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Habitat Availability vs. Flow Rate for the Pecos River, Part I: Depth and Velocity Availability

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Abstract

The waters of the Pecos River in New Mexico must be delivered to three primary users: 1) The Pecos River Compact: each year a percentage of water from natural river flow must be delivered to Texas; 2) Agriculture: Carlsbad Irrigation District has a storage and diversion right and Fort Sumner Irrigation District has a direct flow diversion right; and, 3) Endangered Species Act: an as yet unspecified amount of water is to support Pecos Bluntnose Shiner Minnow habitat within and along the Pecos River. Currently, the United States Department of Interior Bureau of Reclamation, the New Mexico Interstate Stream Commission, and the United States Department of the Interior Fish and Wildlife Service are studying the Pecos Bluntnose Shiner Minnow habitat preference. Preliminary work by Fish and Wildlife personnel in the critical habitat suggest that water depth and water velocity are key parameters defining minnow habitat preference. However, river flows that provide adequate preferred habitat to support this species have yet to be determined. Because there is a limited amount of water in the Pecos River and its reservoirs, it is critical to allocate water efficiently such that habitat is maintained, while honoring commitments to agriculture and to the Pecos River Compact. This study identifies the relationship between Pecos River flow rates in cubic feet per second (cfs) and water depth and water velocity.

Acknowledgments

The authors would like to thank Randy Buhalts and Mike Chapin for their careful work in data collection and review. We would also like to thank Sandia National Laboratories New Mexico Small Business Assistance Program for funding this work.

Note to the Reader:

Sandia National Laboratories has been asked to study the hydrology and morphology of the Pecos River to help water managers determine flow allocations necessary to support a viable population of the threatened Pecos Bluntnose Shiner Minnow (PBSM). Studies performed by the USBR, ISC, and USFWS propose that assessment of water needs of the PBSM, in its most general form, requires the marriage of habitat preference with habitat availability. An exact definition of preferential habitat remains in flux, but it has been proposed by the aforementioned agencies to rely on essential parameters such as water depth, water velocity, and to a lesser extent sediment activity. It is imperative that federal, state, and local agencies understand the relationship between river flow and available habitat.

The purpose of this study is not to specify the preferred habitat of the PBSM – significant efforts have already been directed toward this issue. Rather, we seek to quantify the 'amount' of habitat available to the PBSM at any specified flow rate. That is, our study describes the available habitat yielded by a given flow rate no matter how that preferred habitat is defined. Because the Pecos River is an ephemeral, braided river, it is likely that there exists a specific flow rate that exhibits a point of 'diminishing returns.' For example, perhaps doubling flow rate serves only to increase the available PBSM habitat by a small percentage. This study can be used to identify the optimum flow rate that presents the PBSM with the sufficient habitat with the least flow ('bang for the buck').

The necessity of a habitat availability study is clear. Although the preferred habitat of the PBSM has been (at least preliminarily) identified, data that describe what flow rate maintains this habitat are scattered and incomplete. This study provides high-resolution data and model results that define available habitat as a continuous function of flow for several cross-sections through the northern critical habitat section between Old Fort Sumner Park and ACME gage. The amount (width of river) of available habitat required for PBSM survival, as specified by biologists, can be used as a criterion for water managers to calculate the correlated flow rate. The depth and velocity availability curves should be used to estimate water allocation information for the PBSM during dry, average, or wet years. Ultimately, results presented here should aid in the development of a long-term water management plan.

Sandia National Laboratories plans to publish three reports addressing the topic of available habitat in the Pecos River. The first, Part I (this report), specifies the relationship between depth, velocity, and river flow. Part II will investigate the effects of river flow on in-stream sediment activity – the formation of dunes and ripples in the sediment bed and their subsequent migration rates. Part III will integrate all of the parameters into an overall habitat availability analysis. Presently, water managers using these habitat availability abundance plots have to compare preferred and available habitat one parameter at a time (i.e. treating depth, velocity, and sediment activity as independent variables). Although this is a viable approach, recent studies have indicated that the biologic needs of the minnow are more complex. For example, if a particular width of a cross-section is to be considered suitable habitat, it must comprise acceptable depth, velocity and sediment activity all specific to the species and life stage of interest, not just one of the three. Through this current and future work, regulators, biologists, and the courts can decide what fraction of the river width should be maintained with a habitat suitable for the PBSM and then specify the associated river discharge necessary to maintain these conditions.

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Introduction

Fresh water is a crucial resource to sustainable populations, economic growth and a thriving ecosystem. It is estimated that by 2015, nearly half of the world's population will live in countries that are water stressed (Global Trends 2015, National Intelligence Council). It is becoming increasingly important to conserve water resources, increase water use efficiency, and improve water quality. Such ideals are paramount, particularly throughout the arid and semiarid southwestern United States. "Water promises to be to the 21st century what oil meant to the 20th century: the precious commodity that determines the wealth of nations" (Fortune Magazine, May 15th 2000).

On a daily basis, water issues and events influence the lives of thousands of citizens in the State of New Mexico. The state has a naturally limited water supply and continues to struggle with the requirements for in-state uses, the interstate compact delivery obligations, and the responsibilities necessitated by the Endangered Species Act, especially under drought conditions. Water usage on the Pecos River involves the United States Bureau of Reclamation (USBR), the New Mexico State Engineer (NMOSE), the Interstate Stream Commission (ISC), the Pecos Valley Artesian Conservancy District (PVACD), the Fort Sumner Irrigation District (FSID), and the Carlsbad Irrigation District (CID).

There are three primary consumers of Pecos River water:

1) The State of Texas: For many years, the amount of water available for irrigation was a matter of contention between New Mexico and Texas. In 1948, the two states entered into an agreement known as the Pecos River Compact that required New Mexico to deliver approximately half of the water naturally entering the river in New Mexico to Texas. For years, Texas considered New Mexico deficient in meeting the terms of the contract and in 1974 filed suit. The United States Supreme Court ruled in June 1987 that New Mexico owed Texas 340,000 acre-feet of water for the period between 1950 and 1983, and ordered that New Mexico pay $14 million in compensation. Currently, a Pecos River Master appointed by the Supreme Court oversees New Mexico's compliance. Under the Pecos River Compact agreement, the state cannot accumulate any water delivery deficit to Texas. New Mexico has complied with the Supreme Court order to date, but has a very thin margin of credit.
2) Agriculture: FSID and the CID have the largest surface water diversion rights. In 1995, agriculture accounted for about 69% of net depletions in the river (Wilson, 1997). The rural New Mexico state economy relies heavily on agricultural interests. For example, the activities of the CID account for approximately $12M per year in gross receipts.
3) Endangered Species Act: The amount of water to maintain habitat for the threatened Pecos Bluntnose Shiner Minnow (PBSM) is unknown, but enough water must flow through the critical habitat to ensure a sustained population.

An ISC resolution passed December 15, 1998 asks ISC staff to work with responsible federal agencies to seek a longer-term solution to habitat needs. The ISC also asked the federal agencies to "…carefully determine the requirements of the bluntnose shiner for minimum flows and weigh those requirements and any uncertainty in the justifying data against the increased water depletions and the associated damages and costs to New Mexico and its water users, specifically including the damages associated with reduced water deliveries to the State of Texas under the Pecos River Compact and the associated U.S. Supreme Court amended decree."

Balancing the interests of all water users is a complicated matter. The overarching goal is to efficiently manage water in the Pecos River system to satisfy all concerned parties. To do this, the needs of the three primary water users must be clearly defined such that informed decisions about water management policies are made. During wet years, the total volume of water in the Pecos River Basin easily satisfies all parties and water management is much less a controversial issue. Conversely, in dry years, flows in the Pecos River are intermittent. The amounts of water owed to Texas and to the irrigation districts are specified quantities proportional to the water naturally flowing in the Pecos River, while the amount of water required by the Pecos Bluntnose Shiner Minnow (PBSM) is unknown. Specific habitat requirements (i.e., water depth, velocity, and sediment activity) and the river flows that yield those habitat requirements are under investigation. How much water does the PBSM need to survive? Therein lies the deficiency in the present understanding of the river ecosystem. Scientific investigation should be the foundation for informed water management decisions – decisions that should significantly increase the overall delivery efficiency of the river system. Ultimately, the Pecos River water must be managed efficiently to satisfy all parties.

Results of this study may have far reaching impacts on water usage/management in arid regions, particularly in New Mexico. The purpose of this project is to quantify the amount of habitat available to the PBSM at any flow rate. Given the available biological data defining PBSM preferred habitat (depth and velocity), this work provides data and develops a predictive model that relates river flows to the relative fraction of river width meeting the definition of PBSM preferred habitat. Although data are collected from 11 transects on the Pecos River, they are generalized to apply to much of the critical habitat region.

The Pecos River

The Pecos River, one of the major tributaries of the Rio Grande, rises on the western slope of the Santa Fe mountain range in Mora County, New Mexico and runs south through San Miguel, Guadalupe, De Baca, Chaves, and Eddy counties before it enters Texas just east of the 104th meridian. Through most of its more than 900-mile (1,450-km) course, the Pecos River parallels the Rio Grande. The total drainage area of the Pecos in New Mexico and Texas is about 44,000 mi^2 (1.1×10^5 km^2). Most of its tributaries flow from the west; these include the Gallinas River, the Rio Hondo, Rio Felix, Rio Peñasco, the Black River, Delaware River, Toyah Creek, and Comanche Creek. Entering the Pecos from the east are the Alamogordo, Taiban, Live Oak, and Howard tributaries. The topography of the river valley ranges from mountain pastures in the north, at elevations of more than 13,000 ft (4 km) above sea level, to grasslands, semiarid irrigated farmlands, desert with sparse vegetation, and, in the lowermost reaches of the river, deep canyons. The principal cities along the river in New Mexico are Las Vegas, Santa Rosa, Fort Sumner, Roswell, Artesia, and Carlsbad; in Texas, the main city on the river is Pecos. In the early 2000's, none of these had a population greater than 50,000.

Early-day travelers described the river as generally sixty-five to one hundred feet wide and seven to ten feet deep, with a fast current. Appreciable irrigation from the New Mexico section of the Pecos began in 1877 and by the mid-1980's, there were more than 400,000 acres (1,600 km^2) under irrigation, using both surface and underground water. Currently, the river is usually a shallow, narrow, braided stream with a slow current bordered by desert shrubs. Except during floods, its flow for a considerable distance downstream from the Red Bluff Reservoir consists principally of releases and some reservoir seepage.

In November 1998, the Bureau of Reclamation (BoR) assumed operations of Sumner Dam and provided a minimum flow of 35 ft^3/s (cfs) at Acme gage north of Roswell for protection of the PBSM. The BoR projected that the minimum-flow regime would increase depletions on the Pecos by between 3,000 to 13,000 ac-ft (3.7×10^6 to 1.6×10^7 m^3) per year. To implement the ISC policy goals that Endangered Species Act (ESA) recovery activities take place within the framework of state law and that any new depletions be accompanied by water-rights offsets or compensation, the ISC and BoR entered into a lease agreement on November 13, 1998. The agreement stipulated that the ISC would lease water held in the Pecos Water Conservation Program to the BoR at a rate of $106/ac-ft to offset any depletions caused by the minimum-flow regime. To protect New Mexico's ability to meet its Pecos River Compact obligations, the lease further stated that the BoR would make its best efforts to offset any new depletions with other valid New Mexico water rights. On April 23, 1999, the State Engineer approved two BoR applications for temporary permits to transfer 2,600 ac-ft (3.2×10^6 m^3) of water from wells drilled in the Roswell aquifer as a partial offset to the 3,000–4,000 ac-ft (3.7×10^6–4.9×10^6 m^3) estimated loss from BoR's operations at Sumner Dam.

This study area focuses on a reach of river over 80 miles (129 km) long with a sandy bottom that is often braided and meandering between the riverbanks that extends from the Fort Sumner Reservoir to just north of Roswell at the ACME Gage site. Much of the river runs through private land with limited access via dirt roads and two bridges, one at each of the northern and southern ends. Measurements of bathymetry, sediment activity, and bulk sediment properties have been made at over 30 river cross-sections. Eleven permanent stations have been erected that were used to frequently monitor the Pecos River to assess morphology changes with river discharge.

Next, derived from measured data, an empirical predictive model is used to estimate water depth, wetted area, wetted perimeter, velocity, and sediment activity as a function of river discharge. The model is calibrated and validated by *in-situ* measurements. Model results can be used to identify total linear width or wetted area of river that establishes preferred PBSM habitat requirements. Because the Pecos River is an ephemeral, braided river, there exists a range of flow rates that develop sufficient habitat. During drought years, it may be prudent to release water at the low end of the flow rate range considered necessary to maintain sufficient habitat. The habitat availability curves in this report can be used to identify such flow rates.

The Pecos Bluntnose Shiner Minnow (*Notropis simus pecosensis*)

Background

On August 5, 1991, the PBSM was listed as federally protected due to its status as a Threatened Species in 1987 under the ESA. It inhabits a stretch of the Pecos River between Ft. Sumner and Brantley Reservoirs (~160 river miles) and critical habitat was designated for the PBSM in 1991 to include two river sections. The northern section begins 10 miles (16 km) south of Ft. Sumner Reservoir in De Baca County and extends ~64 miles into the northern part of Chaves county north of Roswell. The southern section begins near the town of Hagerman in Chaves County and extends ~36 miles (58 km) south to the headwaters of Brantley Reservoir near Artesia. Of these 100 miles (161 km), 14 are on Federal land, 8 on State land, and 78 on private land. There have been efforts to address issues relating to PBSM preferred habitat in a contemporary river setting, many of which are ongoing (Hoagstrom, 2002). Clearly, flowing water is vital to ensuring PBSM survival. "The most important factor in the species' decline is reduced flow in the main channel of the river due to water storage, irrigation, and water diversion" (U.S. Fish and Wildlife Service, 1987, p. 5,259). However, preliminary investigations of PBSM habitat suggest that three key parameters comprise minnow habitat preference: 1) water depth; 2) water velocity; and, 3) sediment activity. Unfortunately, only general ranges for these parameters have been identified. Sediment activity will not be discussed in this report because its importance to minnow habitat remains to be determined; however, it will be explored in a subsequent report. Primary threats to Pecos bluntnose shiner are large, extended reservoir releases to meet irrigation needs during the summer reproductive season, seasonal dewatering and artificially depressed river flows, channelization, loss of habitat diversity, and range fragmentation. Detailed information on the PBSM and its habitat can be found on the Internet at:
http://www.fw.vt.edu/fishex/nmex_main/species/010411.htm.

Surface water flows of the Pecos River within the critical habitat of the PBSM are largely controlled by Sumner Dam as operated by the BoR. Goals of the BoR are to avoid operations that: a) result in the long-term drying of the Pecos River upstream of Roswell; and, b) that water releases are timed to benefit PBSM reproduction (high discharge events in the spring signal spawning), c) protect the water supply for the Carlsbad Project.

Existing habitat studies

The U.S. Fish and Wildlife Service has submitted several draft reports to the BoR that attempt to characterize the preferred habitat of the PBSM (Hoagstrom, 1997; 1999; 2000; 2002). PBSM habitat was observed by establishing five study areas within the critical habitat. Typically, twenty river cross-sections (transects) spaced every 30 m were analyzed at each study area by recording water depth and velocity in 1 m increments across all channels of the river. In general, 20 seine hauls were made at each site, one at each transect. All collections were made with a 3.2 mm (0.13 in) mesh seine, 3 m (9.8 ft) long and 1.2 m (3.9 ft) deep. Fish from each seine haul were preserved and sent to a laboratory for identification, length measurement, and cataloguing. PBSM were grouped into one of three length classes: Length-class I consists of 8.68–24.94 mm (0.34–0.98 in) long fish, Length-class II comprises 24.95–36.99 mm (0.98–1.46 in) fish, and Length-class III is composed of 37.00–76.39 mm (1.46–3.01 in) fish. Finally, correlations were made between the number and lengths of fish caught and the local river hydrological characteristics. That is, water depth and velocity were grouped into 1 cm (0.39 in) and 1 cm/s (0.39 in/s) categories and the frequency of fish in each category was calculated for each of the three length classes. Length-class I PBSM preferred depths between 6 and 9 cm (2.4 and 3.5 in) and velocities between 3 and 25 cm/s (1.18 and 9.84 in/s). Length-class II PBSM resided preferentially in 7–32 and 46–58 cm (2.76–12.60 and 18.11–22.83 in) deep water flowing between 3 and 37 cm/s (1.18 and 14.57 in/s). Length-class III fish were found most often in waters between 9 and 32 cm (3.54 and 12.60 in) and between 45 and 58 cm (17.72 and 22.83 in) deep at velocities of 11–56 cm/s (4.33–22.05 in/s) (Hoagstrom, 2002).

Hoagstrom (2002) also presents a study of habitat abundance by dividing river discharges into 24 cfs (0.68 m^3/s) intervals up to 144 cfs (4.08 m^3/s) and measuring the amount of preferred habitat in each interval. It should be noted that his selection of flow rates is divided into unjustifiably wide intervals because, in this study, 140 out of 159 (88%) river discharge measurements were below 48 cfs (1.36 m^3/s) and the maximum discharge ever recorded was 118 cfs (3.34 m^3/s). Hoagstrom (2002) also remarked that preferred habitat abundance initially increased with flow rate, but often decreased with flow rates greater than 48 cfs (1.36 m^3/s).

It must be emphasized that the purpose of this study is *not* to specify the preferred habitat of the PBSM – this task is left to teams of fisheries biologists to identify. Rather, we quantify the abundance of preferred habitat available to the PBSM at any specified flow rate. That is, our study describes the hydrological characteristics (depth and velocity) across the Pecos River at any discharge, regardless of the specifics ascribed to the preferred habitat. Once the preferred habitat parameters are defined, this model can be used to determine what fraction of the Pecos River width is suitable for the PBSM at any given flow rate. This information should prove vital to the BoR when they decide how much water is to be released from Sumner Dam in support of PBSM habitat.

Hydrology and Geomorphology of the Pecos River

Description of Project Area

The project area for investigating habitat availability for the PBSM includes the bank-full-width of the Pecos River between Old Fort Sumner Park and Acme Gage just north of Roswell, representing ~80 river miles (Figure 1), which specifically coincides with the critical habitat designation for the PBSM. This stretch of river has complicated ground water/surface water interactions, but is primarily a losing reach, meaning that surface waters are reduced with downstream travel due to leakage (groundwater recharge), evaporation to the air, and evapotranspiration. Summer thunderstorm runoff provides most of the water in the Pecos River. The river in this stretch is fed by many arroyos that provide both sediment and water influx after precipitation.

Much of the critical habitat for the PBSM is not accessible via public roadways. In fact, only two bridges ford the Pecos River between Old Fort Sumner Park and Roswell. Fortunately, private landowners have been willing to allow SNL access to the Pecos River through their properties so long as SNL stipulates that all data collected will be made publicly available to them. Through both public and private lands, most routes are along dirt roads.

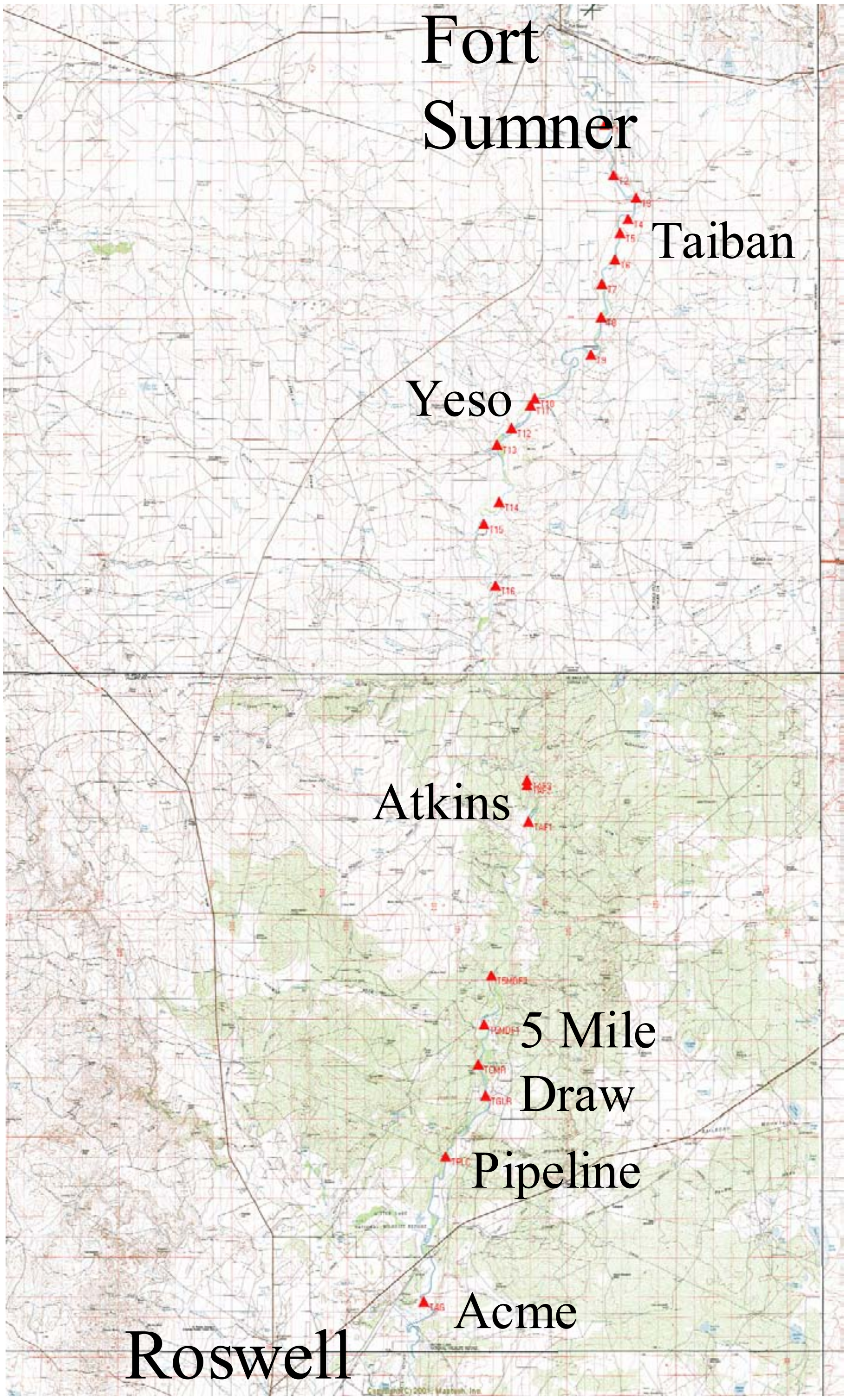

Figure 1: Map of the study area.

Data Collection

Transect placement and number

SNL conducted a preliminary field study in February 2001 from Old Fort Sumner Park to Acme Gage. This work consisted of kayaking and walking 35 continuous river miles from Old Fort Sumner Park to Yeso Gage while stopping to take eleven transect measurements approximately every 3 miles (4.8 km). South of Yeso Gage, cross-sections were measured at 8 points accessible by vehicle. The locations of these cross-sections are labeled on Figure 1 as T12–T16 and TAF1–TAF3. At each cross-section, water velocity and depth were measured every two feet. Additionally, sediment cores approximately 1 foot (0.3 m) in length were retrieved at up five locations across a transect: three within the wetted perimeter, and two in the dry portion of the channel, if possible. Side inflow sediments from arroyo channels were also sampled.

Based on the experience of the first field study, SNL established 11 transects (providing consistent flow and bathymetric monitoring) to investigate the geomorphic changes that occur in the river as a function of flow, time, and channel configuration (braids). The permanent markers are located (from north to south) at Old Fort Sumner Park (TOFP), Taiban Gage (TT), Yeso Gage (TY), Five Mile Draw (T5MD), Carl Madison Ranch (TCMR), Pipeline Crossing (TPLC), and Acme Gage (TAG). The Acme Gage has five permanent markers spaced every 50 ft (15.2 m) – three upstream and one downstream of TAG identified as TAGU3, TAGU2, TAGU1, and TAGD1, respectively. This cluster of transects was established to demonstrate specific reach spatial variability, the dynamic nature of the river and bed sediments, and to gather data to validate a future 3-D model of river morphological changes with discharge. TOFP, TT, and TY are located in the northern half of the project area and were monitored approximately monthly beginning October 30th, 2001 for 1 year. The remaining four transects located in the southern half of the project area were monitored approximately weekly beginning August 10th, 2001 for slightly more than 1 year.

Point measurements

Permanent survey level markers were erected on the banks of both sides of the river at each gage. They establish a reference height for measuring bathymetric river properties. For this set of experiments, a Kevlar tag line marked in 2.0 ft (0.61 m) increments was tightly tied to pins on the survey level markers. Measurements from the tag line to the riverbed are recorded at 2.0 ft (0.61 m) increments across the channel. Each marking on the tag line is considered a measurement station (numbered 0 to N across a transect) and repeatability is ensured. Where there is water in the riverbed, the depth and mean flow velocity are recorded. If there is no water, only the distance from the tag line to the riverbed is recorded.

Because it is impossible to obtain a perfectly level reference height with a tag line, the sag in the tag line was measured relative to the water surface at three points across the wetted channel (approximate center and at either edge). The maximum deflection was less than measurement error (0.05 ft) for the narrowest transect (~100 ft) and 0.20 ft (6.1 cm) for the widest transects (~200 ft). The catenary (distance of the deflection) at each measurement station (i.e., every two feet across a transect) was calculated using the material properties of the Kevlar tag line according to the equation

$$y = \frac{H}{\rho_L}\left[\cosh\left(\frac{\rho_L x}{H}\right) - 1\right] + \eta, \tag{1}$$

where the x,y coordinate system [L] originates at the center of the line (y is positive upward), ρ_L [M/L^3] is the linear density of the tag line equal to 6.891×10^{-5} slug/ft (3.298×10^{-3} kg/m), η [L] is the height from the water to lowest point on the tag line, and H [M/LT^2]is the horizontal tension in the line. Although H is not measured directly, it is calculated by substituting any two sets of measured distances from water surface to tag line into (1), yielding roughly 50 lbs (22.7 kg) at all transects. After specifying H and η, (1) may be used to calculate the catenary at any point across a transect. To maintain a level reference height using the measurements from the tag line, the local catenary was added to measured depth. A laser level will be used in future outings to avoid the complications of tag line deflection.

Measurements from the tag line to the channel bed were made with a standard top setting wading rod that has 0.1 ft (3.1 cm) incremental markings with a 4.0 ft (1.22 m) maximum depth. When depths from the riverbed to the tag line greater than 4 ft were encountered, an extension pole marked every 0.1 ft (3.1 cm) was placed on the top of the wading rod. Depth measurements (both in water and to the dry channel bottom) were recorded to the nearest 0.05 ft (1.5 cm).

Throughout the study area, the Pecos River is wide and shallow. The wetted perimeter is defined as the top width of the river, which was inferred to the nearest 2 feet (0.61 m) using the wetted river edge locations collected along with the water depth measurements. Wetted area is calculated here as the product of the wetted perimeter and the mean flow depth.

The velocity measurements were recorded to the nearest 0.01 ft/s (3.1 cm/s) with a Marsh-McBurney velocity meter every 2 ft across the wetted river channel. To measure the total river discharge, the river is divided into subsections defined by measurement stations located every 2 ft (0.61 m). Along with each velocity measurement, the flow angle parallel to the tag line was also collected (e.g., angles of 75 or 105 degrees are 15 degrees from the normal). The product of velocity, sine of the flow angle, depth, and width of an element (2 ft) is the subsection discharge rate. Summing all of the subsection discharge rates yields the total river discharge at a transect.

Sediment Bulk Property Analysis

For Pecos River sediment bulk property analysis, at least three analysis cores were collected from the riverbed at each of the permanent station cross-sections. At all transects except TOFP and TPLC, the wetted river channel usually does not span bank to bank (for flows below ~80 cfs) and therefore two more sediment analysis cores were collected from portions of the dry riverbed. Sediment analysis cores comprising 2.25-inch (ID) acrylic tubes were driven into the riverbed to extract approximately 12 inches (0.3 m) of sediment. Each core was analyzed for particle size, mineralogy, and organic content. Analysis cores were also sampled near the center of the river and 10 ft (3 m) from either bank.

Most of the Pecos River sediments are composed of coarse-grained, non-cohesive sands. Particle size analysis showed that, in general, sediments became finer down stream (from an average of ~1,000 μm at Fort Sumner Reservoir to ~250 μm at Roswell). In addition, there were often significant changes (usually increases) in particle size with depth in the riverbed. Figure 2 illustrates the particle size distribution at T5MD.

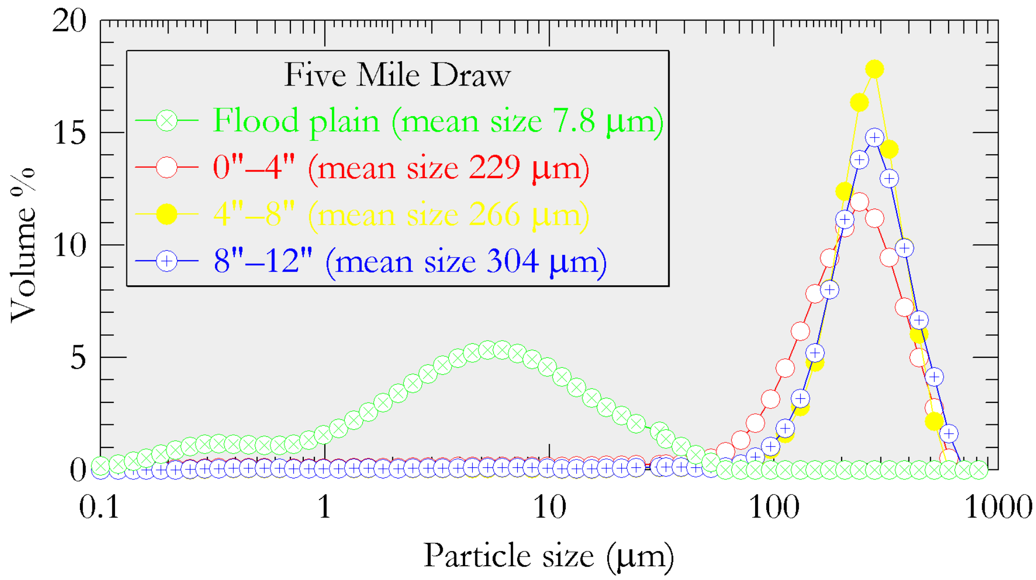

Figure 2: Particle size distributions with depth at Five Mile Draw.

Additional Measurements and Observations

Water temperature was recorded at all transects in an attempt to detect springs and influxes of water at different temperatures. However, because the temperature of any influx is unknown, these data reveal little other than the direct environmental influences (weather) on temperature.

GPS data were initially recorded at the right bank (observer facing downstream) and were collected periodically throughout the year to ensure transect measurements maintained accuracy and repeatability.

Along with visual water clarity observations, any additional items of interest were logged. These included all PBSM sightings, although it should be noted that often the minnows would scatter as soon as the team approached the edge of the water not to be observed again that day at that location.

Data Interpretation

Hydrographs

The river discharge measured at each transect during each sampling trip is presented in Appendix A: Hydrographs. Because the TAG transects are located near the Acme USGS real-time gages, these gage data are included. It is important to note that the hydrographs are snapshots in time of the flow history at a particular location, and that often times, major flow events like storm runoff are not captured. Recall that this study was not designed to accurately measure river discharge. Otherwise, SNL would have selected transects with properties akin to an irrigation canal – unidirectional flow perpendicular to the transect. Rather, this project was designed to characterize minnow habitats as a function of river discharge, thus transect locations were selected in an effort to assess all habitat types, not to most accurately measure discharge. Often, flows were not perpendicular to the transect complicating flow rate measurements – thus the inclusion of gage data when available. Nevertheless, discharge data compare favorably with the gage data with a maximum difference of 68% and an average difference of –2%. It should be noted that the USGS gage can be unreliable at low flow rates because the river may not flow around it. In all likelihood, where SNL and USGS measurements differ, the error is on the side of the USGS.

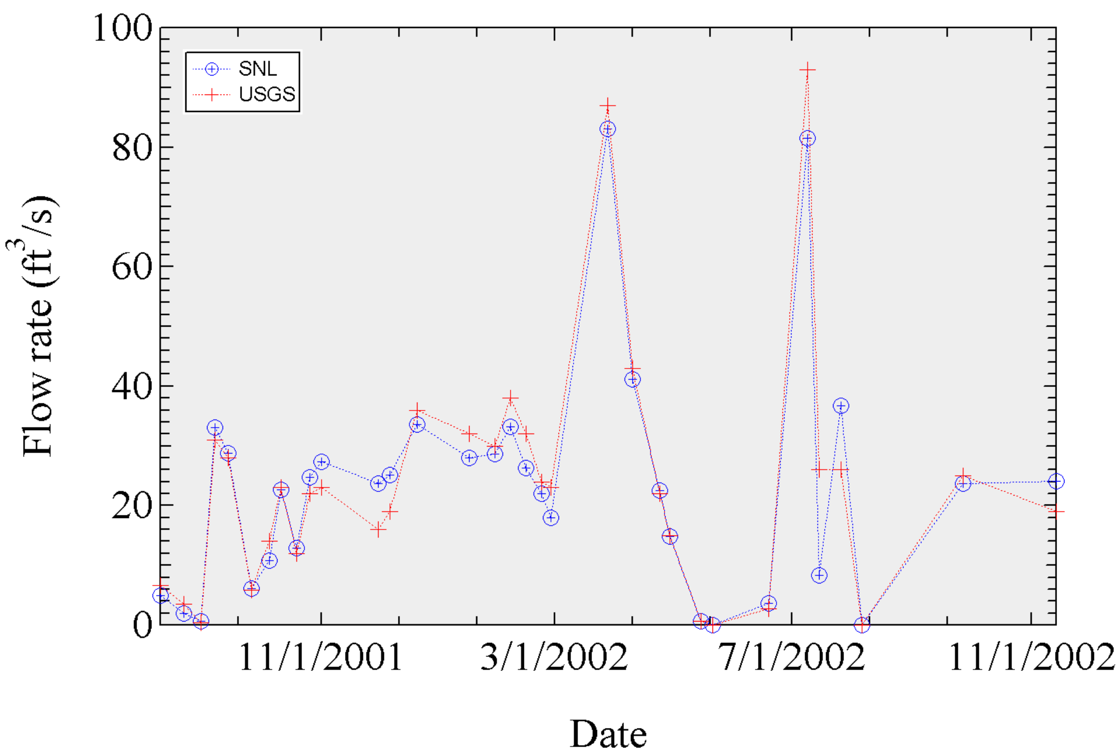

Figure 3: Hydrograph comparing flow measurements by SNL and the USGS at Acme Gage.

An example hydrograph for the Acme gage transect is shown in Figure 3, including both data for this study and from the USGS gage. In general, river flows decrease with down stream travel from losses to groundwater, evaporation, and evapotranspiration. A noteworthy exception is that flows at TOFP are often less than flows at TT (~8 river miles downstream of TOFP). This is a direct result of the influx of FSID irrigation return flows between TOFP and TT. In addition, during times of low flow when the river was intermittent, supplemental wells were pumped just below TCMR to maintain some small flow rate.

Bathymetries

The river depth bank-to-bank profile or bathymetry for each transect and sampling trip are shown in Appendix B: Bathymetries. The bathymetries of each transect vary because of the sandy bottom of the Pecos River that is nearly always active and some sites (e.g., TCMR) were more prone to a shifting bed than other sites (e.g., TPLC).

Changes to the bed profile occurred at all sites. Nevertheless, without a high flow event such as a block release or major storm event, bed profiles were relatively unchanged between samplings. While high flow events reshaped the channel, it is assumed that system morphology is conservative and that the general characteristics describing the riverbed are quasi-steady-state.

For river samplings between 8/10/2001 and 2/28/2002, no extreme flow events altered transect bathymetries. It is possible to break up the bathymetric history of transects into steady-state groups between flow spikes where bathymetry was essentially constant. This is important for modeling purposes because the model input bathymetry must represent current conditions when using a fixed bed assumption. Therefore, Appendix B: Bathymetries gives the bathymetric history of each transect, with groupings defining stable bed conditions. Figure 4 is an example of the varying bathymetric profile at TPLC. Note that there are 5 distinct periods of nearly constant bathymetry (noted with superscripts in the legend). These each correspond to changes due to high flow events. Note that the bathymetry dated 6/19/02 is anomalous, but can be attributed to storm water influx on 6/14/02. Bathymetries may also be dramatically altered due to a block release, which is an efficient method of transferring water between reservoirs where large volumes of water are sent down the river over short time periods.

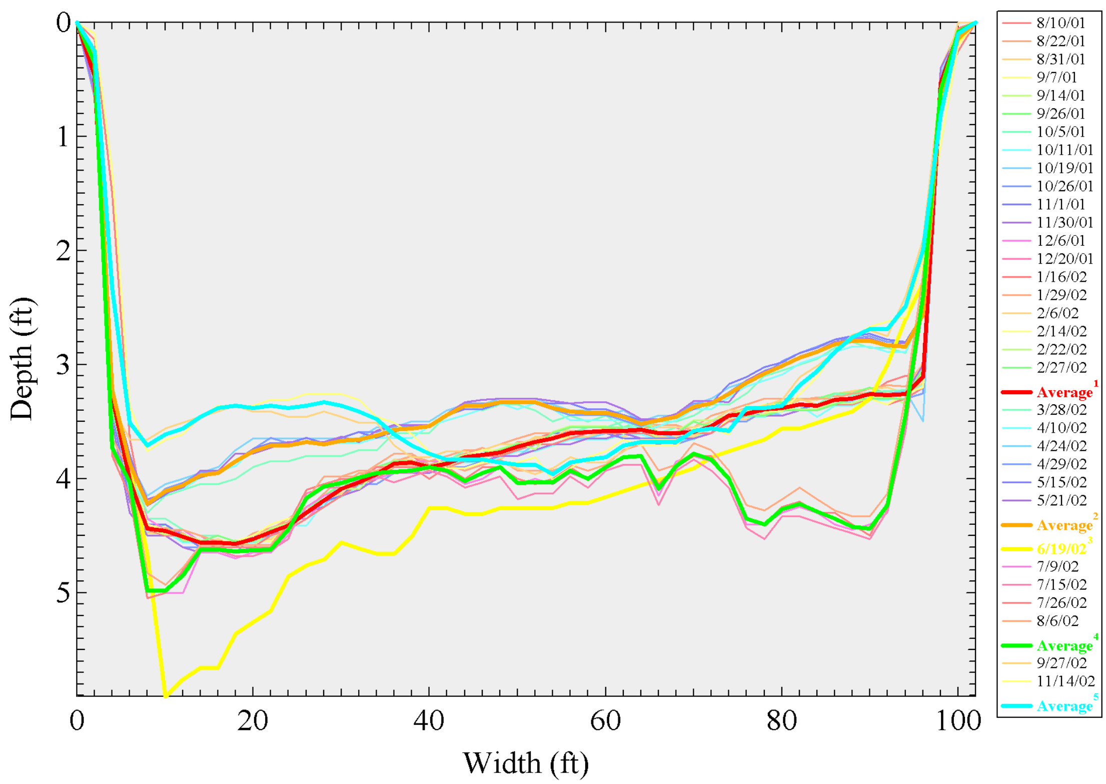

Figure 4: Individual (thin) and representative (thick) bathymetries at TPLC.

Availability Data

The data collected at each permanent transect are plotted to illustrate the relationships between river discharge and depth and velocity available for habitat use. The river width that meets some minimum habitat specification describes habitat abundance. The modeling results associated with these data are presented later. Ponded waters are not included in this analysis.

Depth Availability: Because water depth measurements are taken in two-foot intervals, it is assumed that a particular measured depth is constant over those two feet. The depth of water at each measurement station is sorted according to whether it is less than 2, 4, 6, 8, 10, 12, or 18 inches (5.1, 10.2, 15.2, 20.3, 25.4, 30.5, and 45.7 cm) as shown in Figure 5. Once each station has been categorized according to depth, the river width in each category is calculated (sum of stations multiplied by their length, 2 ft). Note that a constant depth is assumed for the two feet between stations. For example, the length of purple (8 inch deep) bars in Figure 5 is 10 ft (5 bars×2 ft). Because the river discharge is different each time a transect is sampled, it is possible to see how flow rate (and changing bathymetry) affects the river profile. Ultimately, this yields a set of data describing the change in available depth habitat as a function of flow rate.

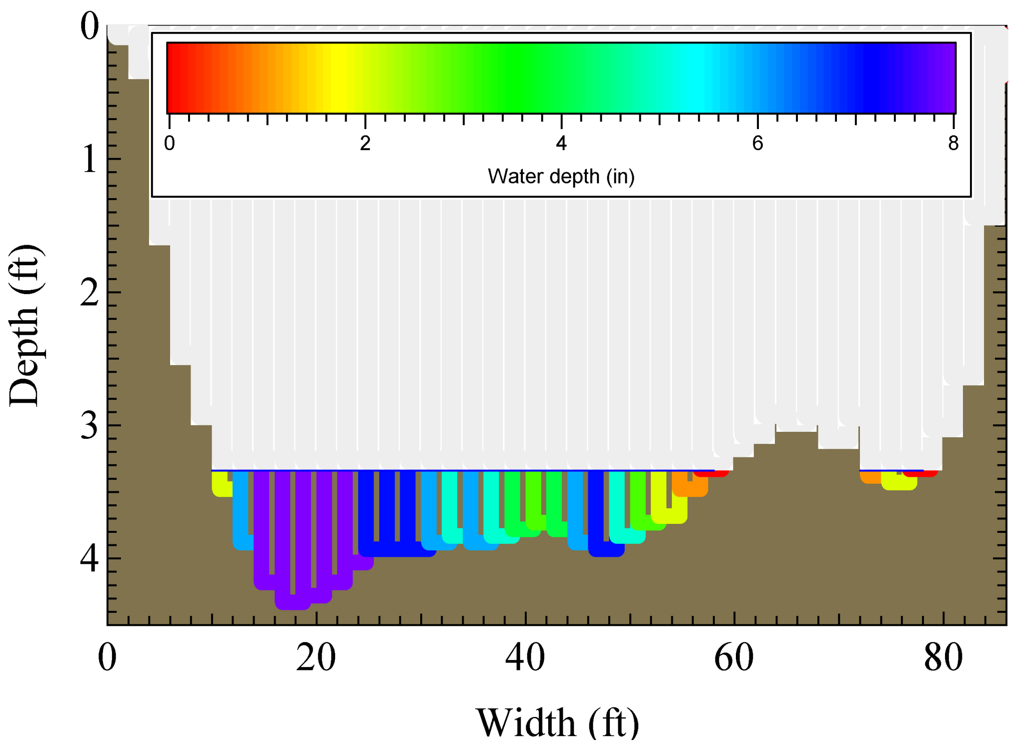

Figure 5: Example of how depth availability is measured at Old Fort Park on November 11, 2002. Shown in brown is the sediment bed profile, gray depicts the air, and the water is multi-colored to show differences in water depth.

Velocity Availability: Water velocity measurements are also taken in two-foot intervals across the river and therefore it is assumed that a particular measured velocity spans two feet. The velocity of water at each measurement station is sorted according to whether it is less than 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, or 1.5 ft/s (3.1, 9.1, 15.2, 21.3, 27.4, 33.5, 39.6, and 45.7 cm/s). Once each station has been categorized, the river width (sum of stations multiplied by their length, 2 ft) in each category is calculated based on the data collected at each transect throughout the study period. Because the river discharge is different each time a transect is sampled, it is possible to infer the river velocity profile. Ultimately, this yields a set of data that describes the width of river containing a minimum velocity of 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, or 1.5 ft/s (3.1, 9.1, 15.2, 21.3, 27.4, 33.5, 39.6, or 45.7 cm/s) as a function of river discharge. These data can be used to select the river discharge that most appropriately fits minnow habitat criteria.

Hydraulic Geometry Parameters

Within the wetted river channel SNL collected water depth and velocity measurements every 2 ft (0.6 m) over the study period. This data set supports the calculation of hydraulic geometry parameters such as wetted perimeter, P, wetted area, A, and mean water depth, D, as well as the overall river discharge, Q. Because the river discharge is different each time a transect is sampled, it is possible to see how flow rates govern the hydraulic geometry of the river and thus the minnow habitat at distinct cross-sections. These relationships are developed for each transect and are shown in Appendix C: Hydraulic Geometry Parameters.

Manning's Roughness Coefficient, n

With the hydraulic geometry, discharge, and river slope known at a particular transect, it is possible to calculate Manning's roughness coefficient, n. Again, as this information is gathered at many different flows it is possible to determine the relationship between n and Q for a given site. Manning's roughness coefficients calculated for each flow measurement at each transect are supplied in Appendix D: Manning's Friction Coefficient.

Sediment Properties

SNL collected sediment and water samples from the Pecos River at several locations between Sumner Reservoir and Roswell, NM from the nine representative locations listed in Appendix E: Sediment Properties. Sediment cores were collected at three locations along each transect. These locations were identified as Left Descending Bank (LDB), Center (C) and Right Descending Bank (RDB) corresponding to the left, center or right part of the river channel, respectively, with the observer looking down stream. The LDB and RDB river channel samples were generally taken between 6 and 10 ft (1.8 and 3.0 m) from the actual riverbank. The cores were between 5 and 18 inches (12.7 and 45.7 cm) in total length with analyses performed every 3 to 6 in (7.6 to 15.2 cm). To better characterize the types of sediment that can be introduced to the river, additional sediment samples were taken from the banks and sandbars near some of the transects.

These samples have been analyzed for mean particle size and particle size distribution. The mean particle size of each sample, of each core, and of each transect are listed in Appendix E: Sediment Properties along with the total suspended solids found at each site at the time of sampling. In general, the mean particle size decreases downstream and often there is a wide range of mean particle sizes in a single core and across a single transect. Additionally, the total suspended solids (or turbidity) increased downstream.

The relationship between sediment properties and sediment activity will be discussed in a separate report.

Water quality

In addition to the sediment samples, water samples were collected, analyzed, and listed in Appendix F: Water Quality. Total dissolved solids increased sharply in the region downstream from the Sumner Reservoir, but were approximately constant throughout the critical habitat. Samples collected on 11/15/00 were somewhat less saline than those collected on 11/30/00 possibly because groundwater inflow on the former date was diluted by bank discharge related to storm-related high river flow in the previous weeks. Water chemistry has potential impacts on both the biological diversity in the river and on water turbidity and the transport of fine sediments, as the amount and composition of the total dissolved solids effects clay flocculation and settling rates.

Data Reduction

To facilitate analysis of the flow characteristics of the Pecos River, the numerous data points were reduced to yield more visually comprehendible results. Because the river discharge is different each time a transect is sampled, it is possible to relate flow rate (and changing bathymetry) to riverbed profile characteristics. Ultimately, this yields a set of data describing the change in available depth habitat as a function of flow rate. All data were binned into 10 cfs (0.3 m^3/s) increments between 0 and 50 cfs (1.4 m^3/s) and the average available habitat is recorded at the midpoint of the corresponding bin. Because of infrequent high flow measurements, two additional bins, 50–70 cfs (1.4–2.0 m^3/s) and 70–100 cfs (2.0–2.8 m^3/s), were selected for the remaining data. The symbol size of the averaged data points corresponds to the number of data points used in the average (between 2 and 8). Figure 6 illustrates the data reduction method and compares binned and raw data points.

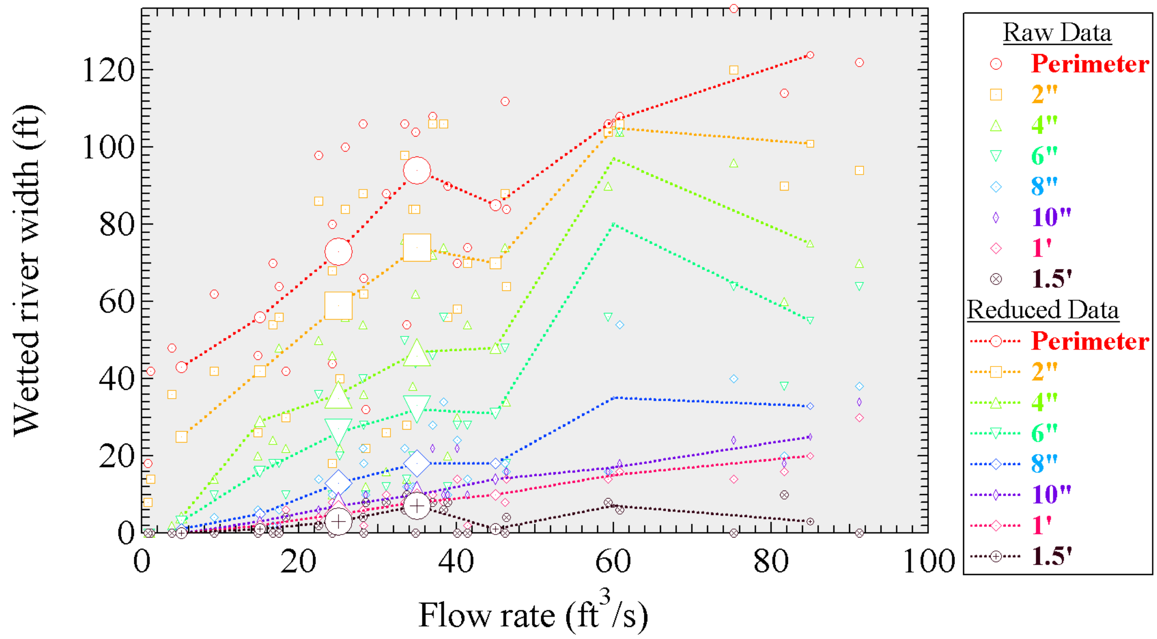

Figure 6: Example data reduction at TCMR. Note that the symbol size of the reduced data corresponds to the number of measurements included in the average (larger symbols are produced with more data, smaller symbols are produced with less data).

High Density Data

The Acme Gage has five permanent markers spaced every 50 ft (15.2 m) – three upstream and one downstream of TAG identified as TAGU3, TAGU2, TAGU1, and TAGD1, respectively. This cluster of transects was established to demonstrate specific reach spatial variability, the dynamic nature of the river and bed sediments, and to gather data to validate a future 3-D model of river morphological changes with discharge. Figure 7 is a schematic of the dense stations on the Pecos River.

Calculated flow rates collected on the same day for each of the closely spaced transects had little variability. The coefficient of variation (standard deviation over the mean) for flow across TAG, TAG-U1, TAG-U2, TAG-U3, and TAG-D1 averaged less than 10% (see Figure 8). This further reinforces the fact that while the goal was not to precisely measure flow rates, the calculated flows were nevertheless accurate. In addition, Manning's n averaged for daily transect measurements had a 12% coefficient of variation (its calculated value is fairly constant, see Figure 9). While same day data for n does not vary greatly over the closely spaced transects, the functional relationship between Q and n can vary significantly over short distances. That is, at different transects, the value of n can be different for identical flow rates (details are below, see Table 1).

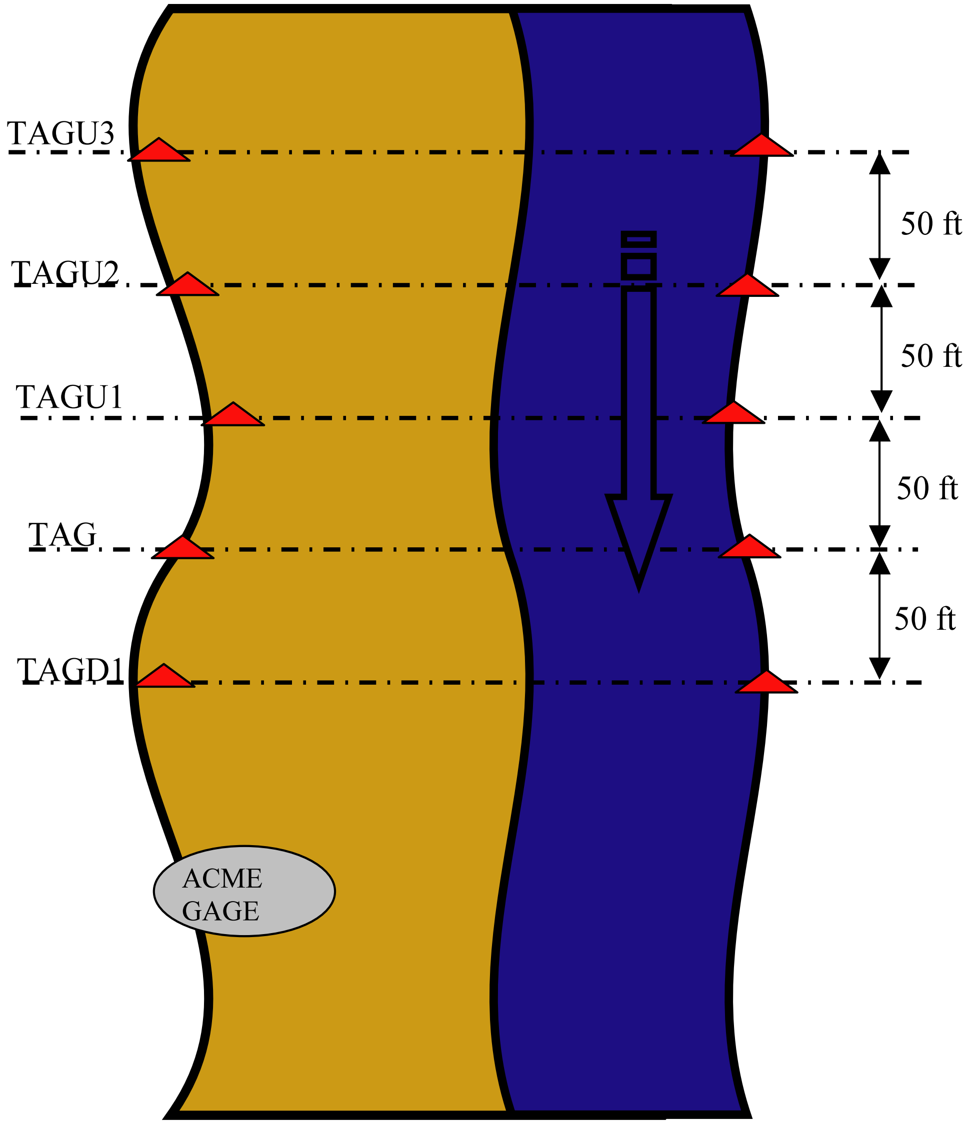

Figure 7: Schematic of the dense data collection stations near ACME gage.

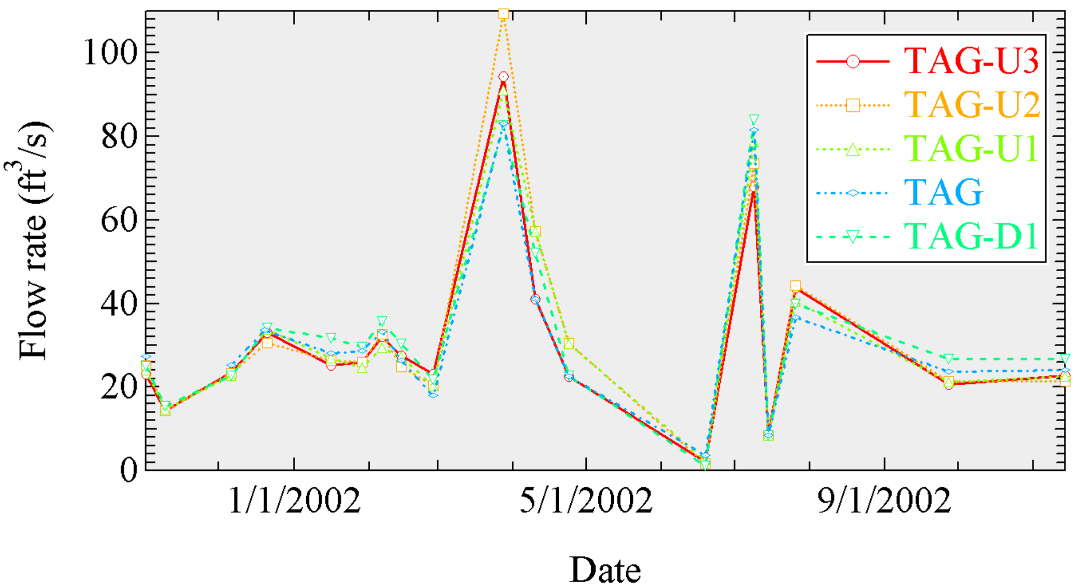

Figure 8: Hydrograph from dense stations near TAG.

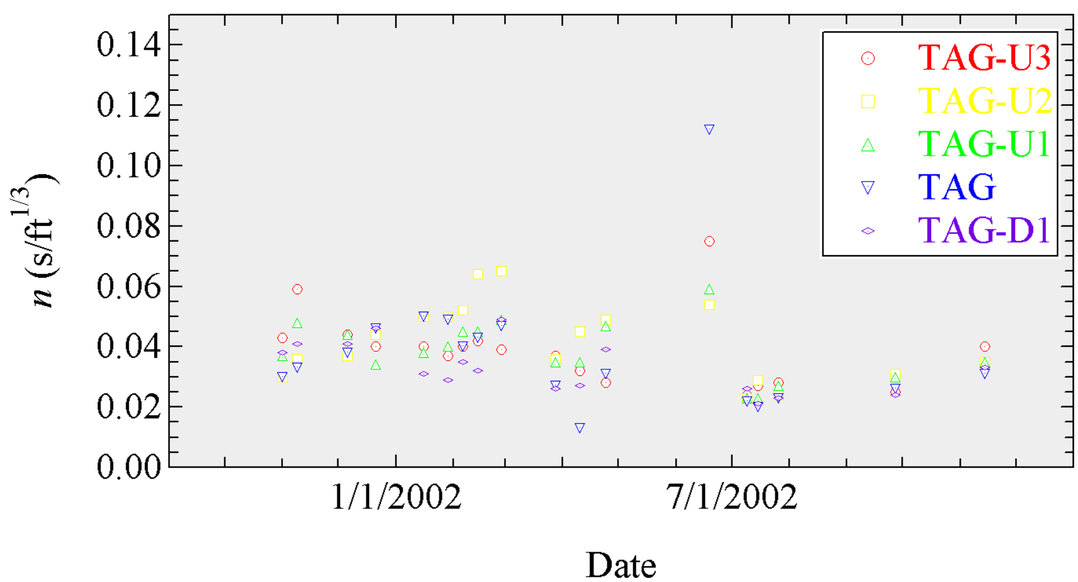

Figure 9: Variation of *n* across closely spaced transects for same day data collection.

The depth availability of both the high density transects (TAG-U3, TAG-U2, TAG-U1, TAG, and TAG-D1) and four other transects (T5MD, TCMR, TPLC, and TAG) were reduced by binning as shown in Figure 6. The results indicate that the spread of data over the 200 ft (61 m) is not significantly less than the spread of the data across transects that are miles apart. Figure 10 compares the wetted perimeter and wetted river width that is at least 6 in (0.15 m) deep for the high density transects and those separated by a significant distance. Overall, this indicates that the correlation length for depth availability is less than 50 ft (15.2 m). That is, transects spaced only 50 ft (15.2 m) apart have just as much available habitat variability as those spaced miles apart.

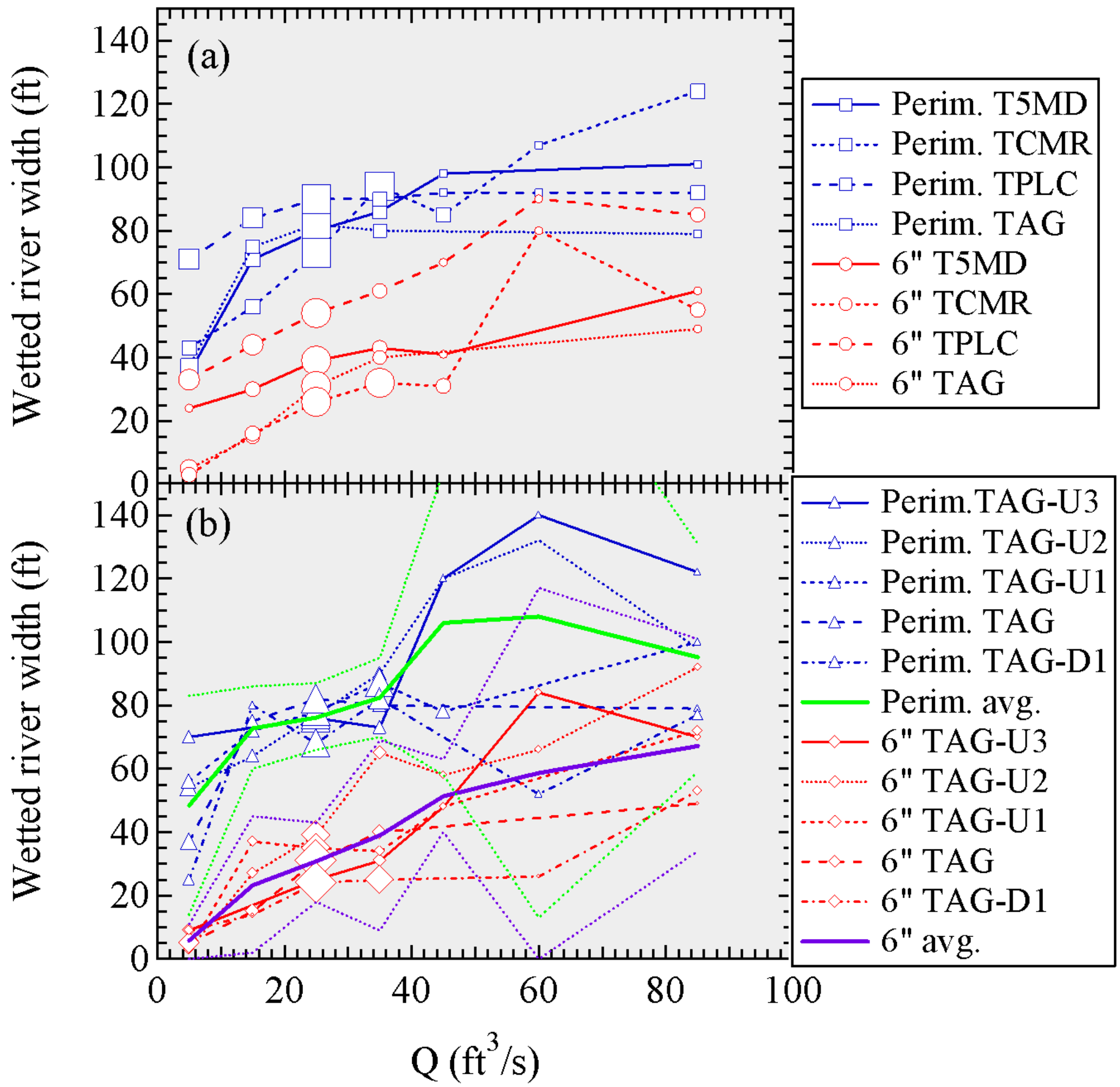

Figure 10: Comparison of the spread of depth availability data between (a) distant and (b) closely spaced transects. Symbol sizes are indicative of the number of data point used in the average. Note that the average wetted perimeter (green) and 6 in depth (purple) for the densely spaced transects are shown along with the 95% uncertainty limits (same colors, but dashed lines).

Modeling

Background

Based on bathymetric data collected in 2 ft (0.6 m) increments across a river transect, modeling predicts water depth, wetted area, wetted perimeter, and velocity as a function of river discharge. Inputting river cross-section profiles, the model yields depth and velocity availability curves that relate PBSM habitat abundance to river discharge. Field measurements at each transect validate model results. The model can be further extended to specify the total linear width of river, or wetted perimeter, that establishes minimum PBSM preferred habitat requirements.

The fundamental mathematical relationship used in the model is the classic Manning Equation (Franzini and Finnemore, 1997; Fox and McDonald, 1998)

$$Q = 1.486 \frac{A^{\frac{5}{3}} S_b^{\frac{1}{2}}}{P^{\frac{2}{3}} n}, \tag{2}$$

that empirically relates river discharge, Q [L^3/t], to the river's hydraulic geometry (specifically, wetted area, A [L^2], and wetted perimeter, P [L]), bed slope, S_b [–], and the Manning roughness coefficient, n [t/L$^{1/3}$]. S_b was measured by interpolation on a topographic map of the Pecos River.

With each collection of water depth and velocity measurements at a transect, all of the parameters in the preceding equation, except for the roughness coefficient, are known. Solving (2) for n reveals a functional dependence of the roughness coefficient upon the combination of measured values. Although n is significantly affected by riverbed composition (e.g., clay, sand, or cobble) and the presence of debris (e.g., plants, brush, and roots), at most transects, these river features varied little between weekly and monthly measurements. Thus, it was possible to determine n as a function of Q, subject to a power law relationship of the form,

$$n = \alpha Q^{\beta}, \tag{3}$$

where α [–] and β [–] are empirical constants. For example, Figure 11 illustrates the variation of n with Q at Pipeline Crossing. A table of α and β for all transects measured is presented in Table 1.

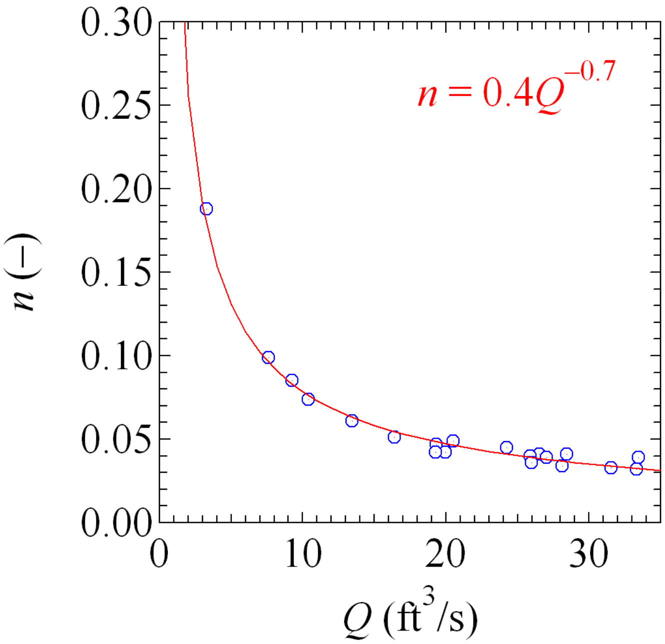

Figure 11: Power law fit to the Manning roughness coefficient varying with flow rate at TPLC.

Table 1: Power law coefficients for the *Q* vs. *n* relationship at each transect.

Transect	α	β
TOFP	0.07	–0.29
TT	0.04	–0.11
TY	0.05	–0.13
T5MD	0.75	–0.88
TCMR	0.05	–0.12
TPLC	0.36	–0.65
TAG	0.08	–0.29
TAG U1	0.06	–0.13
TAG U2	0.05	–0.09
TAG U3	0.07	–0.20
TAG D1	0.31	–0.65

Substituting the empirical relationship described by (3) into (2) yields a predictive equation for flow rate as a function of measured parameters for each transect,

$$Q = \left(1.486 \frac{A^{\frac{5}{3}} S_b^{\frac{1}{2}}}{\alpha P^{\frac{2}{3}}} \right)^{\frac{1}{1+\beta}} . \tag{4}$$

It should be noted that at some transects (TT, TCMR, and TY), parameters in (2) varied significantly between field measurements (shifting of sand caused hydraulic geometry changes) and the power law relationship between n and Q has a low correlation coefficient with the data, $R^2 \approx 0.15$. In these cases a straight temporal average was applied.

Once a relationship between Q and the geometric properties of the Pecos River, A, S_b, and P, has been specified, a characteristic bathymetry at a transect must be selected. At some transects, the river bathymetry was virtually unchanged for all field measurements (see Figure 12). In this case, the input bathymetry was taken as the average of all measured bathymetries. Often there were observed changes in river bathymetry (hydraulic geometry) during field measurements. Although these changes were usually subtle, such as a shifting or splitting thalweg (deep part of the channel that delivers most of the water), it was nevertheless inappropriate to define the characteristic bathymetry as the temporal average. In these cases, a single representative bathymetry was selected from the bathymetric history and used as input for model predictions (see Figure 13).

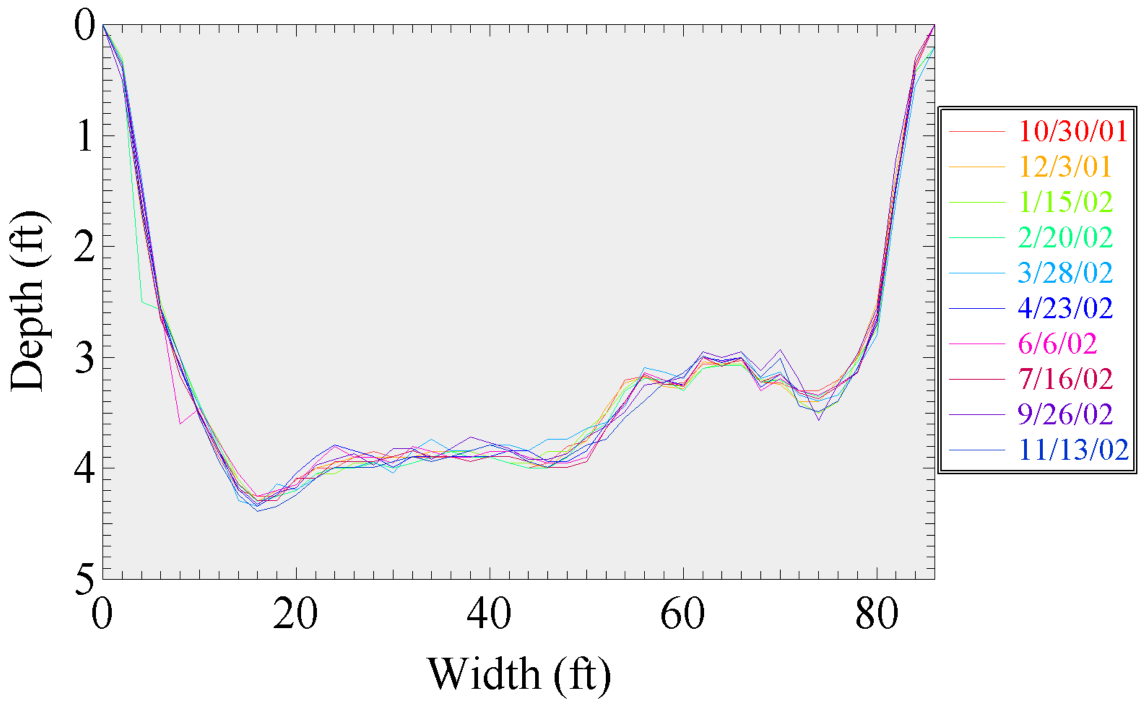

Figure 12: Bathymetry measurements at TOFP taken over one year.

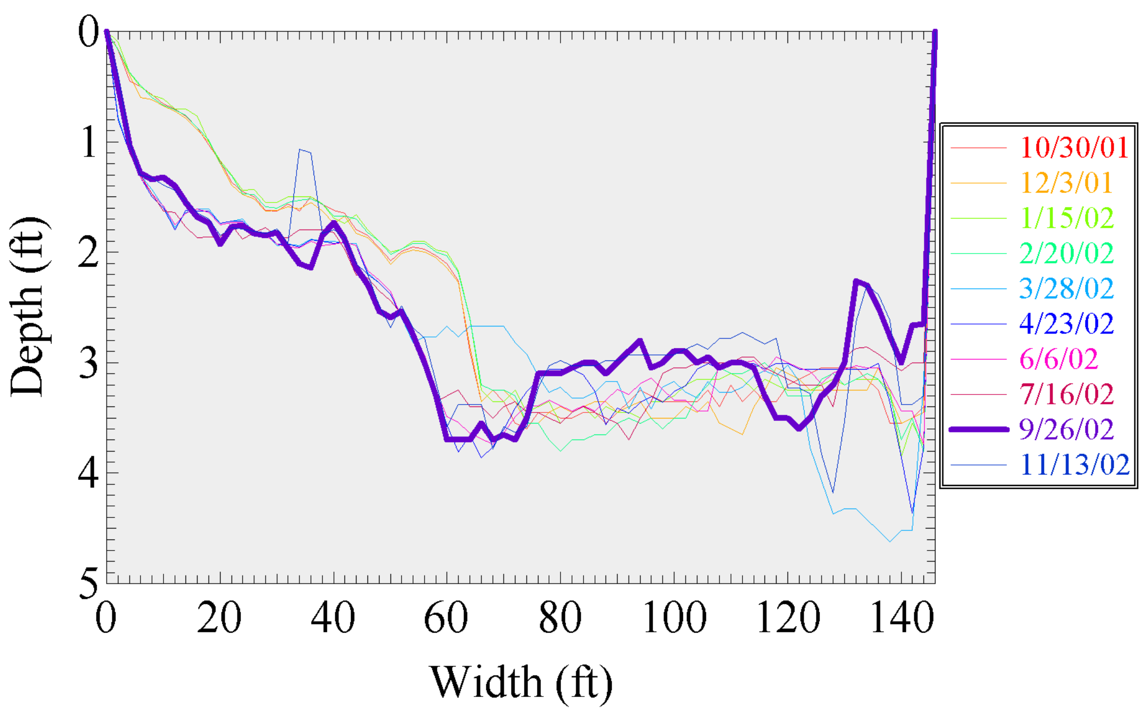

Figure 13: Bathymetry at TY taken over one year. The representative bathymetry is shown in bold.

Once a characteristic or representative bathymetry is identified for each transect, the next step in model development is to calculate the flow rate and hydraulic geometry as a function of river stage. A horizontal line connecting the tops of the permanent markers on either side of the river denotes the reference height from which the model calculates the river stage. The maximum reference height at each transect is equal to the vertical distance from permanent markers to the lowest point of the characteristic or representative bathymetry (e.g., the depth at 16 ft of width in Figure 12). A reference height (depth) of zero corresponds to the bank-full water level (maximum river discharge) and as the reference height increases downward towards the sediment bed, river discharge (calculated as the flow through a transect's characteristic bathymetry below the reference height) decreases. The model may be run deterministically when a user chooses an initial depth (river stage) seeking to find the corresponding flow rate. For example, if the reference height is 3 ft (draw a horizontal line across Figure 12 at 3 ft), the water level is set three feet below the reference line and the model calculates the wetted area, wetted perimeter, and flow rate through the wetted cross-section. Specifically, the characteristic bathymetry is divided according to the 2 ft (0.6 m) distances between the measurement stations (hereinafter referred to as 'elements'). The wetted area is calculated by determining the average water depth of each element (average depth of two adjacent stations), calculating the area of each water element (multiply the average depth by the distance between depth measurements, i.e. 2 ft), and summing the results. Because the Pecos River is much wider than it is deep, we chose to calculate the wetted perimeter as the wetted area divided by the mean water depth. Of course, the model can be run sequentially with an increasing reference height, thereby generating tables of wetted area, wetted perimeter, and river discharge for a suite of reference heights.

Depth Availability Curves

With tables of river discharge and concomitant hydraulic geometries, curves of habitat abundance can be generated by summing the length of all elements that meet some minimum habitat specification. The water depth in each element is calculated and sorted according to whether it is less than 2, 4, 6, 8, 10, or 12 inches (5.1, 10.2, 15.2, 20.3, 25.4, or 30.5 cm). Once each element has been categorized according to depth, the river width (sum of elements multiplied by their length, i.e. 2 ft) in each category is calculated for each flow rate. For example, if the total width of 2-in (5.1-cm) deep river is sought as a function of flow rate, for each sequentially higher reference height (flow rate) supplied to the model, the linear width of river 2 inches (5.1 cm) or more in depth is calculated. Ultimately, this yields a curve describing the change in 2-inch (5.1-cm) deep habitat abundance with flow rate. This process is repeated for all depth categories. The result is a series of curves that describes the width of river containing a minimum depth of 0 (or wetted perimeter), 2, 4, 6, 8, 10, and 12 inches (5.1, 10.2, 15.2, 20.3, 25.4, and 30.5 cm) as a function of river discharge. This curve can be used to select the river discharge that most appropriately fits minnow habitat criteria. Although a full discussion of the application of these curves is presented in subsequent sections, Figure 14 is an example of the modeling results. Note that the field data are also displayed on the figure to support the accuracy of the model. Also, the apparent discontinuity of the model results are caused by abrupt changes in riverbed profile due to discrete measurements (an example can be seen in Figure 13). The model results contain a higher degree of a step-like appearance as the abrupt changes in riverbed profile increase in number and magnitude.

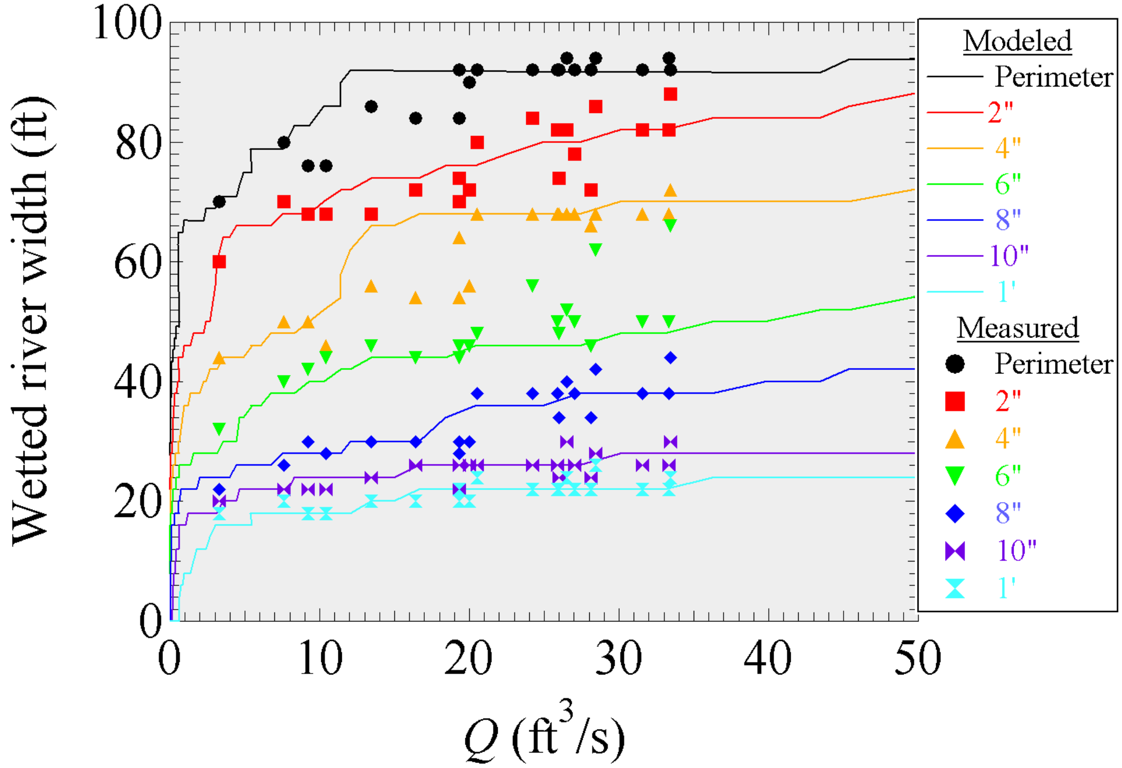

Figure 14: Modeled (curves) and measured (points) depth availability at TPLC.

The intent of the model is to provide hydrological information that will enable informed decisions about water management practices during *low flow* conditions to aid conservation (i.e., when supplemental water must be bypassed from Fort Sumner Reservoir for PBSM habitat requirements). Although the model is based on the premise of a fixed bed (i.e., constant bed surface profile), model results based on a selected characteristic bathymetry have proven accurate in the absence of dramatic morphology changes. While the Pecos River has a sandy bottom that is nearly always active to some degree (in contrast to the fixed bed model assumption), transect and discharge data demonstrate that significant alterations in bathymetry do not occur unless flows exceed ~100 cfs (~2.8 m^3/s).

Velocity Availability Curves

Developing velocity availability curves requires knowledge of the mean river depth (known from the depth availability curves), mass conservation, and a functional relationship distributing flow within each element across a transect. Choosing the distribution of flow that best describes/predicts the conditions in the river system is the key to an accurate model.

One approach is to use data from field measurements to determine the relationship between flow rate within an element and the corresponding area. This effectively captures the conditions of the natural river system and implements them in the modeling framework. Investigation of field data showed that there was a general power law relation between the area and flow rate of an element that held true at most transects. The relation is of the form

$$Q_i \propto A_i^{\gamma}, \tag{5}$$

where γ [–] is an empirical constant, and Q_i [L^3/t] and A_i [L^2] are the volumetric flow rate and area of an element, respectively. Values for γ at each transect are presented in Table 2. The average of γ is quite close to 1.8, and this value is used in all subsequent modeling and calculations. Using the preceding relation, it is possible to distribute flows across elements while conserving mass in the system. This is achieved by allocating flow through each element according to

$$Q_i = Q\left(\frac{A_i^{\gamma}}{\sum_i A_i^{\gamma}}\right). \tag{6}$$

Recall that the velocity in element i is related to flow rate and area as

$$v_i = \frac{Q_i}{A_i}. \tag{7}$$

Table 2: Average empirical constant, , for each transect.

Transect	γ
TOFP	2.0105
TT	1.8868
TY	1.7280
T5MD	1.8296
TCMR	1.6943
TPLC	1.8298
TAG	1.7818
TAGU1	1.6431
TAGU2	1.8798
TAGU3	1.8124
TAGD1	1.7657

Substituting (6) into (7) yields an expression for the velocity within each element across a transect

$$v_i = Q\left(\frac{A_i^{\gamma-1}}{\sum_i A_i^{\gamma}}\right). \tag{8}$$

The model assumes that the velocity is constant across each 2 ft (0.6 m) wide element. The linear width of the channel meeting a minimum specified velocity is simply equal to the sum of the widths of the elements that demonstrate said velocity. This is repeated at sequentially increasing reference heights corresponding to different flow rates to yield velocity availability curves as a function of river discharge. Currently, the model generates wetted river width as a function of river discharge for threshold velocity values of 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, and 1.5 ft/s (3.1, 9.1, 15.2, 21.3, 27.4, 33.5, 39.6, and

45.7 cm/s). A full discussion of the application of these curves is provided later, but an example is shown in Figure 15. Note that the highest velocity recorded at this transect is 0.7 ft/s (21.3 cm/s).

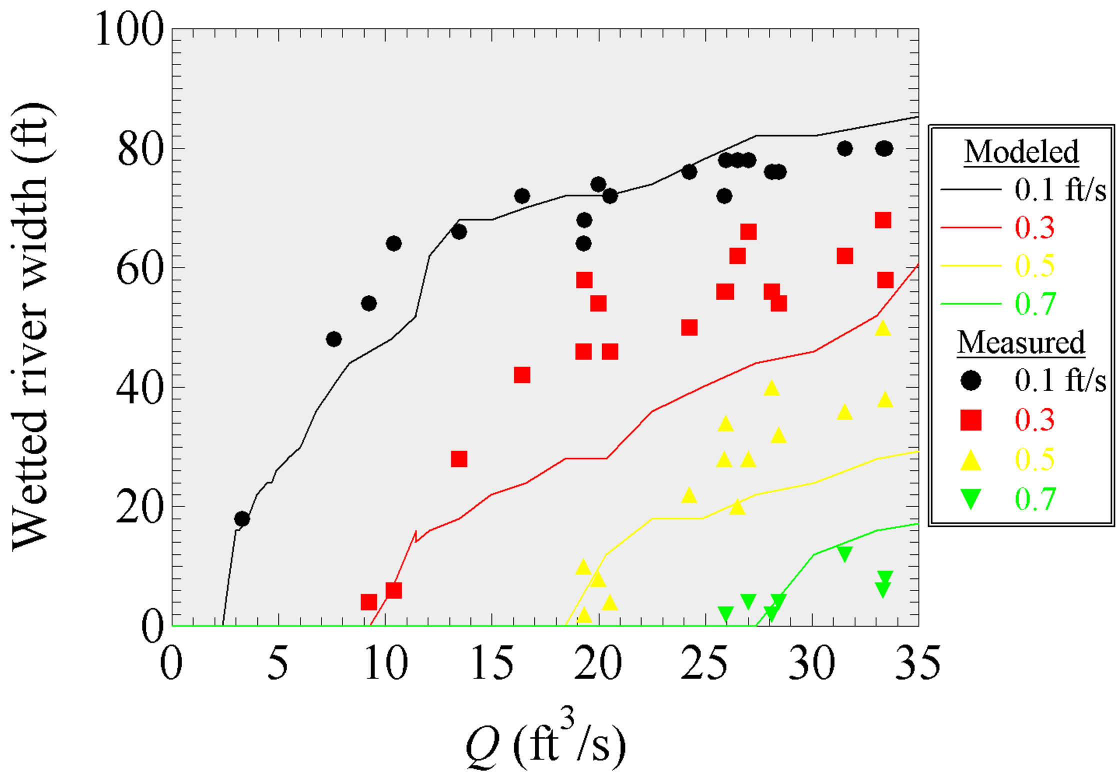

Figure 15: Modeled (curves) and measured (points) velocity availability at TPLC.

Error Analysis

Characterizing depth and velocity as functions of the physical dimensions and discharge along the Pecos River clearly involves numerous assumptions. Nevertheless, because this work is primarily based upon data collection, most of the error analysis can be covered by a review of data collection precision. Recall that depth measurements were recorded to the nearest 0.05 ft (1.5 cm) and velocity measurements were recorded to 0.01 ft/s (0.3 cm/s) accuracy. One of the primary sources of error arises from the assumption of uniformity in both depth and velocity between the two-foot measurement intervals. In an attempt to quantify the error that is introduced through this assumption, a uniformly distributed error between ±1 ft (±0.3 m) is assigned to each measurement. The square root of the sum of these squared errors yields an approximation to the error in wetted perimeter. This error increases with increased number of measurements and can be expressed as:

$$\text{error} \cong \pm\sqrt{\frac{\text{Wetted Perimeter}}{6}}, \tag{9}$$

which ranges up to ±3.8 ft (±1.2 m) at TOFP to ±5.6 ft (±1.7 m) at TY. The preceding equation can be used for any data point by simply inserting the calculated wetted perimeter and calculating the corresponding error.

Although the only data comparing our measured flow rates with another independent source are at TAG, the results shown in Figure 3 and the associated analysis show excellent agreement (–2% average difference). Thus, the error in wetted perimeter is considered the most significant source of error.

As far as modeled results are concerned, the primary source of error arises from the assumption of an average bed profile or through use of a single representative bed profile in the analysis. The errors introduced are difficult to quantify, although it is reasonable to assume that the errors could also be approximated by (9), but that they are completely independent of the errors in the measured values.

Discussion

Habitat availability curves have been created for 11 different cross-sections over approximately an 80-mile (129 km) stretch of the Pecos River between TOFP and TAG. The question is now a matter of how to implement the curves. While it must be kept in mind that full implementation of the habitat availability curves is not possible without the proper definitions of PBSM habitat requirements provided by the fisheries biologists, lets assume for the purposes of this discussion that these habitat requirements are known.

The first issue to address is the spatial distribution of the transects. Between TOFP and TAG the river is primarily a losing reach with flow efficiencies dependent on many factors including climate, season, discharge rate, side inflows, and other less quantifiable phenomena. River efficiency along a reach is defined as the flow rate at the bottom of the reach divided by the flow rate at the top of the reach. At natural flows less than 40 cfs as recorded at Taiban Gage (the northern most gage in this reach), river efficiencies in this reach are quite low and range from about 0–60% with a mean of about 7% in mid-summer and 39% in mid-winter (Stockton, 2003). Also important to note is that efficiencies drop sharply as flow approach 0 cfs from 40 cfs. This means that when there is no rain in the area to provide side inflows, approximately about 7–39% of the flow at Taiban Gage will reach Acme Gage. Therefore, it is recommended that the habitat availability curves from the most down stream gage be used to select a minimum flow requirement, in this case Acme Gage (location of TAG). An exception to this rule is described later.

Selecting the minimum flow requirement is not a trivial process and should be well thought out (at any transect) to optimize water use such that fraction of favorable to unsuitable habitat is maximized as a function of discharge. For example, Figure 14 is the depth-availability plot for the Pecos River at Pipeline Crossing with data (symbols) and modeled (curves) shown. The plot is read as follows: Consider, hypothetically, that the PBSM prefers a depth habitat of 6 inches (15.2 cm). The width of river that is at least 6 inches (15.2 cm) deep is read using the green curve by noting the wetted river width and flow rate at any point along it. For example, the width of the river (perimeter or black line) is approximately 80 ft (24.4 m) at a flow rate of 10 cfs (find the intersection of a vertical line from 10 cfs with the black depth-availability curve). Note also that the green line indicates at least 6 inches (15.2 cm) of depth for 40 ft (50%) of the river width at 10 cfs (0.29 m^3/s). Let us examine the effects upon this available habitat as a result of doubling the flow to 20 cfs (0.6 m^3/s). The width of the river increases to 92 ft (28.0 m) and the width of the river that is at least 6 inches (15.2 cm) deep increases to 44 ft (48% of the river width). Doubling the flow rate at this stretch of river serves to add only 4 ft

(1.2 m) of 6-inch (15.2-cm) deep habitat (a 2% decrease in relative width). Furthermore, the increased wetted perimeter will be subject to evaporation, evapotranspiration, and infiltration. Clearly, there is a point of diminishing returns, and water regulators will need to compromise between river flow and the width of habitat yielded. Further, note that increasing the flow rate beyond 20 cfs (0.6 m^3/s) has a minimal impact on the amount of 6-inch (15.2-cm) deep available habitat.

Once the target flow is selected, the next step is to calculate the discharge rates at the remaining upstream transects using any of the modeling techniques recommended by the Pecos River Hydrology Working Group. Then use the availability curves generated at the upstream transects to quantify the available habitat at each transect. Because there is increased flow upstream (before the losses), there will most likely be a concurrent increase in habitat. Although unlikely, it is possible upstream transects might not meet the specified minimum habitat requirements at the estimated discharge. Alternatively, there might be an overabundance of habitat at the upstream transects, further complicating the analysis of selecting the downstream target flow rate. Essentially, instead of looking at habitat on a transect by transect basis, habitat could be summed over the entire reach. In this case, a target flow could be selected at Acme Gage that supplies little to no preferred habitat locally, but one that provides the rest of the reach with sufficient habitat to ensure a thriving PBSM population.

It should be noted that Acme Gage is below the critical habitat designation for the PBSM and therefore habitat need not be maintained at this location. Also, as closely as our measurements reveal, the drop in discharge from TT to TAG is fairly consistent, but often there can be erratic and quite large drops in efficiency from T5MD to TAG (about an equal percentage loss in ⅓ the distance). It would be ideal if there were a gage at the end of the critical habitat to use as the downstream reference for selecting target flow. Because T5MD is the closest transect to the southern end of the critical habitat, it could be used as the reference location, but a daily stream flow record is currently not available here.

Conclusions

Among the most contentious and technically difficult issues related to water resources management in New Mexico is the effect of enforcement of the Endangered Species Act for the threatened PBSM in the Pecos River. This issue has divided environmental groups, federal and state agencies, municipalities and scientific disciplines. Part of the division relates to the different management responsibilities and mandates, but a second component relates to the lack of scientific consensus concerning the habitat requirements and in-stream flow requirements for maintaining a healthy environment for the PBSM. The conflict has been exacerbated recently by the extended and extensive drought that affects the entire basin of the Pecos River. The drought has limited the management options and management flexibility enjoyed by this basin in years past.

With the recent drought conditions, the lack of water in the Pecos River Basin has provided acute and highly volatile problems for commitments to Texas, New Mexico's farmers, and wildlife. It is therefore imperative that the best science be put forth to determine efficient water use (and this means garnering input from as many sources as possible). New Mexico's Pecos River water commitments to Texas and its farmers is well understood and legally bound. However, while New Mexico is also legally bound to protect its threatened wildlife (i.e., the PBSM) it is not known how much water is required to maintain a thriving habitat. To determine this requires both biological and hydrological expertise (morphologists could also play a large role). Biologists need to determine the preferred habitat of the species (in terms of depth, velocity and other parameters) as well as minimum habitat requirements necessary to ensure species survival in years of reduced water. Hydrologists need to determine river discharge that meets the habitat requirements set forth by the Biologists (the focus of this report). Currently, target river flows set to meet PBSM needs have been specified without an understanding of the relationship between discharge and the associated available habitat.

To date, neither the preferred habitat nor the minimum habitat requirements have been definitively specified. This is in part due to the general difficulty in observing PBSM preferences in the field. In the absence of this data, SNL hydrologists and engineers have developed a means to predict the available river habitat as a continuous function of river discharge through both monitoring and modeling techniques. Both the monitoring and modeling methods were performed with unprecedented horizontal spatial resolution such that available habitat is determined every 2 ft (0.6 m) across the channel. Other models considered state-of-the-art (e.g., HEC-RAS or Flow 2D) have much lower resolution for determining water depth and velocity across a transect (~10–20 ft increments) and would provide few data points across a river of this size. When the preferred and minimum habitat requirements are understood, these habitat availability curves will aid water management decisions for target river flows necessary to meet the ascribed requirements.

Once the appropriate river discharge has been decided, it will be possible, for the first time, to estimate the total yearly volume of water necessary to maintain suitable PBSM habitat over varying climatic conditions. This will likely play a critical role in the State’s long-term water storage and management policies.

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Hoagstrom, C.W., 2000. Pecos River fishery investigations: Status of Pecos River fishes between Sumner Dam and Brantley Reservoir, New Mexico, with emphasis on Sumner Dam operation, discharge-flow regime regulations, and federally and state threatened Pecos Bluntnose shiner (*Notropis simus pecosensis*). U.S. Fish and Wildlife Service.

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Appendix A: Hydrographs

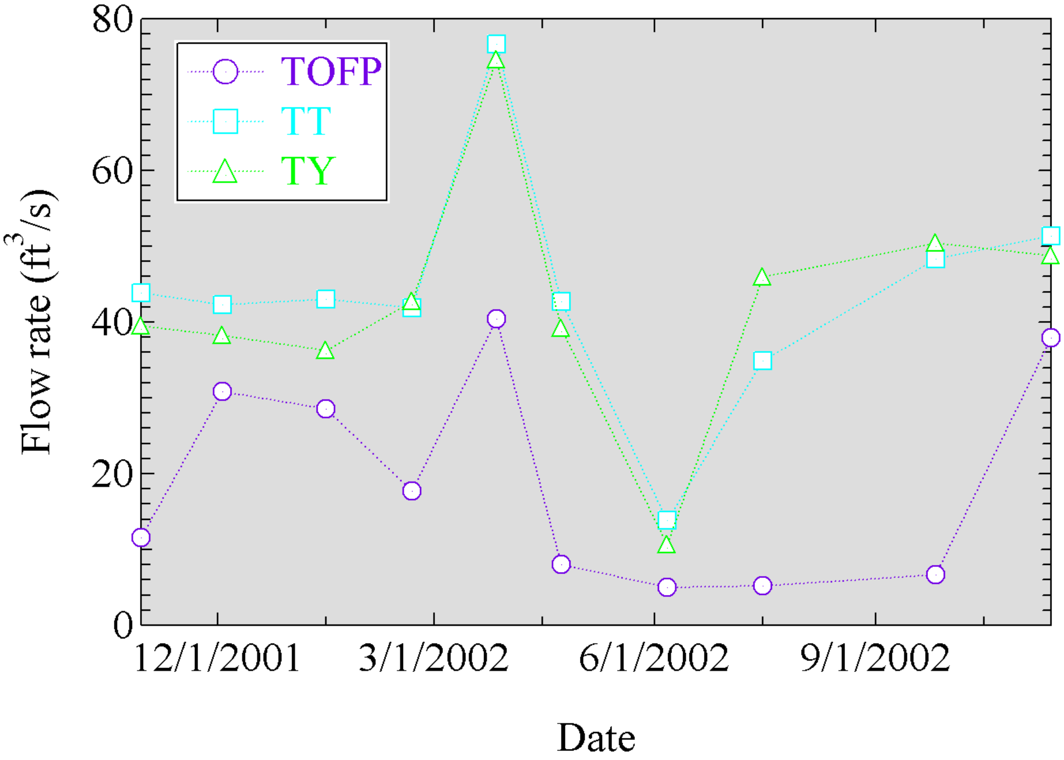

Figure 16: Hydrographs of the upper three stations.

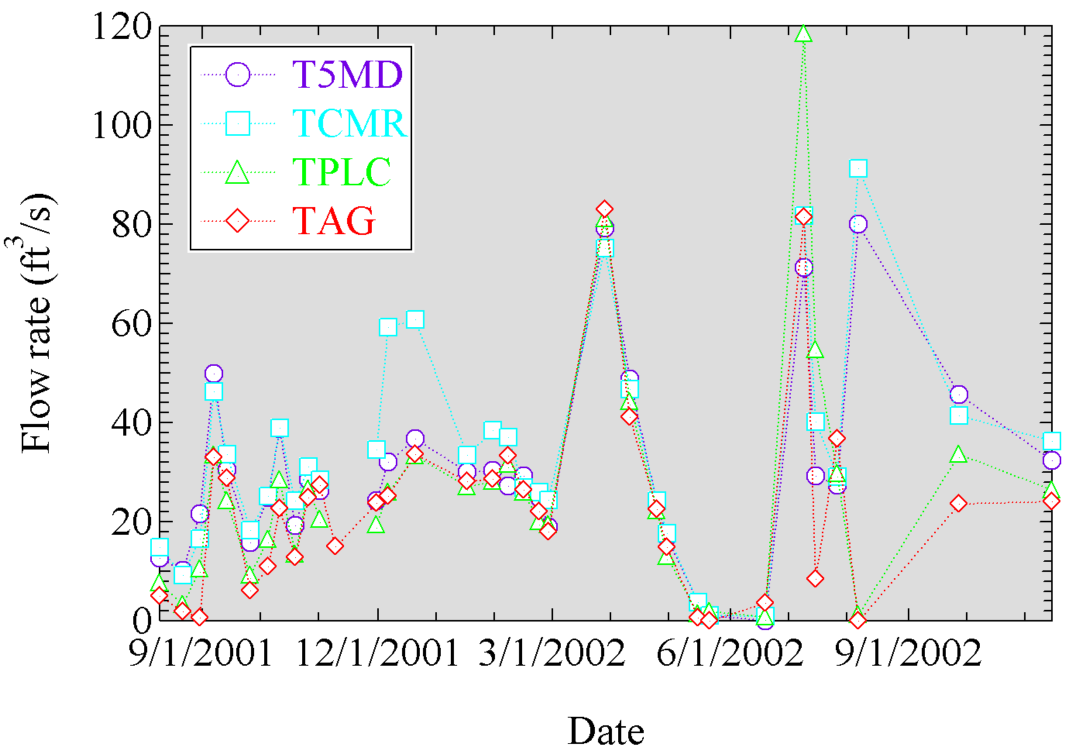

Figure 17: Hydrographs of the lower four stations.

Appendix B: Bathymetries

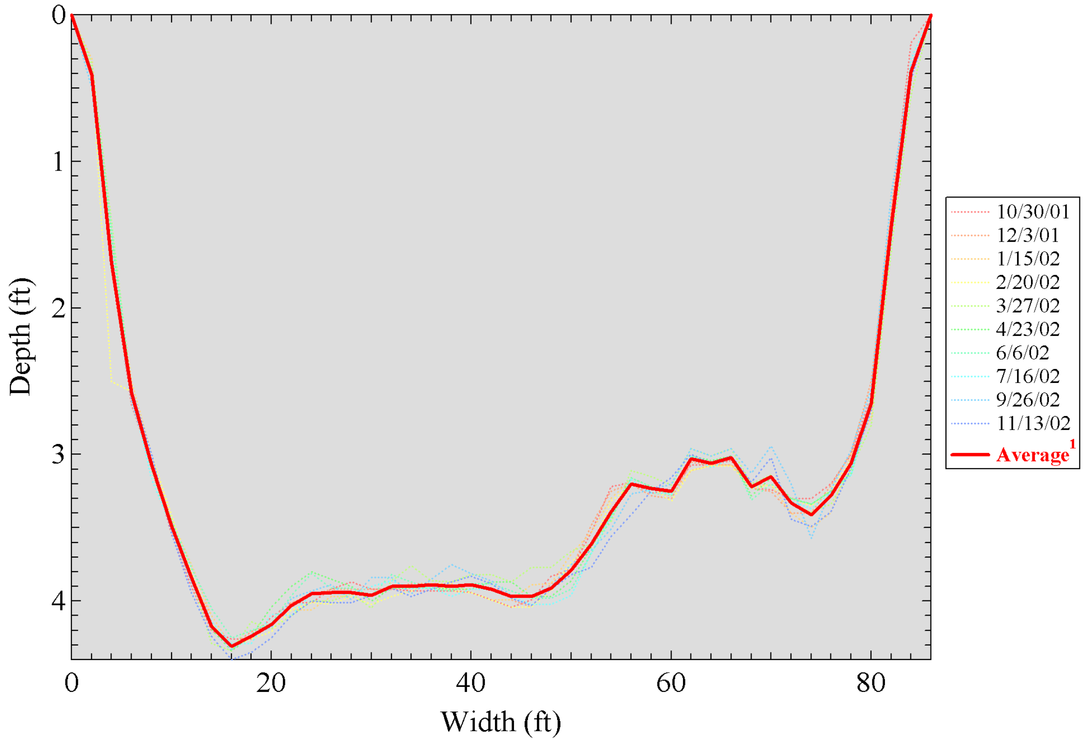

Figure 18: Measured bathymetries at TOFP with representative and average bathymetries bolded.

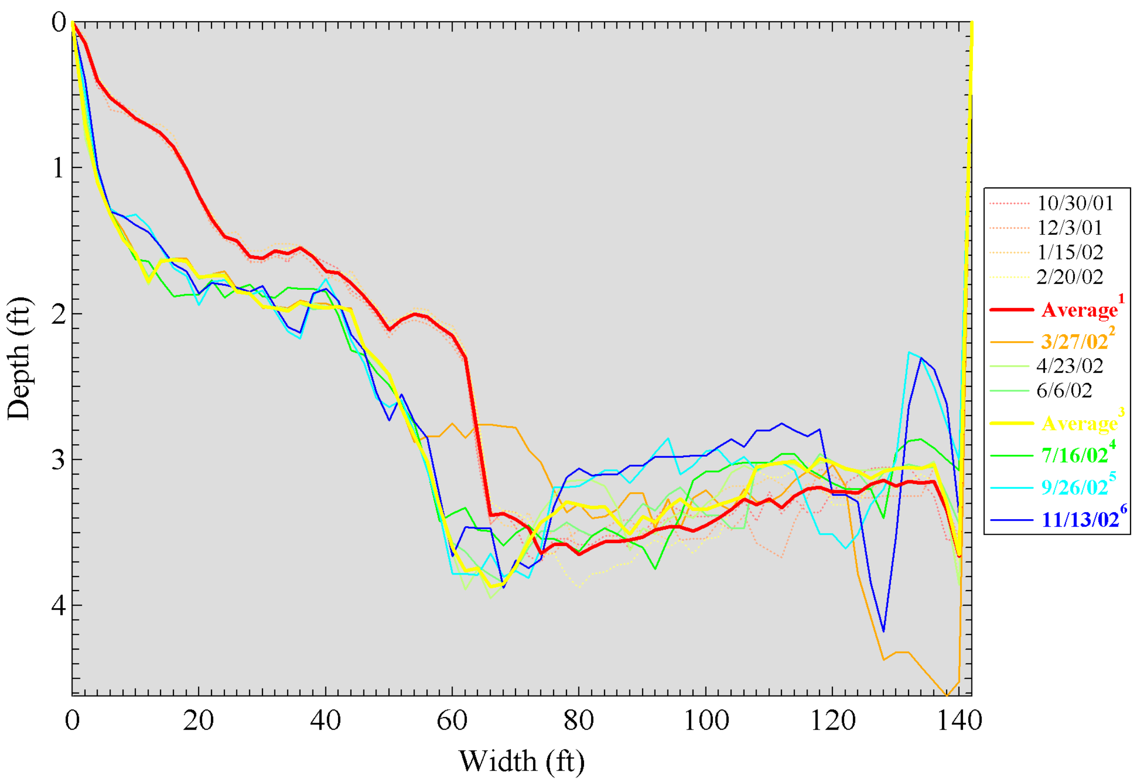

Figure 19: Measured bathymetries at TT with representative and average bathymetries bolded.

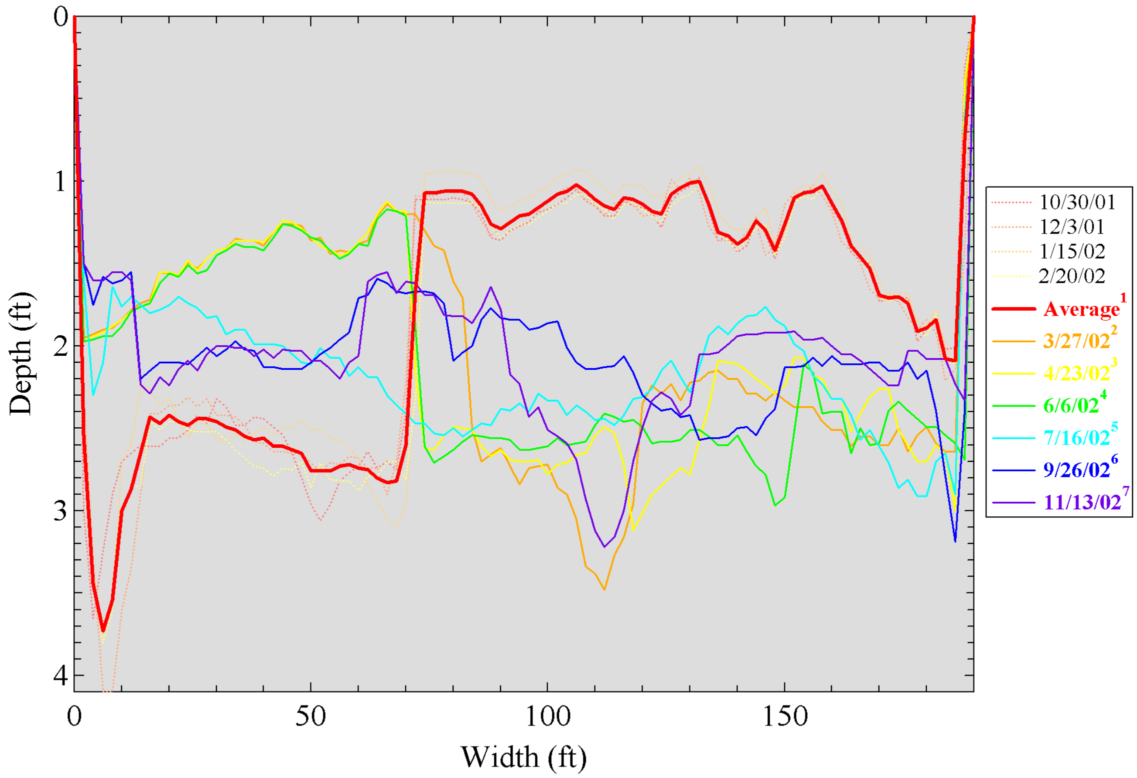

Figure 20: Measured bathymetries at TY with representative and average bathymetries bolded.

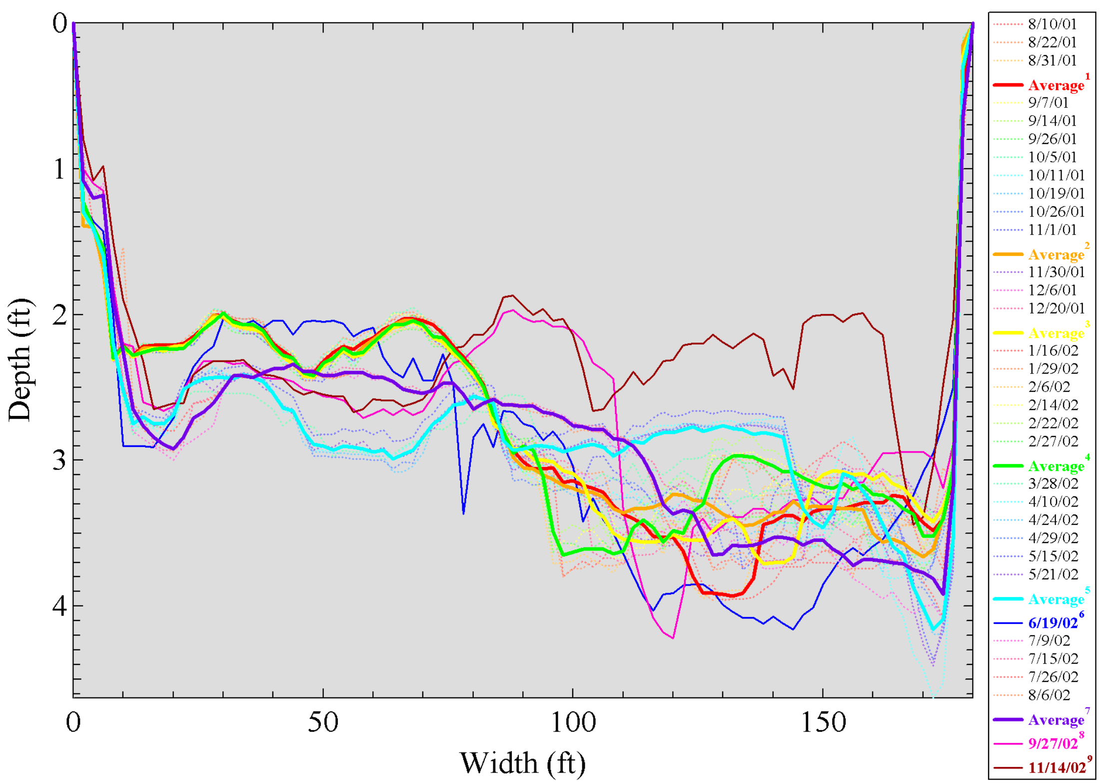

Figure 21: Measured bathymetries at T5MD with representative and average bathymetries bolded.

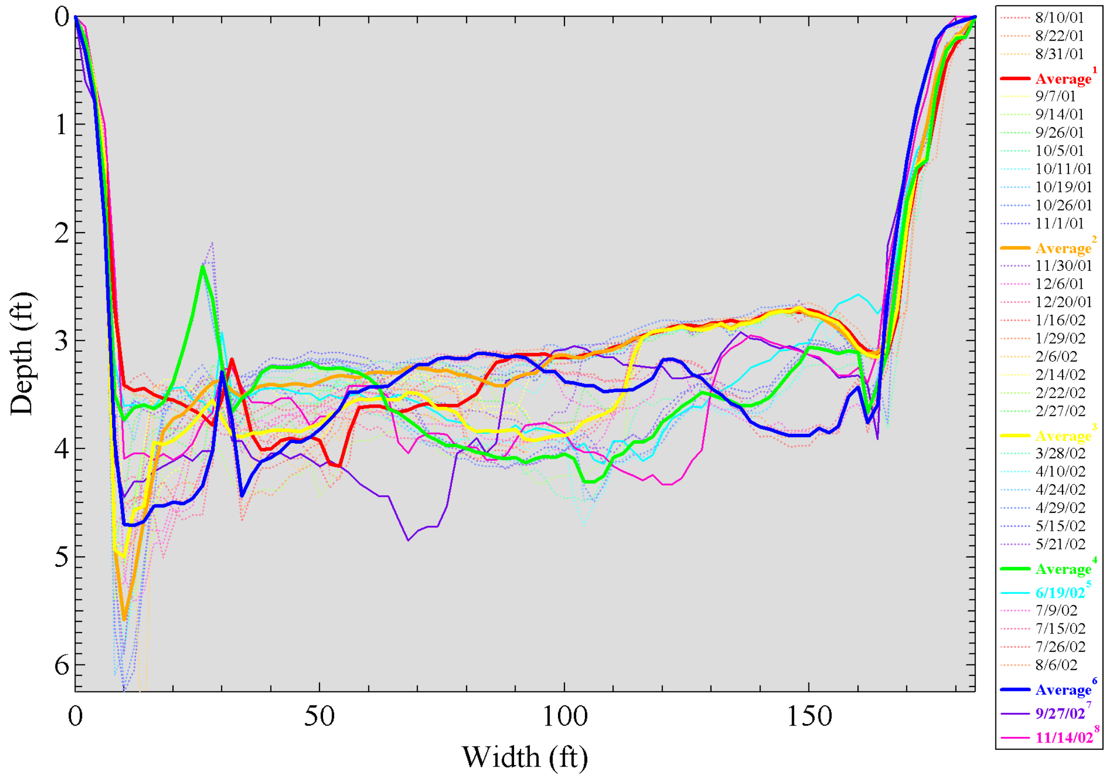

Figure 22: Measured bathymetries at TCMR with representative and average bathymetries bolded.

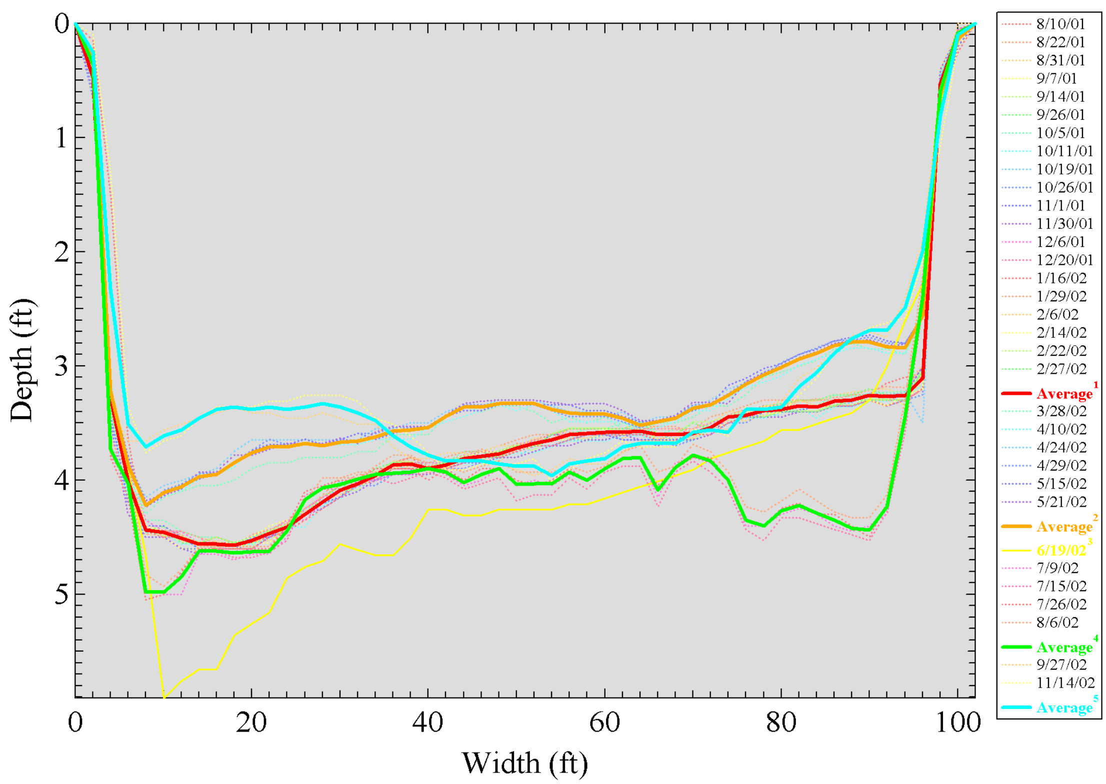

Figure 23: Measured bathymetries at TPLC with representative and average bathymetries bolded.

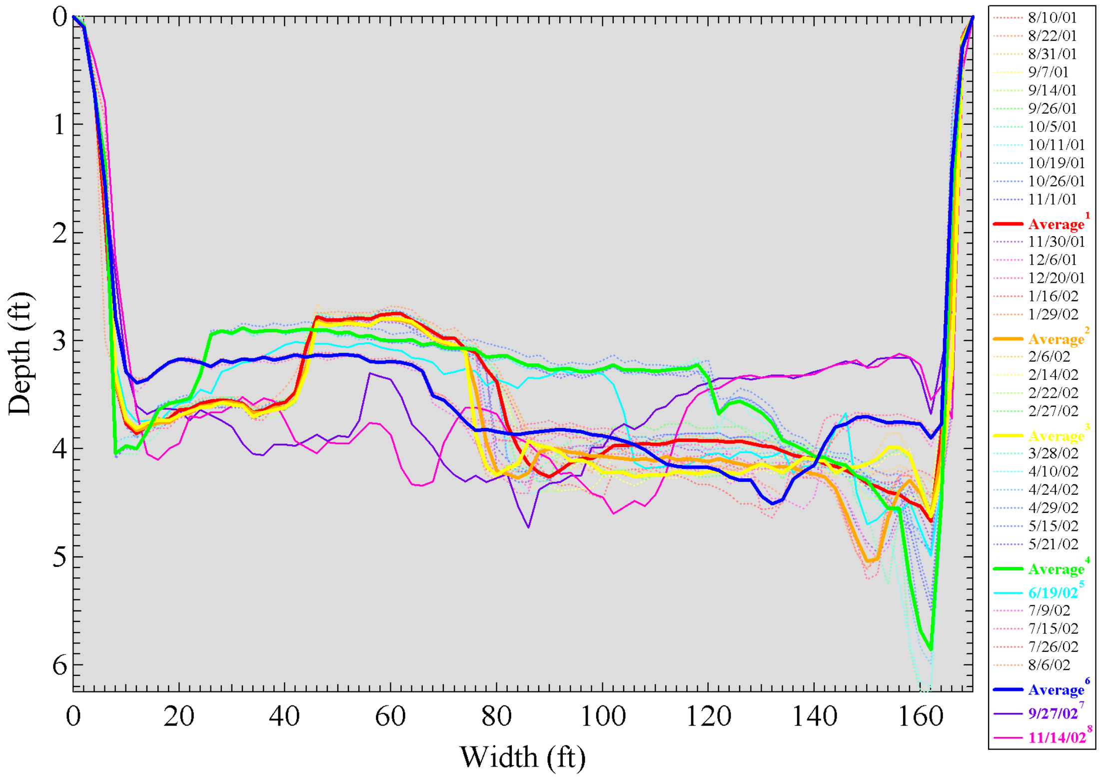

Figure 24: Measured bathymetries at TAG with representative and average bathymetries bolded.

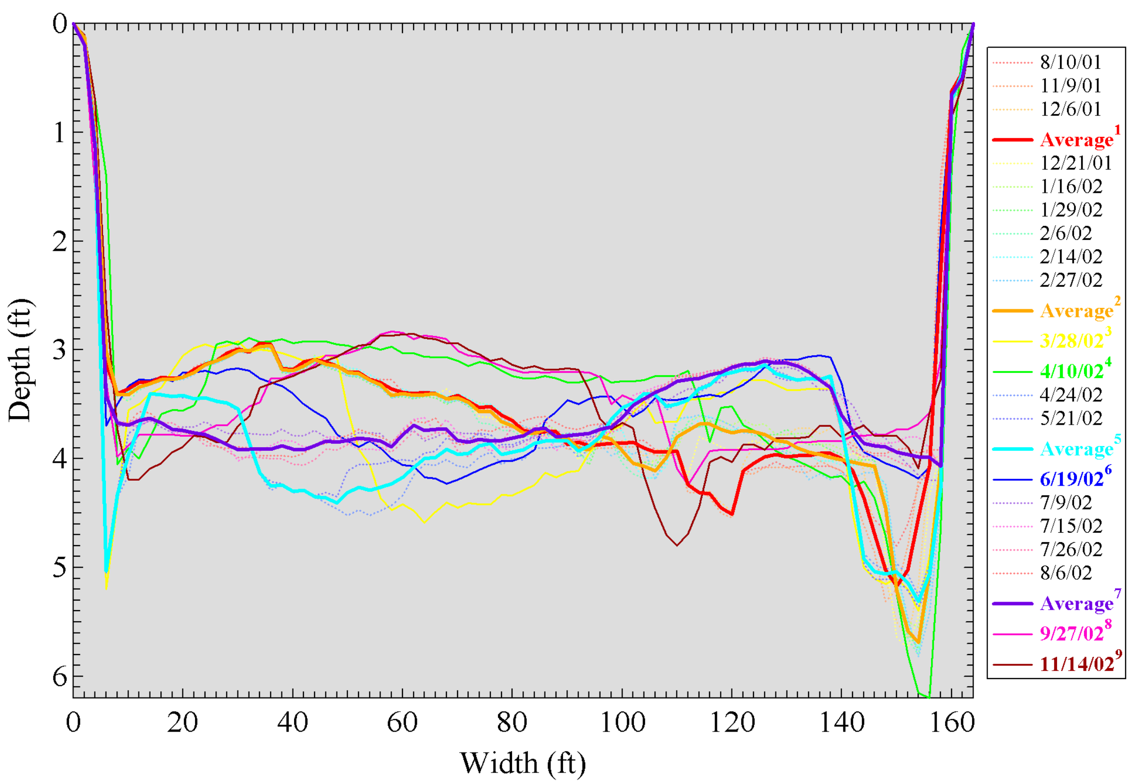

Figure 25: Measured bathymetries at TAGU3 with representative and average bathymetries bolded.

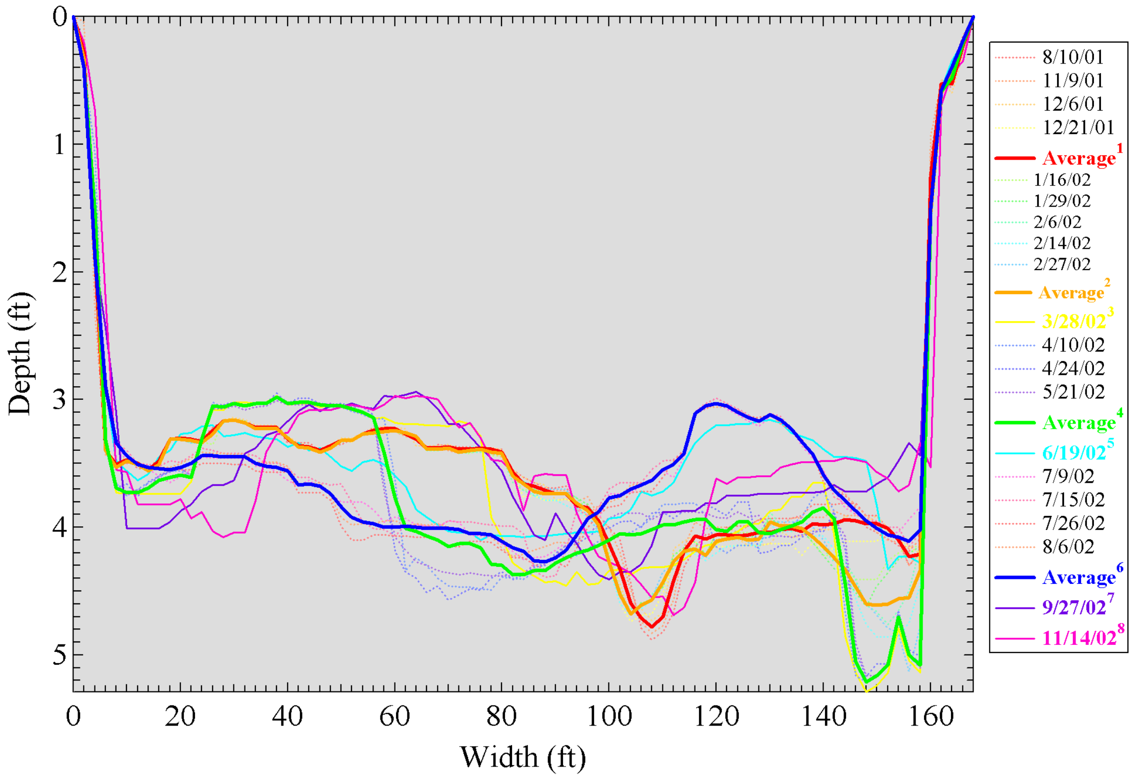

Figure 26: Measured bathymetries at TAGU2 with representative and average bathymetries bolded.

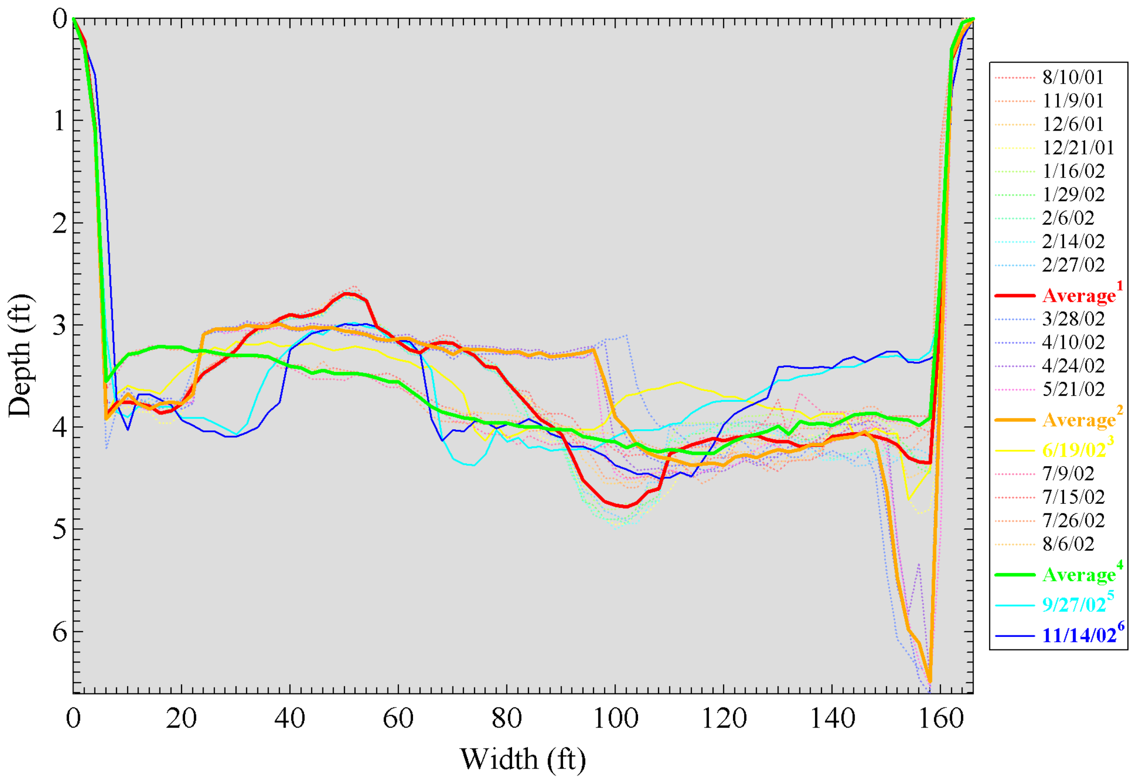

Figure 27: Measured bathymetries at TAGU1 with representative and average bathymetries bolded.

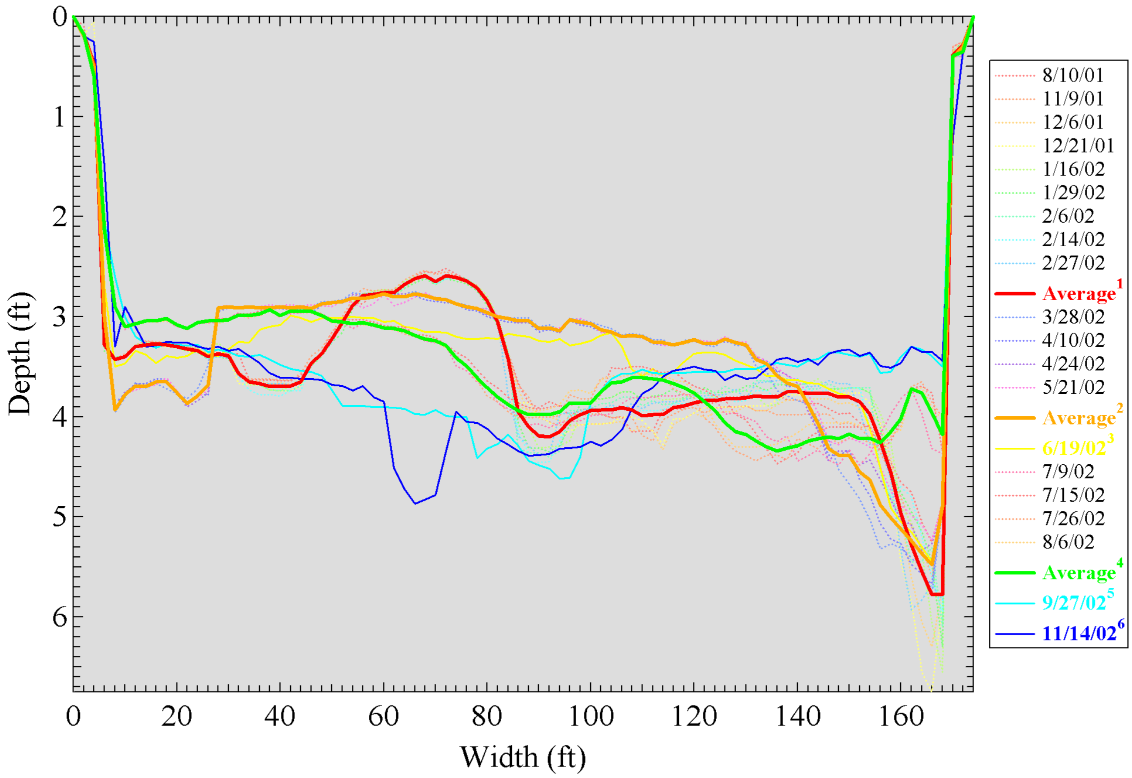

Figure 28: Measured bathymetries at TAGD1 with representative and average bathymetries bolded.

Appendix C: Hydraulic Geometry Parameters

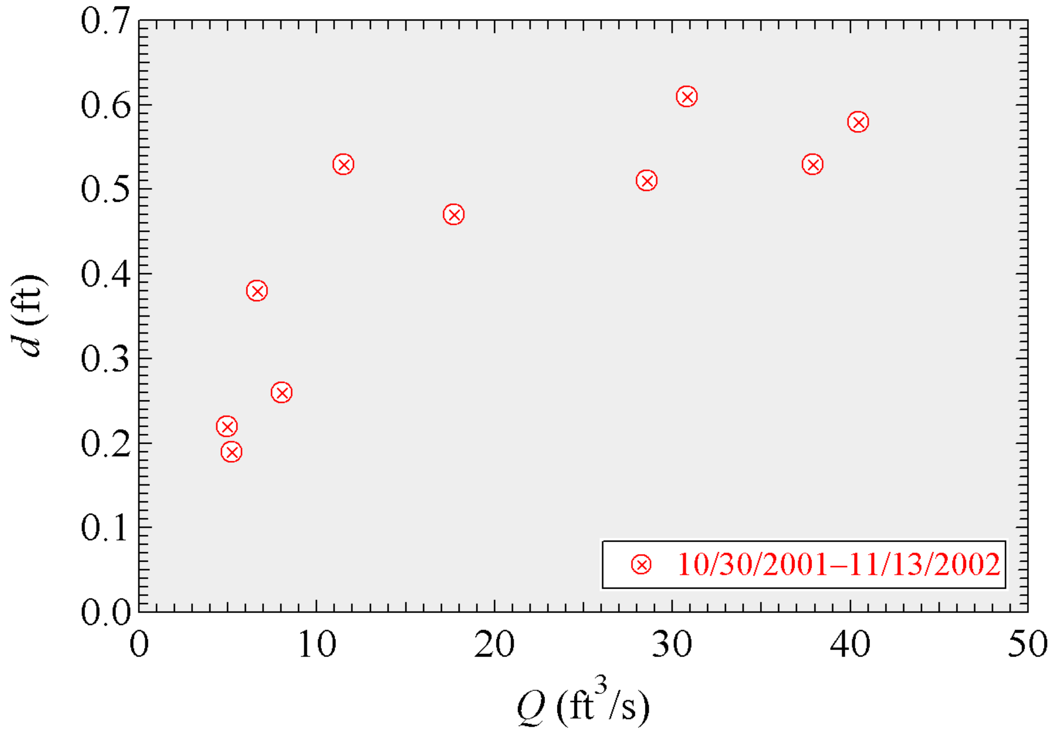

Figure 29: Mean depth vs. flow rate at TOFP.

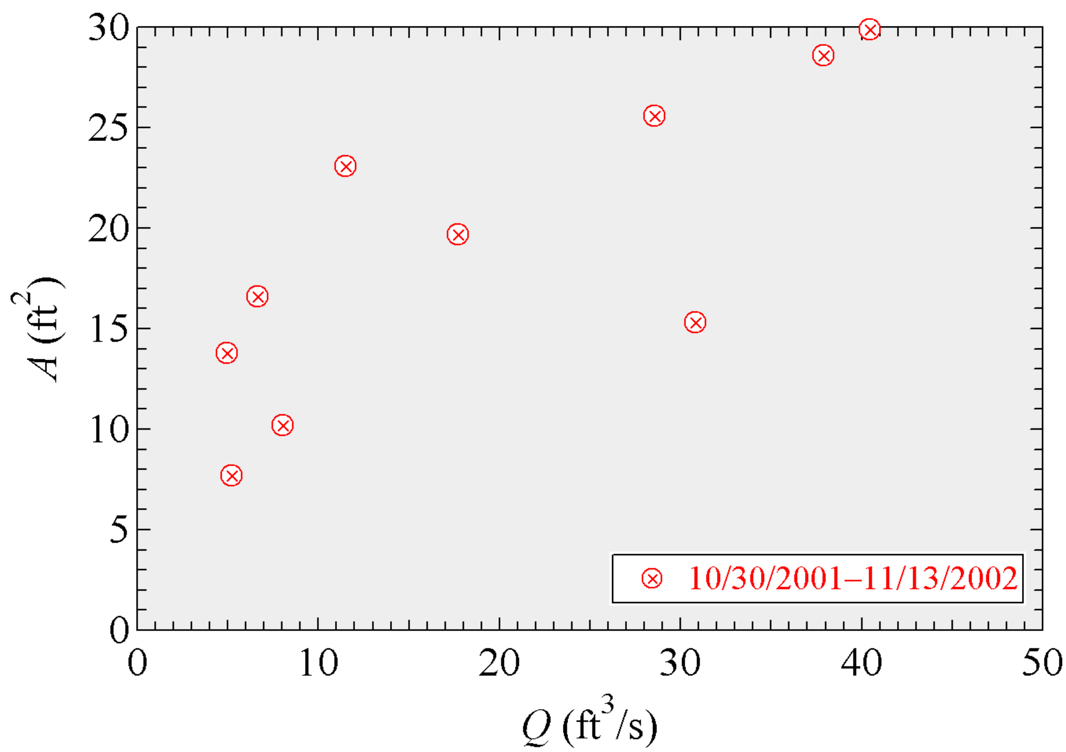

Figure 30: Wetted area vs. flow rate at TOFP.

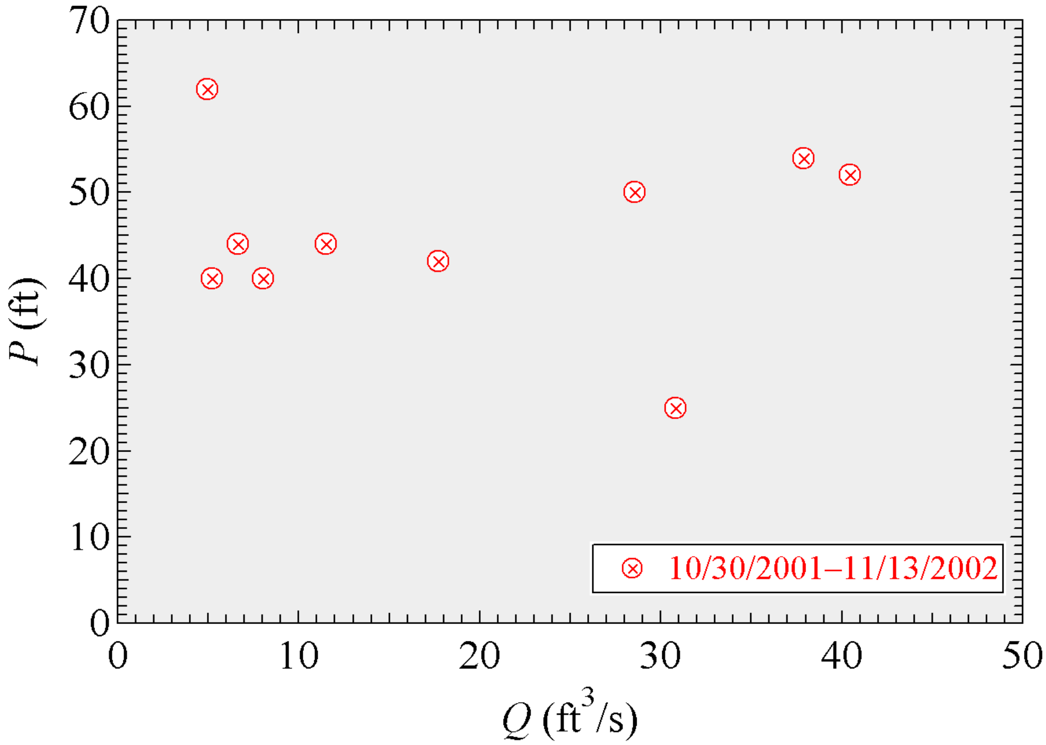

Figure 31: Wetted perimeter vs. flow rate at TOFP.

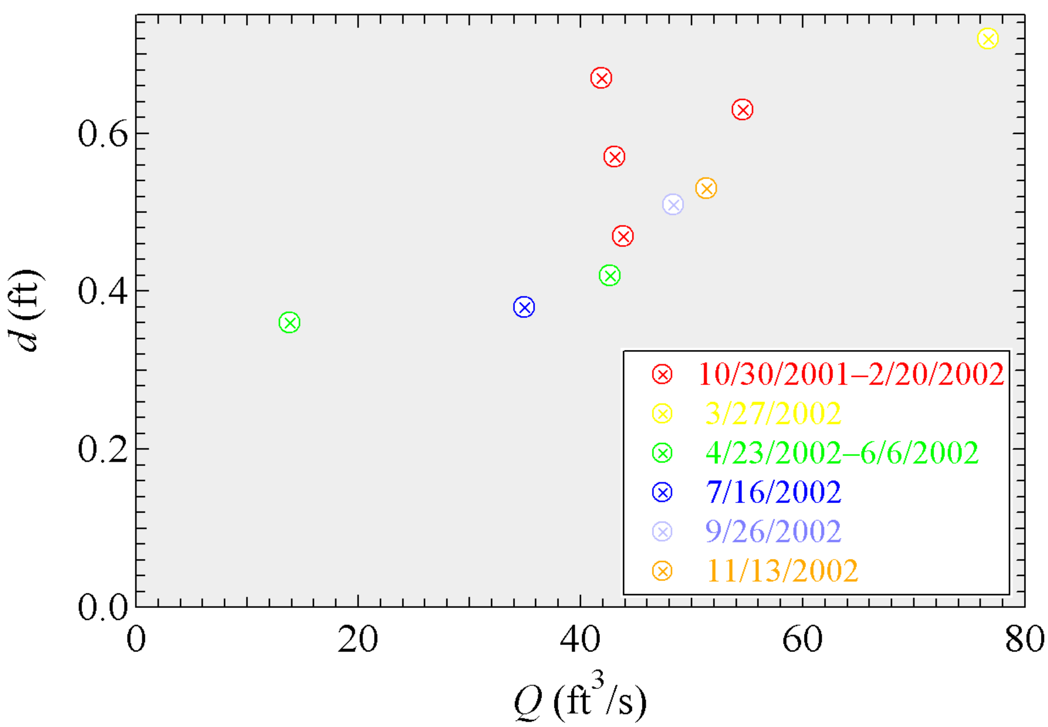

Figure 32: Mean depth vs. flow rate at TT.

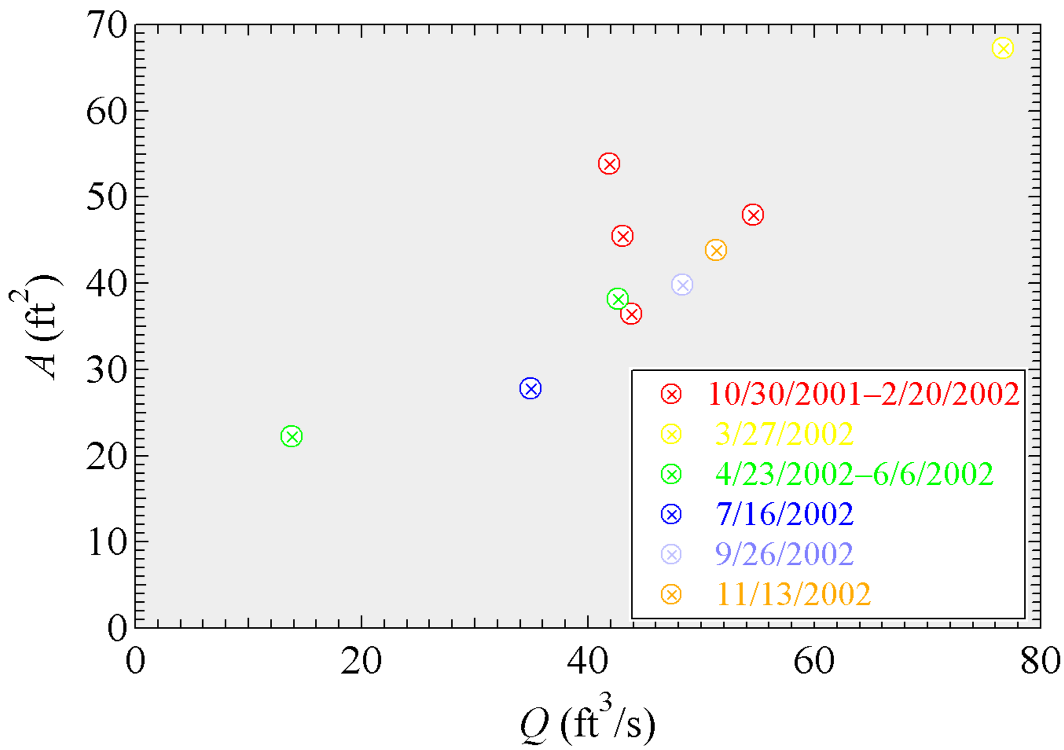

Figure 33: Wetted area vs. flow rate at TT.

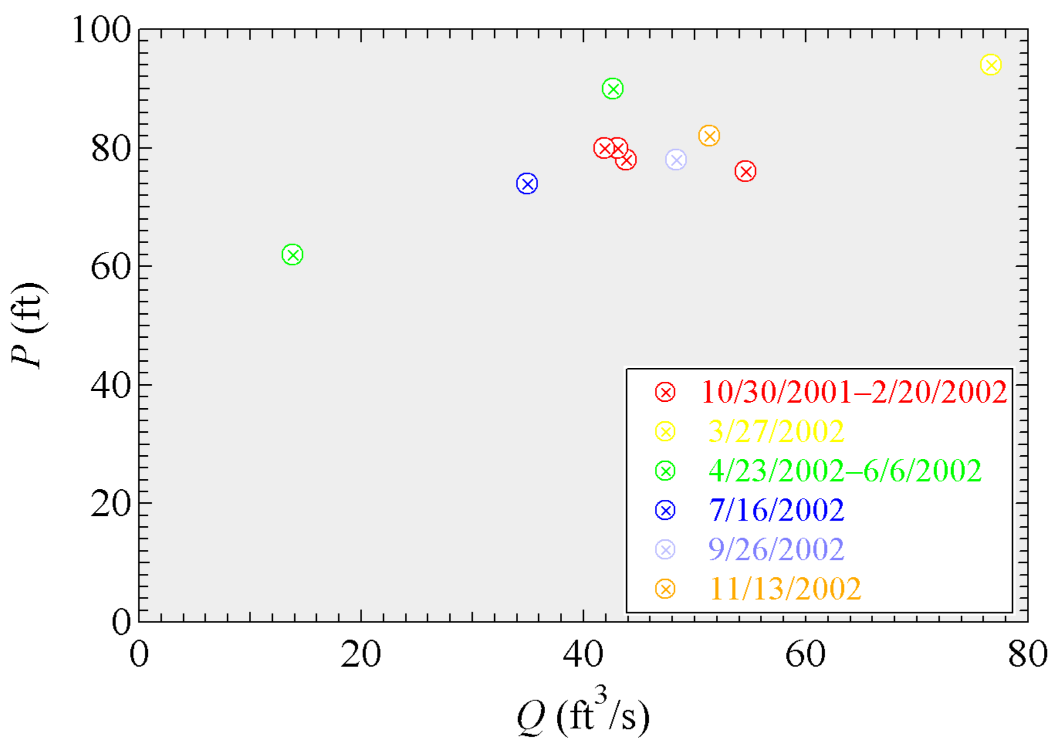

Figure 34: Wetted perimeter vs. flow rate at TT.

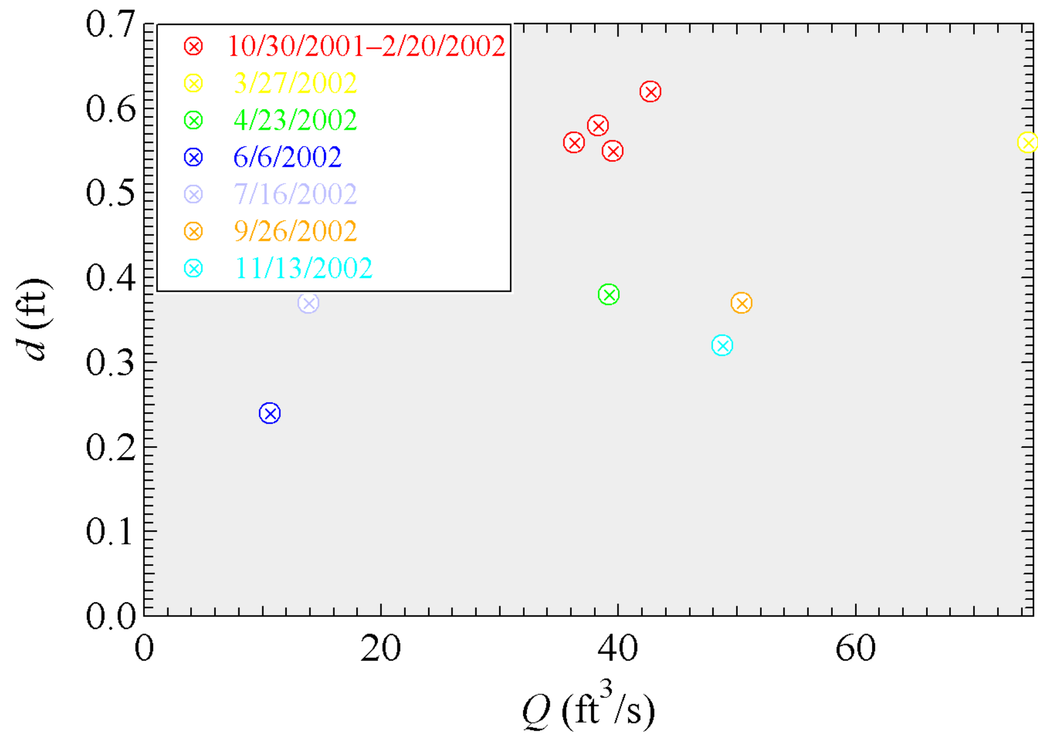

Figure 35: Mean depth vs. flow rate at TY.

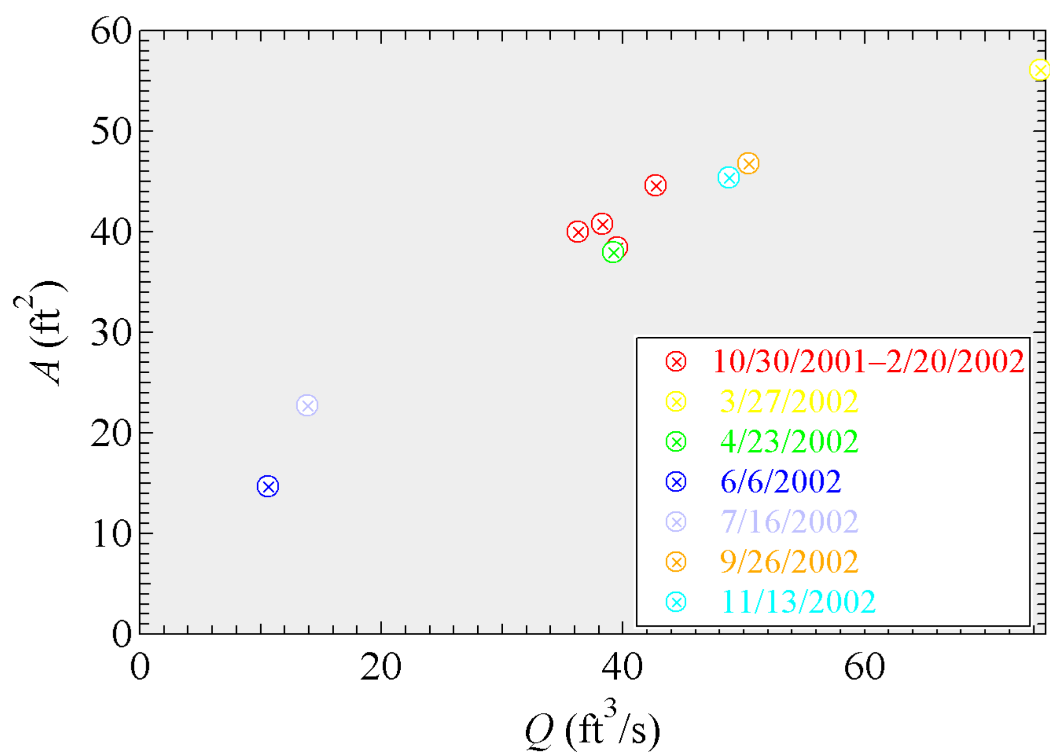

Figure 36: Wetted area vs. flow rate at TY.

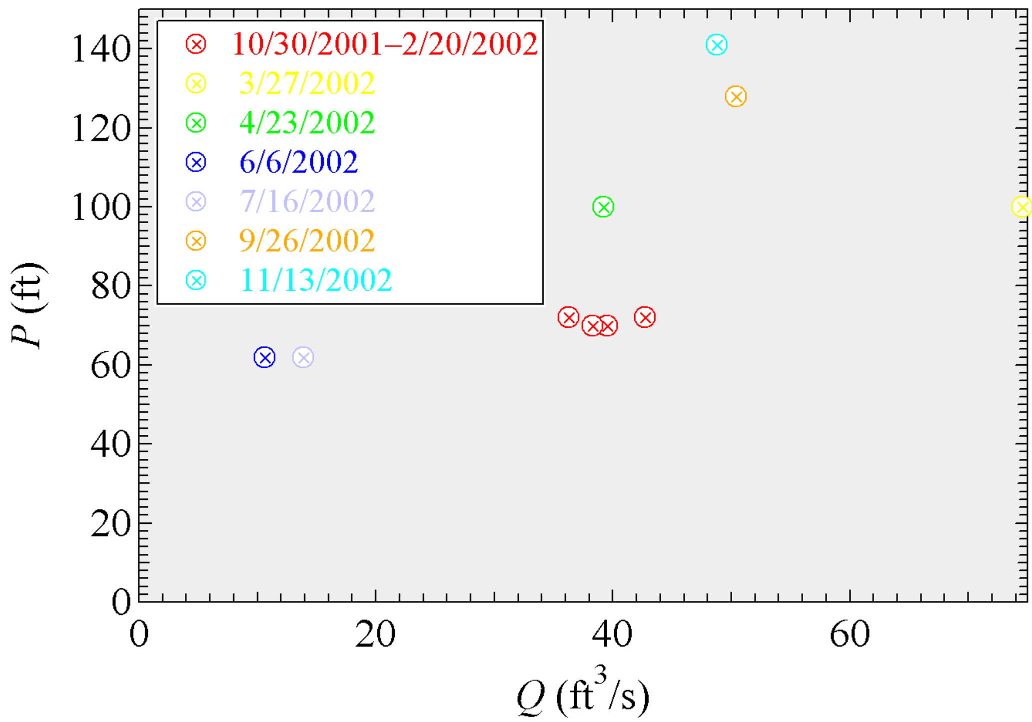

Figure 37: Wetted perimeter vs. flow rate at TY.

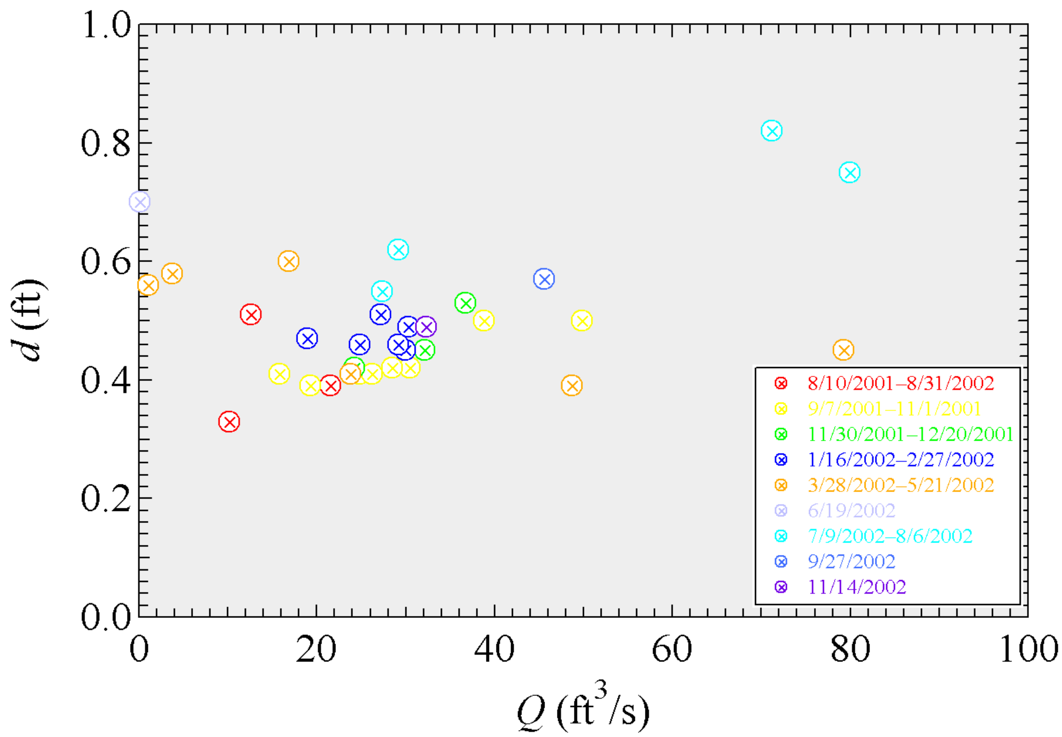

Figure 38: Mean depth vs. flow rate at T5MD.

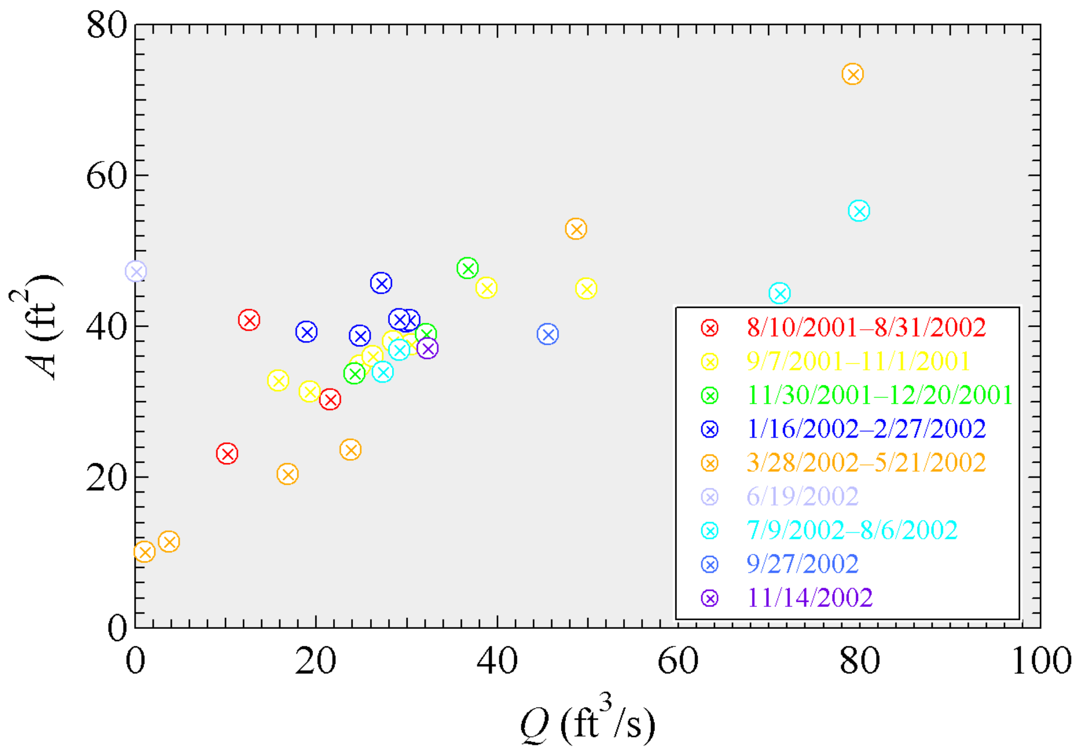

Figure 39: Wetted area vs. flow rate at T5MD.

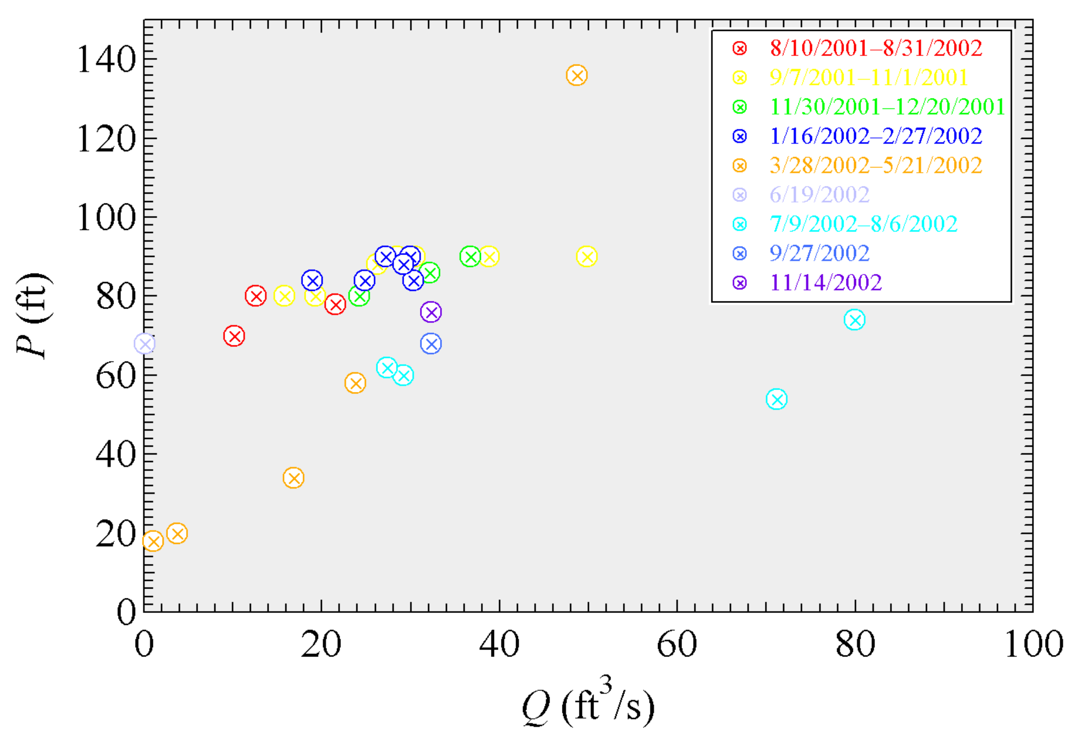

Figure 40: Wetted perimeter vs. flow rate at T5MD.

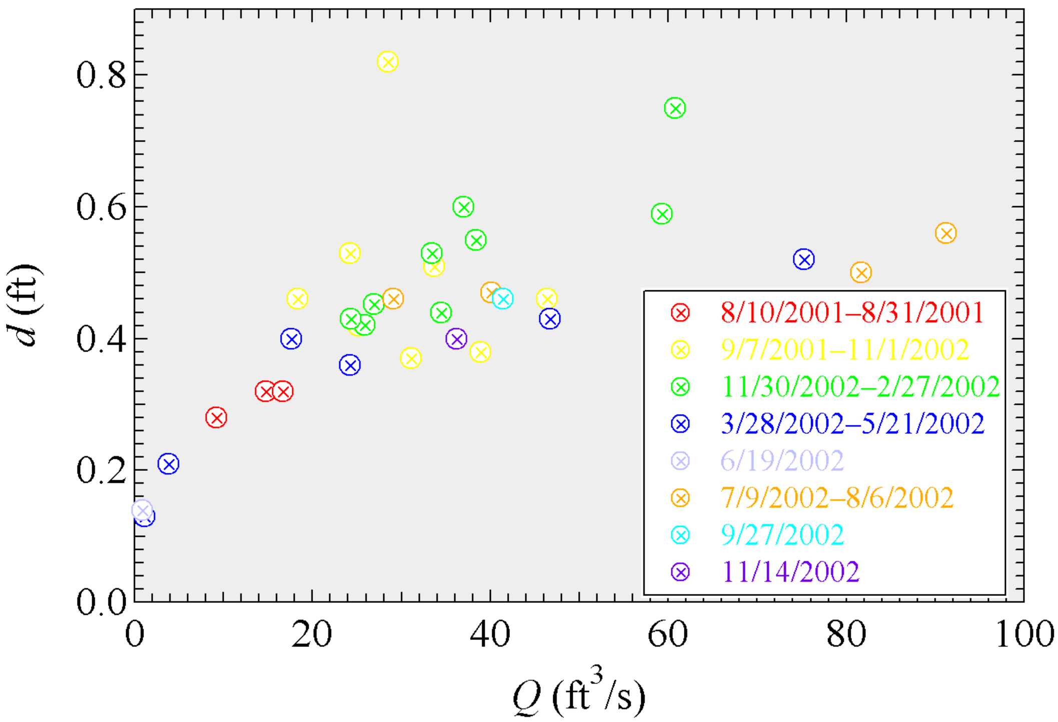

Figure 41: Mean depth vs. flow rate at TCMR.

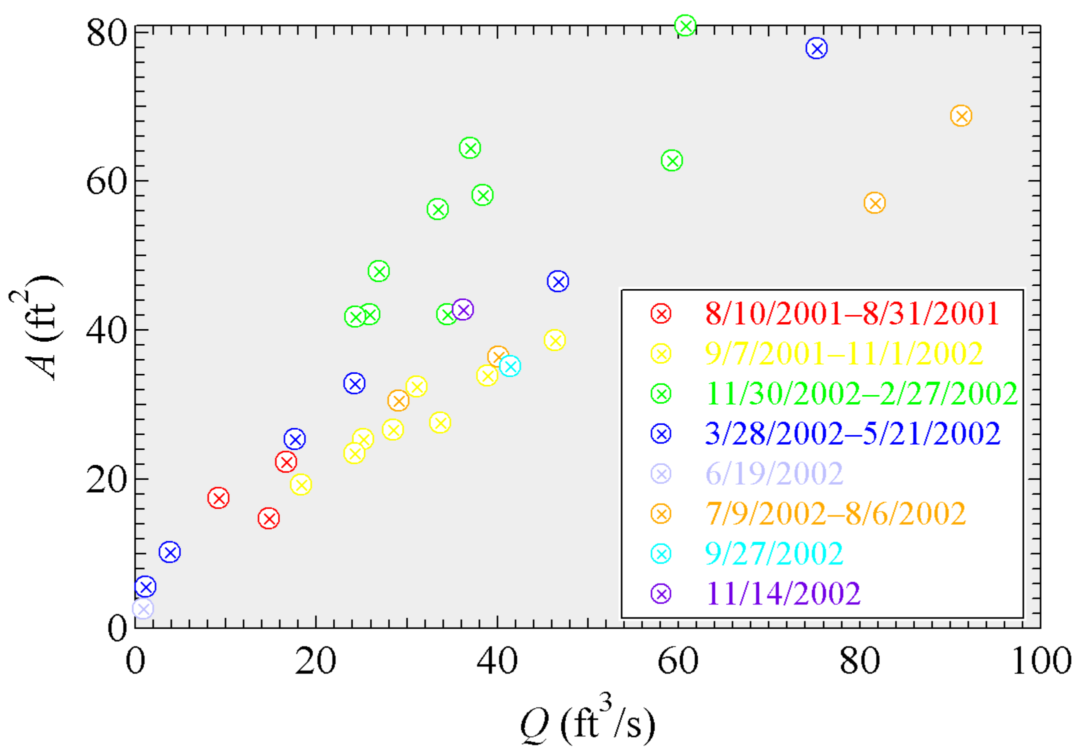

Figure 42: Wetted area vs. flow rate at TCMR.

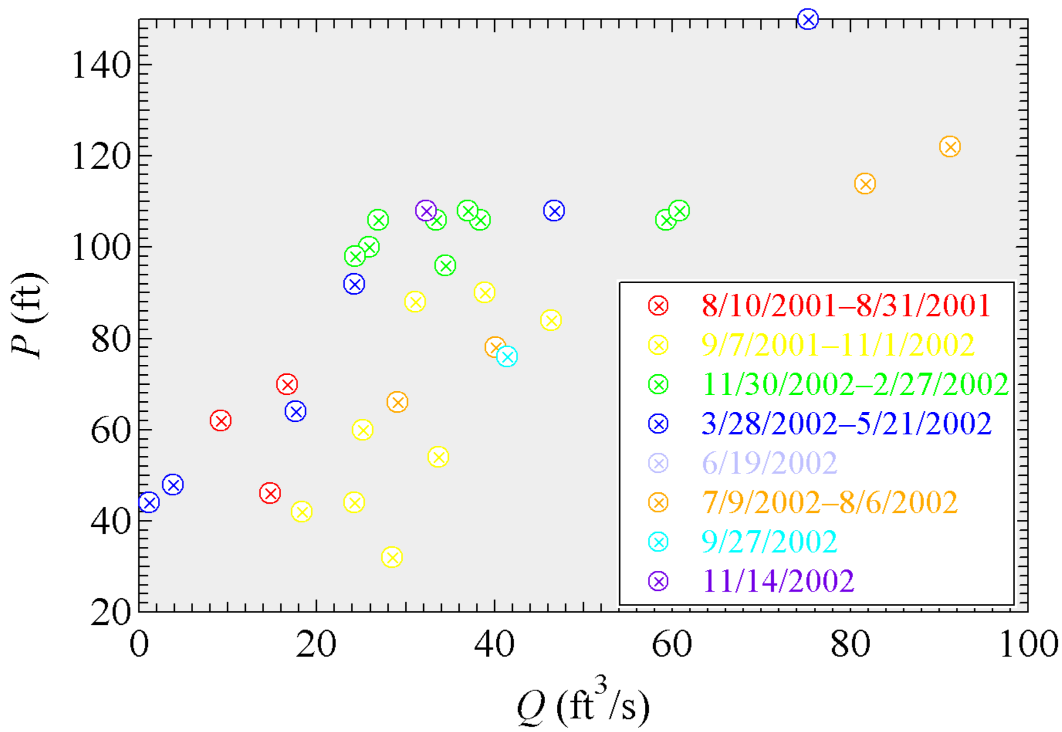

Figure 43: Wetted perimeter vs. flow rate at TCMR.

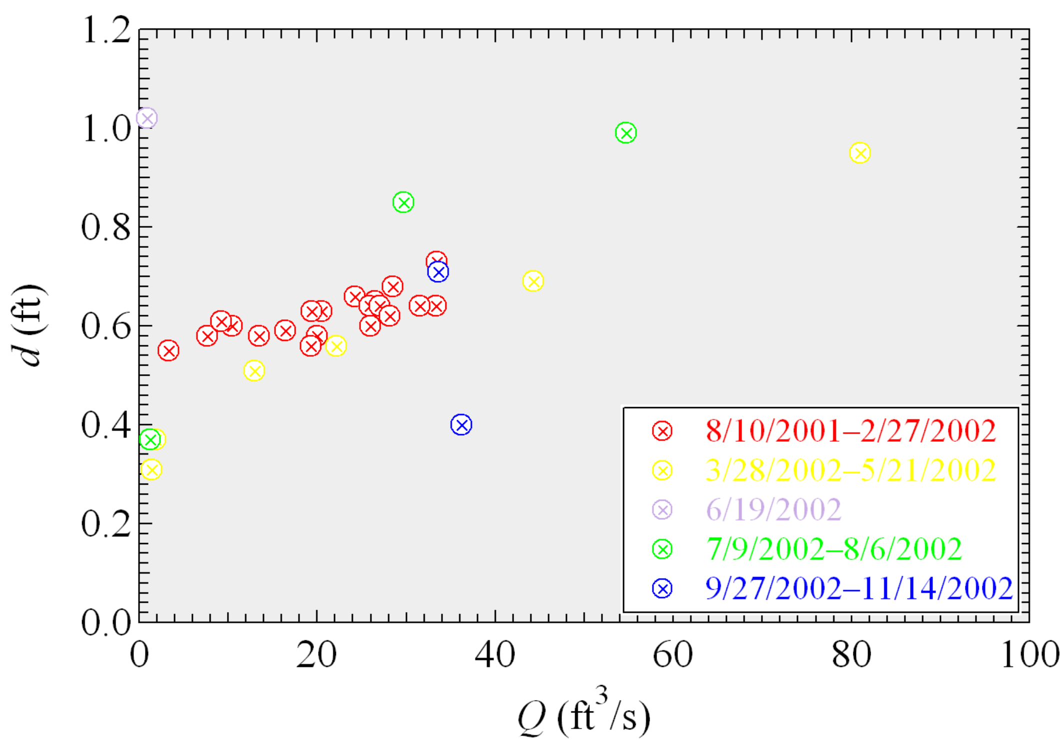

Figure 44: Mean depth vs. flow rate at TPLC.

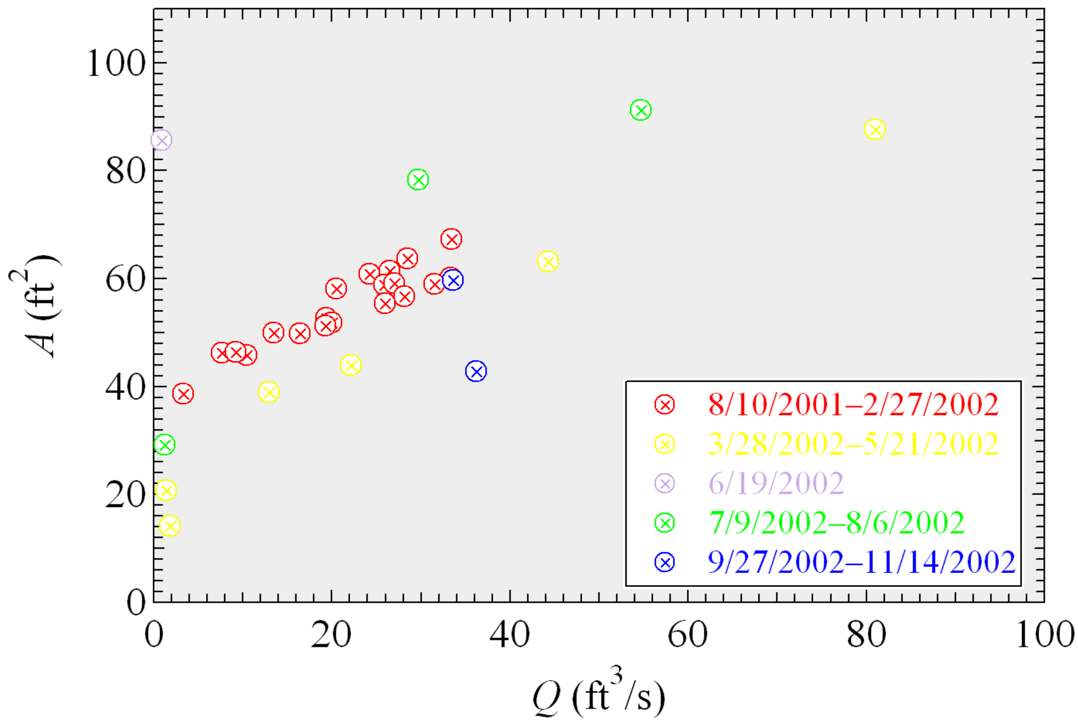

Figure 45: Wetted area vs. flow rate at TPLC.

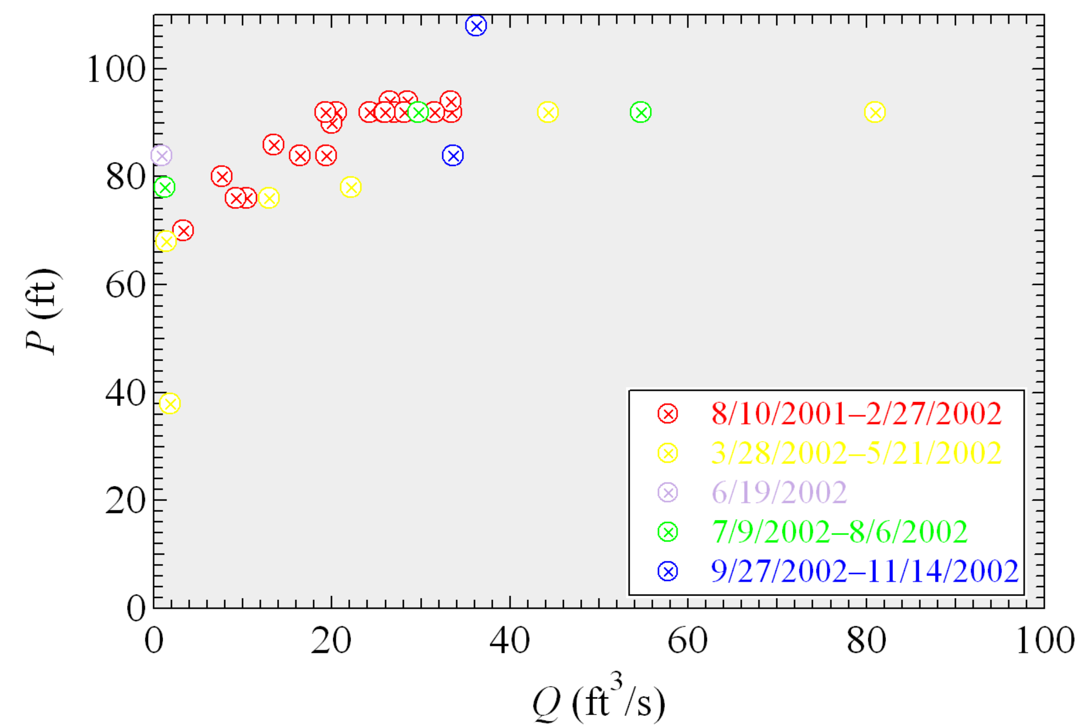

Figure 46: Wetted perimeter vs. flow rate at TPLC.

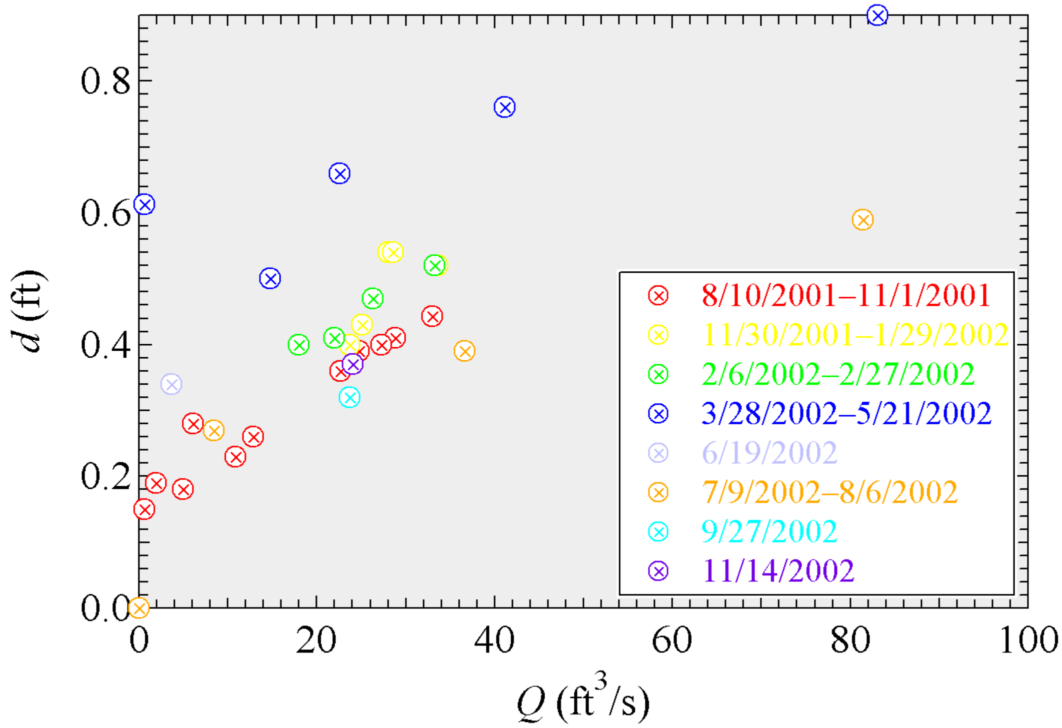

Figure 47: Mean depth vs. flow rate at TAG.

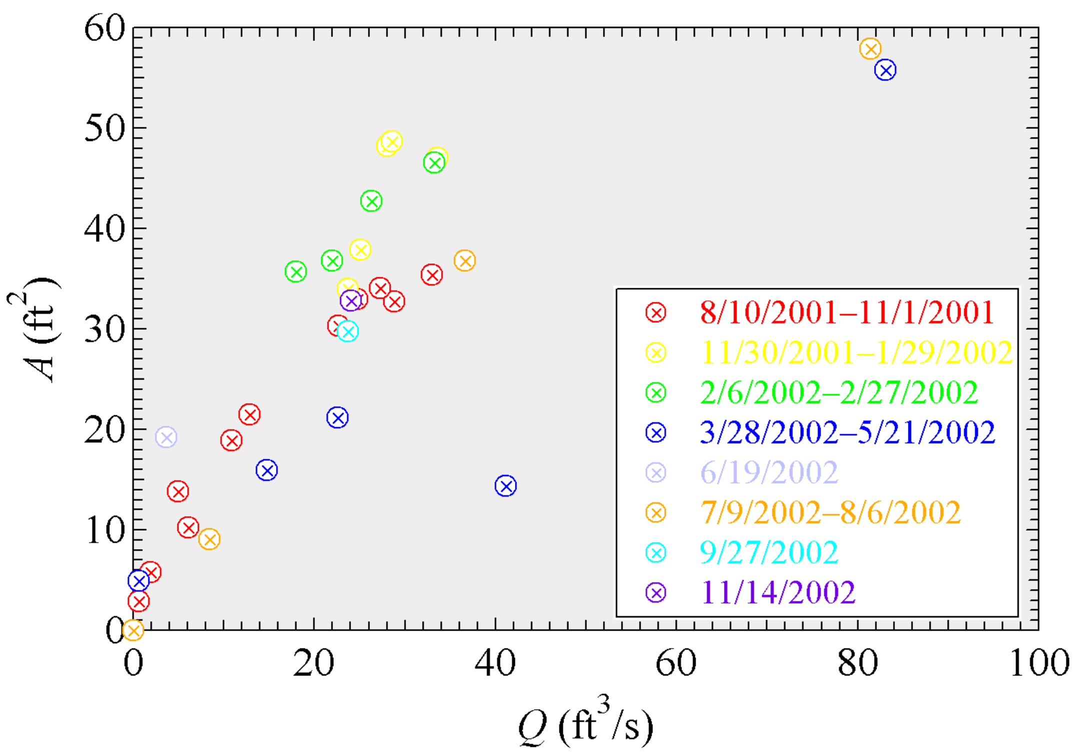

Figure 48: wetted area vs. flow rate at TAG.

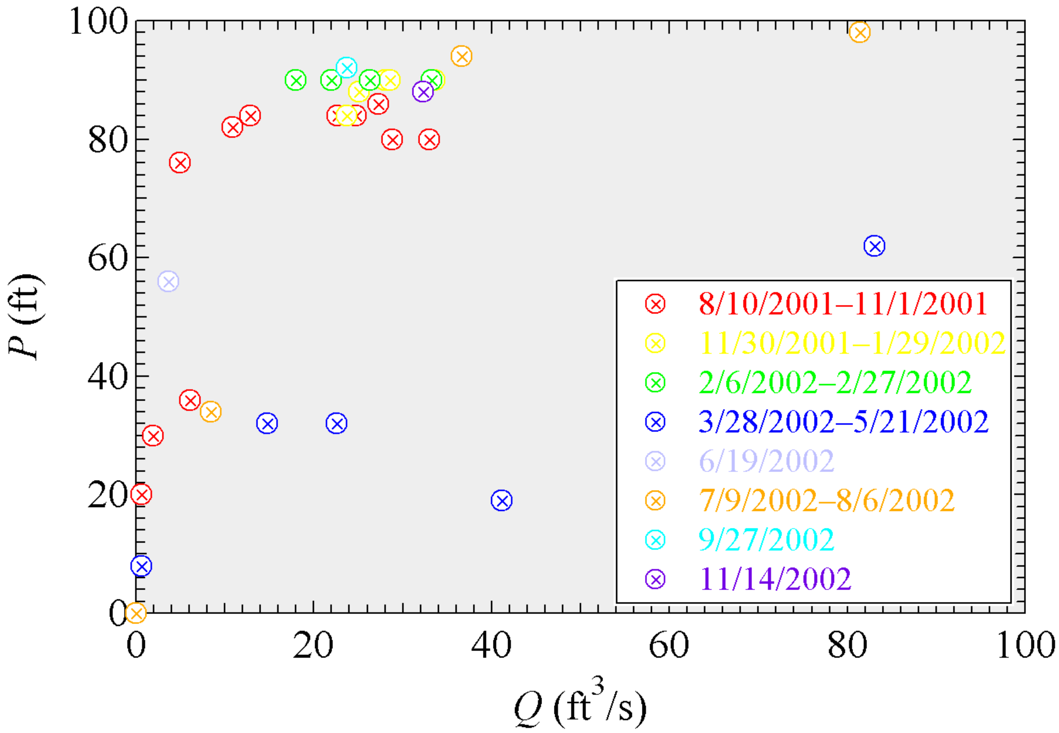

Figure 49: Wetted perimeter vs. flow rate at TAG.

Appendix D: Manning's Friction Coefficient

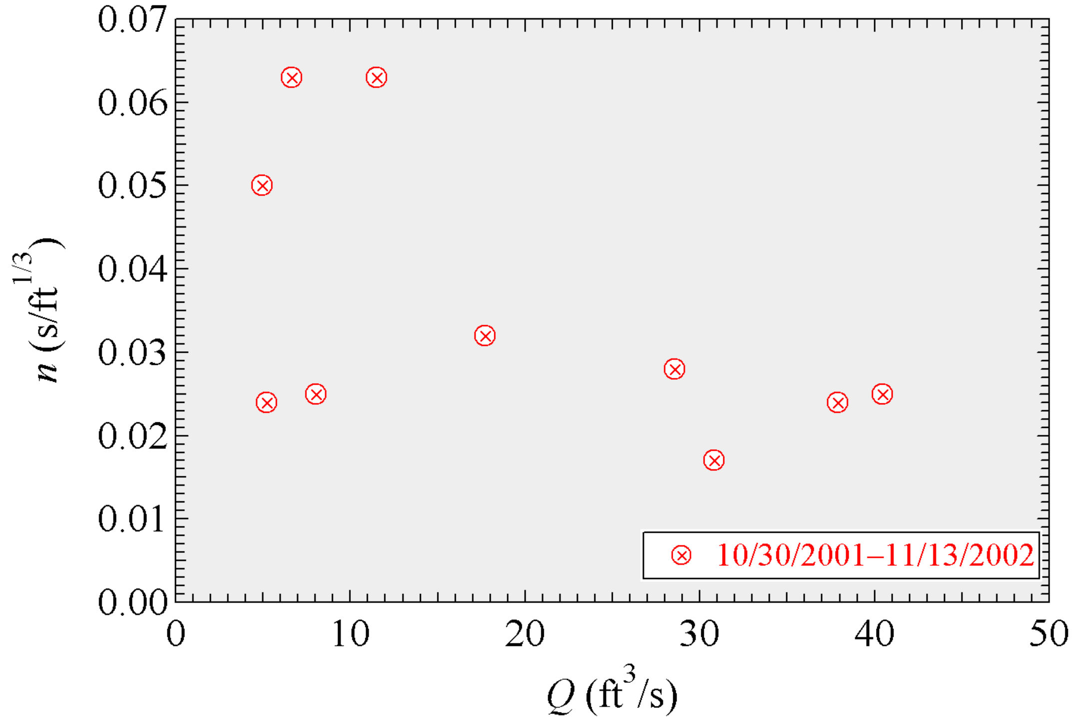

Figure 50: Manning's friction coefficient as a function of flow rates at TOFP.

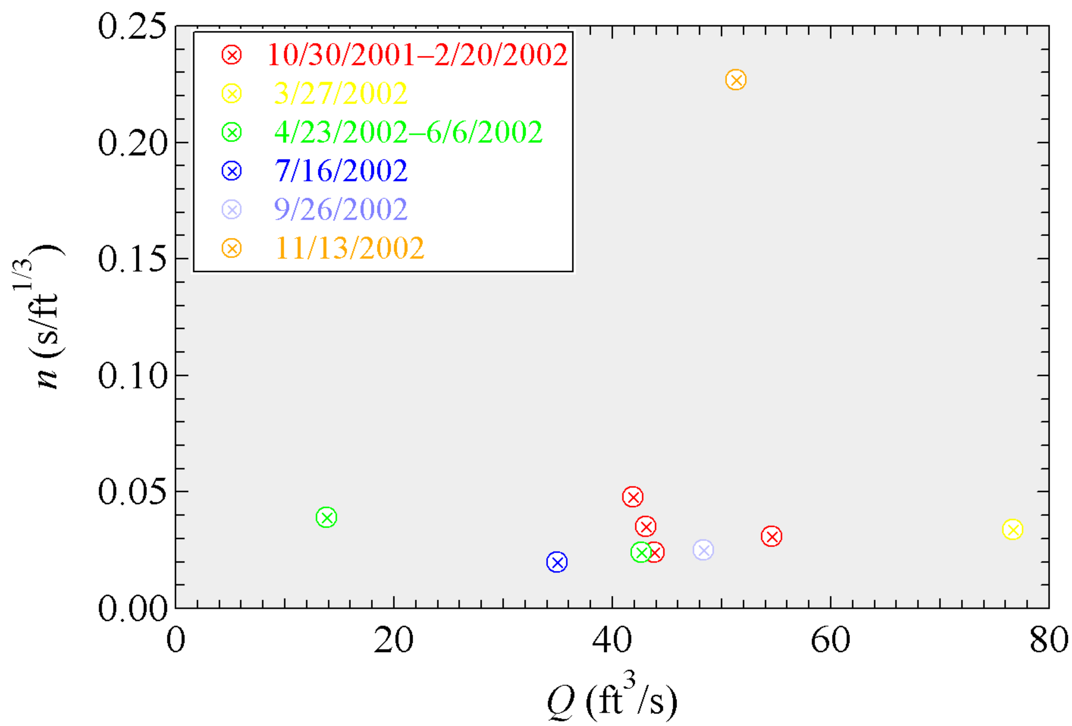

Figure 51: Manning's friction coefficient as a function of flow rates at TT.

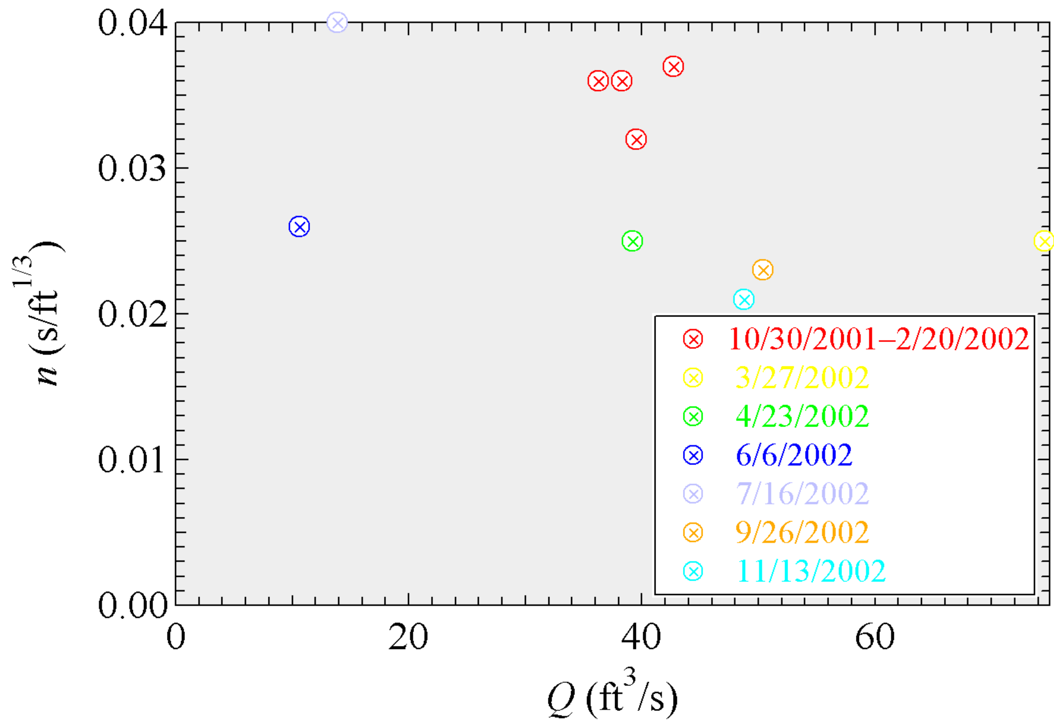

Figure 52: Manning's friction coefficient as a function of flow rates at TY.

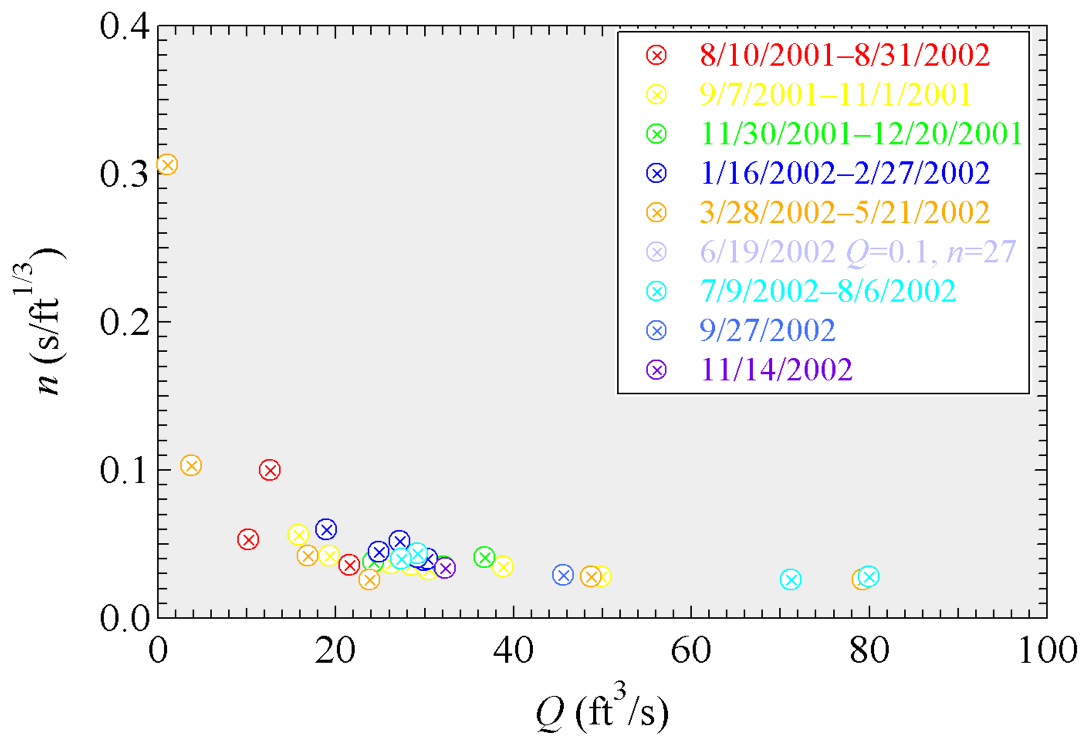

Figure 53: Manning's friction coefficient as a function of flow rates at T5MD.

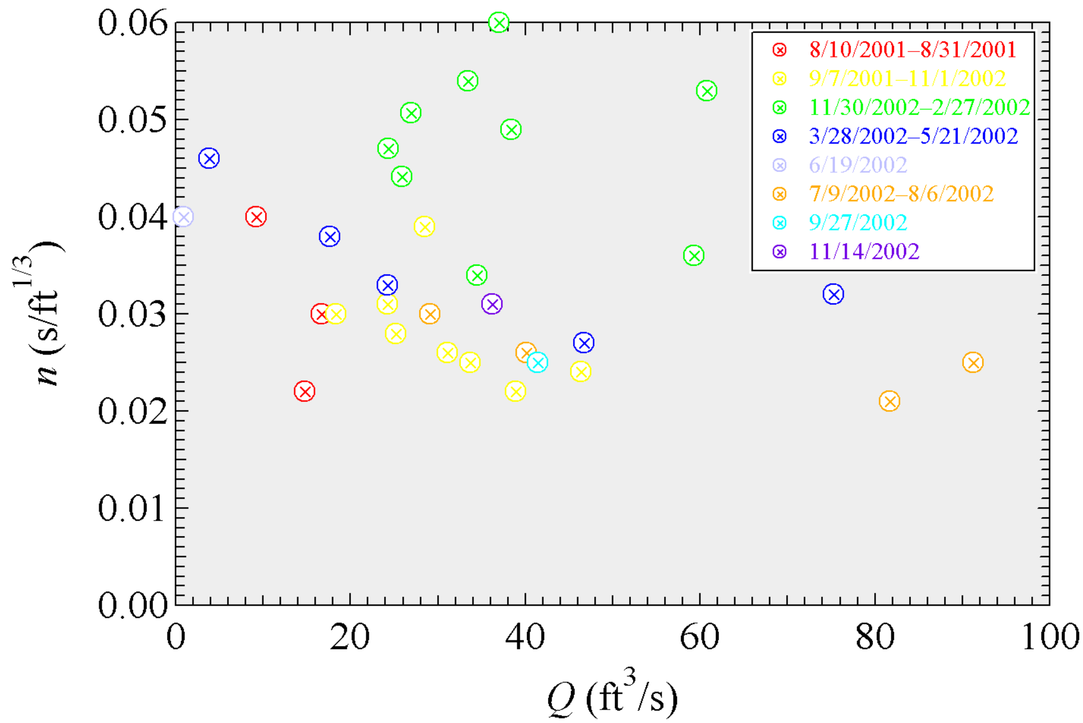

Figure 54: Manning's friction coefficient as a function of flow rates at TCMR.

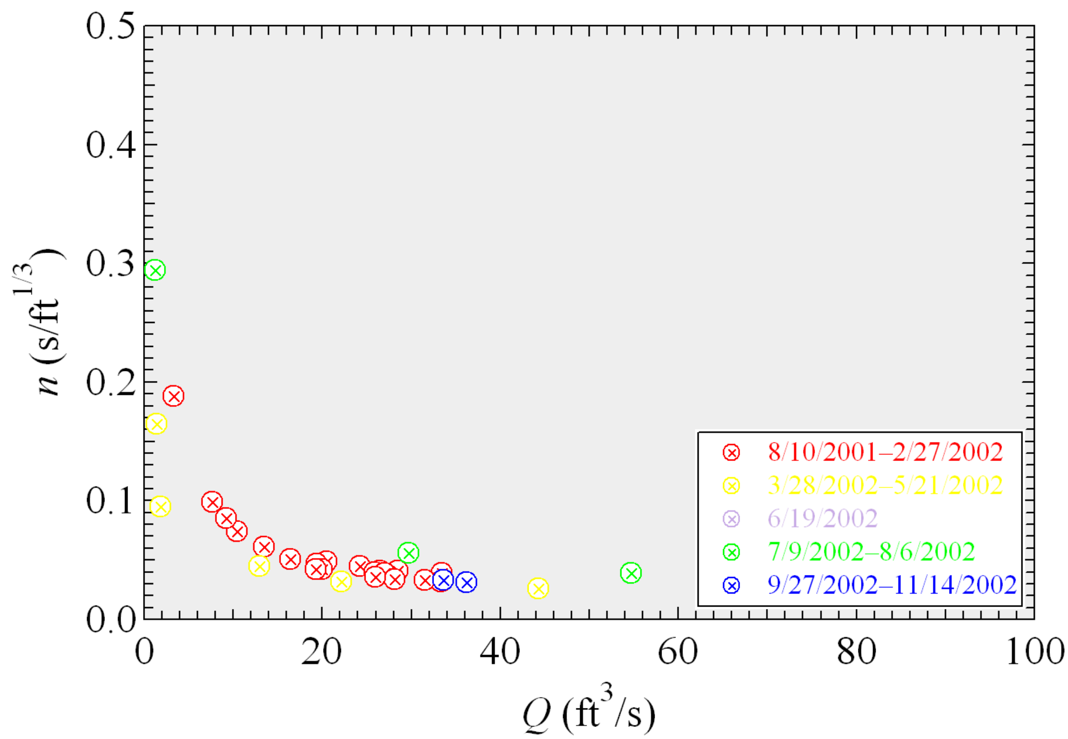

Figure 55: Manning's friction coefficient as a function of flow rates at TPLC.

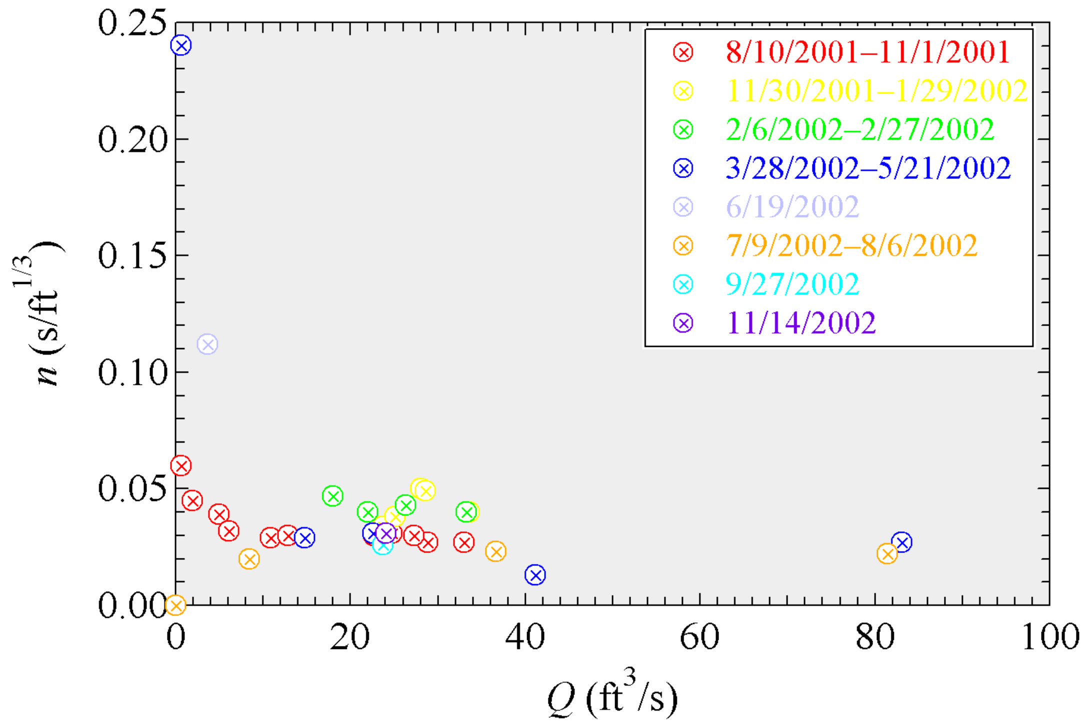

Figure 56: Manning's friction coefficient as a function of flow rates at TAG.

Appendix E: Sediment Properties

Table 3: Pecos River sediment properties.

Transect	Location	Sample Length (in)	Sample MPS* (μm)	Core MPS* (μm)	Transect MPS* (μm)	TSS** (mg/L)	Sample Date
USGS RR Crossing	LDB	0–5.5	634	–	–	0.7	11/15/00
	RDB	Bedrock (Bank)	86.4				
Old Fort Park	LDB	0–4	3100	2530	1980	2.7	11/15/00
		4–8	1950				
		Bank	106	–			
	C	0–4.5	2380	2230			
		4.5–6	2070				
	RDB	0–3	764	1170			
		3–6	689				
		6–10	2060				
		Bank	299	–			
Taiban	LDB	0–4	1420	1290	1150	3.5	11/30/00
		4–8	1280				
		8–12	1170				
	C	0–6	890	952			
		6–13	796				
		13–20	1170				
	RDB	0–5	1190	1220			
		5–11	1230				
		11–17	1240				
Yeso	LDB	0–5	944	764	672	14.0	11/15/00
		5–10	694				
		10–15	720				
		15–20	698				
	C	0–3.5	558	621			
		3.5–7	520				
		7–10	686				
		10–13.5	720				
	RDB	0–3.5	542	631			
		3.5–5.5	720				

Transect	Location	Sample Length (in)	Sample MPS* (μm)	Core MPS* (μm)	Transect MPS* (μm)	TSS** (mg/L)	Sample Date
Dunlap	LDB	0–5	882	625	544	16.0	11/30/00
		5–10	501				
		10–15	491				
	C	0–4	571	433			
		4–8	445				
		8–13	283				
	RDB	0–5	690	573			
		5–11	511				
		11–16.5	519				
Atkins	LDB	0–5	401	395	393	21.0	11/30/00
		5–10	542				
		15–20 (extra)	242				
	C	0–5.5	299	262			
		5.5–11	225				
	RDB	0–4	454	521			
		4–7.5	588				
Five Mile Draw	LDB	0–4.5	377	390	325	56.7	11/15/00
		4.5–7	442				
		Bank	201	–			
	C	0–4	290	328			
		4–8	314				
		8–12	349				
		12–17	359				
	RDB	0–4	229	258			
		4–8	266				
		8–12	280				
		Flood Plain Mud	10.4	–			
Pipe Line Crossing	LDB	0–4	245	268	289	61.0	11/15/00
		4–9	267				
		9–14.5	291				
	C	0–4	328	312			
		4–9	296				
	RDB	0–4	310	286			
		4–8	252				
		8–12	295				

Transect	Location	Sample Length (in)	Sample MPS* (μm)	Core MPS* (μm)	Transect MPS* (μm)	TSS** (mg/L)	Sample Date
Acme	LDB	0–4	340	382	326	61.0	11/15/00
		4–8	436				
		8–12	370				
	C	0–3	344	332			
		3–7	381				
		7–11	271				
	RDB	0–3	254	265			
		3–6	250				
		6–10	291				
		Sand Bar	214	–			

*MPS stands for Mean Particle Size
**TSS stands for Total Suspended Solids

Appendix F: Water Quality

Table 4: Pecos River water chemistry.

Sample Site	Sampling	T	pH	HCO_3^-	Mg^{2+}	Ca^{2+}	Na^+	K^+	P	SO_4^{2-}
	Date	ºC*		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
USGS RR Crossing	11/15/2000	6.8	7.35	168	52	279	66	3.2	< 0.1	770
OFB	11/15/2000	8.1	7.83	261	94	432	117	5.1	< 0.1	1234
Taiban	11/30/2000	–	8.30	207	121	508	181	4.7	< 0.1	1870
Yeso	11/15/2000	9.0	8.27	173	90	385	217	6.9	< 0.1	1190
Dunlap	11/30/2000	5.6	8.20	138	74	303	232	6.7	< 0.1	1172
Atkins	11/30/2000	11.3	8.40	123	90	372	273	7.9	< 0.1	1456
5 Mile Draw	11/15/2000	11.1	8.03	123	84	357	216	7.5	< 0.1	1169
Pipe Line Road	11/15/2000	10.0	7.85	121	85	362	219	7.9	< 0.1	1151
Acme	11/15/2000	9.5	8.08	119	84	363	222	7.5	< 0.1	1139

*Temperature variations are probably due in part to collection time

Appendix G: Data Reduction

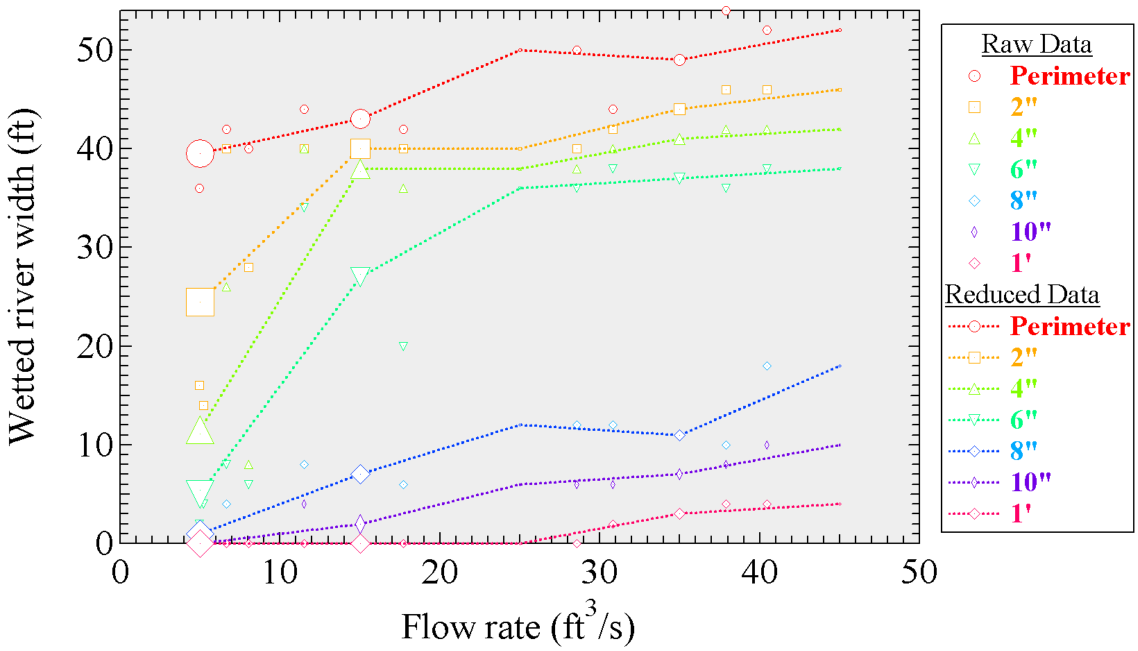

Figure 57: Raw and reduced data showing depth availability as a function of flow rate at TOFP.

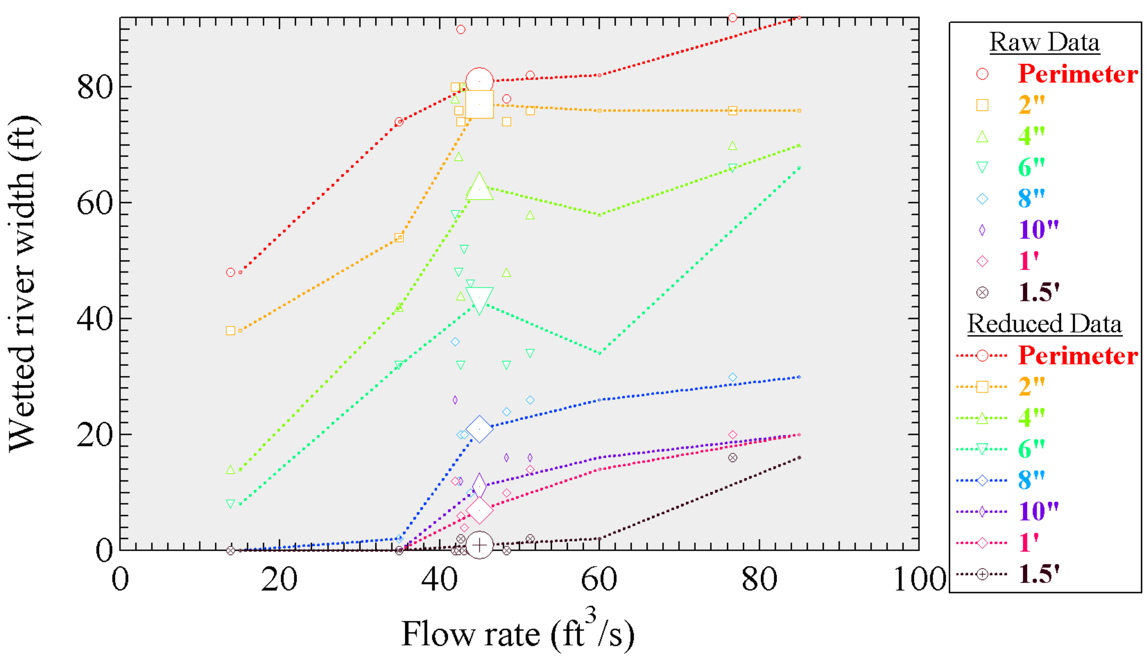

Figure 58: Raw and reduced data showing depth availability as a function of flow rate at TT.

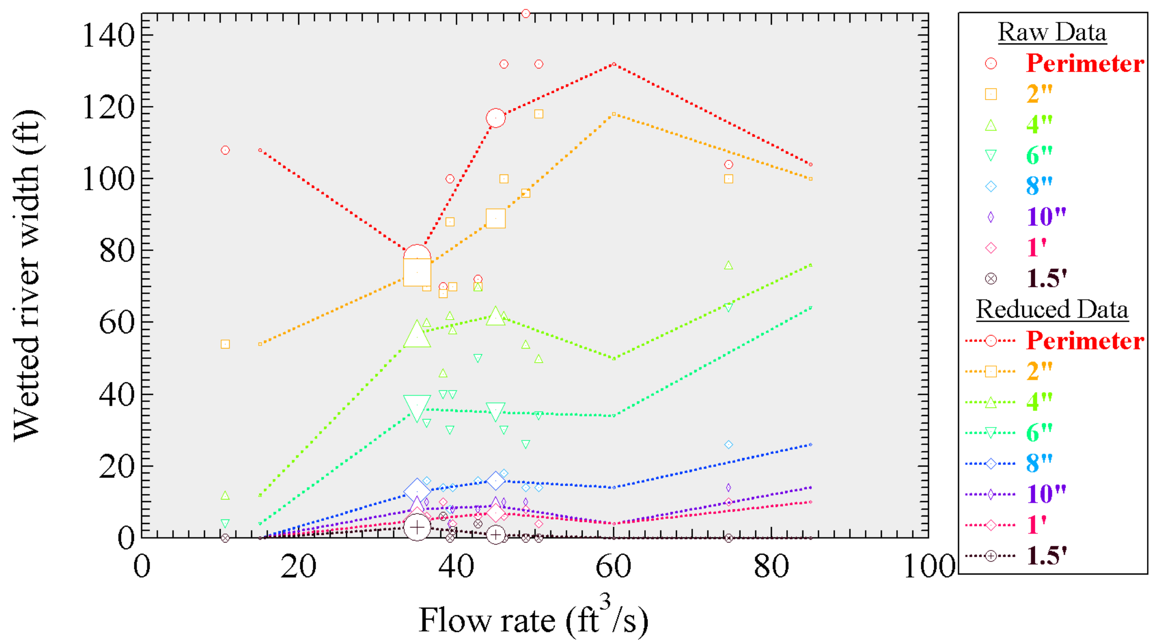

Figure 59: Raw and reduced data showing depth availability as a function of flow rate at TY.

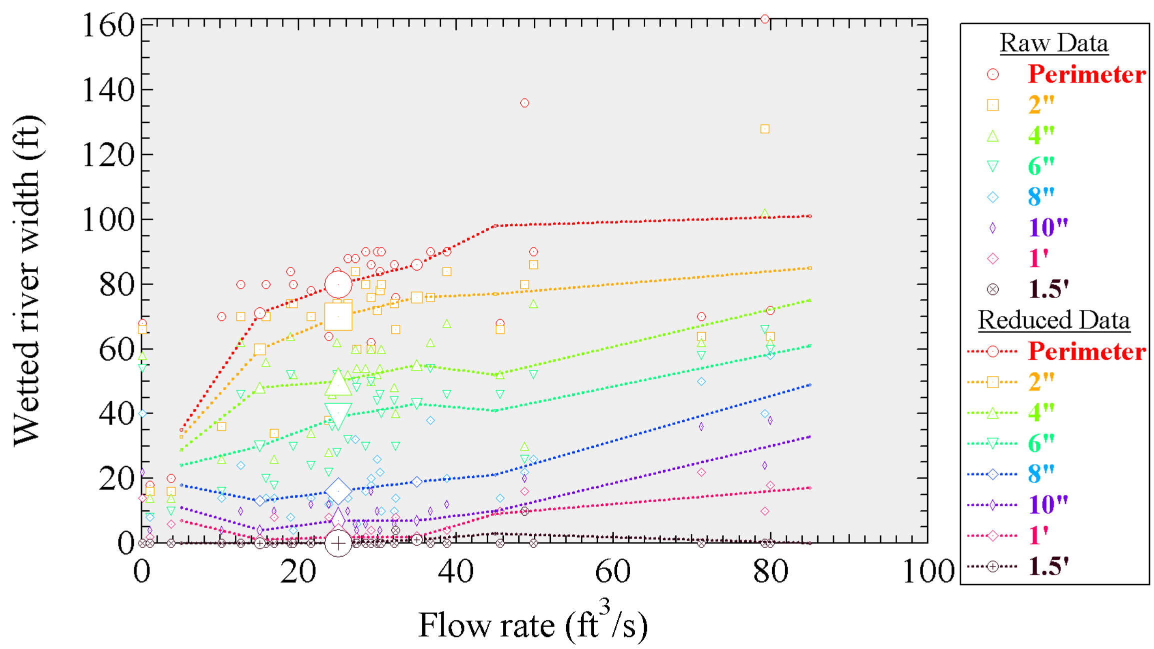

Figure 60: Raw and reduced data showing depth availability as a function of flow rate at T5MD.

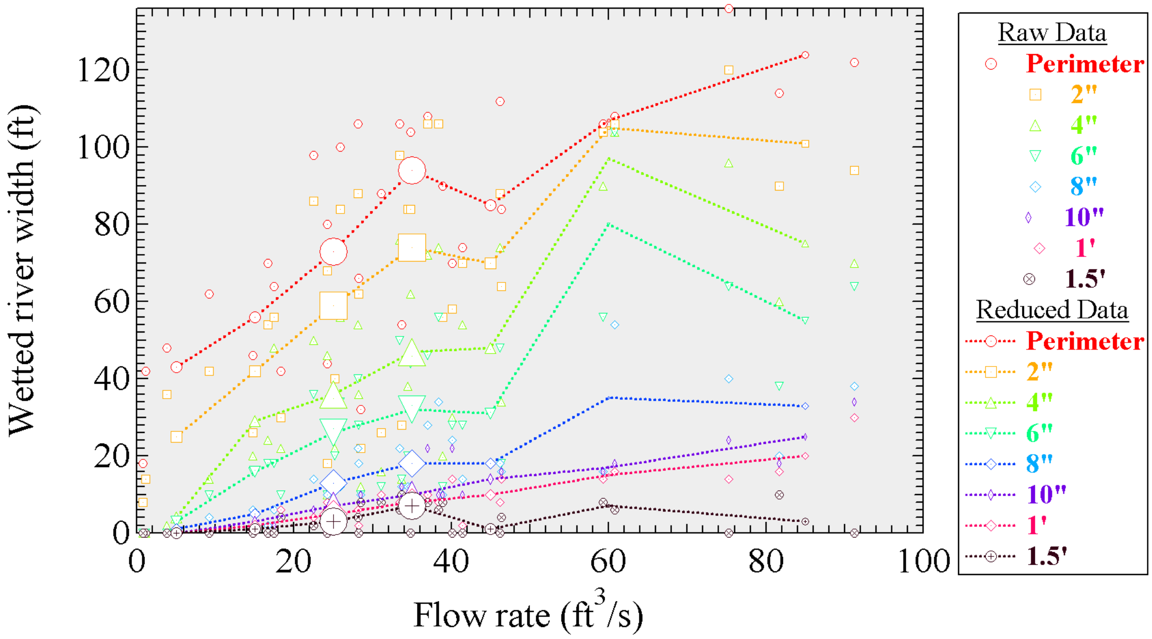

Figure 61: Raw and reduced data showing depth availability as a function of flow rate at TCMR.

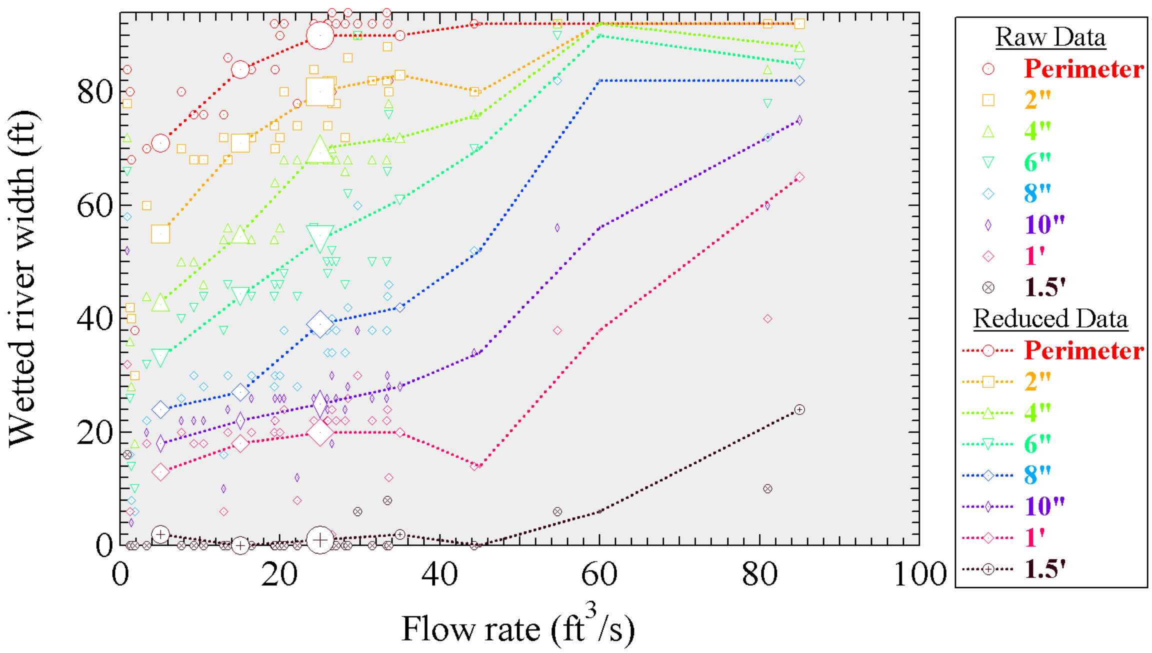

Figure 62: Raw and reduced data showing depth availability as a function of flow rate at TPLC.

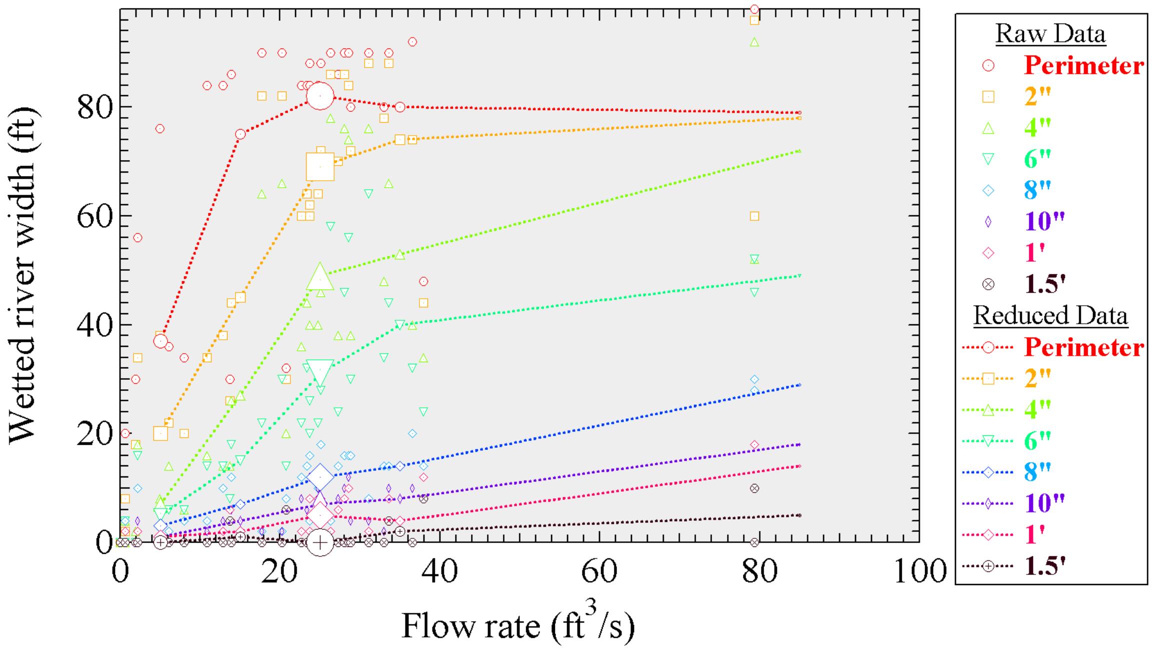

Figure 63: Raw and reduced data showing depth availability as a function of flow rate at TAG.

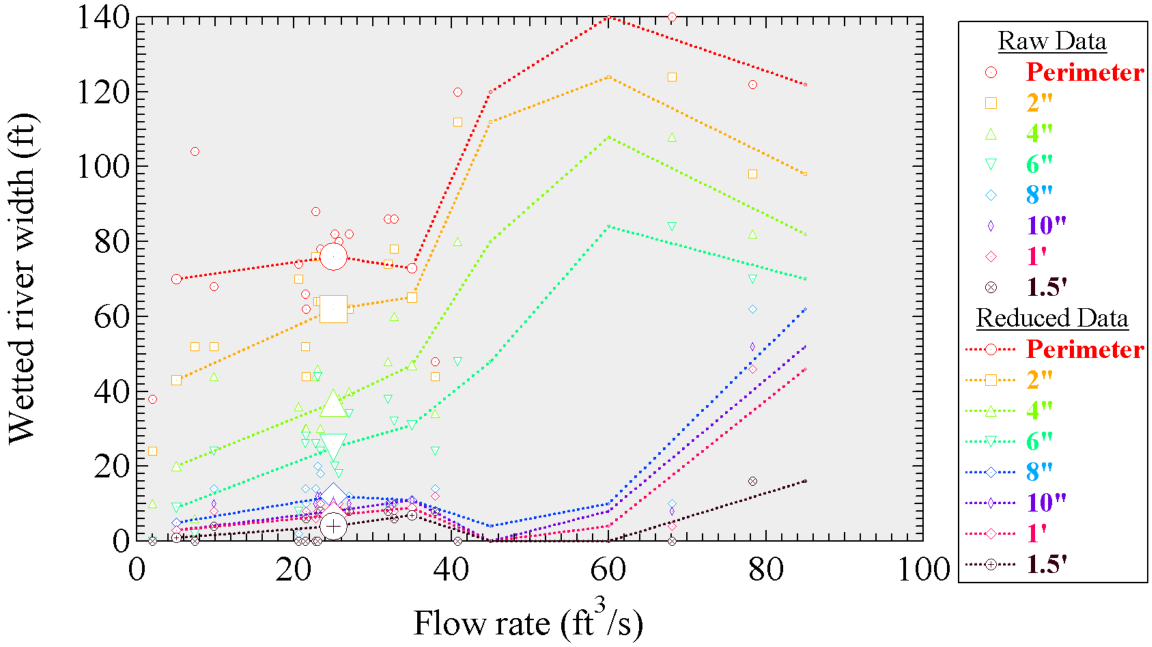

Figure 64: Raw and reduced data showing depth availability as a function of flow rate at TAGU3.

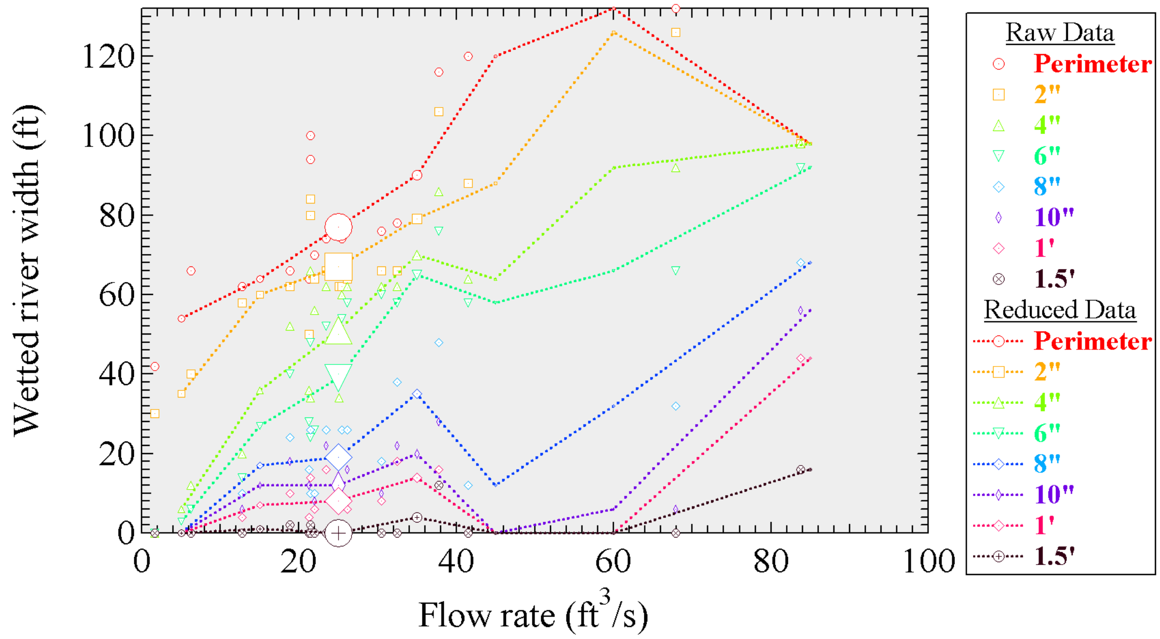

Figure 65: Raw and reduced data showing depth availability as a function of flow rate at TAGU2.

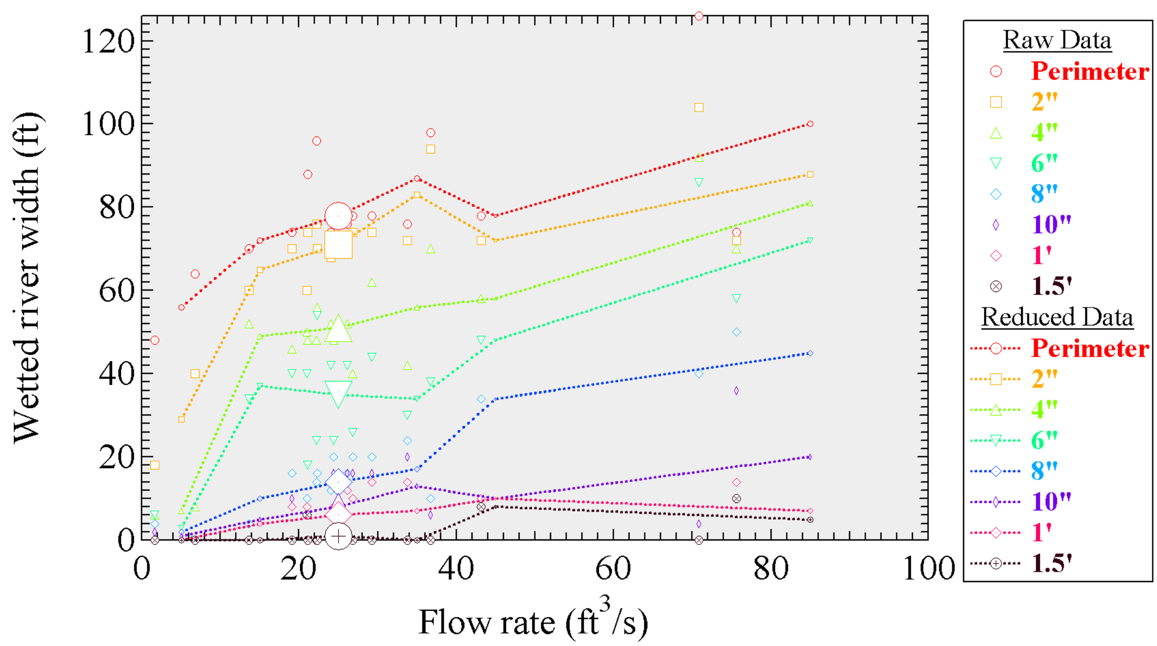

Figure 66: Raw and reduced data showing depth availability as a function of flow rate at TAGU1.

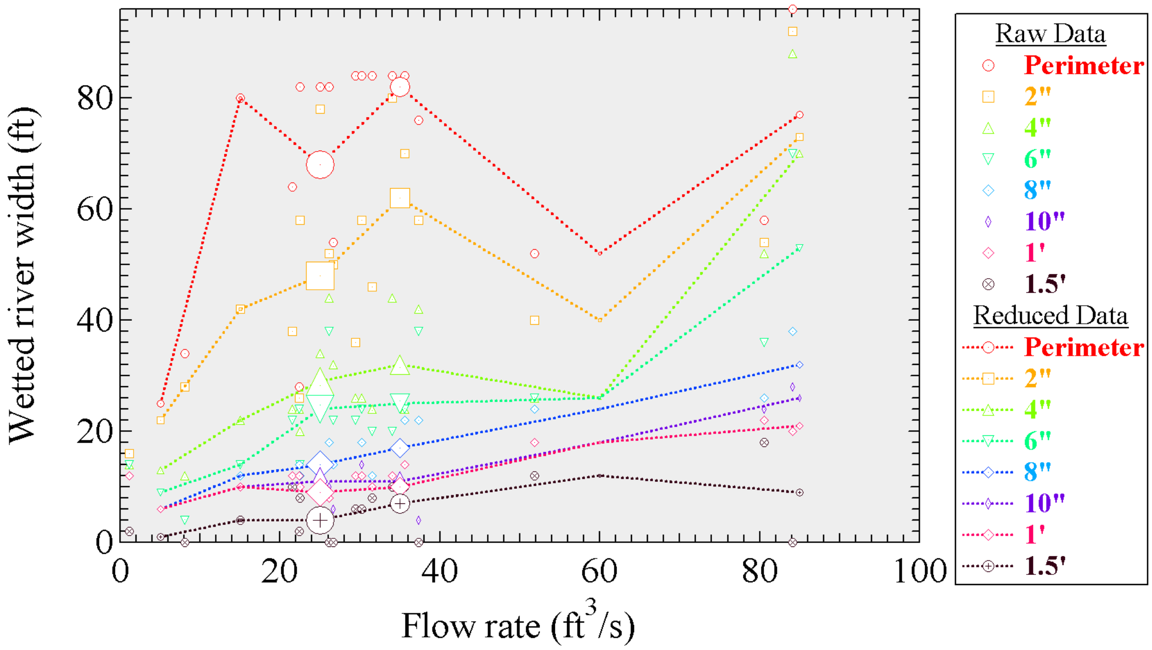

Figure 67: Raw and reduced data showing depth availability as a function of flow rate at TAGD1.

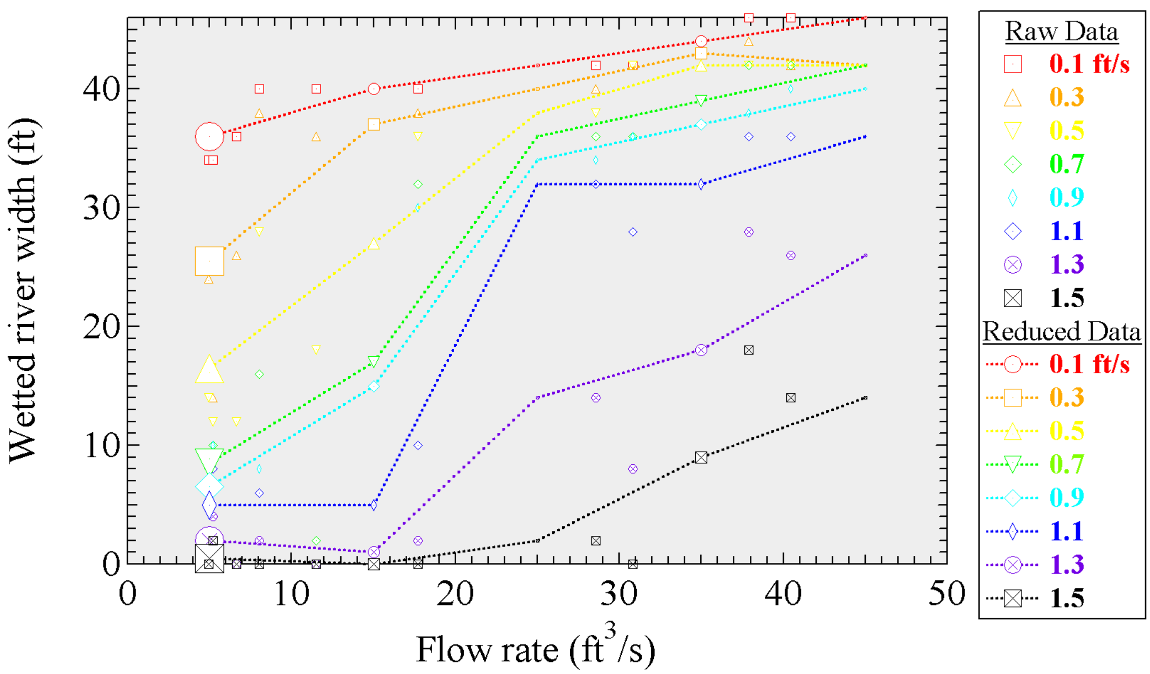

Figure 68: Raw and reduced data showing velocity availability as a function of flow rate at TOFP.

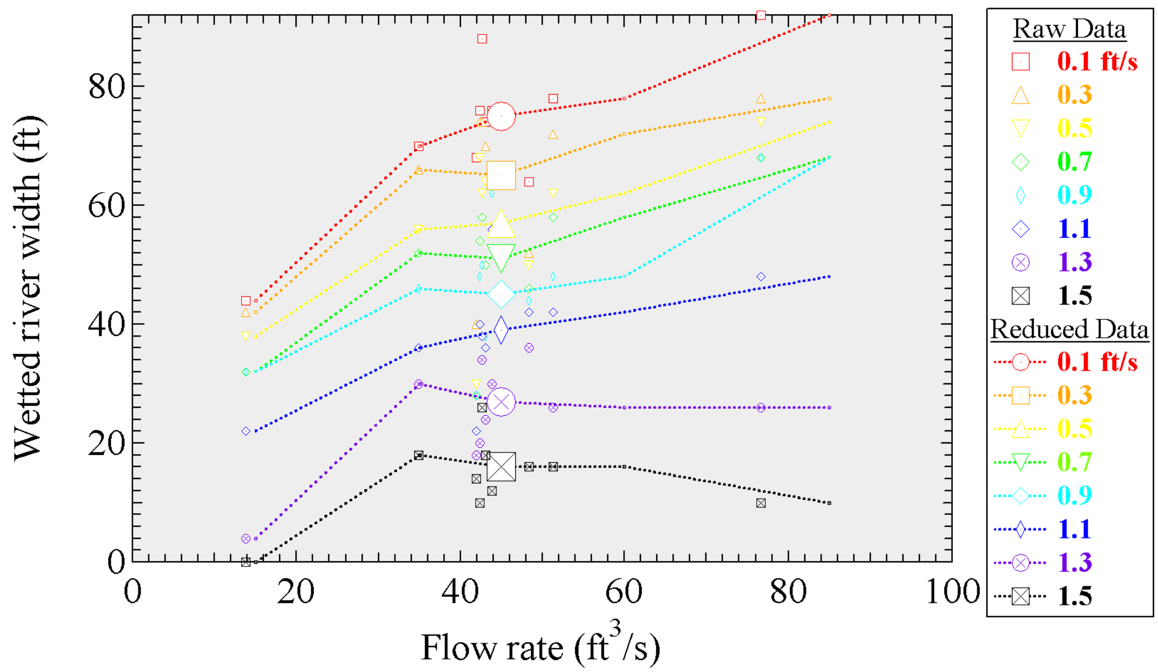

Figure 69: Raw and reduced data showing velocity availability as a function of flow rate at TT.

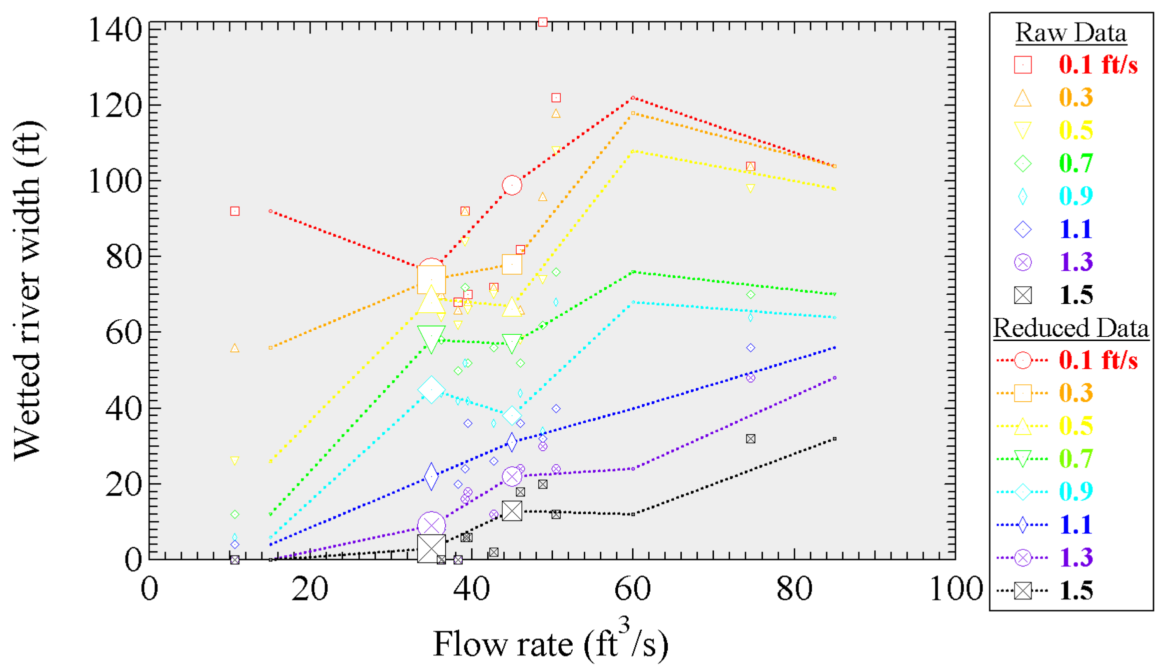

Figure 70: Raw and reduced data showing velocity availability as a function of flow rate at TY.

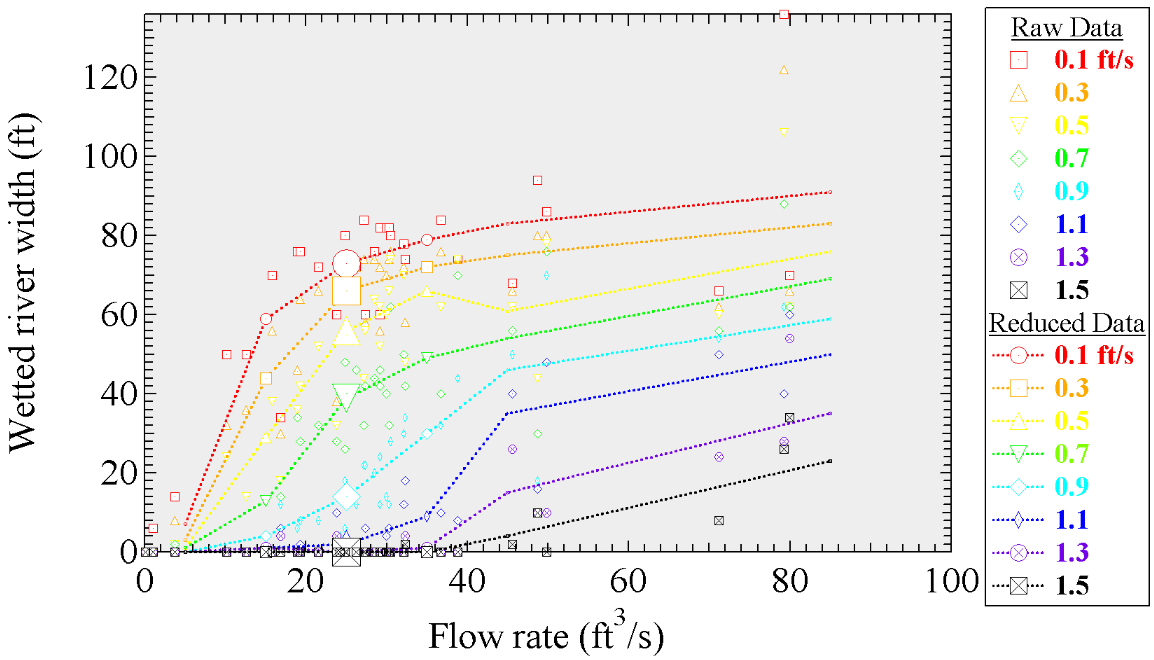

Figure 71: Raw and reduced data showing velocity availability as a function of flow rate at T5MD.

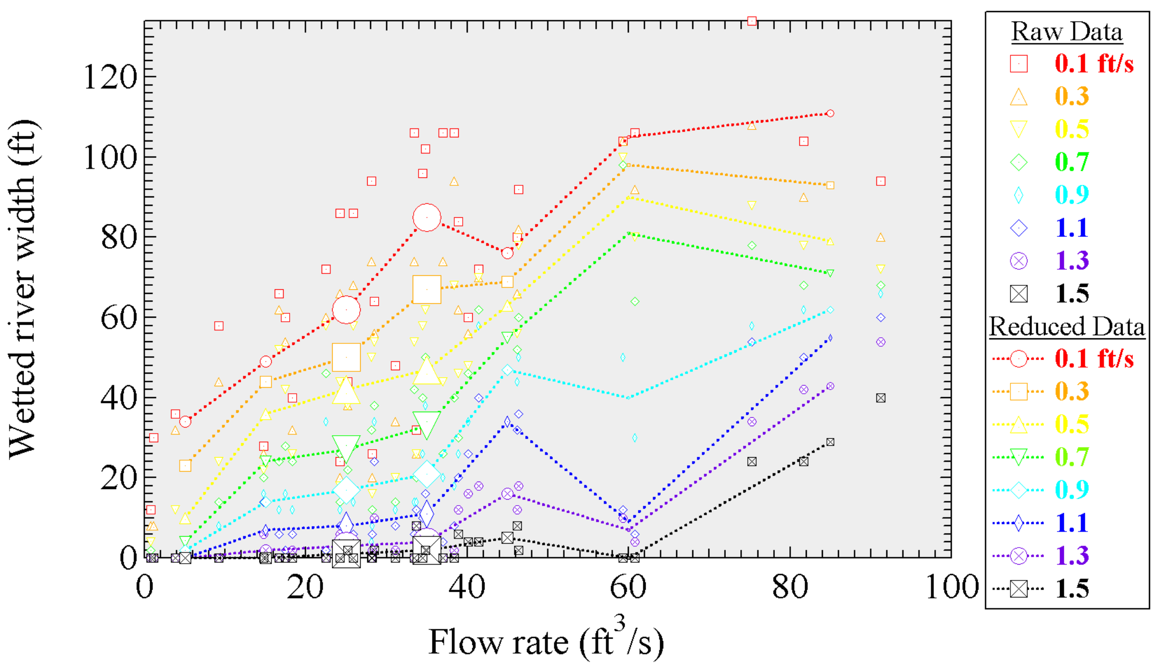

Figure 72: Raw and reduced data showing velocity availability as a function of flow rate at TCMR.

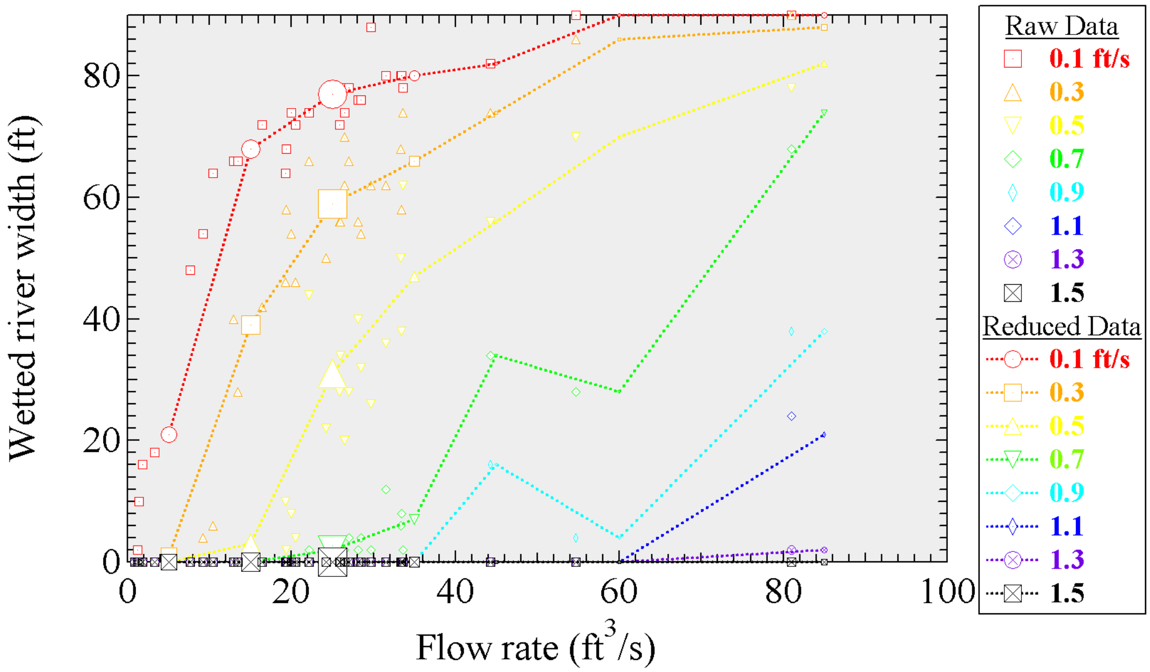

Figure 73: Raw and reduced data showing velocity availability as a function of flow rate at TPLC.

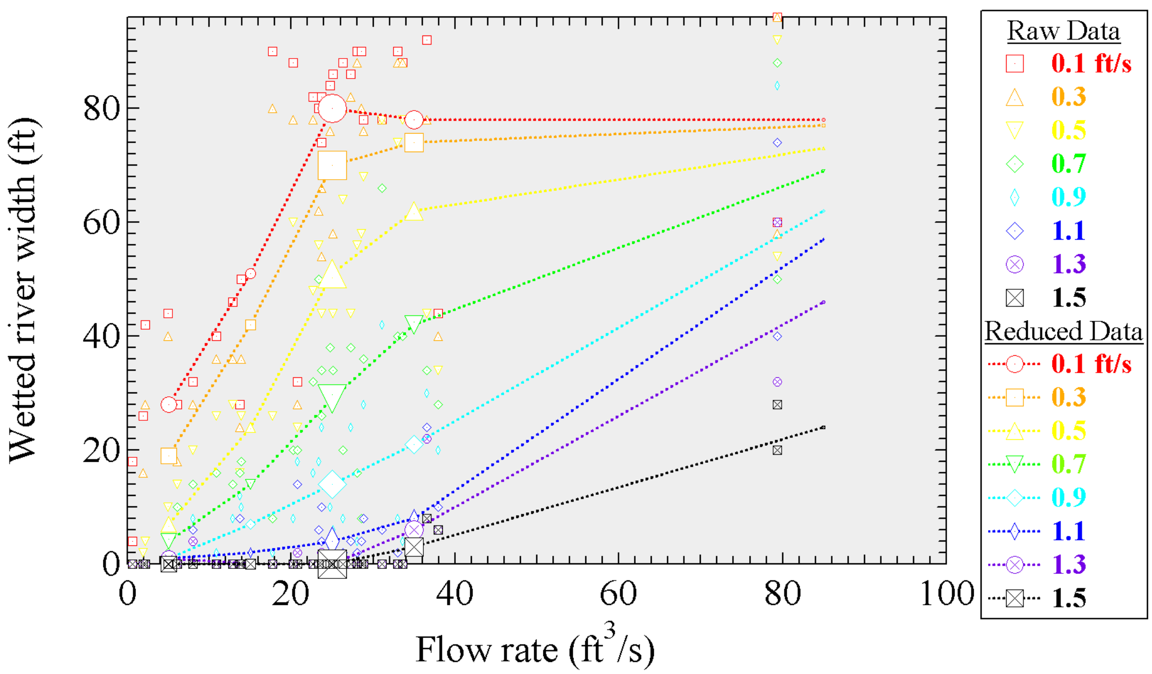

Figure 74: Raw and reduced data showing velocity availability as a function of flow rate at TAG.

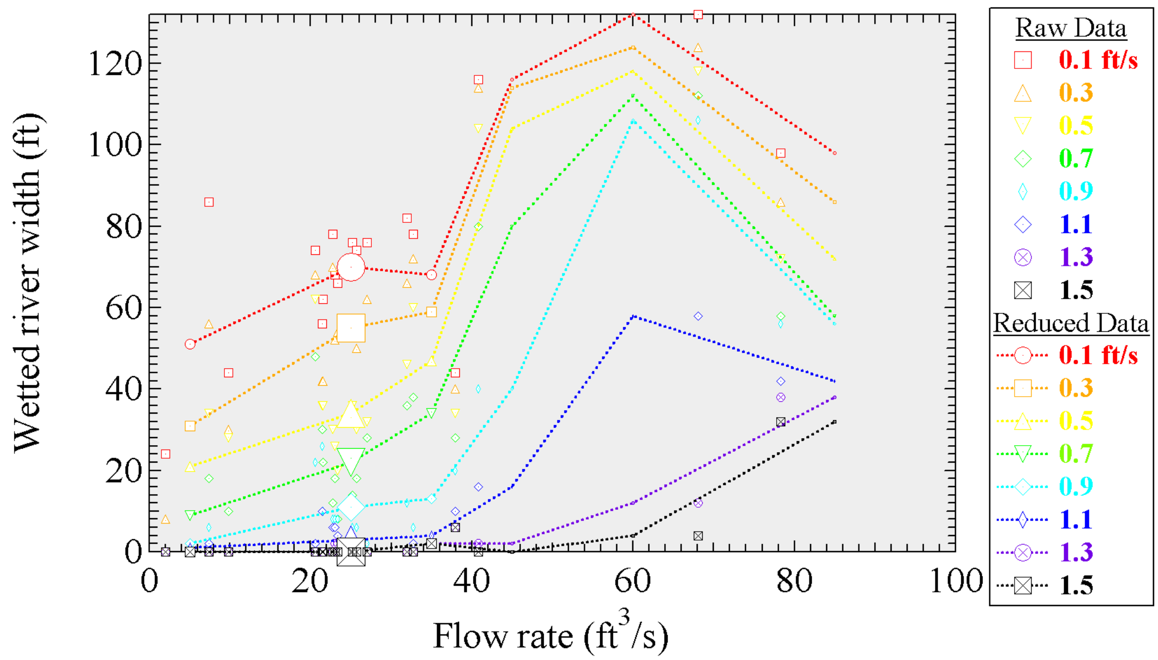

Figure 75: Raw and reduced data showing velocity availability as a function of flow rate at TAGU3.

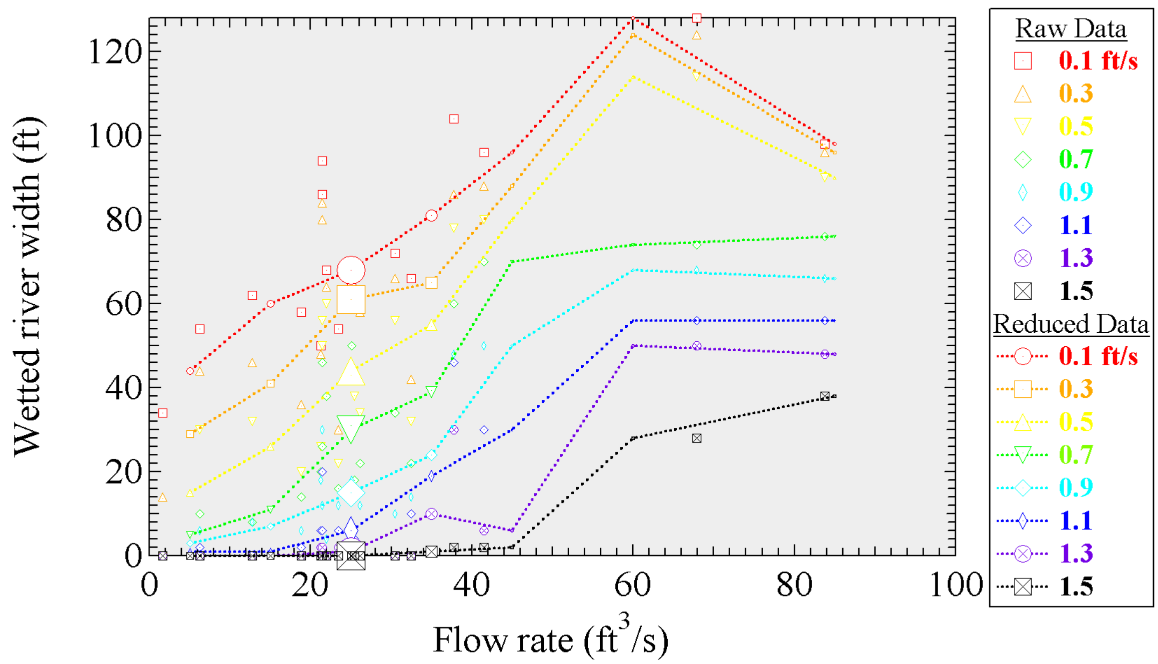

Figure 76: Raw and reduced data showing velocity availability as a function of flow rate at TAGU2.

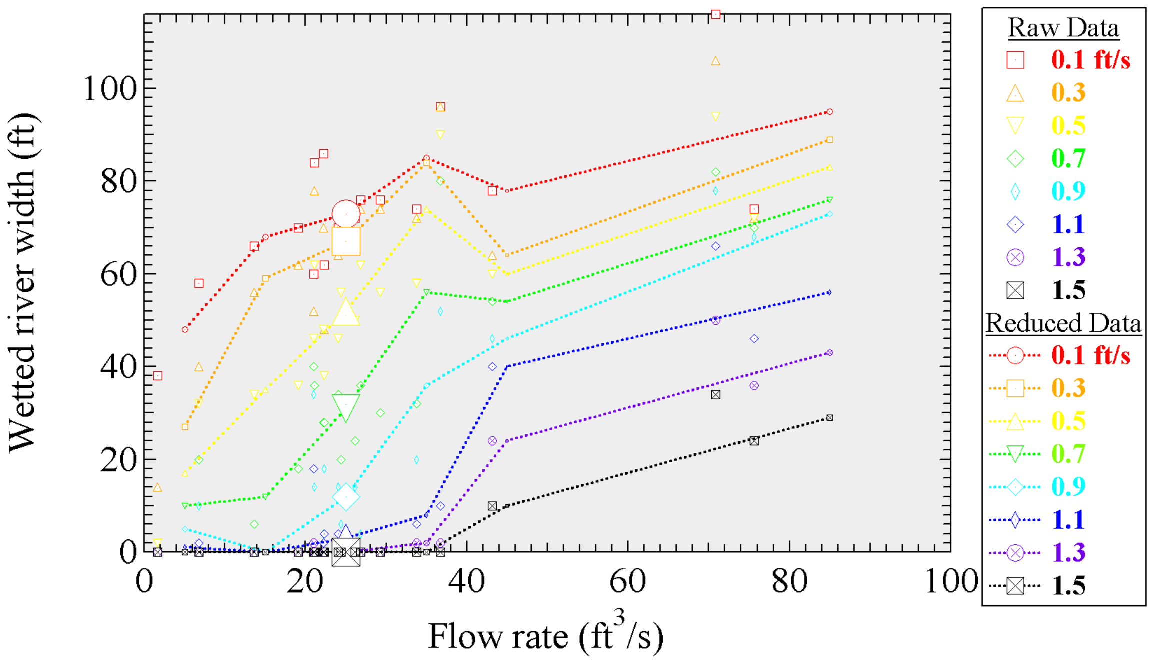

Figure 77: Raw and reduced data showing velocity availability as a function of flow rate at TAGU1.

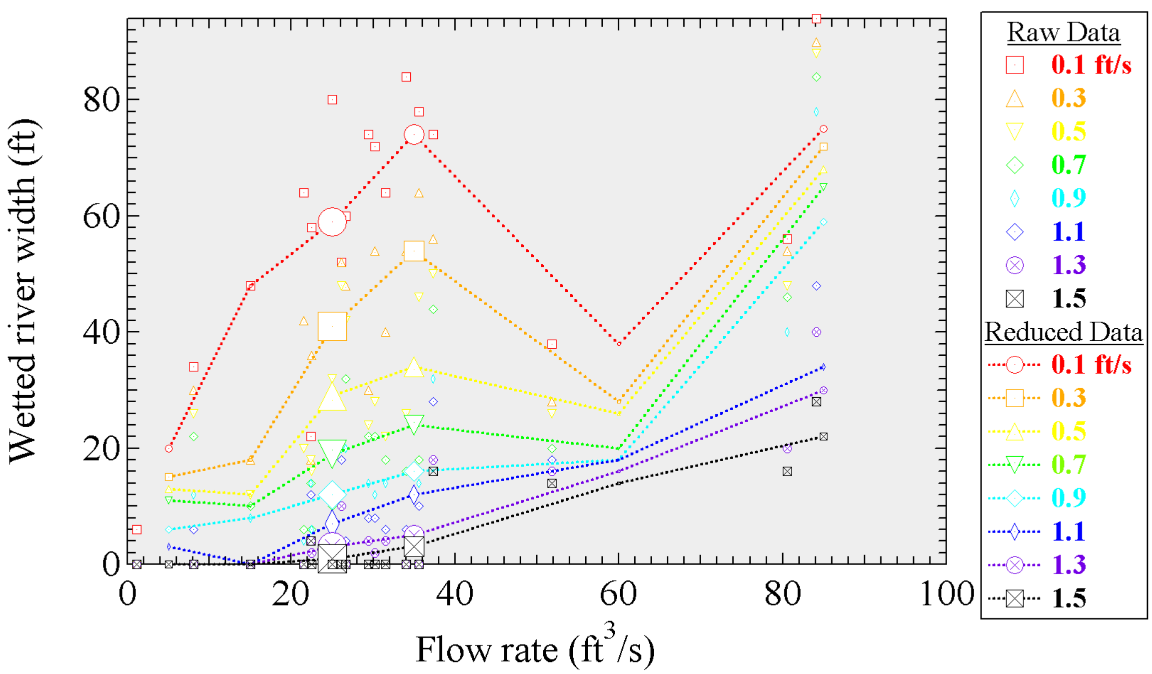

Figure 78: Raw and reduced data showing velocity availability as a function of flow rate at TAGD1.

Appendix H: Depth Availability

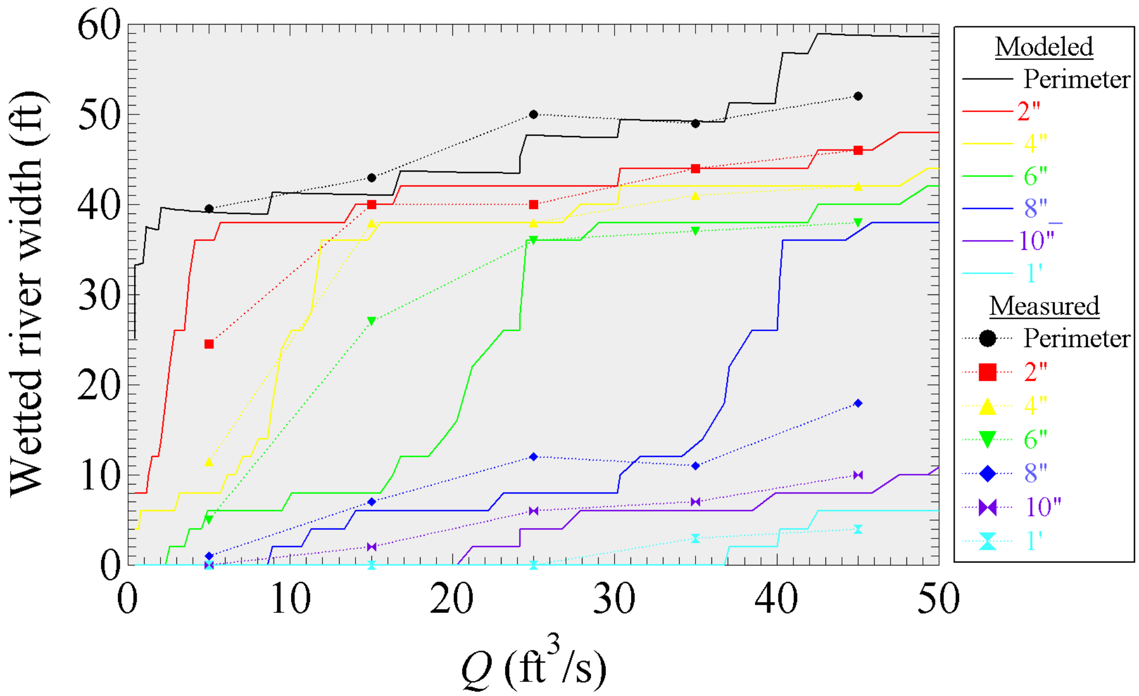

Figure 79: Measured (symbols) and modeled (curves) depth availability at TOFP.

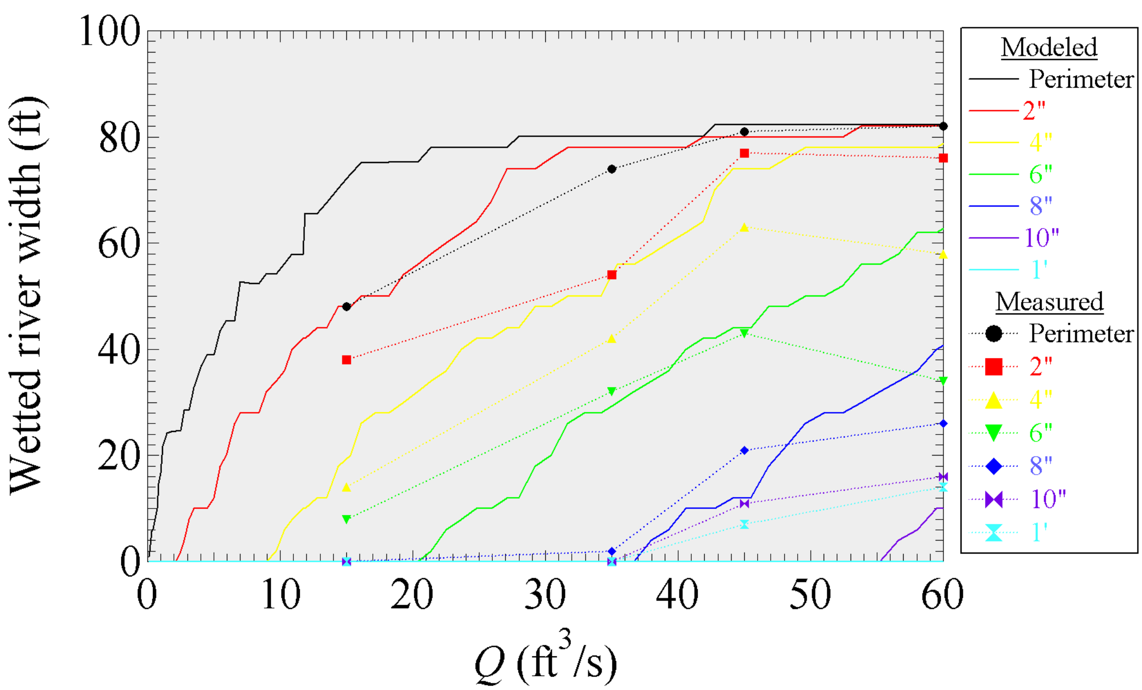

Figure 80: Measured (symbols) and modeled (curves) depth availability at TT.

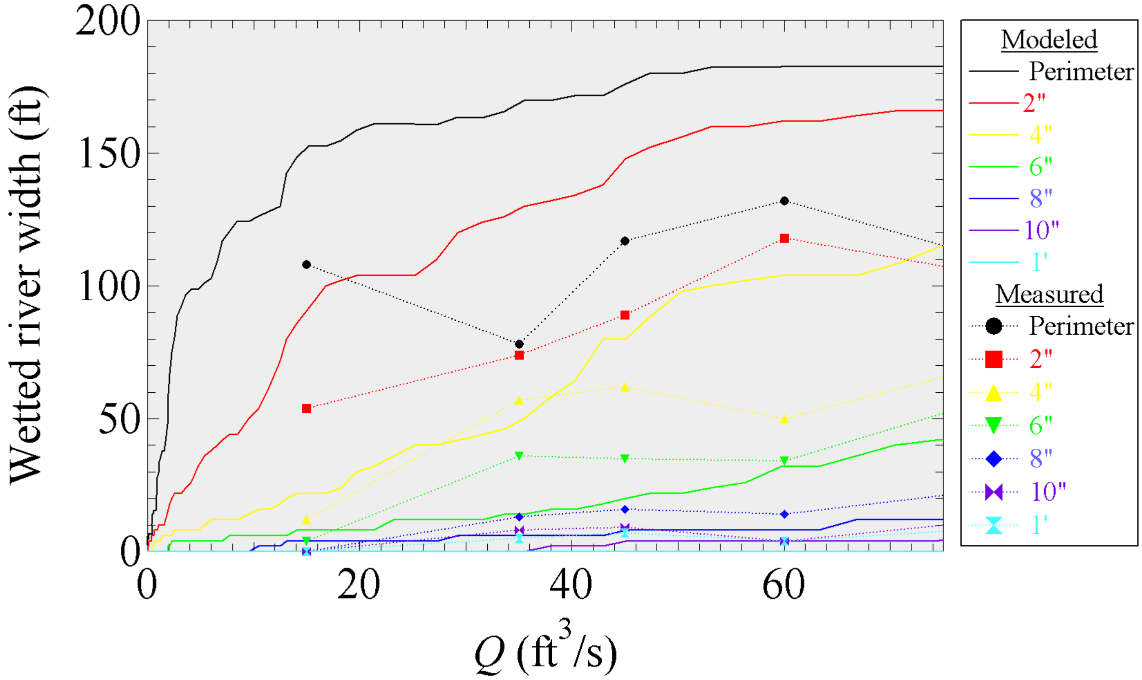

Figure 81: Measured (symbols) and modeled (curves) depth availability at TY.

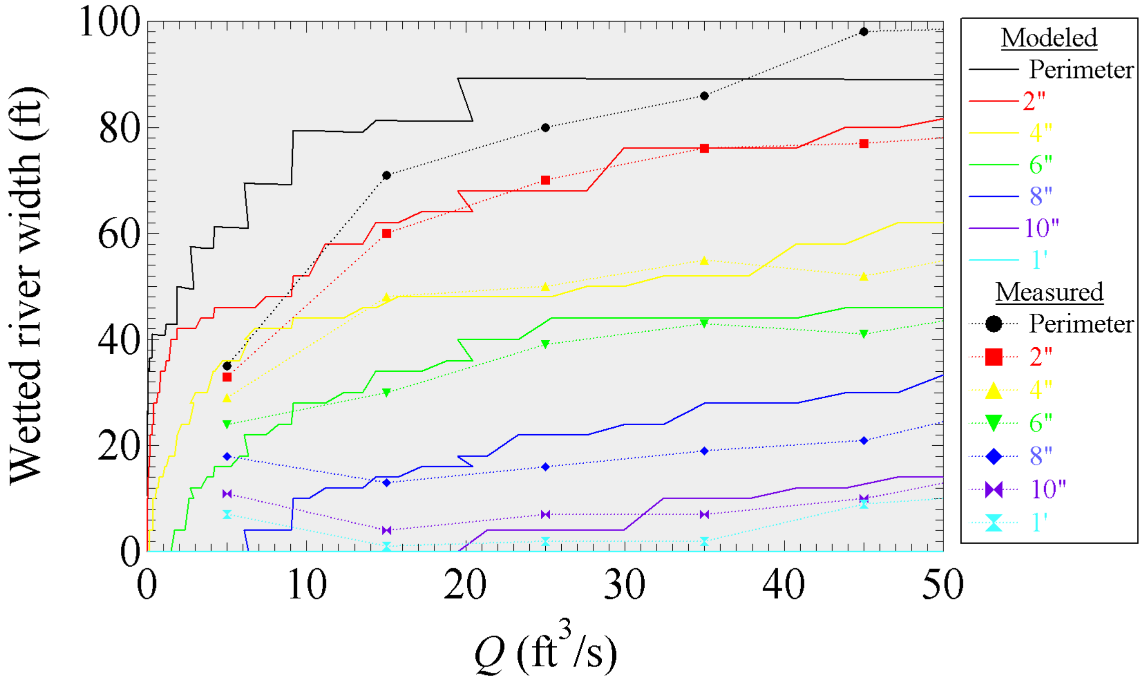

Figure 82: Measured (symbols) and modeled (curves) depth availability at T5MD.

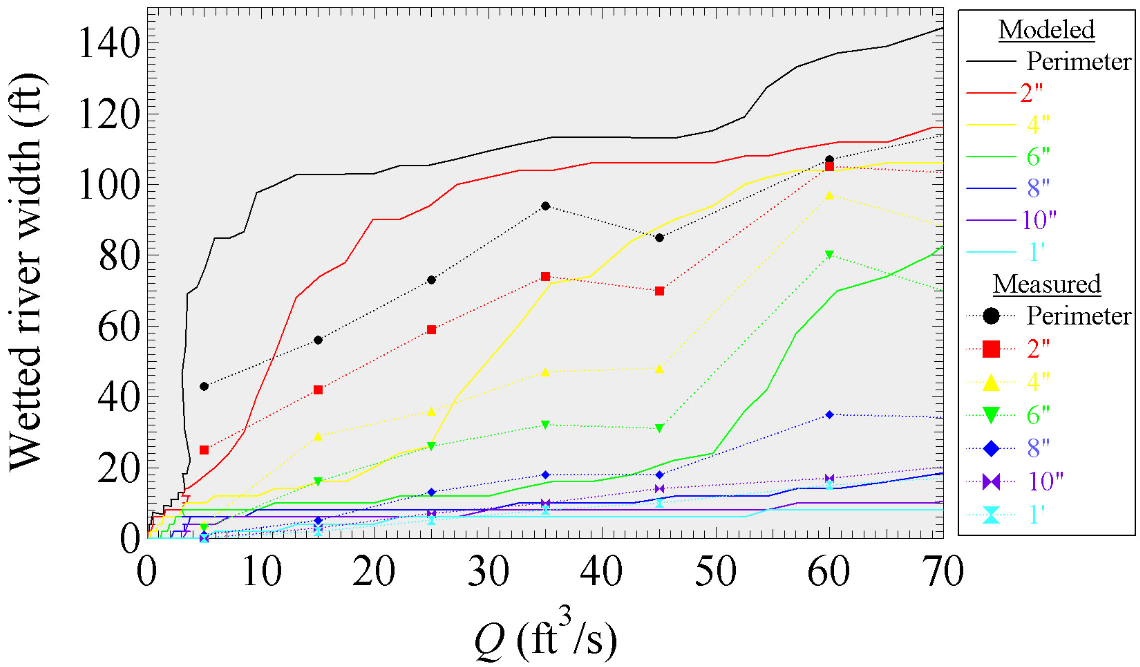

Figure 83: Measured (symbols) and modeled (curves) depth availability at TCMR.

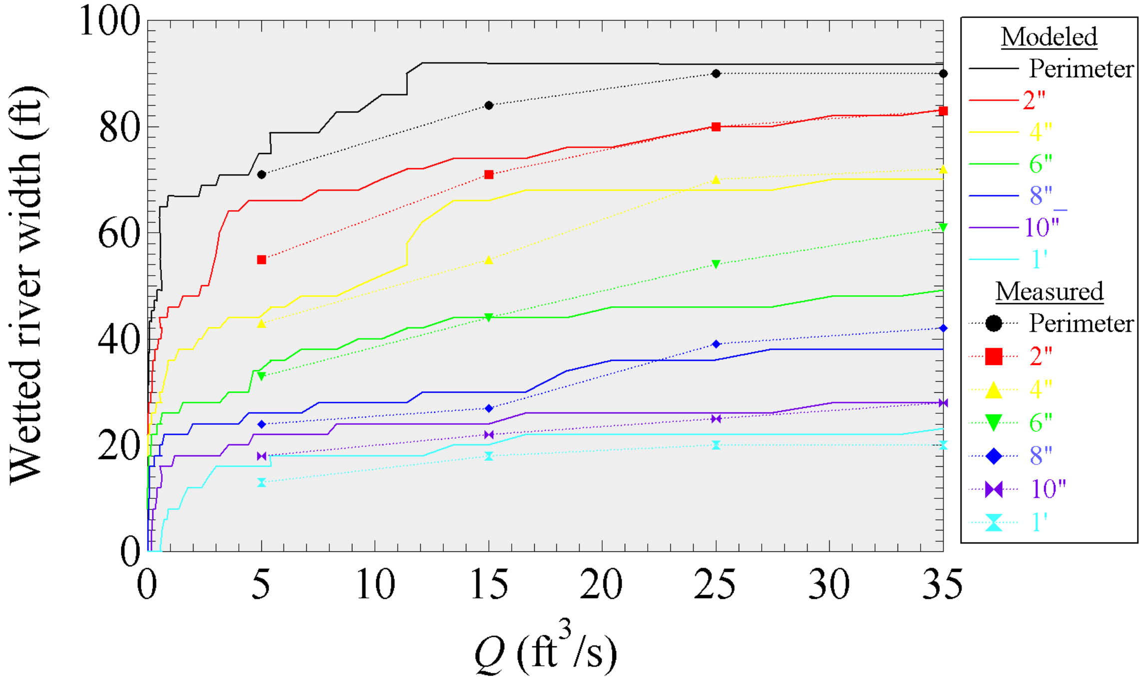

Figure 84: Measured (symbols) and modeled (curves) depth availability at TPLC.

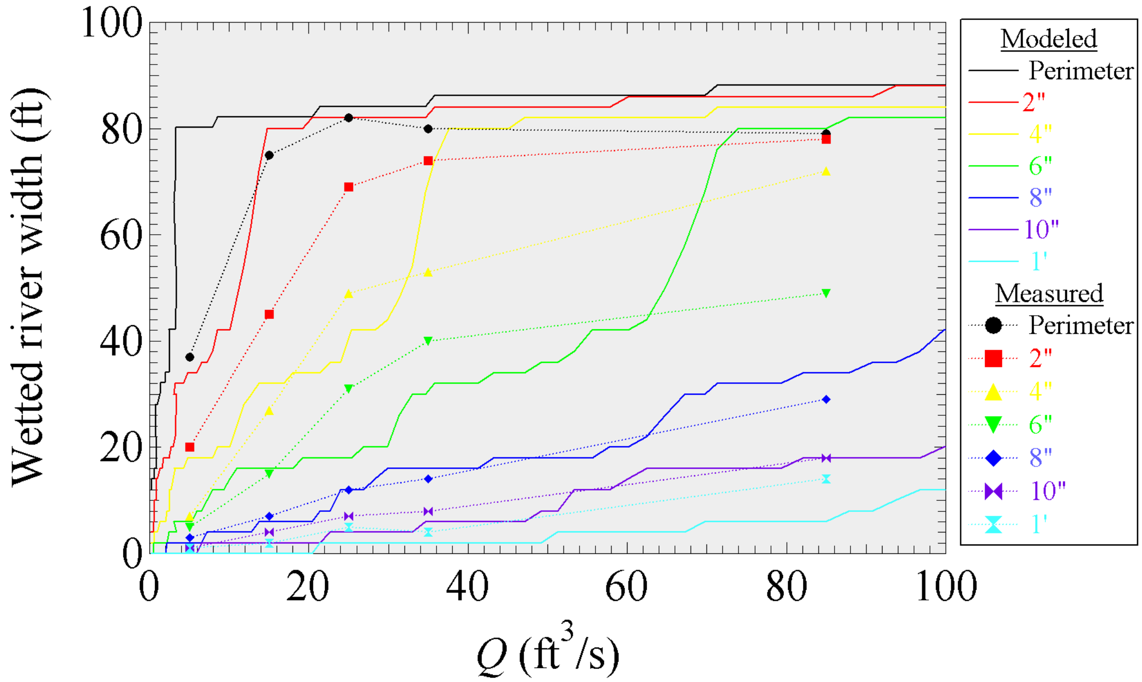

Figure 85: Measured (symbols) and modeled (curves) depth availability at TAG.

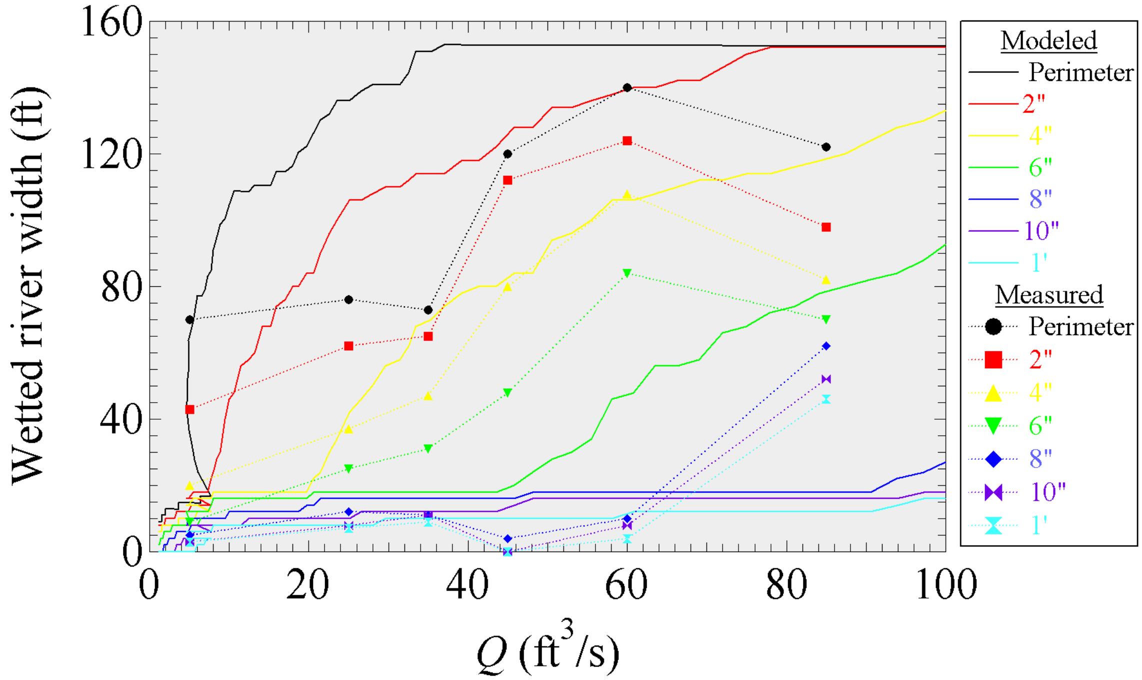

Figure 86: Measured (symbols) and modeled (curves) depth availability at TAGU3.

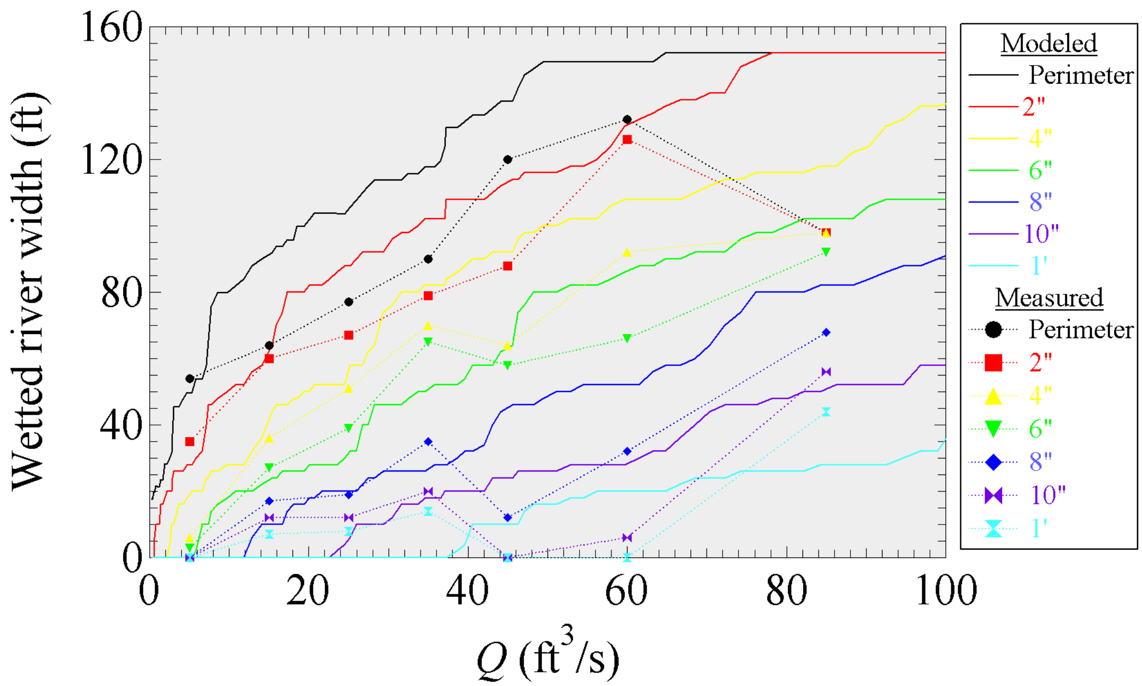

Figure 87: Measured (symbols) and modeled (curves) depth availability at TAGU2.

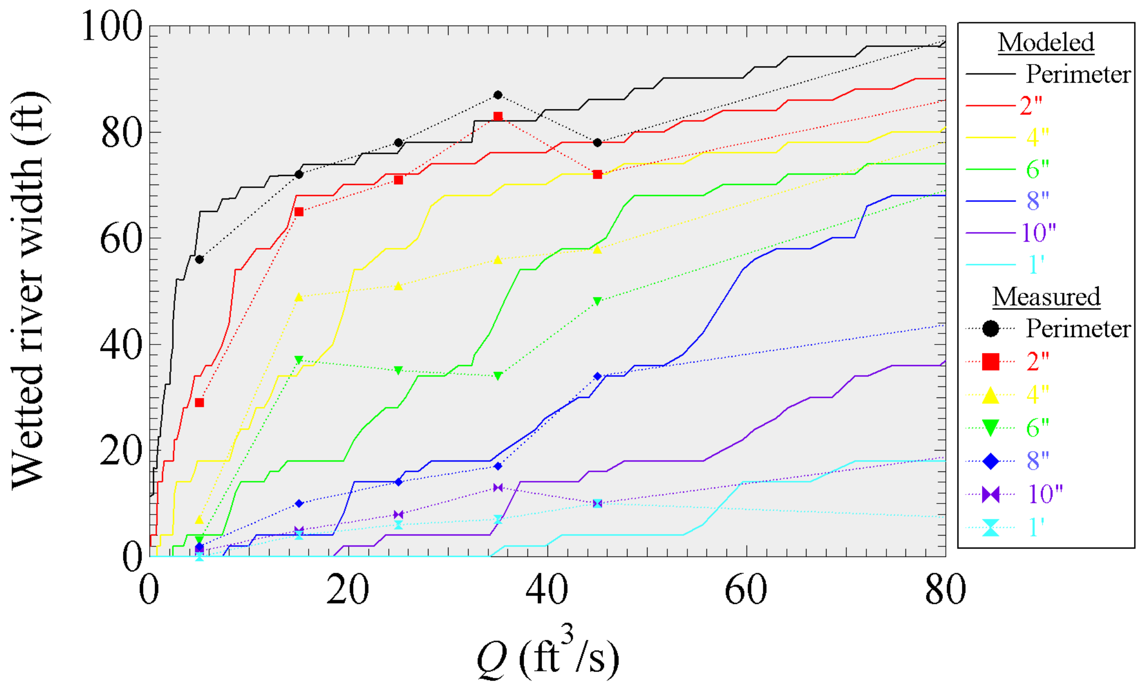

Figure 88: Measured (symbols) and modeled (curves) depth availability at TAGU1.

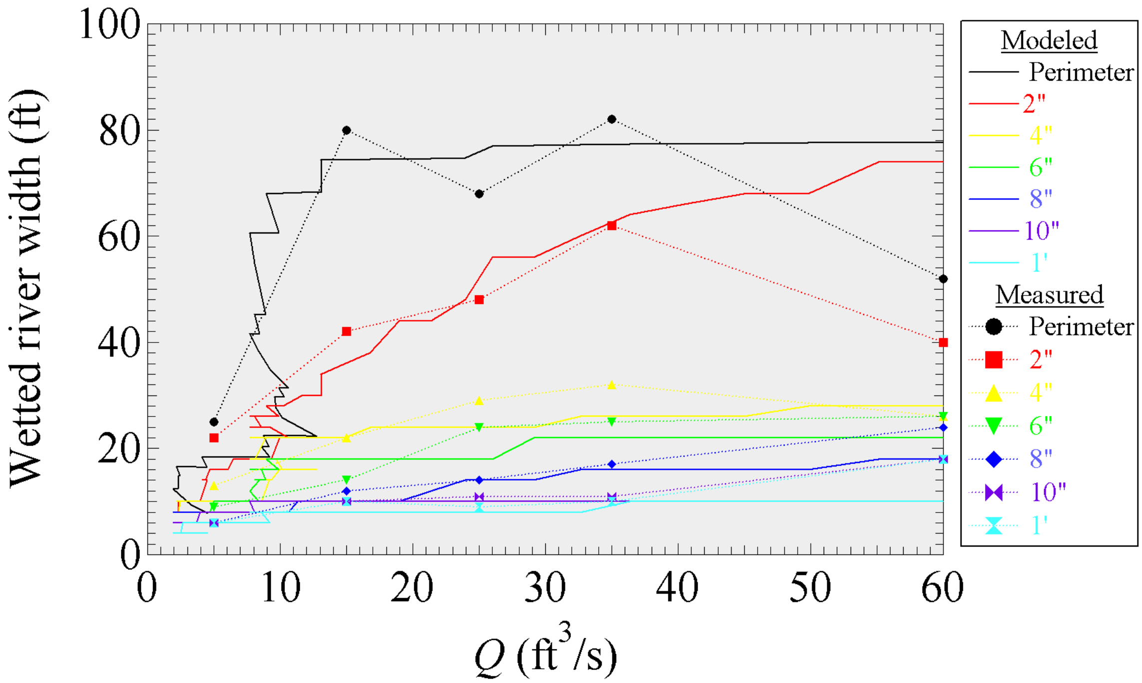

Figure 89: Measured (symbols) and modeled (curves) depth availability at TAGD1.

Appendix I: Velocity Availability

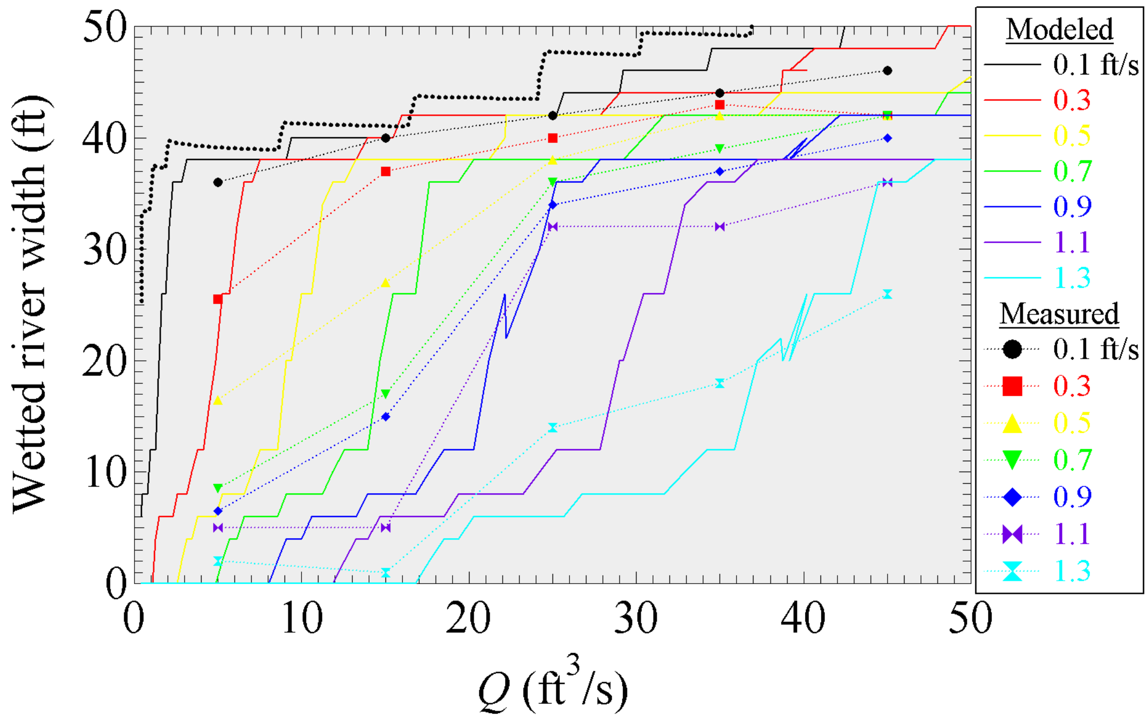

Figure 90: Measured (symbols) and modeled (curves) velocity availability at TOFP (total wetted width of river is illustrated with the dashed black line).

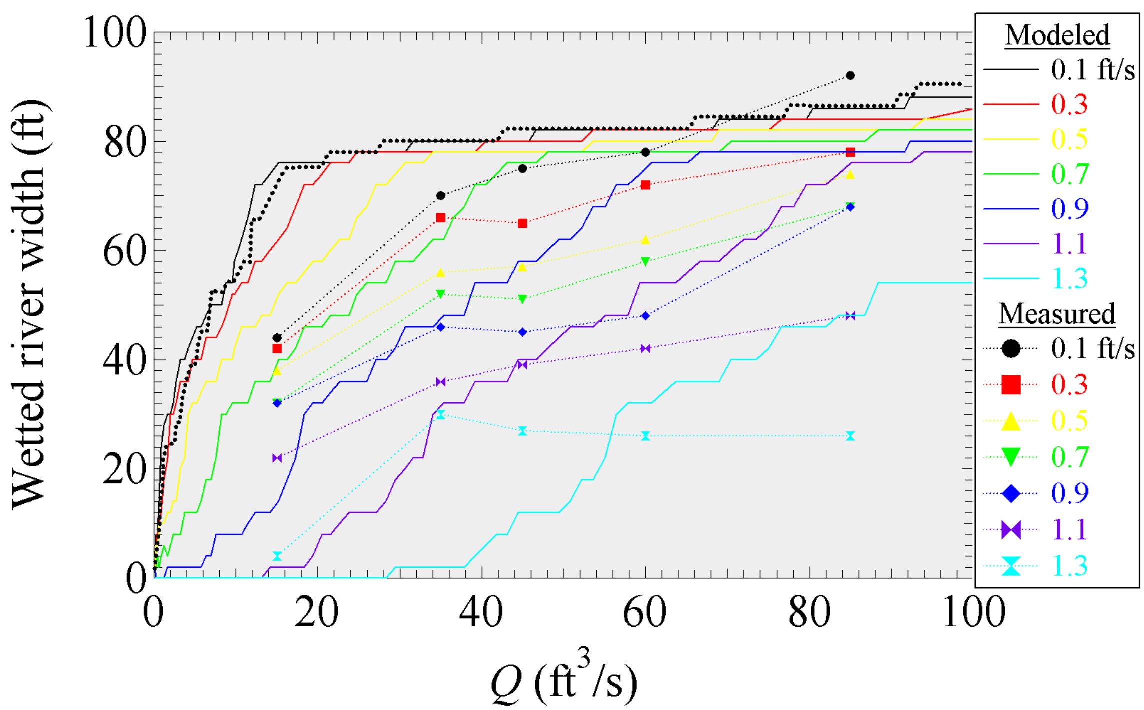

Figure 91: Measured (symbols) and modeled (curves) velocity availability at TT (total wetted width of river is illustrated with the dashed black line).

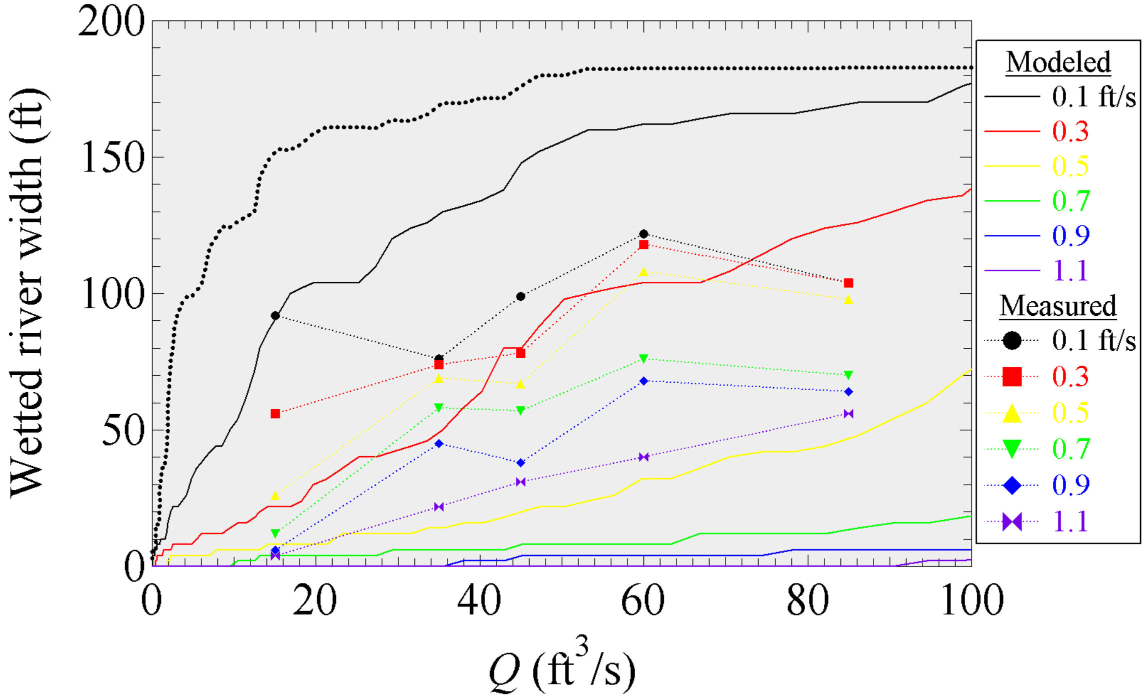

Figure 92: Measured (symbols) and modeled (curves) velocity availability at TY (total wetted width of river is illustrated with the dashed black line).

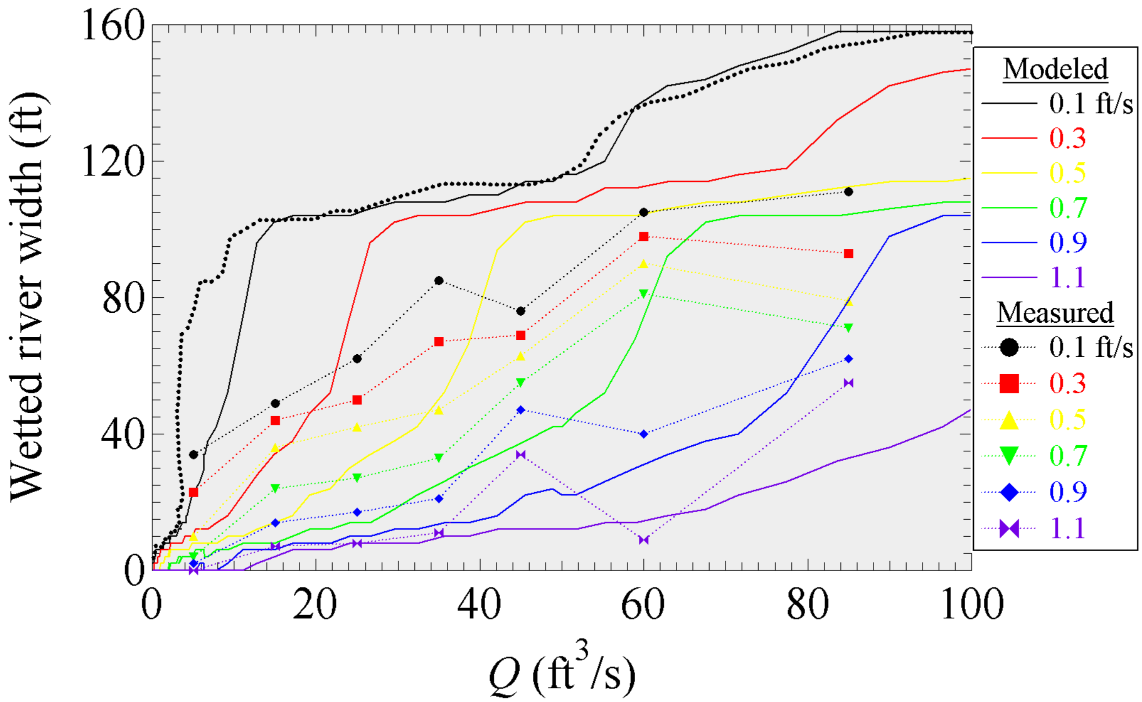

Figure 93: Measured (symbols) and modeled (curves) velocity availability at TCMR (total wetted width of river is illustrated with the dashed black line).

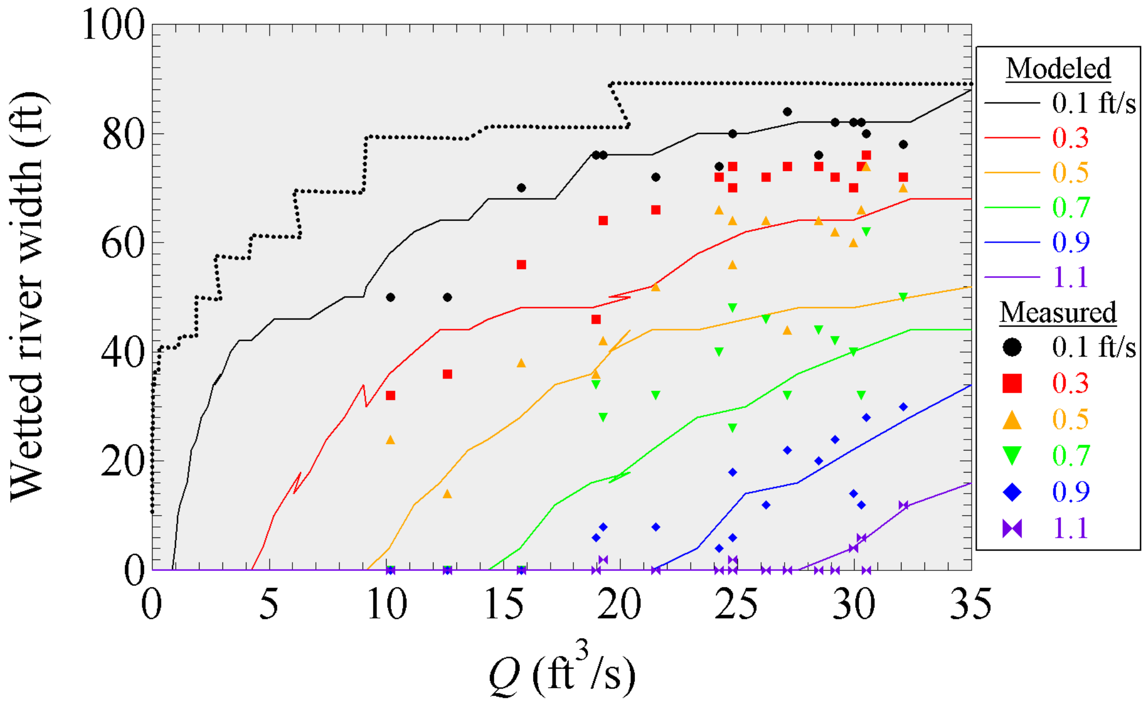

Figure 94: Measured (symbols) and modeled (curves) velocity availability at T5MD (total wetted width of river is illustrated with the dashed black line).

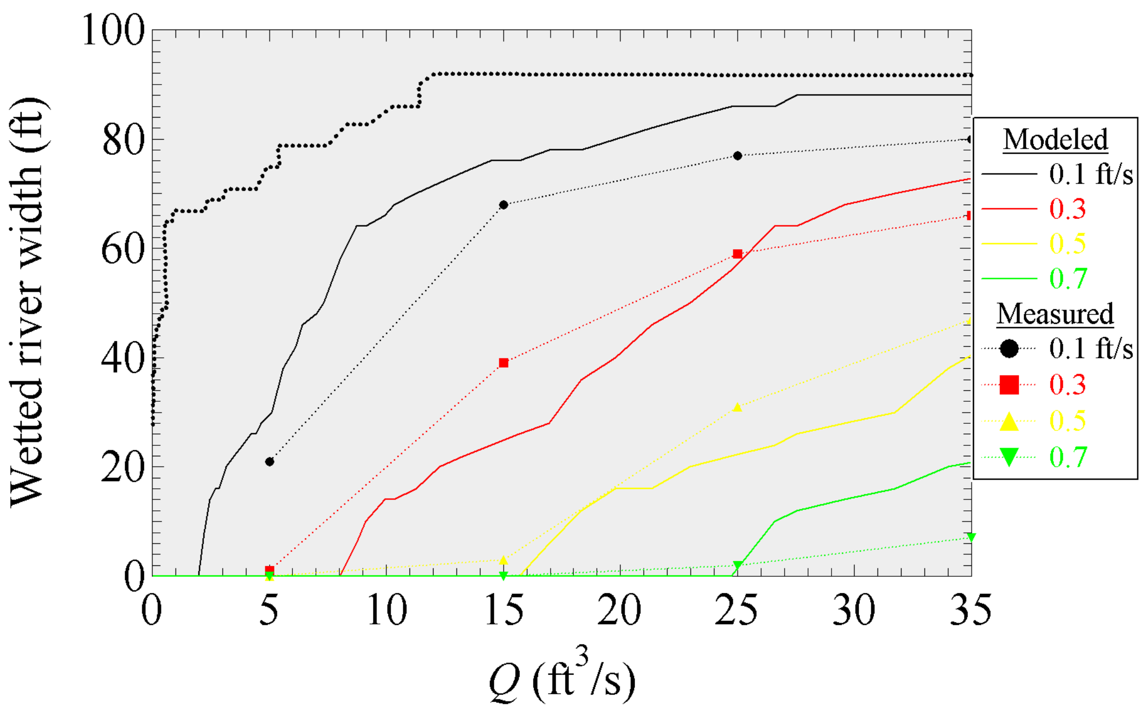

Figure 95: Measured (symbols) and modeled (curves) velocity availability at TPLC (total wetted width of river is illustrated with the dashed black line).

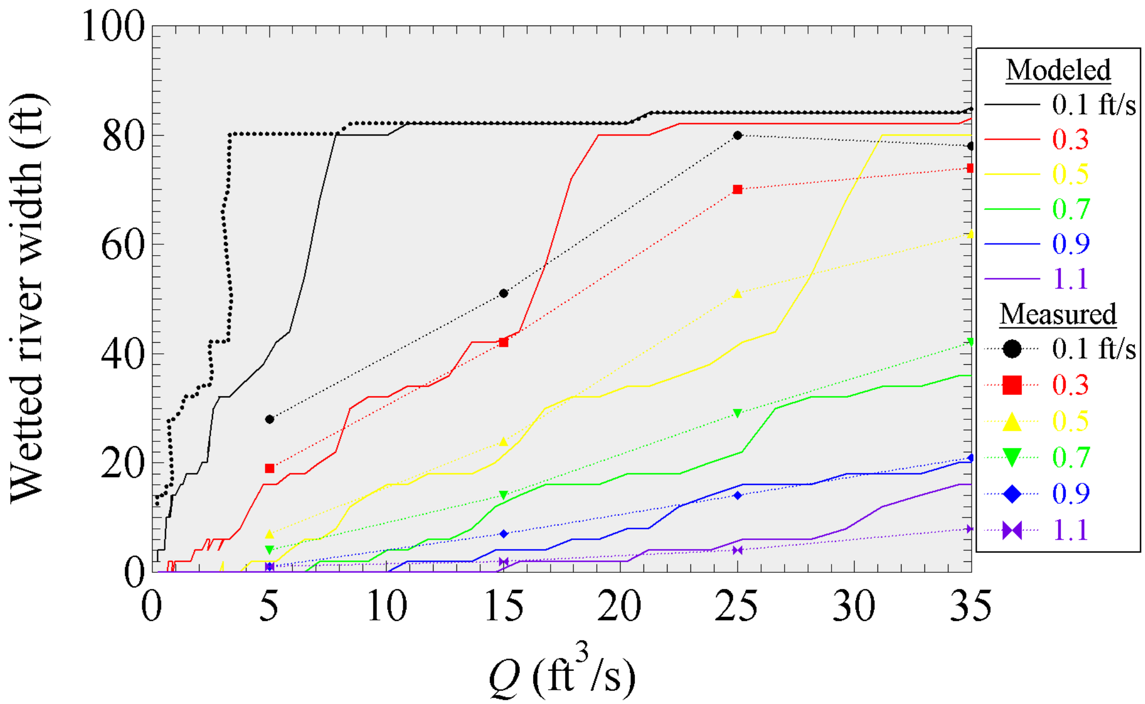

Figure 96: Measured (symbols) and modeled (curves) velocity availability at TAG (total wetted width of river is illustrated with the dashed black line).

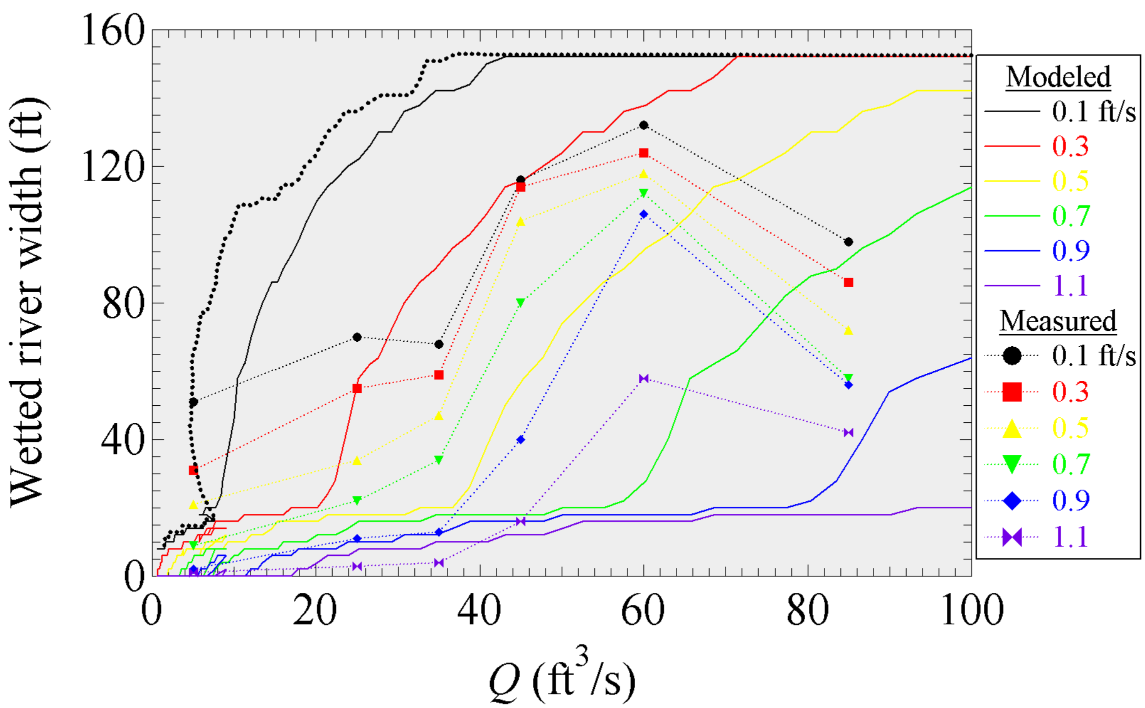

Figure 97: Measured (symbols) and modeled (curves) velocity availability at TAGU3 (total wetted width of river is illustrated with the dashed black line).

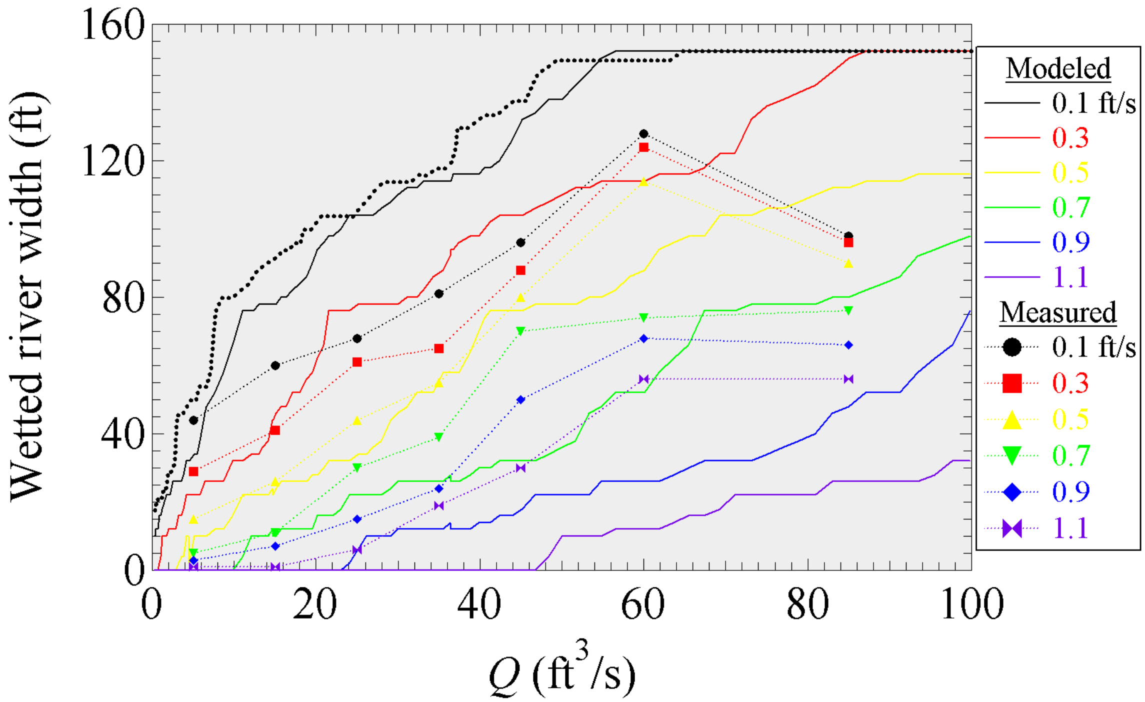

Figure 98: Measured (symbols) and modeled (curves) velocity availability at TAGU2 (total wetted width of river is illustrated with the dashed black line).

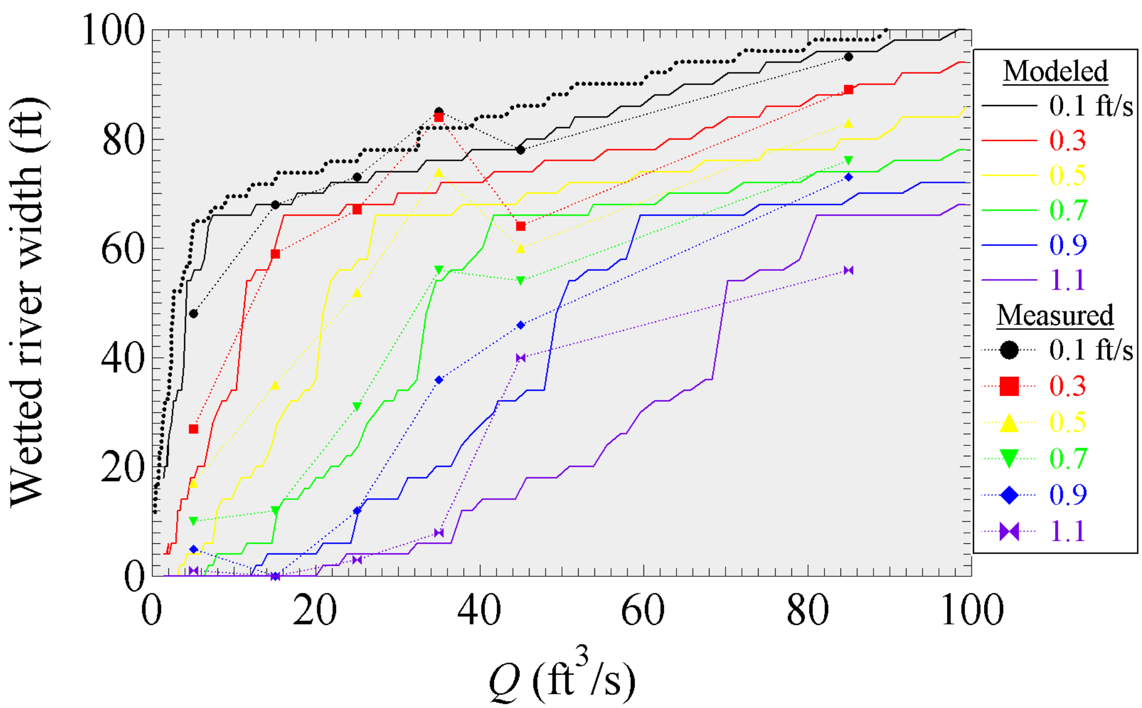

Figure 99: Measured (symbols) and modeled (curves) velocity availability at TAGU1 (total wetted width of river is illustrated with the dashed black line).

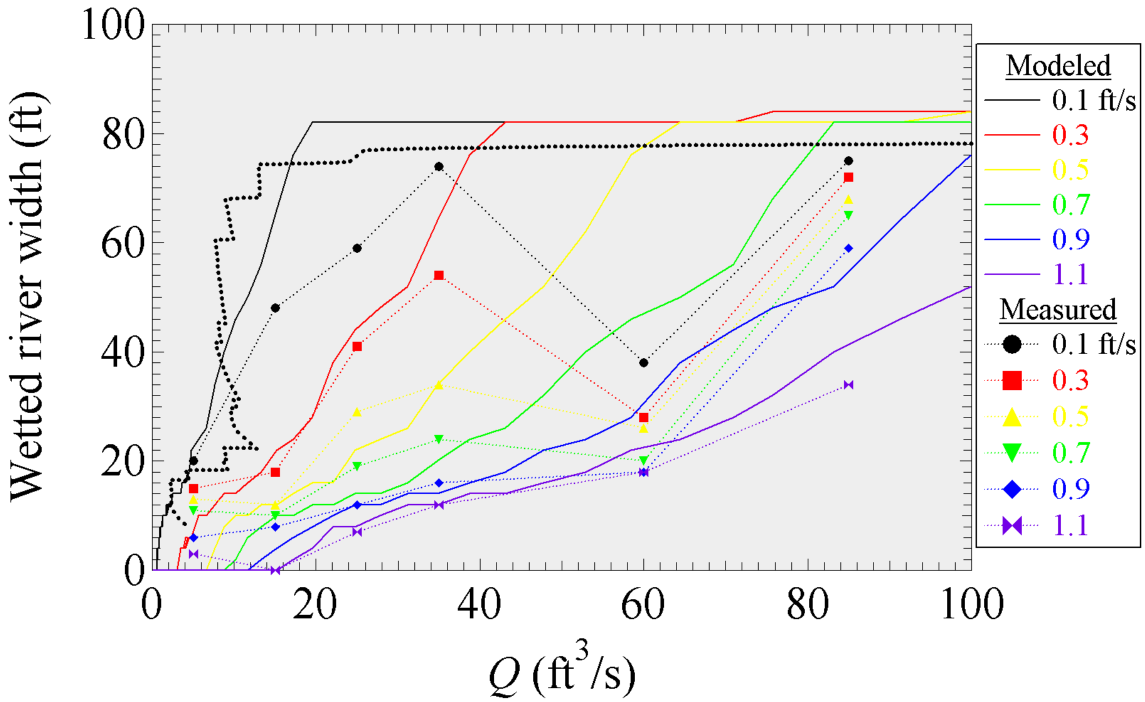

Figure 100: Measured (symbols) and modeled (curves) velocity availability at TAGD1 (total wetted width of river is illustrated with the dashed black line).

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