where measurements take place is usually described in the station description. It is common to have two cross-sectional locations—one on the control feature of the stream for low-flow measurements and one across the bridge for high flows.

Energy slope and Manning's n are not included in the measurement notes. After calculating an average reach slope from topographic maps, Manning's n can be calculated using Manning's equation by approximating the hydraulic radius by the hydraulic depth d = flow

area/top width from the discharge measurement notes for a given discharge. Manning's *n* can vary considerably with depth of flow. Streams characteristically have high roughness at low flows and become hydraulically smoother as depth of flow increases. It is also important to note that this is a normal depth assumption and may not represent the flow levels due to any backwater effects that may occur. More information on the normal depth assumptions and computer modeling approaches is provided in NEH654.06.

Site reconnaissance

Before setting up the surveying equipment, a reconnaissance along the reach is prudent to select optimum station setups and minimize the overall number of setups and turns. During this reconnaissance, team members should assess the reach to determine if it is

a stable form of the river, as it would have developed under natural conditions. The team can make this assessment by asking the following questions:

- Is there a low water ford or cattle access present that changes the channel geometry?

- Is accelerated bank erosion occurring?

- Are there undercut banks and trees falling in?

- Has bank vegetation been grazed, removed, sprayed, or cleared away?

- Is there one long continuous pool upstream from the gage?

The team should also assess the location of sections to be surveyed. Identification of riffle locations or the heads of glides, selection of cross-sectional locations, flagging bankfull indicators, and deciding the length of the reach to survey prior to setup may actually save field time. Figure TS5–1 provides an example of a sur-

Figure TS5–1 Example plan view of a site
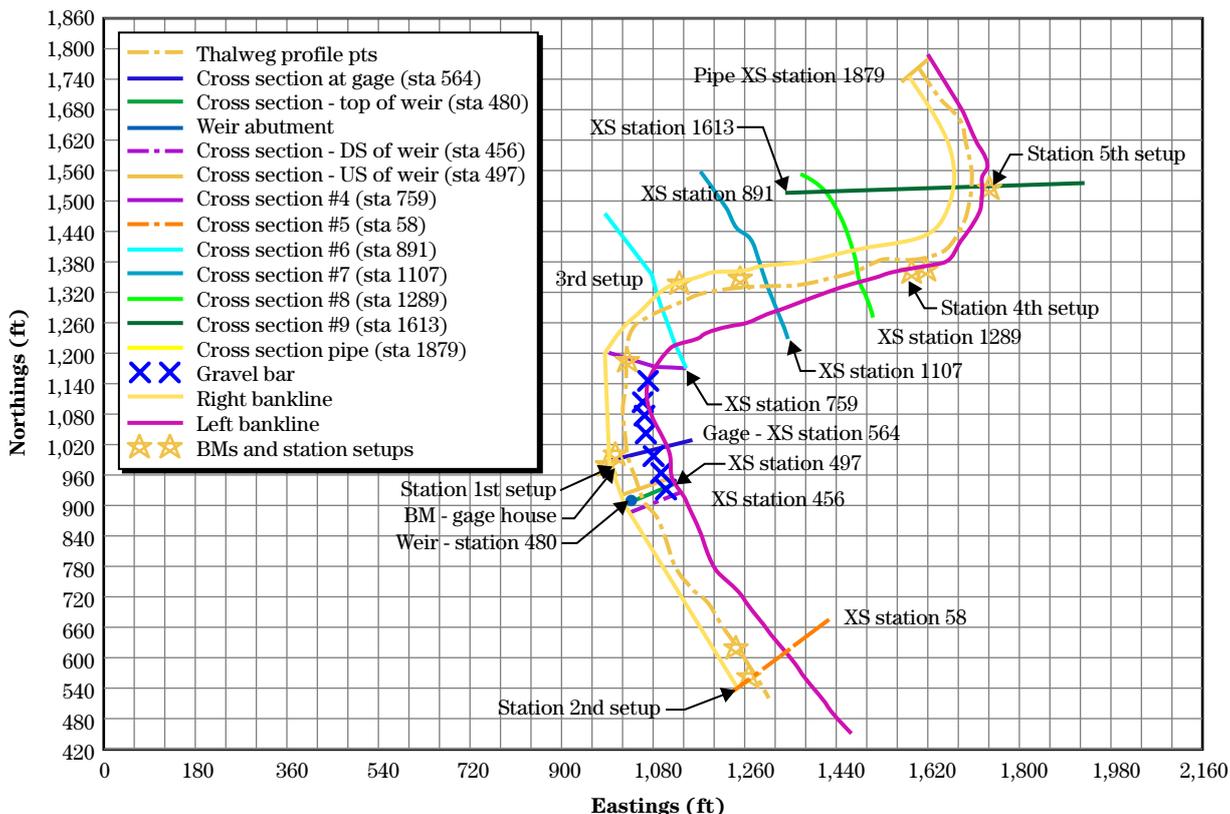
vey using a total station survey instrument and shows station setups, benchmarks, thalweg profile, bank lines, cross sections, instream weir, and pipe crossing.

Station setups, benchmarks, and reference marks

The first step in beginning a survey is to tie survey elevations into the gage datum using the USGS reference marks. From the USGS station gaging description, the team should find all existing reference marks. These are published elevations with respect to the gage datum and allow the survey to be tied to an official datum. These marks may be chiseled Xs or chiseled squares on bridge abutments, gage houses, elevations of check bars on an outside wire weight gage, USGS or U.S. Department of Transportation (DOT) brass caps, staff gages, or bolts in trees or telephone poles. A shovel may be needed to scrape away dirt and overgrown weeds over concrete surfaces. The team should assure that at least two reference marks are visible from the initial station setup.

When using a total station instrument, the resection method for determining the station location requires coordinates for two known elevations. A measuring tape, compass, and calculator will be required to determine these coordinates in northings and eastings. The coordinate system may be arbitrary on setup, but afterwards, it must remain consistent, or the true alignment will be lost. Figure TS5–2 shows a station setup just upstream of a gage house along a riffle section where USGS discharge measurements are conducted.

Cross sections

Estimating a bankfull discharge may be accomplished by surveying a single section that is upstream of the gage and correlating it to the gage rating curve. However, for regional curve development, several cross sections for two to three full meander wavelengths for a detailed HEC–RAS model is recommended. Since the profile of the river reach will vary between the relatively steep riffle sections and the long relatively flat pool sections, the use of the HEC–RAS model will allow the practitioner to reconstruct the bankfull water surface elevations along the survey reach back to the gage site and, ultimately, prepare the rating table to determine discharges.

The survey data are to be used to develop a HEC–RAS model, so a cross section that represents the rating table is required. This cross section will be very important in calibrating the model. The station description usually describes where in the reach (in relation to the gage) low-flow discharges are measured. More than likely, this is on a riffle or upstream in a pool from a manmade control point, such as a cross-channel weir. Surveying a cross section over the end of the pressure transducer pipe is also wise, for this may be the section that represents the USGS rating table. Several cross sections should be surveyed downstream from the gage. The furthest one from the gage must be sufficiently far enough downstream that any erroneous assumptions of starting the flow conditions at normal depth are negligible at the gaging cross section. A good location for the first cross section may be in the next downstream riffle section, usually six to eight bankfull widths downstream.

The practitioner should survey several cross sections in the middle of three to four riffle sections above the gage cross section. This will help assure that the average reach geometry is not dependent on just one or two cross sections. All cross sections should start at or above the 100-year flood plain, or high on the valley wall, and extend across the valley to the opposite valley wall, or end above the 100-year flood plain. It

Figure TS5–2   Station setup is just upstream of gage house

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is normal protocol to define a cross section looking downstream with the stationing (in the cross section) increasing from left to right.

Figure TS5–3 shows a cross-sectional view near the gage house shown in figure TS5–2. The HEC–RAS computed rating curve at this cross section was compared to the USGS rating curve to complete calibration. Note in the cross-sectional view that the bankfull elevation corresponds to the top of a gravel bar feature near the left bank.

## Profile—channel bed, water surface, bankline, flood plain, and terraces

Between cross sections, the survey should locate the thalweg profile, water depth, bankline profiles, and flat depositional features adjacent to the stream, known

as the active flood plain. With a four-person team, one person operates the instrument with three people each with a survey rod; one along the right bank, one along the thalweg, and one along the left bank. This technique lends itself well to defining bankfull elevations because there will be at least two opinions on bankfull features. Every shot of the survey should include a recorded description of the particle size of the bed material that is found under the survey rod.

Bankfull indicators

Bankfull flow elevations and discharges are associated with sediment transport and, therefore, are closely tied to particle sizes moved and deposited in gravel and cobble dominated bed streams. In sand-bed streams, there may not be a differentiation of particle sizes from the channel and the active flood plain, but there

Figure TS5–3   Cross-sectional survey
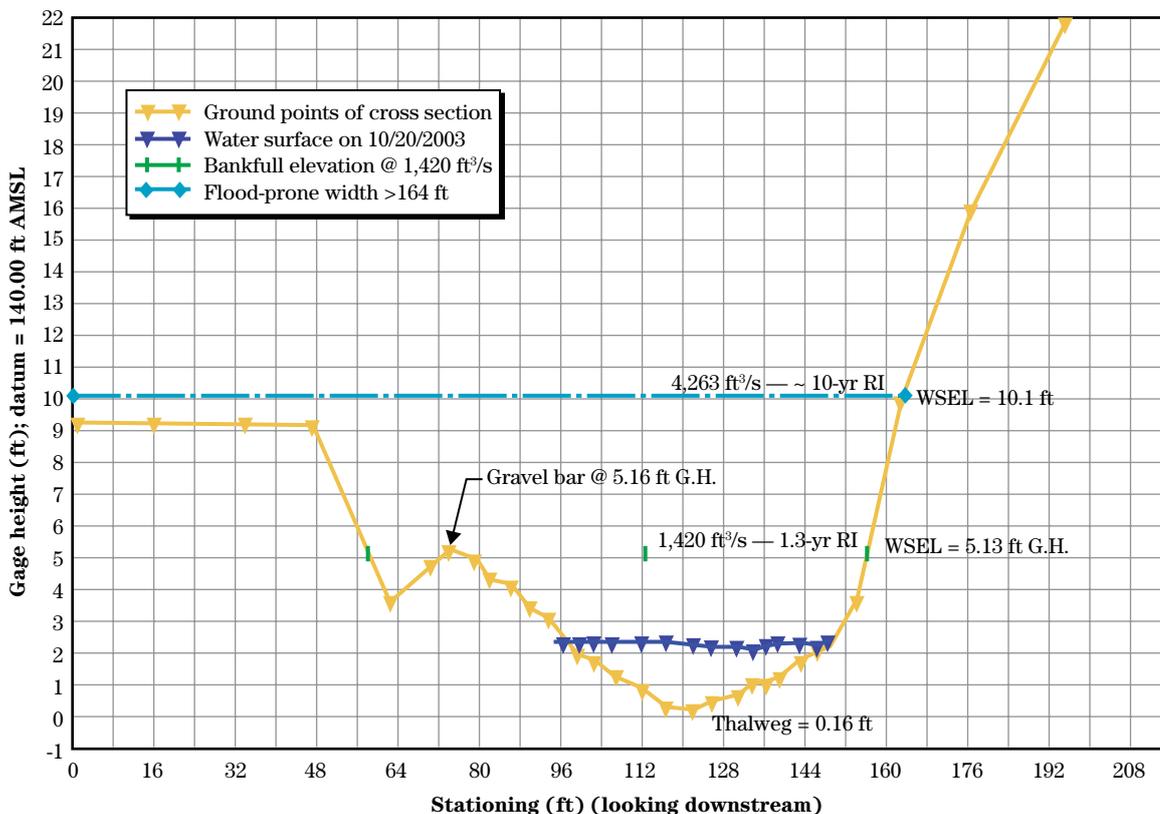
should be a break in slope. Flat depositional features, breaks in slope, height of point bars, and vegetation features are other bankfull indicators that should be used. One of many bankfull indicators is a change in particle size distribution from gravels to fine grained sands. More information on bankfull indicators is provided in NEH654.05.

Characterization of bed material

The typical technique used for sampling the bed material is the Wolman pebble count. Wolman pebble counts are conducted in the riffle sections for several purposes and are described in more detail in NEH654 TS13A.

Data processing and analysis

HEC–RAS model input

The cross-sectional data are used to build a conventional HEC–RAS hydraulic model. It is recommended to use the thalweg stationing to set the channel distances between cross sections (required input to HEC–RAS model). All water surface elevations generated by the model will be in reference to the channel distances, which may be different from the bankline distances.

Calibrating to USGS rating curves

After the initial input of cross-sectional data, a HEC–RAS computational model run can be made to determine if the model has sufficient cross-sectional data to compute the actual water surface elevations recorded along the reach measured during the day of survey. Plotting computed water surface elevations along with channel bed and measured water surface elevations is helpful in pointing out areas along the profile that could use refinement or more definition. Depending on the level of agreement, additional refinement may be done by either returning to the field to take more measurements or by adding in interpolated cross sections based on the thalweg profile. It should be noted that this approach may be problematic in streams where the flows were very low at the time of the survey.

When the model definition is robust enough to match measured low-water surface elevations, calibration of the model by changing Manning's coefficients and contraction/expansion coefficients can proceed to match the USGS rating curve at the gaging cross section. Figure TS5–4 shows a comparison of rating curves between the calibrated model results at the gage cross section. As shown in this figure, the model calibration is good up to discharges of 4,000 cubic feet per second, which is well beyond the bankfull discharge of 1,420 cubic feet per second.

Selecting the channel-forming discharge

Once the model is calibrated to the USGS rating curve, a selection of the channel-forming discharge can be made. This will entail running a range of discharges in the HEC–RAS model and comparing computed water surface elevations along the longitudinal profile to measured bankfull indicators and associated bankfull elevations. The criterion for consistency is that the profile of bankfull-stage elevations should plot approximately parallel to the longitudinal profile of the water surface at some given discharge through the reach (Kilpatrick and Barnes 1964). The channel-forming discharge is the discharge that comes closest to the surveyed bankfull indicators: flood plains, benches, breaks in slope, change in particle sizes, and vegetation indicators along the reach.

Hydraulic geometry relationships at bankfull

Once the channel-forming discharge or bankfull discharge is known and the corresponding water surface elevations computed, the hydraulic geometry in the stable riffle cross sections can be estimated. Cross-sectional flow area, hydraulic radius, hydraulic depth, and top width can be selected as output variables from the HEC–RAS Profile Output Table. The hydraulic geometry for the reach is best represented by an average of three or four stable riffle cross sections. The hydraulic geometry relationships at bankfull should then be plotted with respect to drainage area on the regional curve (fig. TS5–5). These relationships are useful in a variety of channel assessment and design applications.

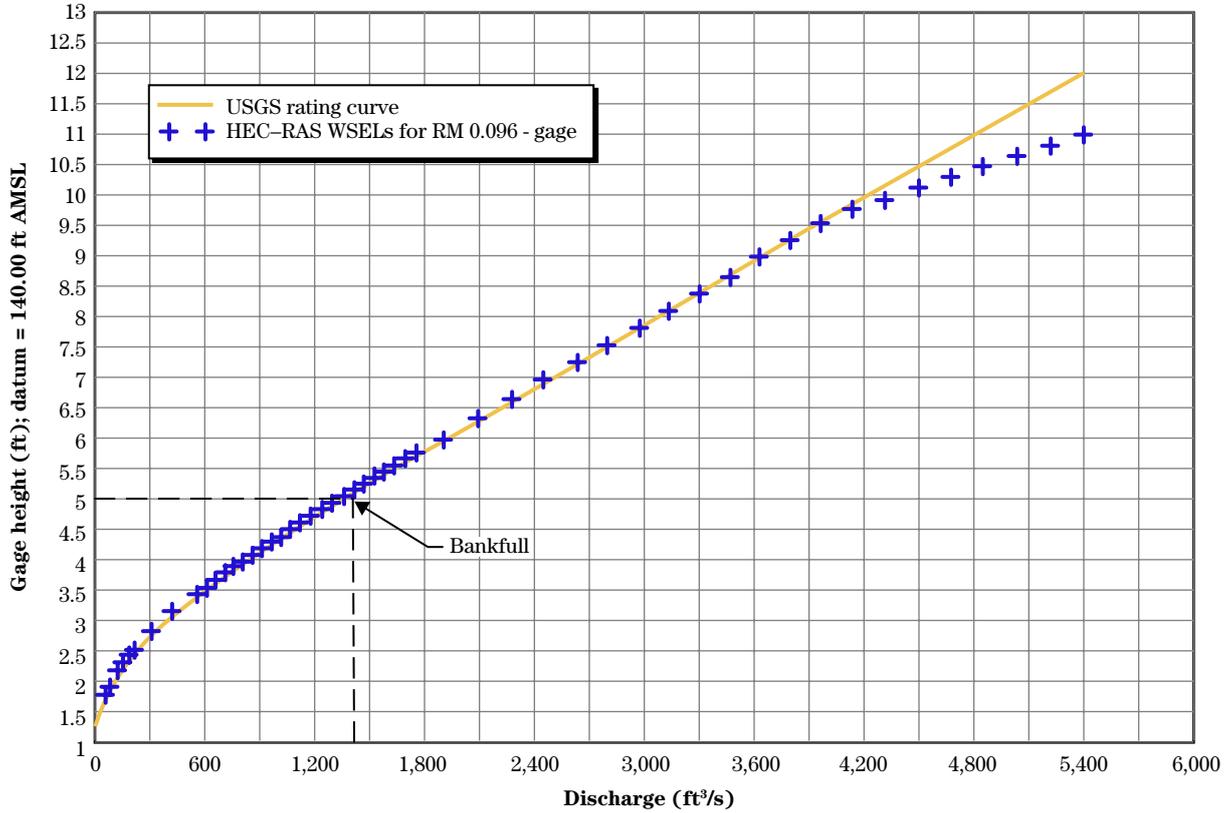**Figure TS5–4**   Comparison of USGS rating curve with HEC–RAS

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Figure TS5–5   Regional curves for hydraulic geometry