THESIS

INSTREAM FLOW METHODOLOGIES: AN EVALUATION OF THE TENNANT METHOD FOR HIGHER GRADIENT STREAMS IN THE NATIONAL FOREST SYSTEM LANDS IN THE WESTERN U.S.

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JENNIFER L. MANN ENTITLED INSTREAM FLOW METHODOLOGIES: AN EVALUATION OF THE TENNANT METHOD FOR HIGHER GRADIENT STREAMS IN THE NATIONAL FOREST SYSTEM LANDS IN THE WESTERN U.S. BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF **THESIS**

INSTREAM FLOW METHODOLOGIES: AN EVALUATION OF THE TENNANT METHOD FOR HIGHER GRADIENT STREAMS IN THE NATIONAL FOREST SYSTEM LANDS IN THE WESTERN U.S.

In 1976 Donald Tennant introduced a method for determining instream flow requirements for fish, known as the 'Montana method', or more commonly the Tennant method. The method uses a percentage of average annual flow (AAF) to determine fish habitat quality. From 58 cross sections from 11 streams in Montana, Nebraska, and Wyoming, Tennant concluded that 10% of AAF is the minimum for short term fish survival, 30% of AAF is considered to be able to sustain fair survival conditions, and 60% of AAF is excellent to outstanding habitat. These quantities are employed internationally, regardless of physical and hydrologic setting, due to the simplicity of using only the average annual hydrograph.

The purpose of the current study was to determine under what conditions Tennant's fixed percent AAF values apply, to specifically evaluate Tennant's original width, depth, and velocity measurements, to evaluate the applicability of Tennant's percent of AAF, as compared to other methods of determining minimum instream flows, and to determine if there are regional characteristics that relate to the applicability of the Tennant method. Tennant's method was tested to see if percent AAF actually can be used as a surrogate for other hydraulic measures, such as width, depth, and velocity. These physical parameters have been used in other studies to quantify instream flow used for fish. The two other methods that were used in the comparisons were the wetted perimeter method and the physical habitat simulation system (PHABSIM). A set of regional characteristics were used to look for region specific patterns. These characteristics including: stream type, state, ecoregion, and hydro-climatic regime. A total of 151 cross sections were analyzed on seventy river segments throughout the western U.S. (California, Colorado, Idaho, Montana, Oregon, Utah, and Washington). The streams were classified as pool-riffle, plane bed, step-pool, and dune-ripple. This study will offer resource managers additional information on the applicability of the Tennant method for determining instream flow needs for the physical, biological, and social setting.

This study concluded that Tennant's original dataset was not representative of streams in the western United States. Data collected from lower gradient streams in Nebraska followed the patterns set forth by Tennant much more closely, and therefore the Tennant method is more applicable in similar low gradient streams (slope less than 1%). In higher gradient streams the use of the Tennant method should be with caution and be restricted to planning stages of instream flow recommendations. Further validation and method adaptation is recommended when using the Tennant method for higher gradient stream types. The Tennant method should be used in instream flow protection scenarios and not in restoration scenarios because of the method's assumption that the current average annual hydrograph represents the optimal fish habitat.

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“The care of rivers is not a question of rivers but of the human heart.”

~ Tanaka Shozo (1841-1913)

Chapter 1

1.0 Background

There is currently a growing conflict in the use of the water resources within the U.S. and throughout the world (Jackson et al. 2001). In 2001 it was stated that "…over half of accessible freshwater runoff globally is already appropriated for human use" (Jackson et al. 2001 p.1027) citing (Postel et al. 1996). And it is estimated "…that human appropriation of accessible runoff could climb to 70% by the year 2025" (Postel 2000 p.941). In the western United States the flow that is left in the streams has been greatly diminished by diversions for off stream uses (Gillilan and Brown 1997). "…At least 90% of total water discharge from U.S. rivers is strongly affected by channel fragmentation from dams, reservoirs, interbasin diversions, and irrigation…" (Jackson et al. 2001 p.1027). In the western U.S., the main governing law over water rights is the prior appropriation doctrine that was put into place over a century ago. The prior appropriation doctrine upholds the right of private property owner to use water for specified uses, and protects senior water rights holders from junior water rights holders. Prior to the growing environmental awareness, in the 1960's and 1970's, the prior appropriation doctrine precluded obtaining instream flow rights for aquatic dependent species such as fish. To protect plants and animals that rely on water, there needs to be a continued shift in the ability to obtain instream flow rights. "…Globally, 20% of freshwater fish species are threatened or extinct…" (Jackson et al. 2001 p.1027). The major instream flow needs currently are recreation, such as fishing and boating, aquatic life or wildlife, channel maintenance, and aesthetics (Tennant 1975, Brown 1991, Brown et al. 1991, McBain and Trush 1997, Mahoney and Rood 1998, Cooper et al. 1999, Rood et al. 2006). Off-stream water rights are mainly used for agricultural, industrial, and municipal uses. This conflict between instream and off channel water uses necessitates further investigation into the quantity of water that instream resources need. This study will look at three methods for determining instream flow needs to maintain fish habitat, particularly rainbow trout.

1.1 Instream Flow Requirements

Determination of instream flow poses many challenges, many of which have yet to be overcome. One of the main problems is determining the aspect of the ecosystem on which to base the requirements, and the conflict with human demands. In many cases the needs of different users are in conflict. For example, should the flow of the river be determined by what expert kayakers see as ideal flow to create class III or greater conditions or should the flow focus on the protection of a particular fish species or macroinvertebrates? In either case, the ideal stream flow for kayakers is different than the ideal flow for the fish species. The difference in target velocity complicates the process of determining the flows needed to meet the multiple requirements of the stream. Besides balancing multiple uses, there are also the dynamics within the target flow for any given use that needs to be incorporated into the flow regime.

The dynamics within a flow regime consist of "five critical components … (that) regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing, and rate of change of hydrologic conditions" (Poff et al. 1997 p.770). "Naturally variable flows create and maintain the dynamics of in-channel and floodplain conditions and habitats that are essential to aquatic and riparian species" (Poff et al. 1997 p.774). Variation in the magnitude and frequency of high flows (inter-annual variation of the peak flow) are necessary for floodplain inundation and plant regeneration, and provide connectivity to different floodplain wetlands (Poff et al. 1997). Similarly magnitude and frequency of low flows (inter-annual variation of the base or low flow) provide ecological benefit through access to frequently inundated floodplains for plant recruitment (Poff et al. 1997). Conversely the timing and duration of high flows (intra-annual variation of the peak flow) are important in life cycles of riparian plants and aquatic species through providing cues to fish species for spawning, egg hatching, and other transitions, along with impacts on seed dispersal, germination, establishment, and other transitions of riparian plants (Poff et al. 1997). The complexity of required flow regimes complicates the process of choosing an appropriate methodology for determining instream flow requirements.

An accepted methodology for fisheries instream flow requirements may be to use a percent of average annual flow (AAF) technique. The percent of AAF method has its pros and cons like any other method. The percent of AAF method does not account for inter-annual variation. This method is only possible when the data exist to put together an accurate average annual flow. If the AAF that is used does not reflect the true nature of the stream's flow regime, then the percent of the AAF that is implemented will likely not produce the desired end result. Additionally, since this method is based on the average annual hydrograph it tends to not incorporate the intra-month variation that helps maintain channels and support different parts of the ecosystem (McBain and Trush 1997, Dunham et al. 2002, Glenn and Nagler 2005). Another possible technique is to try to incorporate some of that complexity instead of staying with a simple method. Because we know that we are not able to model the true complexity of the system, we know that outcomes will always fall short of the natural system. This leads us back to finding a balance between simplicity and expense of the use of the method and how closely we are able to model the necessary characteristics. On the other end of this spectrum from the percent of AAF method is the incremental method, which employs a more complex model such as PHABSIM, a physical habitat simulation system (Stalnaker et al. 1995). Incremental implies that the resulting regulation has a window of acceptable flows that were determined through multiple or variable rules (Stalnaker et al. 1995). Because this methodology is more complex, it tends to be used in situations where there is a high level of debate about the use of the water and supports analysis of alternatives and negotiations to agree on a flow value (Stalnaker et al. 1995).

Those two examples are on opposite sides of the spectrum of the methods available for determining instream flow needs for fish habitat (Table 1.1). The Tennant method is a simple method, that developed in the 1960's and 1970's and has since been applied internationally (Gillilan and Brown 1997, Lamb et al. 2004).

Table 1.1 Table of method types with examples of each methodology type

Methodology Type	Example Method	Method Input	Components	Reference
Standard Setting or Hydrological Methods	Tennant Method	Average Annual Flow	Width, Depth, Velocity, Substrate & Side Channels, Bars & Islands, Cover, Migration, Temperature, Invertebrates, Fishing & Floating, Esthetics & Natural Beauty	Tennant, D. L., 1975.
Transect or Hydraulic Rating Methods	Wetted Perimeter Method	Cross Section Coordinates (x,y) and Slope (with use of a Cross Section Analyzer)	Depth, Velocity, and Spawning Discharges	Collings, M., 1972.
Incremental or Habitat Simulation Methods	PHABSIM	Multiple Cross Sections longitudinally along the Stream Segment with Discharge and Water Surface Level Calibration Pairs	Velocity, Depth, Channel Index, and Temperature	Bovee, K., 1982.

1.2 Tennant Method

The Tennant method was originally called the "Montana method" by Tennant because it was created using data from the Montana region (Tennant 1975), and was developed through field observations and measurements. Data were collected on 58 cross sections on 11 different streams within Montana, Nebraska, and Wyoming. Tennant collected detailed cross section data that characterized different aspects of fish habitat. These included width, depth, velocity, temperature, substrate and side channels, bars and islands, cover, migration, invertebrates, fishing and floating, and esthetics and natural beauty. Tennant looked at both warm water fisheries and cold water fisheries. These metrics were related to a qualitative fish habitat quality. This allowed for a determination of discharge to fish habitat through the correlation of physical geometric and biological parameters to discharge. Tennant then related percent of the average flows would relate to fish habitat qualities (Tennant 1975).

So through a somewhat complex methodology Tennant produced an easy to apply standard that can be used with very little data. The technique utilizes only the average annual flow for the stream. It then states that certain flows relate to the qualitative fish habitat ratings, that is used to define the flow needed to protect fish habitat that is of the quality desired (Table 1.2). This allows professional staff working in a regulatory environment to set the required flow by using the percent of the average annual flow (AAF) without further onsite data collection.

Table 1.2 Instream flow for fish, wildlife, and recreation (Tennant 1975)

Narrative Description of flows*	Recommended base flow regimens	
	Oct.-Mar.	Apr.-Sept.
Flushing or maximum	200% of the average flow	
Optimum range	60%-100% of the average flow	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	10% of average flow to zero flow	

*Most appropriate description of the general condition of the stream flow for all parameters listed in the title of this paper.

The obvious benefit of this method is that regulators or land managers are able to set flow requirements without expensive field data collection, or processing. The Tennant method is considered a standard setting method, meaning that it is uses a single, fixed rule as a minimum base flow. This means that it is easy to apply to any situation without collecting lots of data or being expensive. But it also means that it treats all situations the same and uses a single criterion in all circumstances, because Tennant did not provide criteria that a stream must meet for this method to be applicable (Gordon et al. 1992). So even though the Tennant method is easily applied it may not always be applicable. One study of the Tennant methods applicability in Oklahoma showed that the season breaks used to separate spawning from rearing periods that Tennant originally used did not fit as well (Orth and Maughan 1981). Tennant split his flow recommendations into two different segments of the year, October to March and April to September (Tennant 1975). Orth and Maughan (1981) felt that July to December and January to June would fit the data better in Oklahoma. Beyond altering the time of year that the higher flows should occur, the study concluded that the Tennant method is applicable in Oklahoma (Orth and Maughan 1981). Another article concludes that "the Montana method, has severe limitations, and should be restricted to reconnaissance level planning" (Mosley 1983 p. 152). Similarly because the Tennant method is a standard setting method and yields a point value, it is not well suited for a negotiation framework. This study concluded that without further data collection and analysis it would be hard to further evaluate the applicability of the Tennant method.

Alternative methods for determining instream flow include: Hoppe method, Washington method, wetted perimeter method, Idaho method, empirical observation, PHABSIM, Instream Flow Incremental Methodology (IFIM), and many other simulation programs. These methods fall in three main categories: standard-setting methods, transect methods, and incremental methods. The first is that of standard-setting methods or historic flow methods. Standard-setting techniques are single, fixed rules based on very limited data (usually an average annual flow value) to establish a minimum flow (usually a percent of that average annual flow) that does not incorporate system variability (Stalnaker et al. 1995). Standard-setting methods tend to be inexpensive to implement because they require little collected data before use. Standard-setting methods tend to be used in protection scenarios where preventing degradation is the main focus; in contrast to projects that are trying to restore damage to systems that has already occurred (Stalnaker et al. 1995). Incremental or habitat methods are the other side of the spectrum of methods. These methods are used in complex situations where the current flow regime is unable to support the biota or other uses for which the stream is being managed (Stalnaker et al. 1995). Transect methods are more complex than standard-setting methods but do not fulfill the requirements of incremental methods. Many of these methods may be considered transect or hydraulic methods where some field data are collected but there is not any actual habitat data collected or considered on an individual stream basis. Transect methods involve collection of field data at several transects, generally in riffles, along the stream length and use relationships between discharge and other physical variables to determine a critical or optimum flow requirement (Gordon et al. 1992, Gippel and Stewardson 1998). This study focuses on one of each of these methods: Tennant method (standard-setting), Wetted Perimeter method (transect method), and PHABSIM (habitat method).

1.3 Wetted Perimeter Method

The wetted perimeter method is a variation of the Washington method and considered a transect method (Gordon et al. 1992) and was described in Collings (1972). The wetted perimeter method looks at the general relationship between the stream discharge and the wetted perimeter (Gillilan and Brown 1997). The wetted perimeter is the length of stream bottom substrate that is wet along a cross section oriented perpendicular to the river. Cross section data are typically taken from several riffles along the stream length at several different flows (Gordon et al. 1992). This produces a curve of the relationship between discharge and wetted perimeter (Figure 1.1) that can be analyzed for the breakpoint or inflection point (Reinfelds et al. 2004). This is predicated on the observation that wetted perimeter (a surrogate for fish habitat) increases a relatively smaller amount above the breakpoint for each unit of discharge compared to points below the breakpoint (Gordon et al. 1992). There is an ongoing discussion about how the breakpoint should be defined. The wetted perimeter method, as originally set forth, defined the breakpoint as the first point of the curve where the slope decreases (Gordon et al. 1992). Allowing the break in slope to be subjectively chosen reduces the scientific validity of this method (Gippel and Stewardson 1998). Possible mathematical methods of breakpoint determination are either by defining the point of maximum curvature or by selecting the point of the curve where the slope is equal to a designated value (Gippel and Stewardson 1998). The latter method has a subjective aspect to it because the slope value is chosen by the managers or researchers; slopes that are less than one will have a relatively lower discharge recommendation than the recommendation from a slope greater than one (Gippel and Stewardson 1998). The negative aspect of this is that it introduces error through the subjectivity, but the advantage is that it allows for the consideration of the management objectives for the stream segment (Gippel and Stewardson 1998).

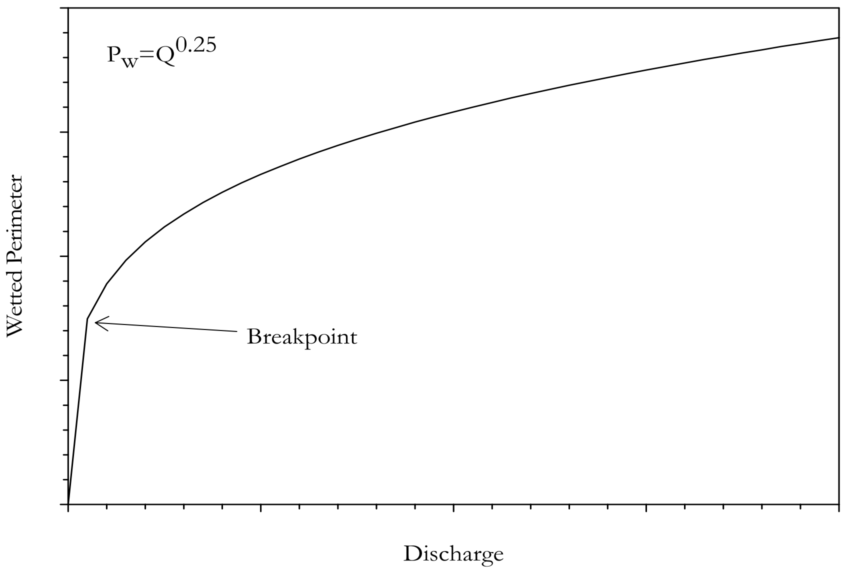

Figure 1.1 An example of a wetted perimeter curve and breakpoint

1.4 PHABSIM (Physical Habitat Simulation System)

PHABSIM (Physical Habitat Simulation System) in one of the commonly used instream flow models. PHABSIM uses four hydraulic criteria that are calculated from field measurements and relate to fish habitat quality. The hydraulic variables included in the model are water depth, flow velocity, substrate, and cover (Gillilan and Brown 1997). The required field data include cross section survey. The data collected at each point are the elevation of the channel, cover, substrate, mean column velocity, and water surface elevation (Waddle 2001). This allows PHABSIM to use species suitability criteria that are generally from other biological habitat studies that must be provided to PHABSIM as well (Stalnaker et al. 1995, Gillilan and Brown 1997). The outputs of PHABSIM are weighted usable area (WUA) curves that relate discharge to a fish habitat index for different life stages of fish species of interest, and habitat guild (Waddle 2001)(Figure 1.2).

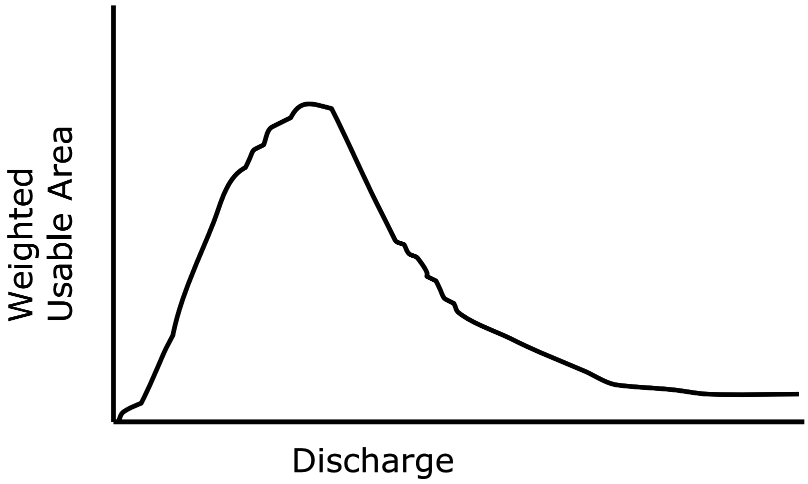

Figure 1.2 An example of a PHABSIM Weighted Usable Area curve

Instream Flow Incremental Methodology (IFIM), developed by the U.S. Fish and Wildlife Services, is unlike the previous methods, in that it is more of a process that is followed instead of a specific program like PHABSIM or desktop method like the Tennant method and is described in Bovee (1982). In IFIM the investigator examines more than a snapshot of the microhabitat characteristics of the stream to determine minimum flow, IFIM also considers at macrohabitat characteristics like stream temperature and water quality longitudinally down the stream channel (Gillilan and Brown 1997). These two analysis techniques combine to produce a habitat time series that shows how the fish habitat changes over time as a function of discharge (Gillilan and Brown 1997). IFIM is a process that is followed using other methodologies and tools instead of a method on its own. This process generally employs one of several methods to get to the final outputs. Commonly either PHABSIM or Habitat Quality Index (HQI) can be used, although PHABSIM is more common (Stalnaker et al. 1995). IFIM tends to be used to determine the effect of an activity on habitat, and in restoration situations once the effect of the activity is better understood (Gordon et al. 1992). IFIM was evaluated by the National Ecology Research Center, Fort Collins, Colorado and found that most users within the U.S. Fish and Wildlife Service found

IFIM to either be too complicated to apply (too expensive, not trained well enough, or took too much time), or too simplistic (models or curves needed improvement) (Armour and Taylor 1991). This would suggest that this method may not be the best choice unless the resources necessary to apply this technique are worth the results that may be obtained.

Other methods that would fall within the middle category of types include the modified Tennant approach and multiple attribute standard-setting methods. The modified Tennant method goes back through Tennant's original methodology to come up with percent flows that are specifically tailored to each individual stream (Stalnaker et al. 1995). An example of a multiple attribute standard-setting method is the HQI where the habitat qualities are regressed against the fish crop for the individual stream to get a set of parameters to compare to discharges to determine flow recommendations (Stalnaker et al. 1995). Another method that is not just a standard-setting method but would not be considered a habitat model is the Range of Variability Approach (RVA) that uses long-term streamflow data to determine a flow regime recommendation (Richter et al. 1997). Transect methods other than the wetted perimeter method include the Idaho method which is designed for large unwadable rivers (Gordon et al. 1992), and Pool Quality Index method which is designed for low-order, high-gradient streams (Azzellino and Vismara 2001). Other habitat methods include MesoHABSIM, RHYHABSIM, RIMOS, and R2 Cross (Gordon et al. 1992, Parasiewicz 2001, Hardy et al. 2003).

1.5 Previous Instream Flow Methodology Analyses

There have been aspects of many instream flow methods that have been evaluated over the years of use, including many summaries of available methods and comparisons between methods (Annear and Conder 1984, Jowett 1997, Tharme 2003, Acreman and Dunbar 2004). The type of evaluation that was used in each study varied to cover differing aspects of method reliability (Annear and Conder 1984). One step in model validation is evaluation of the model mechanism (Annear and Conder 1984). Annear and Conder (1984) went a step further in their evaluation of instream flow methods by looking at the resulting flow recommendations and comparing the methods to provide a sense of how methods differ from each other.

Several studies have specifically evaluated the Tennant method or included it in the set of methods that were evaluated. Two main papers specifically focused on the Tennant method (Elser 1972, Orth and Maughan 1981). Orth and Maughan (1981) focused specifically at evaluating the Tennant method in Oklahoma. The primary focus of the study was to determine if the seasons that Tennant used for the flow recommendations lined up with the flow regime in Oklahoma. The study found that to appropriately apply the Tennant method in Oklahoma that the seasons should be shifted to better reflect the flow regime of the area such as shifting Tennant's seasons (Orth and Maughan 1981). This study concluded that the method was adequate for initial general planning but is not suited to define a long-term flow level (Orth and Maughan 1981). Elser (1972) looked at a different aspect of the method, instead of looking to apply the method in a different area and evaluating the seasons that should be used, the study focused on checking Tennant's physical channel measurements. This study used three transects on regulated rivers in Montana and measured width, depth, and velocity at 10%, 30%, and 60% of average annual flow (Elser 1972). The study found that Tennant's velocity measurement of 1.5fps for 30% flow is approximately the same on the streams included in this study (Elser 1972). This study concluded that 30% of average flow is sufficient for trout spawning citing work by Hope and Finnell (1970) and Lewis (1969) (Elser 1972). This was concluded because a study by Hoppe and Finnell (1970) found that the minimum velocity required for trout egg survival was 1.5 ft/s; along with

Lewis (1969) concluding that velocity and cover accounted for two thirds of the variation in trout location (or preferred habitat).

Summary papers that looked at the Tennant method along with other methods tended to look at other aspects of the Tennant method. Tharme (2003) took a global trend perspective on current instream flow methods being used including Tennant. Tharme (2003 p.404) looked at 207 individual methods being used in 44 different countries and made observations on the popularity of methods, stating that the Tennant method is the "most commonly applied hydrological methodology worldwide". Acreman and Dunbar (2004) studied the potential applicability of each method instead of the present trend of use, concluding in their study that the Tennant method is useful only for scoping studies, national water audits, or basin-scale planning. Acreman and Dunbar state that "this approach (Tennant Method) can be used elsewhere (outside the Mid-Western U.S.), but the exact indices would need to be re-calculated for each new region" (2004 p.864). Annear and Conder (1984) went a step even further with their methodology study by looking at the bias trends for each method. This study looked at the bias trend of each method by first compiling the recommendations from each method for each study site then creating a range of acceptability (unbiased) for each study site by taking the mean of the flow recommendations and then the 95% confidence interval (Annear and Conder 1984). Annear and Conder (1984) concluded that the Tennant method had an overall low level of bias, using the 30% AAF recommendations, where 10 out of 13 streams fell within the acceptable range and the remaining three streams had a value lower than the acceptable range. When Annear and Conder (1984) looked at the recommendations using the 10% AAF, they found that the values were consistently very low compared to the unbiased range. Therefore they concluded that using the 10% AAF recommendation, even as a minimum flow, was taking

Tennant's data out of context (Annear and Conder 1984). This study concluded that the Tennant method, although overall was fairly unbiased, did not take into account biological data directly (Annear and Conder 1984). Additionally the Tennant method had no method for determining tradeoffs, and therefore had a limited applicability, which coincided with other studies conclusions about the Tennant method (Annear and Conder 1984).

The global acceptance of the Tennant methodology with out on site or regional validation in spite of previous reviews is troubling. These studies leave a significant gap in the overall knowledge and evaluation of the Tennant method. Tennant's width, depth, and velocity measurements still have not been evaluated outside of the original study area or with a larger sample size. Also, the applicability has not been tested in other regions or stream types except for the seasonality study in Oklahoma (Orth and Maughan 1981).

Chapter 2

2.0 Purpose and Objectives

The purpose of this study is to determine if Tennant's original results (percent of average annual flow) apply, and under what situations, to streams in the mountainous West (U.S.). Professional staff for water management agencies can use the results of this study to determine when the Tennant method is appropriate for use in quantifying the amount of flow needed in the stream to maintain fish habitat. The three objectives for this study are to determine if: 1) Tennant's original width, depth, and velocity characteristics represent western mountainous streams, 2) Tennant's fixed percent of average annual flow (AAF) values are constant across mountain streams, and 3) there are any regional characteristics that affect the applicability of Tennant's method.

The first objective is to evaluate Tennant's original width, depth, and velocity measurements. The values that Tennant suggested for the average width (percent width), depth, and velocity for each percent of AAF value will be tested. The range of values calculated in this study for width, depth, and velocity will then be compared to the values that Tennant employed using a standard hypothesis test to determine if the mean of the study population is different from Tennant's values.

The second objective is to evaluate Tennant's percent AAF findings. To test this objective the Tennant method will be compared to other methods of determining minimum instream flows. Tennant stated that 10% AAF was the minimum for short term survival and 30% AAF as fair fish habitat during the months of April through September. This range of

10 to 30 % will be used in comparison to other instream flow methodologies. To better test the Tennant method against other methods a transect method and an incremental method (more complex model) will be used in the comparisons. This objective will be developed into two sub objectives, allowing each alternative method to be tested separately. The first method is the wetted perimeter method described by Collings (1972), and updated by Gippel and Stewardson (1998). This method will be run on the dataset of the stream segment cross sections from the western U.S. The recommended flow from the wetted perimeter method will first be compared to Tennant's 10% AAF value using a two-sided hypothesis test, then to Tennant's 30% AAF in the same manner. The next sub objective is to test the Tennant method against the PHABSIM (Physical Habitat Simulator) method. This comparison will be done through the use of a stream segment in each of three stream types (pool-riffle, step-pool, and plane bed), which have sufficient data to run the PHABSIM model. Tennant's 10% and 30% AAF recommendations will then be compared to the habitat index to see how much habitat is available at Tennant's recommended flows.

The third objective is to determine if there are any regional or climatic differences in the applicability of the Tennant Method. This objective will be tested using two different types of comparisons; categorical differences like stream type, state, and ecoregions, and continuous differences like average annual precipitation, average daily maximum temperature, and average daily minimum temperature. The categorical regional differences will be analyzed by running pair-wise least squares means test with the Tukey-Kramer adjustment for multiple comparisons to see if there are differences between the stream types, states, and ecoregions. Continuous climatic data will be analyzed by using linear regression.

These three objectives will systematically test the assumptions that are made when applying the Tennant method. 1) By testing to see if the width, depth, and velocity characteristics for this study are similar to Tennant's findings. 2) By determining if the user would end up with a similar flow recommendation if another method was used instead of the Tennant method. 3) By determining the regional and climatic characteristics where the Tennant method is most applicable. The result of this process will be a set of guidelines of when and where to use the original Tennant method or an adjusted approach so that instream flows can be more accurately calculated and defended.

An additional objective is to further evaluate Tennant's original width, depth, and velocity measurements against a dataset of Nebraska cross-sections. This objective will attempt to replicate the values that Tennant stated for the average width (percent width), depth, and velocity for each percent of AAF value in an area more similar to the original study. The range of values calculated in this study for width, depth, and velocity will then be compared to the values that Tennant stated using a standard hypothesis test to determine if the mean of the Nebraska population is different from Tennant's values. This will allow for further testing the assumption of the Tennant method's validity.

Chapter 3

3.0 Data and Methodology

3.1 Data Collection

Data were collected on stream segments throughout the western United States, where each segment represents a U. S. Geological Survey (USGS) gage station and the mile(s) upstream and downstream that are not significantly affected by other features such as tributaries, diversions, or changes in gradient or bedform. Each potential stream segment was included or excluded from this analysis based on several criteria: 1) The amount of data for the stream segment. Segments were required to have a cross section profile that includes horizontal and vertical measurements for the bankfull width, to be included in this study. The segment must also have at least 20 years of daily streamflow data. 2) Stream type or size. The focus of this study is on smaller streams (wadeable) because the objective of this study is to determine the applicability of the Tennant method on streams within the Forest Service administered lands, and the majority of streams on Forest Service administered lands are lower order. Wadeable streams can be considered streams where the stream order (Strahler 1952) is less than or equal to 5, a drainage area less than 1600 km^2, a mainstem length less than 100 km, or a mean annual discharge less than 15cms (530cfs) (Wilhelm et al. 2005). For streams to be included in the study they must have a monthly average (for the entire period of streamflow record) streamflow of less than 75 cfs for one month out of the year. The hydrology was determined using the National Water Information System (NWIS), an online database (USGS 2005), and retrieving the monthly streamflow statistics. The

NWIS mean monthly streamflow values were used to determine if one of the twelve months falls below the selected level of 75cfs. The 75cfs threshold was selected to keep the size of the streams representative of streams commonly found on National Forest Service lands. The threshold is not so stringent to preclude an adequate sample size for analysis. Initially a cutoff of 50cfs was used but was found to limit the database beyond the purpose of the study. The monthly average 75cfs threshold allowed for a wider range of stream segments to be included in the study. Streams included in the analysis ranged from: 1) streams with higher disparity between the snowmelt runoff peak and the low summer baseflows; 2) smaller regulated streams that have little monthly variation in streamflow; 3) arid ephemeral streams that have high short peaks; and 4) rainfall dominated streams that have a yearly variation from wet season to dry season but to a lesser extent than snowmelt streams.

To collect the necessary data stream segments were chosen that are close to USGS gages so that the daily streamflow can be used in the analysis. The cross section information came from two main sources. The first source is USDA Forest Service data of detailed cross section information. The USDA Forest Service data was the most detailed source of information. Discharge measurements that the USGS collected as a part of the calibration of stream gages. The USGS collect several discharge measurements each year at fixed transects; allowing the USGS to develop and update a stage discharge rating curve for the stream. The data included in this study were selected by choosing measurements that were collected during high flows so that the cross section reached a high stage (at least the bankfull level). The streamflow data, annual statistics and daily mean flows, were collected from the NWIS database (USGS 2005). The data are organized around USGS Gage sites. Some gages had multiple usable cross sections for the analysis. A usable cross section is one that reaches bankfull. Stream segments with multiple cross sections are either studies where cross sections were taken at multiple locations along the stream segment, or the cross section was surveyed at multiple times, or both. As long as the cross sections were not identical in shape, all the cross sections were included in the dataset.

The ideal set of attributes for each segment include: channel geometry at each cross section, daily stream flow data, rating curve, bankfull measurements, channel classification, substrate information, and slope. Each segment must include cross section geometry, streamflow data, slope, bankfull width, and Montgomery-Buffington stream type (Montgomery and Buffington 1997).

3.2 Data Description

This analysis includes 151 cross sections from seventy river segments (or USGS gages) throughout the western U.S. (Figure 3.1). The river segments occur in California, Colorado, Idaho, Montana, Oregon, Utah, and Washington, and represent pool-riffle, plane bed, step-pool, and dune-ripple stream types (Table 3.1, Table 3.2). Fifty six stream segments have at least one monthly average stream flow below 50cfs, and the other fourteen stream segments have at least one monthly average stream flow below 75cfs. The average annual streamflow (AAF) for all seventy stream segments is 258cfs, and ranges from 7.5 to 1472cfs (See Appendix Table B.1).

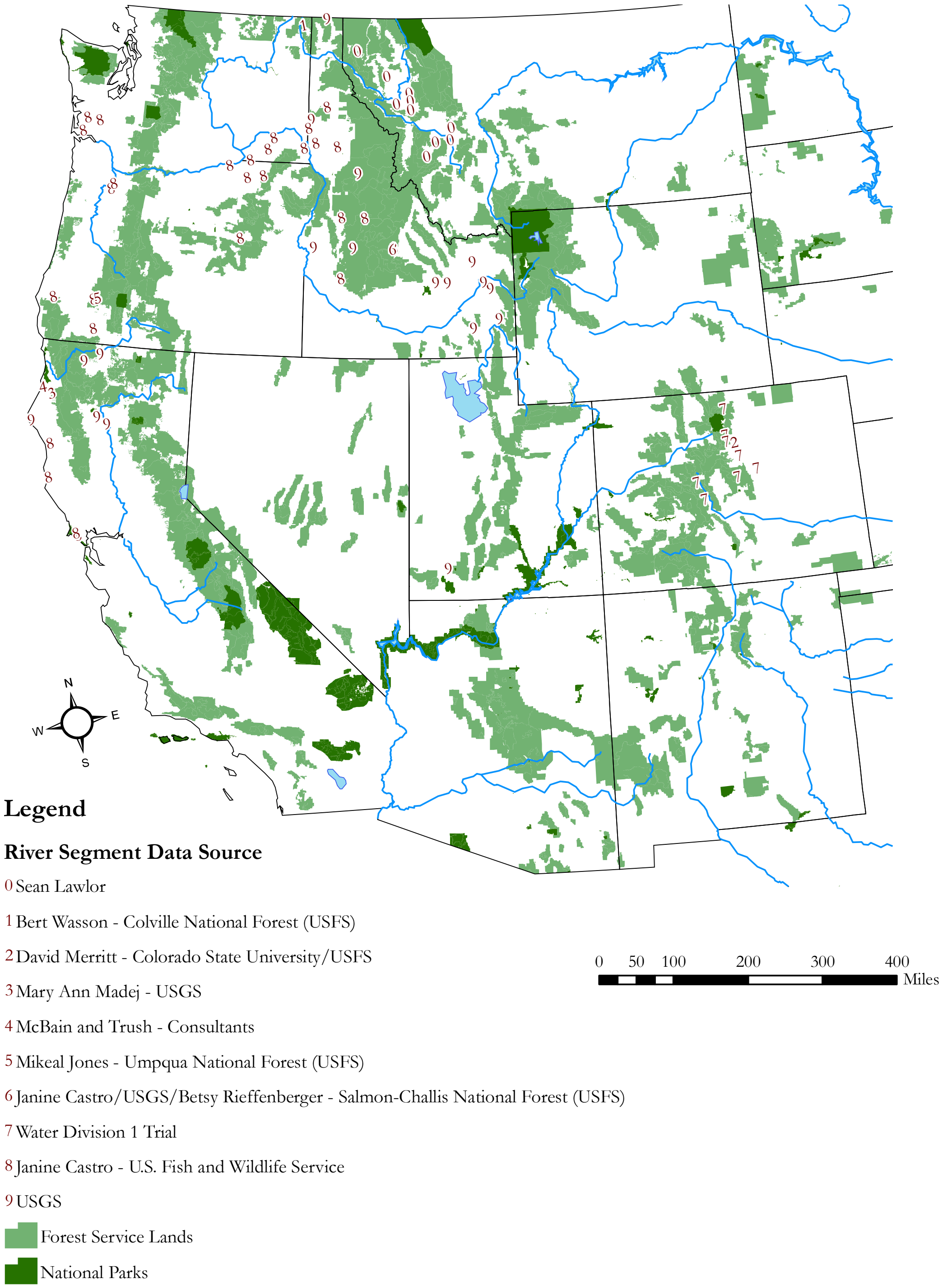

Figure 3.1 Locations of stream segments (Appendix Table B.1) throughout the western U.S. included in this study. Base map data were obtained from ESRI and national atlas (USDOI 2004b, ESRI 2005).

A second dataset was compiled of cross sections occurring only with in Nebraska (Figure 3.2). This dataset includes 20 cross sections along 18 river segments. There are eleven dune-ripple cross sections and nine pool-riffle cross sections (Table 3.3). The average annual flow (AAF) of these 18 river segments is 98.26cfs, ranging from 8.82 to 212.25cfs (See Appendix Table B.2).

Table 3.1 Summary of the number of cross sections within each state

State Summary (#)	
California	22
Colorado	58
Idaho	25
Montana	26
Oregon	11
Utah	1
Washington	8
Total	151

Table 3.2 Summary of the number of cross sections in each Montgomery-Buffington stream type

Stream Type Summary (#)	
Pool-Riffle	46
Plane Bed	68
Step-Pool	34
Dune-Ripple	3
Total	151

The PHABSIM data collected for this study consisted of three datasets. There is a PHABSIM dataset for pool-riffle, plane bed, and step-pool stream types. The three PHABSIM reaches occur in Colorado streams. These reaches were located on Halfmoon Creek, Stevenson Creek, and West Willow Creek (plane bed, step-pool, and pool-riffle respectively). Each dataset contained three calibration discharges with velocity measurements, and multiple cross sections along the longitudinal profile of the stream reach. The multiple cross sections were used to model fish habitat for multiple macro-habitat types (pools, runs, and riffles).

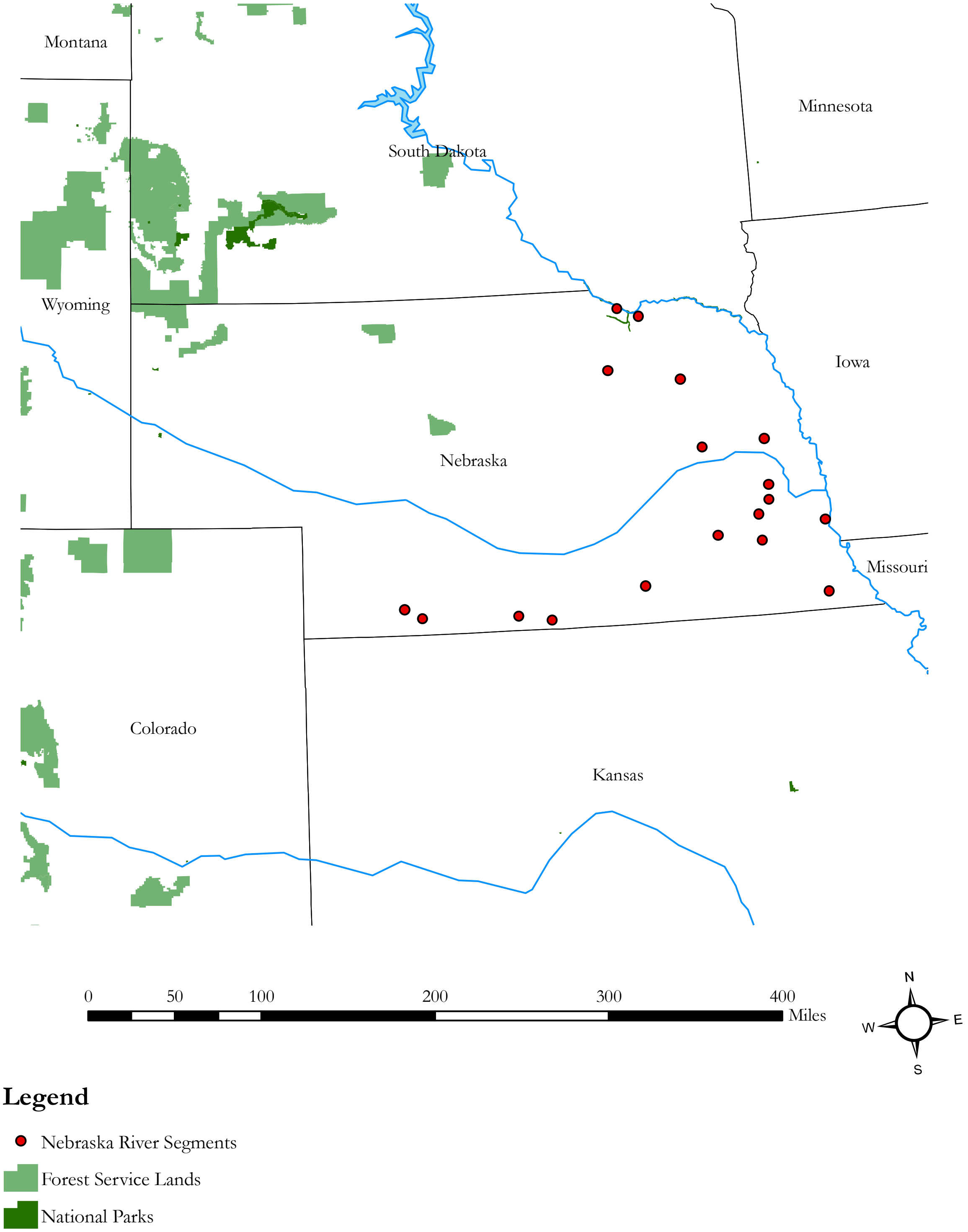

Figure 3.2 Locations of stream segments (Appendix Table B.2) in Nebraska used in additional Tennant analysis. Base map data were obtained from ESRI and national atlas (USDOI 2004b, ESRI 2005).

These four stream types (pool-riffle, plane bed, step-pool, and dune-ripple) are not found equally within the western U.S. or Tennant's study locations. The step-pool stream type is partially defined through the slope of the stream bed, requiring a slope from three to ten percent. Pool-riffle and plane bed have somewhat overlapping slope ranges of 0.1 to 2% and 1 to 3% respectively. These three stream types are common on National Forest Service administered lands, especially the mountainous, western U.S. Dune-ripple streams are characterized by slopes less than 0.1%. Flatter regions of the U.S. will be less likely to have step-pool streams and to a lesser degree plane bed streams. The data collected in Nebraska only contained streams with slopes less than 1%. Streams in mountainous areas of the western U.S. had a smaller occurrence of dune-ripple streams showing a tendency towards higher gradient streams. Tennant's original dataset contained stream reaches from Montana, Wyoming, and Nebraska. Even though this study was unable to determine the actual locations of the stream reaches within these states, there is a high likelihood that the streams were on average of a lower gradient than the stream segments in the main dataset of this study. Therefore this study will use the Nebraska dataset to try to better represent Tennant's original data in the specific context of replicating Tennant's width (percent width), depth, and velocity measurements.

Table 3.3 Summary of the number of cross sections in the Nebraska dataset in each Montgomery-Buffington stream type

Stream Type Summary (#)	
Pool-Riffle	9
Dune-Ripple	11
Total	20

3.2.1 Data Sources

Data for this study came from two main types of sources; USGS gage discharge measurements, and USDA Forest Service project data (See Appendix Table B.1). All of the streamflow data and the majority of the rating curves were from the NWIS database (USGS 2005). The USGS gage discharge measurements were located through out the western U.S. and were a limited source of data. The Nebraska cross sections were exclusively from this USGS source. These discharge measurements are taken at different stages and discharges to create a rating curve. Measurements chosen for this study were at high stage levels so that the cross section profiles were wider, since the USGS only surveys to the edge of the water.

Data from Janine Castro (USDA Forest Service) are all located in the Pacific Northwest (Figure 3.1). These data were collected for use in her graduate work at Oregon State University (Castro 1997). These data were more complete than the USGS discharge measurements. Most of these sites had field measurements of slope and Manning's n, in addition some included Wolman pebble counts (Table 3.4).

Table 3.4 Summary of the data sources used in this study

Data Source	Number of Gages	Number of Pebble Counts	Number of Rating Curves	Number of Cross Sections
Bert Wasson	1	0	0	1
David Merritt	1	0	2	6
Janine Castro	28	4	10	28
Mary Ann Madej	1	1	1	1
McBain and Trush	1	1	1	11
Mikeal Jones	1	2	2	2
Janine Castro/USGS/Betsy Rieffenberger	1	4	1	3
Sean Lawlor	10	10	0	26
USGS	18	0	9	21
WD1	8	12	2	52

Data from the Colorado Water Division 1 Trial (WD1) were provided by the USDA Forest Service (Figure 3.1). These data were originally used in a water rights trial where the United States asserted federal reserved water rights for channel maintenance instream flow purposes (Gordon 1995). The data selected included multiple cross sections for each stream segment, slope, and pebble count information (Table 3.4).

Sean Lawlor (USGS) provided data collected in western Montana (Figure 3.1). These data were used in a USGS scientific investigations report (Lawlor et al. 2004) looking at the channel morphology and peak flows in western Montana. Each of the ten sites, from this source, had detailed information that included a Wolman pebble count, Manning's n, and slope, along with several cross sections per gage (Table 3.4).

The other six data sources are from USFS employees that had done work at single USGS gage sites and are spread throughout the western U.S. (Table 3.4, Figure 3.1). PHABSIM data was obtained from several projects done in Colorado by environmental consulting firms, USGS, and USFS studies.

3.3 Tennant Method Calculations

Tennant defined his percent average annual flow, which is a surrogate for habitat quality, through three physical stream parameters: depth, velocity and percent width (Tennant 1975). These physical parameters along with biological and recreational considerations were used to determine the percentage of the average annual flow (AAF) that correspond to Tennant's perception of fish habitat quality. Tennant stated that the most crucial range of flow is from zero to ten percent of AAF (Table 3.5). Tennant claimed that it is the most crucial range because that is where the parameters (width, depth, and velocity) changed the most rapidly with increased discharge (steepest slope, Figure 3.3) (Tennant 1976). Tennant recognized that although ten percent flow could temporarily sustain the aquatic ecosystem, flows that low were not sufficient for long-term health (Tennant 1976).

Table 3.5 Results of Tennant's original study published in 1975, calculated from field data on 58 cross-sections

Percent AAF	Percent Width	Depth (ft)	Velocity (ft/sec)
0	0	0	0
10	60	1	0.75
30	65	1.5	1.5
100	100	2	2
200	110	3	3.5

The first step in evaluating the Tennant method is to calculate the three physical parameters (depth, velocity, and percent width) for 10, 30, 100, and 200 percent of average streamflow for each of the stream segments collected to see if these independent results yield similar results to Tennant's original study (Tennant 1975)(Figure 3.4). To calculate 10, 30, 100, and 200 percent of the AAF, the mean annual flow for each calendar year was acquired from the NWIS Database (annual streamflow statistics) (USGS 2005). The years were then averaged to determine the average annual flow. Simple multipliers of 0.1, 0.3, 1.0, and 2.0 were used to calculate the discharge at the four percent categories of AAF.

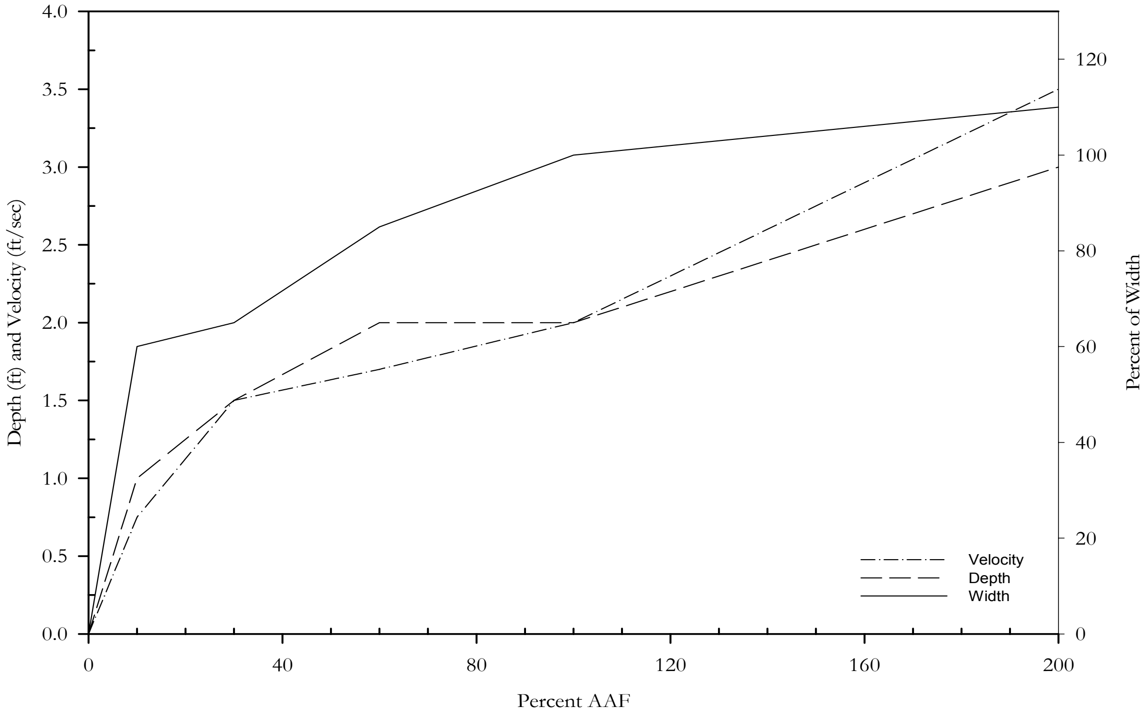

Figure 3.3 Results of Tennant's original study published in 1975, calculated from field data on 58 cross-sections

Tennant was unclear on the calculation of percent width in the original study. The current study will define percent width as the percent of the width at 100% AAF. Tennant's purposed values were 100% width at 100% AAF. Defining percent width for this study around that 100% point from Tennant's study will allow for initial comparability. The validity of this assumption is unsure, therefore conclusions drawn from the percent width data in the current study are suspect and should be treated as such.

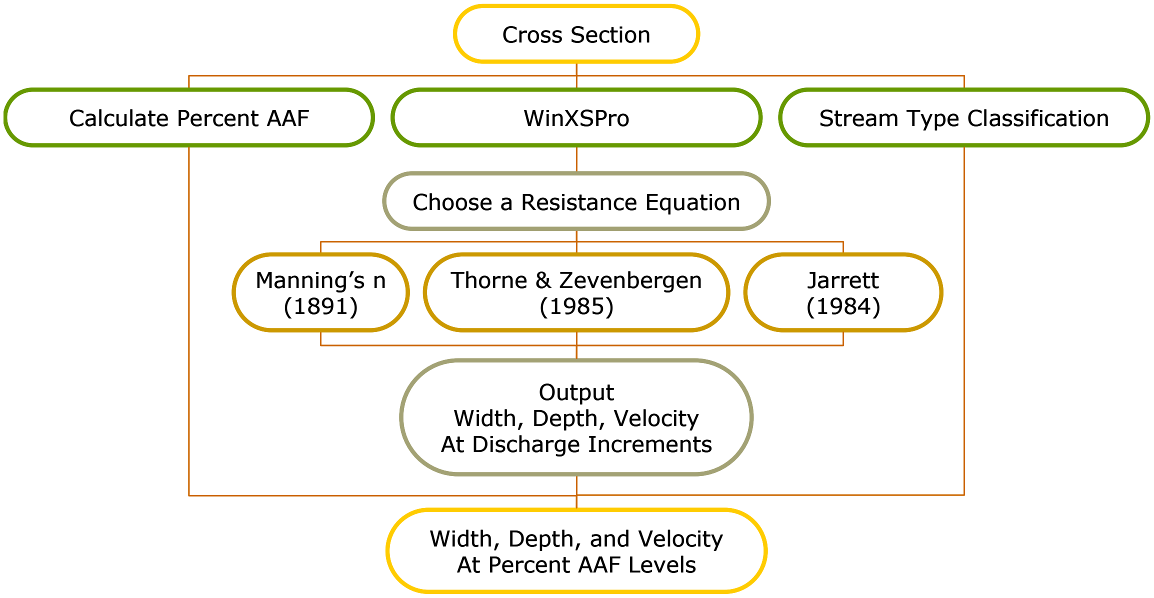

Figure 3.4 Tennant method calculations flow chart

3.3.1 WinXSPro: A Channel Cross-Section Analyzer

Width, depth, and velocity were calculated from the stream segments through the use of WinXSPro. WinXSPro is a cross section analysis program developed by the Stream Systems Technology Center (USDA Forest Service)(Hardy et al. 2005). WinXSPro uses several inputs to calculate a range of parameters including discharge, velocity, width, and wetted perimeter for each stage increment. This program initially requires a cross section profile, and uses one of the four integrated flow resistance equations to calculate the output.

Resistance equations are used to calculate the average cross section velocity (Hardy et al. 2005) at each stage increment. The other parameters such as surface width and wetted perimeter are geometric calculations based solely on the cross section profile.

The first of the four resistance equations is the 'Nelson, et al method'. This resistance equation will not be used in this analysis because it requires detailed information about bed particle geometry that is not available from this dataset (Hardy et al. 2005).

A combination of the other three resistance equations will be used in this analysis to calculate physical stream parameters and flow parameters by the WinXSPro software. The type and detail of the data for each individual cross section profile helped determine the selection of the preferred resistance equation. This allows for the best estimation of geometric and hydraulic parameters that the data permits.

The first flow resistance equation used in this study is the Thorne and Zevenbergen method (1985). This method uses the water surface slope and the d84 (diameter of the secondary axis of the 84th percentile stream bed particle, calculated from a pebble count) to calculate the average flow velocity (Bathurst 1978, Hey 1979, Hardy et al. 2005). Thorne and Zevenbergen's method is prone to overestimating cross section velocities but this error is partly due to sampling errors (Thorne and Zevenbergen 1985). Even with this method's tendency to overestimate velocities as an obvious drawback, it is included as a possible method since it incorporates an added measure of roughness (particle size/d84) that is lost in other methods (Hardy et al. 2005). The Thorne and Zevenbergen method uses one of two equations depending on the inverse relative roughness (R/d84). When the value of the relative roughness is greater than one then the equation developed by Hey (1979)(Equation 1) is used, if the value is less than or equal to one then Bathurst's (1978) equation (Equation 3) is used (Hardy et al. 2005). This means that streams with coarser bed material will be analyzed with Bathurst (1978) and finer bed material with Hey (1979) (Hardy et al. 2005). The equation that Hey (1979) used to describe the velocity of streams with gravel beds relies on the assumption that skin friction, and not spill resistance, is the dominant factor. Hey then developed an equation that uses sediment particle size (d84) to estimate roughness and therefore velocity, within uniform stream beds and flow conditions (Hey 1979). Conversely, Bathurst showed that streams with large-scale roughness require a separate flow resistance equation because these streams do not fit one of the assumptions of small-scale roughness equations; stream beds cannot be considered uniform with large-scale roughness features (Bathurst 1978).

For Finer Bed Material – Hey (1979)

$$\frac{V}{(gRS)^{\frac{1}{2}}} = 5.62\log\left(\frac{a'R}{3.5d_{84}}\right) \tag{1}$$

$$\text{Where: } a' = 11.1\left(\frac{R}{D_{\max}}\right)^{-0.314} \tag{2}$$

V = mean cross-section velocity

g = acceleration due to gravity

d_{84} = intermediate axis for the 84th percentile particle size

D_{max} = maximum depth of section

For Coarser Bed Material – Bathurst (1978)

$$\frac{V}{(gRS)^{\frac{1}{2}}} = \left(\frac{R}{0.365d_{84}}\right)^{2.34}\left(\frac{W}{\overline{D}}\right)^{7(\lambda_E - 0.08)} \tag{3}$$

$$\text{Where: } \lambda_E = 0.039 - 0.139\log\left(\frac{R}{d_{84}}\right) \tag{4}$$

V = mean cross-section velocity

g = acceleration due to gravity

d_{84} = intermediate axis for the 84th percentile particle size

$\overline{D}$ = mean flow depth

W = water surface width

The next method is the user-defined Manning's n. This method allows the input of a Manning's n for the whole stage range or for the input of two n's at different stage levels that are then used to calculate a changing n with the changing stage (Hardy et al. 2005).

Manning's equation (Equation 5) uses hydraulic radius, energy slope, and n, a roughness coefficient to calculate velocity (Manning 1891).

$$V = \frac{k}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{5}$$

V = average velocity in the cross section (ft/s or m/s)

k = unit conversion constant

n = Manning's roughness coefficient

R = Hydraulic radius (ft or M)

S = energy slope (ft/ft or m/m) (water-surface slope for uniform flow)

For use of this method, slope and n are required. Arcement and Schneider's (1989) "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains" is a good resource for understanding the complicated set of parameters that effect the n value. The roughness coefficient starts with a base value which is chosen depending on channel substrate and then adds in several correction factors as follows: 1) the degree of irregularity which takes into account the width-depth ratio of the stream and the banks (exposed roots or rock obstructions, or sloughed or eroded banks), 2) channel cross section variations which adds a factor for the change of the channel in the downstream direction, 3) obstructions like stumps, logs, and boulders found in the channel 4) vegetation since vegetation at various stages can have a large effect on channel roughness, and 5) channel meandering (Arcement and Schneider 1989).

The last resistance equation was developed by Jarrett (1984). Jarrett's equation (Equation 6) calculates an n value for the channel from slope and hydraulic radius and then uses this n in Manning's equation to calculate velocity.

$$n = 0.39 S^{0.38} R^{-0.16} \tag{6}$$

n = Manning's roughness coefficient

S = The energy gradient or friction slope

R = The hydraulic radius

Jarrett's equation is used when the initial data does not include an n value or d84, since the only required input is slope (Hardy et al. 2005). Jarrett's equation was mainly tested on high-gradient streams (Jarrett 1984). Use of Jarrett's equation for those streams that do not fit this category can produce errors (Jarrett 1984). Jarrett's equation is retained in this study since high-gradient streams are a focus of this study. Jarrett's equation is also used for stream segments with limited data because of the ease of use stemming from the limited necessary data inputs.

All three resistance equations, included in this study, require slope to complete the necessary computations. Since the slope was not always available from field data there needed to be a methodology for calculating slope for cross sections without direct slope measurements. This was done by looking up the site area on a topomap and measuring the distance of the stream between contour line crossings and calculating slope from that distance.

3.4 Methodology Comparisons

The first part of this study focused on going back to Tennant's original study and recreating the study to determine if it would produce similar results for higher gradient stream types in the western U S. The second part of the analysis is focused on the discharge recommendations that Tennant's methodology produces compared to other methodologies.

For this comparison the main focus will be on the wetted perimeter method as described in Collings (1972). The wetted perimeter method is based on the "breakpoint" in the stream discharge versus wetted perimeter curve (Collings 1972). Defining this point on the curves produces a single discharge that is assumed to represent the preferred salmon rearing habitat (Collings 1972, Gordon et al. 1992). This discharge can then be compared to the discharge range recommendation for fair fish habitat from the Tennant method which is 30% of the AAF, and the minimum requirement of 10% of the AAF (Tennant 1975, Annear and Conder 1984). The decision to compare other methods primarily to the 30% AAF point is based on it's use in Annear and Conder (1984) where they state that 30% AAF is commonly used for recommendations along with 10% AAF as a recommended minimum.

3.4.1 Wetted Perimeter Comparison

Win XS Pro calculates the wetted perimeter at each stage increment along with the discharge. This allows for direct usage of cross section data from the previous section of analysis. Wetted perimeter versus discharge curves were produced from the WinXSPro outputs. The original method of determining the breakpoint is subjective since it is strictly a visual determination (Gippel and Stewardson 1998). This determination is prone to inconsistency errors due to scaling discrepancies in graphs (Gippel and Stewardson 1998). Therefore a more objective determination of the breakpoint will be used for this analysis to gain a more consistent result. This study will use one of the methods set by Gippel and Stewardson (1998), which uses the point on the wetted perimeter curve where the slope of the line equals one (is in unity). This method was chosen over the point of maximum curvature method because it should produce a more comparable point on each curve since the value of the maximum curvature may be different for each cross section. To follow this method the wetted perimeter and discharge data need to be normalized to allow for the point of slope unity to represent an equal, percent of maximum, change in both wetted perimeter and discharge (Gippel and Stewardson 1998).

To determine the point on the curve where the slope of the tangent is in unity (equals one), the curve of the WinXSPro output needs to be described with a regression line. Different channel geometries tend to be best modeled by different types of equations. Triangular geometries tend to be best represented by power equations (Equation 7). And rectangular channel geometries are better described with logarithmic equations (Equation 9).

The slope of the line is then determined by taking the derivative of the function used to describe the data (Equation 8 or 10). This line is then plotted with the percent of maximum discharge data, which is calculated from the regression, to determine what the discharge is at the point where the slope equals one. This discharge, which is a percent of the maximum discharge, is then used to back calculate the discharge in cubic feet per second. This discharge is then divided by the AAF to determine the percent of AAF that is considered the preferred flow for fish habitat from the wetted perimeter (Figure 3.5).

$$P_w = Q^b \tag{7}$$

$$\frac{dy}{dx} = bQ^{b-1} \tag{8}$$

$$P_w = a\ln(Q) + 1 \tag{9}$$

$$\frac{dy}{dx} = \frac{a}{Q} \tag{10}$$

P_w = Wetted Perimeter (percent of maximum)

Q = Discharge (percent of maximum)

$\frac{dy}{dx}$ = slope of the tangent to the curve

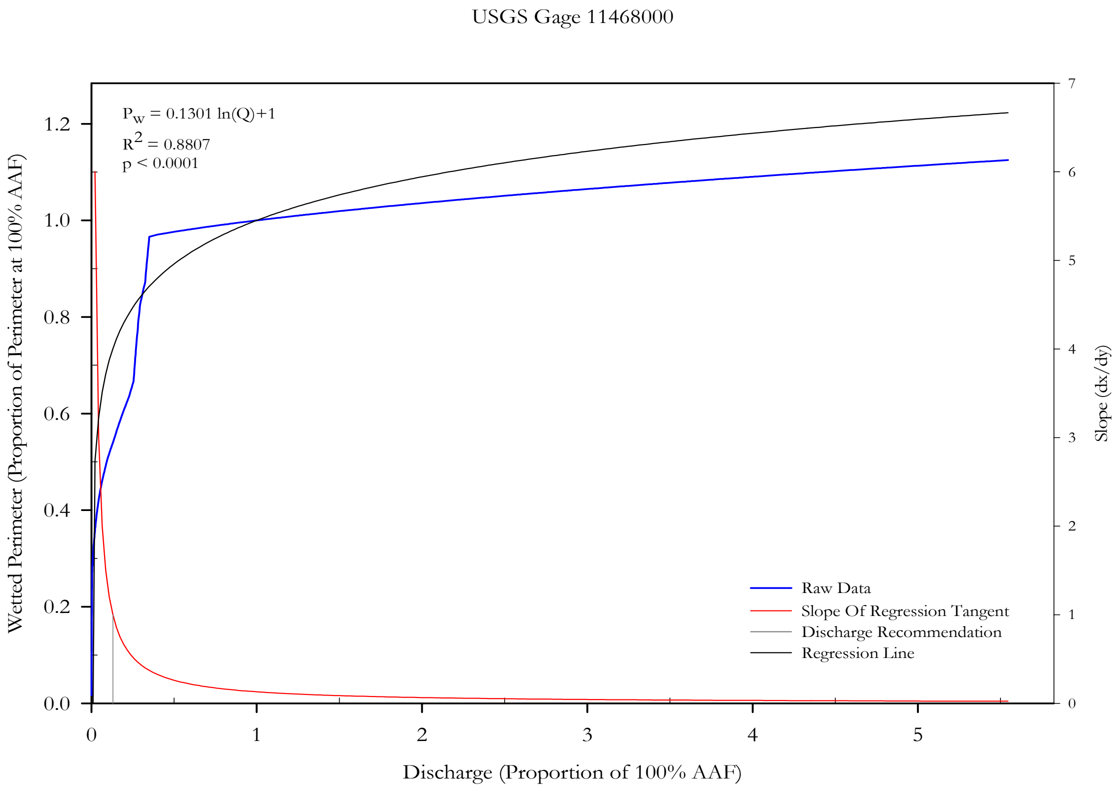

Figure 3.5 Example of a wetted perimeter analysis using data from USGS Gage # 11372000

3.4.2 PHABSIM Comparison

To compare thresholds from the Tennant method to a quantifiable fish habitat index, the PHABSIM data for the three stream segments in Colorado were used. PHABSIM produces a fish habitat index over a range of discharges. The discharges overlap the results from the Tennant method and allow for direct comparison.

3.4.2.a PHABSIM Model

There are three main models that have to be run in PHABSIM to process the data. The data are input as cross sections with information on the x,y coordinates of each point measured in the stream. There are several (each stream segment in this study had three) calibration discharges where the mean column velocities were measured for each point in the cross section and related to the water surface elevation at the calibration discharge. The three models produce a stage discharge relationship, establish mean column velocities, and then integrate fish habitat criteria to produce habitat indices over a range of discharges.

The other initial inputs into PHABSIM are Habitat Suitability Curves (HSC's). Each HSC generally contains two to four curves describing different habitat characteristics (depth, velocity, temperature, and channel index) and relating them to measure habitat use by the selected species. For this study the HSC's used were three sets of curves describing rainbow trout (*Oncorhynchus mykiss*) habitat use. Each HSC used in this study have two curves, one relating the depth to fish preference and the other relating velocity. Temperature and channel index curves were not used because the PHABSIM data did not include these parameters. The three HSC sets represent juvenile rainbow trout, adult rainbow trout in small streams, and adult rainbow trout in medium sized streams.

The PHABSIM model and the steps required to run it are outlined in the "PHABSIM for Windows®: User's Manual and Exercises" by Terry Waddle (2001). There are three models run for each stream reach.

The first model that is run in PHABSIM is the water surface level (WSL) model. There are three possible options to run the WSL model including stage discharge regression (STGQ), Manning's equation (MANSQ), and a water surface profile model (not used in this study). The STGQ model determines the best fit linear regression for the calibration points at each cross section. Then the STGQ model uses these linear regressions (one for each cross section in the reach) and creates water surface elevations for each of the discharges that are going to be simulated using PHABSIM (these discharges are set by the user and should be kept to an acceptable range around the calibration discharges). The MANSQ model applies Manning's equation to determine the water surface level at each simulated discharge. The user supplies a value for Manning's n at each cross section and optionally a beta/D50 value (the mean particle size at the cross section measuring the secondary axis). The model uses these inputs and a simplified version of Manning's equation to determine the water surface elevations at the specified discharges.

The second step in PHABSIM is to run the velocity model (VELSIM). This model determines velocities for each computational cell (half way to the other measurement points is used in the area calculations of each cell) by using the velocities from the calibration discharge measurements. The velocities computed for discharges above the highest calibration discharge will be set by only the highest calibration set, and discharges below the lowest discharge will be calculated only from the lowest calibration set. Discharges between these calibration points will have velocities that are calculated from a combination of the calibration velocity sets. The velocities are calculated through a mass balance approach and using back calculated Manning's n values to calculate velocities with Manning's equation.

The final step in PHABSIM is the habitat model. There are several choices of models to use, for this project the HABITAE model is used, which is the main habitat program. The HABITAE model calculates the weighted usable area (WUA) by integrating the HSC's with the cell depths and velocities. This WUA is an index of how likely the target fish species is to use that area of the stream. PHABSIM produces a relationship between discharge and WUA showing what discharges will correlate to different amounts of fish habitat. Caution is recommended for selecting discharges because the discharge WUA relationship can produce results where the peak value is at a discharge that is greater than the range of natural discharges. For this study the weighted usable area curves will be standardized (proportion of maximum WUA) for comparison across streams and the term 'peak habitat flow' will be used to describe the habitat and discharge and the highest point on the PHABSIM curves.

3.5 Regional Analyses

The focus of this section will be to go back to Tennant's original measurements and determine if there are regional or climatic differences that affect the applicability of the Tennant method. To determine if there are any regional or climatic differences in the applicability, this study will use two different types of comparisons; categorical differences like stream type, state, and ecoregions, and continuous differences like average annual precipitation, average daily maximum temperature, and average daily minimum temperature. Data will be $\log_{10}$ transformed to better conform to the assumptions of all statistical tests run as part of the regional analyses.

3.5.1 Stream Types

The stream type differences will be analyzed using ANOVA followed by performing pair-wise least squares means test with the Tukey-Kramer adjustment for multiple comparisons to see if there are differences between the stream types. This study used the Montgomery-Buffington stream classification. Some streams were independently classified when stream type was not part of the original information.

3.5.1.a Stream Classification

The data for this study came from many different sources; information on each segment was not consistent. So some streams had already been classified into the Rosgen stream types (Rosgen 1996), but most did not have any initial field classification. Streams in this study were classified into the Montgomery-Buffington classification (Montgomery and Buffington 1997). A combination of methods were used to classify each stream. If there was a Rosgen classification, that classification was used with a Montgomery-Buffington/Rosgen synonymy (Cinderelli personal communication) to reclassify the segment. Other streams were classified through the use of a discriminant function developed by Wohl and Merritt (2005). This discriminant function uses bankfull width, d84, and slope to classify streams into one of three stream types, pool-riffle, plane bed, and step-pool channel types (Wohl and Merritt 2005). Since not all of the stream segments contained a d84, field notes were used to estimate this value and ranges were inserted into the function to minimize misclassifications. Any stream segments that had slopes out of the range for mountain streams (below 0.01 percent) were determined from the available data through classification guides (Cinderelli personal communication), in addition all the segments were rechecked using this guide to make sure the resulting classification made sense.

This method of classifying each stream segment allows for the separation of the different stream types for individual analysis. The stream types included in this study will be plane bed, pool riffle, step pool, and dune ripple. The separated data will be examined to see if the trends differ significantly from the trend seen in the first analysis. This will determine if the Tennant method applies to a diversity of stream types. This will allow for an applicability recommendation for the Tennant methodology.

3.5.2 Ecoregions

The ecoregion differences will be analyzed using ANOVA followed by performing pair-wise least squares means test with the Tukey-Kramer adjustment for multiple comparisons to see if there are differences between the ecoregions. This study will use Bailey's ecoregions which will be linked to stream reaches using USGS Gage locations with ecoregion data in ArcGIS (Figure 3.6)(Bailey 1995, USDOI 2004a). There are eight ecoregion divisions that contain stream segments; the number of cross sections in each of these eight divisions is not evenly distributed, therefore three of the ecoregions have sufficiently low number of cross sections that they will not be discussed fully throughout the rest of this study.

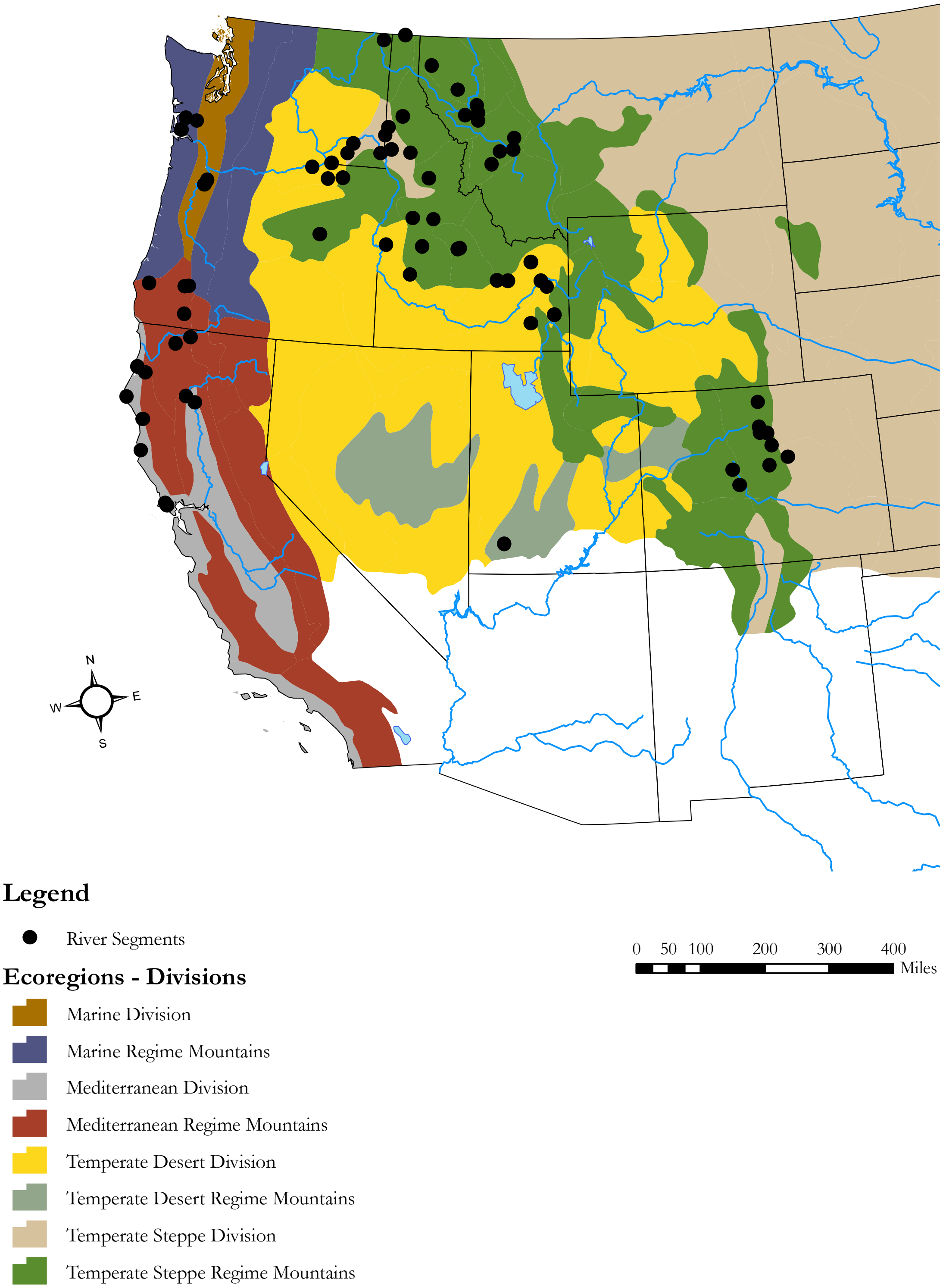

Figure 3.6 Map of Bailey's ecoregions throughout the western U.S. included in this study, for use in the regional analysis. Map data were obtained from ESRI and national atlas (USDOI 2004a, ESRI 2005).

3.5.3 States

The differences between states will be analyzed by running pair-wise least squares means test with the Tukey-Kramer adjustment for multiple comparisons to determine differences in Tennant's original data compared to this study's dataset.

3.5.4 Hydro-Climatic Data

The hydro-climatic data (PRISM data) for this study are three grids composed of average annual precipitation, average daily maximum temperature, and average daily minimum temperature (PRISM 2004a, 2004b, 2004c). These data, unlike the categorical data used in the rest of the regional analyses, are continuous data. The data will be associated with the USGS Gage data through ArcGIS as was the ecoregion data. The Hydro-Climatic data will be used in regressions with the study dataset to look for significant relationships (using r-square and p-values).

3.6 Nebraska Data Comparison

To further evaluate Tennant's original width, depth, and velocity measurements the data collected in Nebraska will be compared to Tennant's original values. This comparison will attempt to replicate Tennant's original values through use of data that more closely represents the original dataset. The range of values calculated in this study for width, depth, and velocity will then be compared to the values that Tennant stated using a standard hypothesis test to determine if the mean of the Nebraska population is different from Tennant's values.

Chapter 4

4.0 Results

4.1 Tennant Method Calculations

The width, depth, and velocity calculation results for all cross sections are summarized in Table 4.1, Table 4.2, and Figure 4.1 to Figure 4.3. Means of calculated parameter values were compared to Tennant's values. Differences were tested using two-sided t-tests. The significance level for this study is a p value less than 0.05 unless otherwise stated.

Table 4.1 Summary statistics from width, depth, and velocity calculations, on the 151 cross sections in this study, in comparison to Tennant's results from his 1975 study.

	Width as Percent of the Width at 100% AAF			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	60.00	65.00	100.00	110.00
Average	59.85	77.48	100.00	116.35
Standard Deviation	16.91	13.68	0.00	16.55
Minimum	21.78	32.95	100.00	100.00
Maximum	99.14	99.56	100.00	208.57
Number of Stations	151	151	151	151
	Depth (ft)			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	1.00	1.50	2.00	3.00
Average	0.76	1.12	1.72	2.24
Standard Deviation	0.44	0.62	0.90	1.18
Minimum	0.16	0.25	0.45	0.64
Maximum	3.48	4.29	6.60	8.76
Number of Stations	151	151	151	151
	Velocity (ft/sec)			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	0.75	1.50	2.00	3.50
Average	1.33	1.89	2.87	3.66
Standard Deviation	0.64	0.85	1.23	1.52
Minimum	0.35	0.60	1.08	1.45
Maximum	4.27	5.03	6.51	8.10
Number of Stations	151	151	151	151

4.1.1 Depth Calculations

Tennant's depth results showed the stream to be deeper than the streams in the current study for all percent AAF categories (Figure 4.1). The spread of the depth data increased when looking at the higher percent AAF values, and the distribution of the points within each percent AAF are visually skewed towards shallower depths than Tennant's results. Even though the data show Tennant's results to be deeper than the 75th percentile, they are within one standard deviation from the mean of the data. The average of the depth data in this study are 0.76, 1.12, 1.72, and 2.24 ft which are the 10%, 30%, 100%, and 200% AAF respectively, with standard deviations of 0.44, 0.62, 0.90, and 1.18 respectively (Table 4.1). These standard deviations are large enough to question the significance of the differences between the depths at each percent AAF because it therefore includes a considerable amount of overlap in each percent category. The means of all variables tested were significantly different than Tennant's values (t-test, $p<0.05$) (Table 4.2).

Table 4.2 ANOVA table of Tennant calculations showing differences between data collected in this study and Tennant's original values (Tennant 1975).

Variable	Degrees of Freedom	t Value	Pr > |t|
Width 10% AAF	150	-0.11	0.9145
Width 30% AAF	150	11.21	<0.0001
Width 100% AAF	150	-	-
Width 200% AAF	150	4.72	<0.0001
Depth 10% AAF	150	-6.56	<0.0001
Depth 30% AAF	150	-7.48	<0.0001
Depth 100% AAF	150	-3.76	0.0002
Depth 200% AAF	150	-7.87	<0.0001
Velocity 10% AAF	150	11.24	<0.0001
Velocity 30% AAF	150	5.66	<0.0001
Velocity 100% AAF	150	8.71	<0.0001
Velocity 200% AAF	150	1.27	0.2060

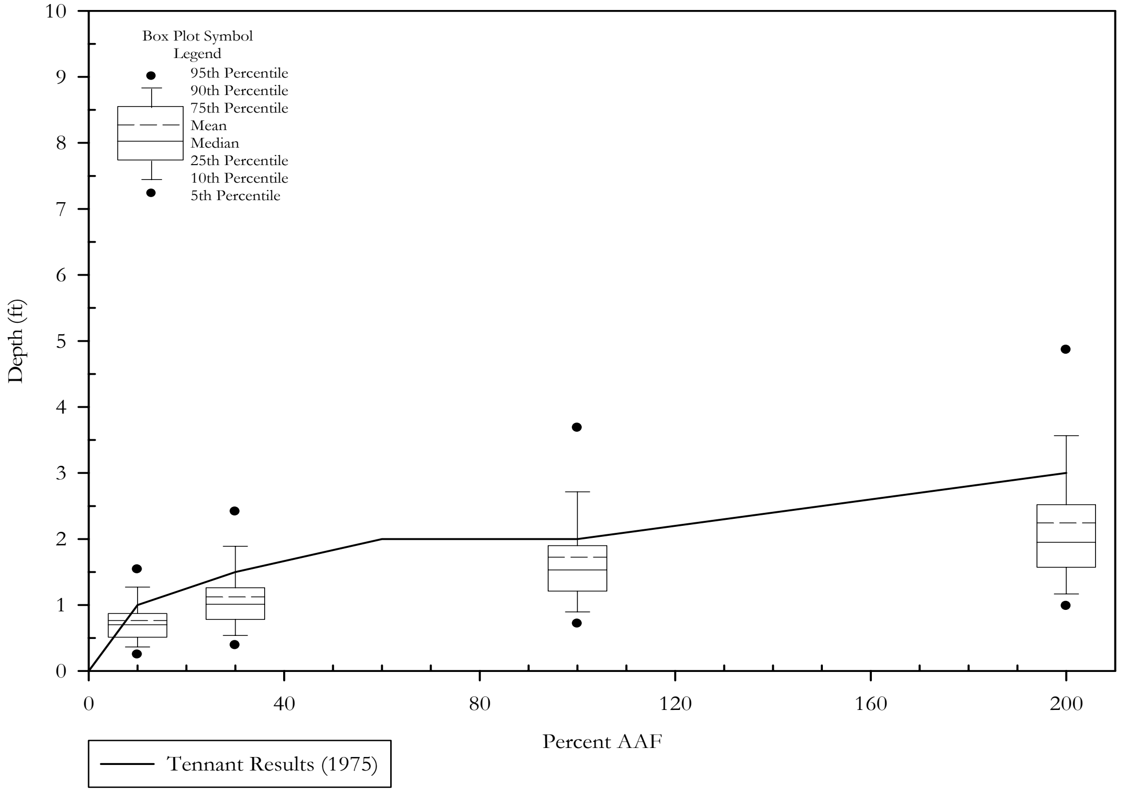

Figure 4.1 Box plot showing the results of the depths corresponding to each %AAF being tested in the Tennant method analysis. This graph shows that Tennant's original calculations of depths at each %AAF are higher than the data from this study demonstrates (above the 75th percentile).

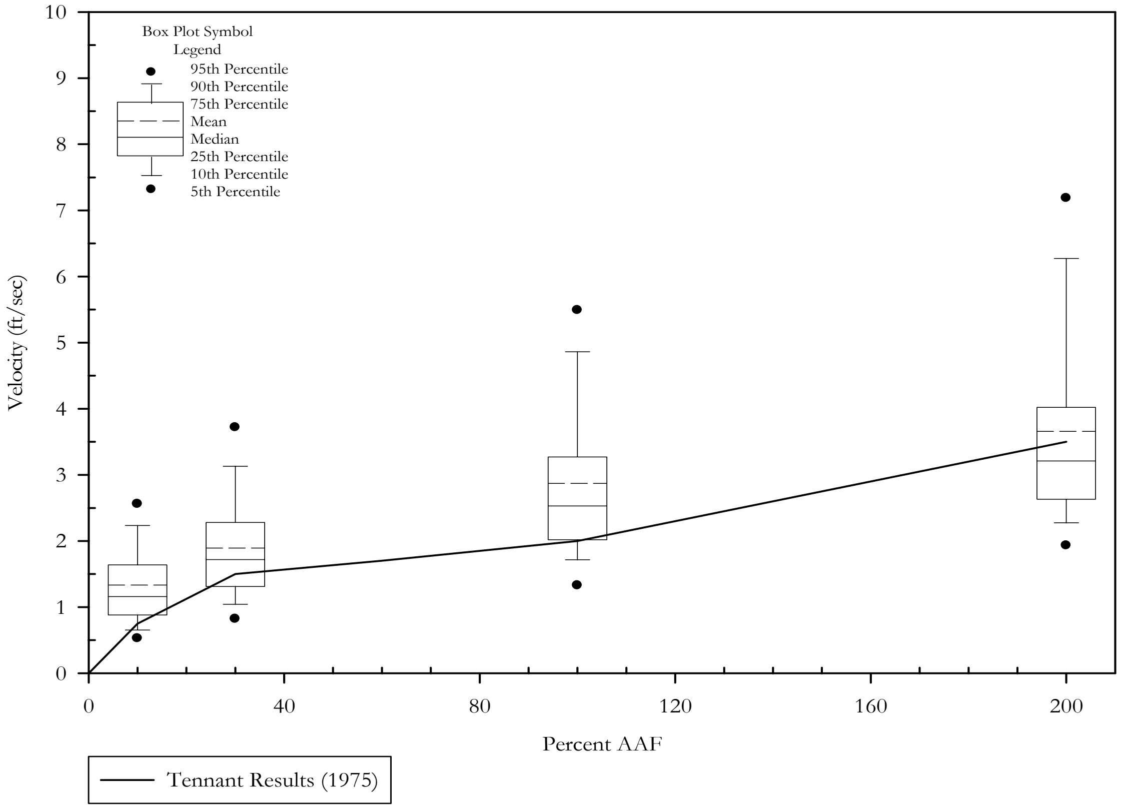

Figure 4.2 Box plot showing the results of the velocities corresponding to each %AAF being tested in the Tennant method analysis. This graph shows that Tennant's original calculations of velocities at each %AAF are lower than the data from this study demonstrates.

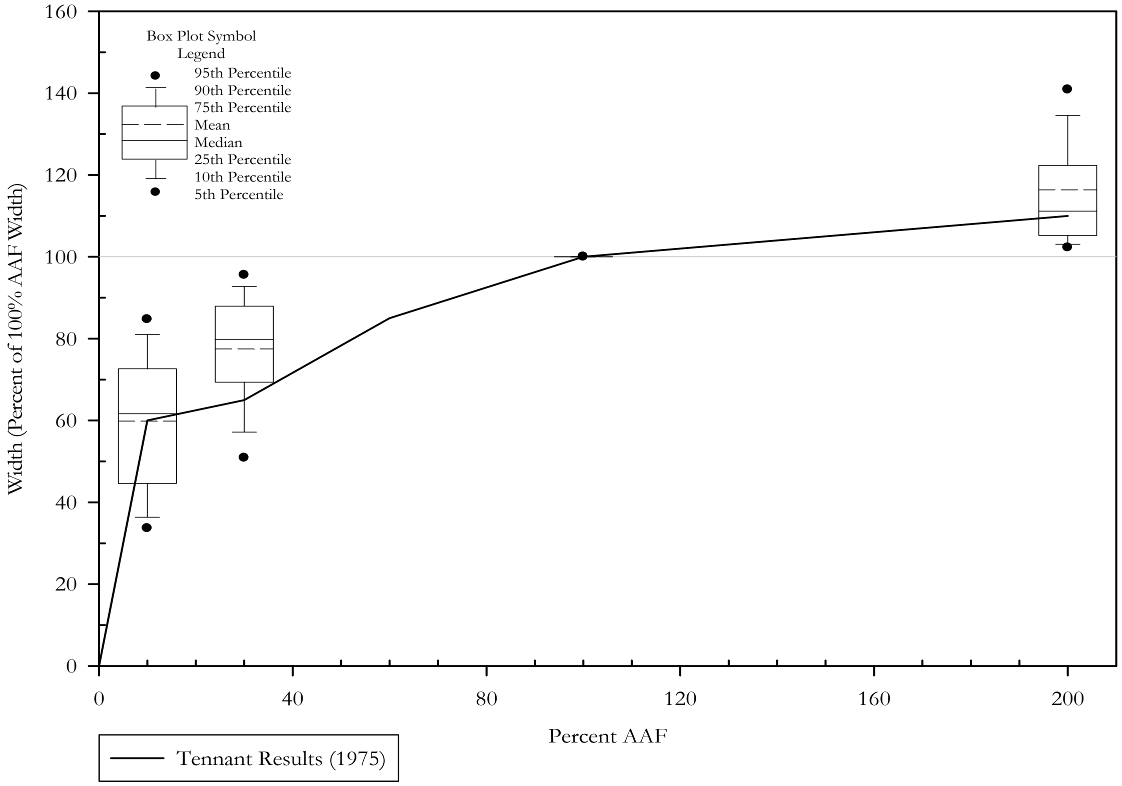

Figure 4.3 Box plot showing the results of the widths (percent of the width at 100% AAF) corresponding to each %AAF being tested in the Tennant method analysis. This graph shows that Tennant's original calculations of percent width at each %AAF are approximately equal to the data from this study except for the percent width at 30% AAF where Tennant's percent width is well below the data from this study (below the 25th percentile).

4.1.2 Velocity Calculations

Although the velocities that Tennant put forth are lower than the data indicates in this study (Table 4.1, Figure 4.2), the velocities are within one standard deviation of the mean. The velocities for 10%, 30%, 100%, and 200% AAF are 1.33, 1.89, 2.87, and 3.66 ft/sec, respectively, with standard deviations of 0.64, 0.85, 1.23, and 1.52 respectively. The velocities at each percent AAF are not well separated from each other and are visually skewed towards the lowest point velocity. Tennant's velocity at 200% AAF, which is 3.5 ft/sec, is the closest velocity point since it is between the mean of 3.66 and the median of 3.21 ft/sec. The velocity data at 200% AAF is also not significantly different from

Tennant's value of 3.5 ft/sec (t value = 1.27, p value = 0.2060, DF = 150). The other three percent AAF categories were significantly (p value less than 0.05) different than Tennant's values (Table 4.2).

4.1.3 Width Calculations

The results of the width calculations show that the percent of stream width at 10% AAF and 200% AAF are similar to Tennant's original results; the average stream width at 30% AAF was lower on the streams in the Tennant study (Table 4.1, Figure 4.3). The data indicates that at 10% AAF the percent width is 59.9%, with a standard deviation of 16.9 where as Tennant stated 60%. With a calculation of 60-65% width at 30% AAF, Tennant's number is marginally within of one standard deviation (13.7) away from the average of 77.5%. There is some variation seen in the distribution of the data at each percent AAF level. This variation seems to be a factor of defining the width at 100% AAF as 100% therefore creating a barrier that prevents data at 30% AAF and 200% AAF from crossing the 100% point; creating a skewed data set towards 100%. The data at 30 and 200% AAF are significantly different from Tennant's values, but the width data at 10% AAF is not significantly different from Tennant's values (Table 4.2).

4.2 Methodology Comparisons

4.2.1 Wetted Perimeter Method

The wetted perimeter method results are summarized in Table 4.3, Table 4.4, Figure 4.4, and Figure 4.5. The results from this method are discharge recommendations from each of the cross sections and the percent of AAF that is represented by that discharge recommendation. To be consistent with Tennant's work, the current study examines percent AAF. The mean for the entire dataset in the current study is 16.13% AAF with a standard deviation of 4.38. This mean is significantly different from both 10 and 30% AAF values (Table 4.4).

Table 4.3 Summary statistics from the wetted perimeter calculations, on the 151 cross sections in this study, in comparison to Tennant's 30% AAF rating from his 1975 study.

	Wetted Perimeter Recommendation				
	Discharge	Percent of AAF	Rsqr	Regression Type	
Average	23.75	16.13	0.9309	Power	99
Standard Deviation	36.38	4.38	0.0538	Log	52
Minimum	0.94	8.62	0.6976		
Maximum	219.70	30.98	0.9986	Power Rsqr	0.9316
Number of Stations	151	151	151	Log Rsqr	0.9295

The wetted perimeter method used in this study includes two regression equations that are fitted to the data and then the one that fits better (higher r^2 value) is used for the discharge recommendation. The results of each regression type follow: 1) log regressions have a mean of 13.57% AAF and a standard deviation of 2.96, and 2) power regressions had a mean of 17.48% AAF and a standard deviation of 4.41. The two regression types were significantly different from each other when compared to both percent AAF values (10% AAF: Satterthwaite unequal variance t-test, t value = -23.02, p value < 0.0001, DF = 140; 30% AAF: Satterthwaite unequal variance t-test, t value = -56.14, p value < 0.0001, DF = 140).

Table 4.4 ANOVA table of percent average annual flow calculations showing differences between data collected in this study and Tennant's 10 and 30 % AAF values (Tennant 1975).

Variable	Degrees of Freedom	t Value	Pr > |t|
10% AAF	150	17.23	<0.0001
30% AAF	150	-38.95	<0.0001

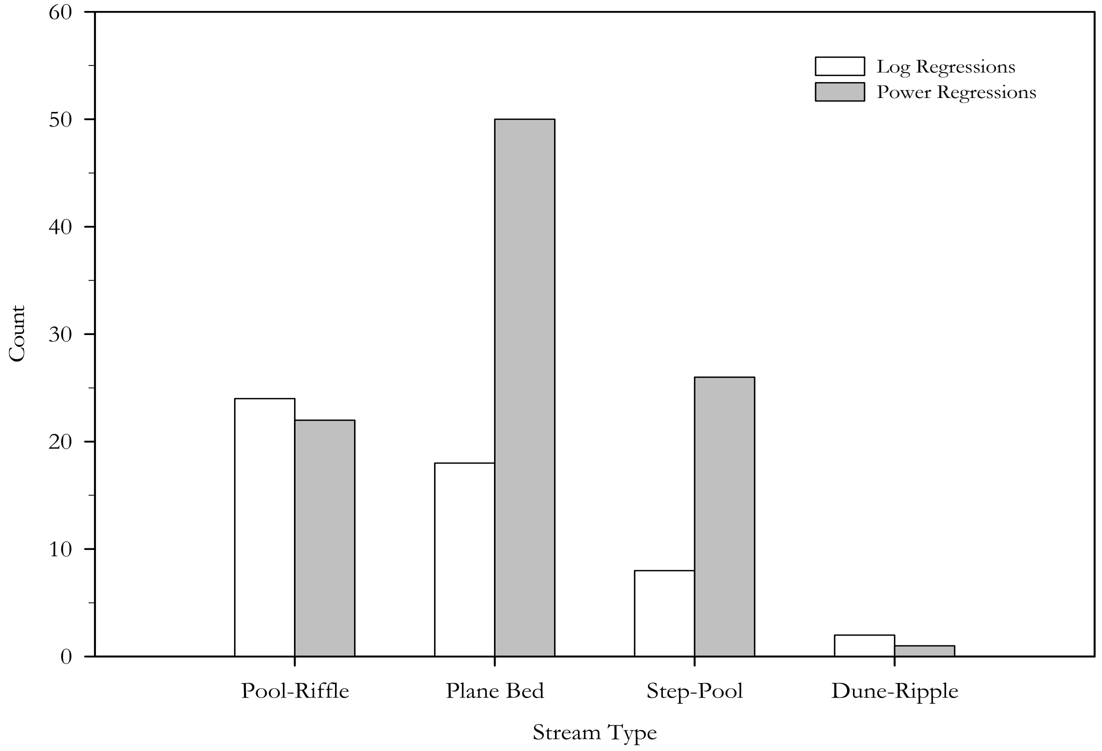

Figure 4.4 A histogram showing the distribution of cross sections that are in each stream type that had either a log or a power equation used to characterize the sites' wetted perimeter curves.

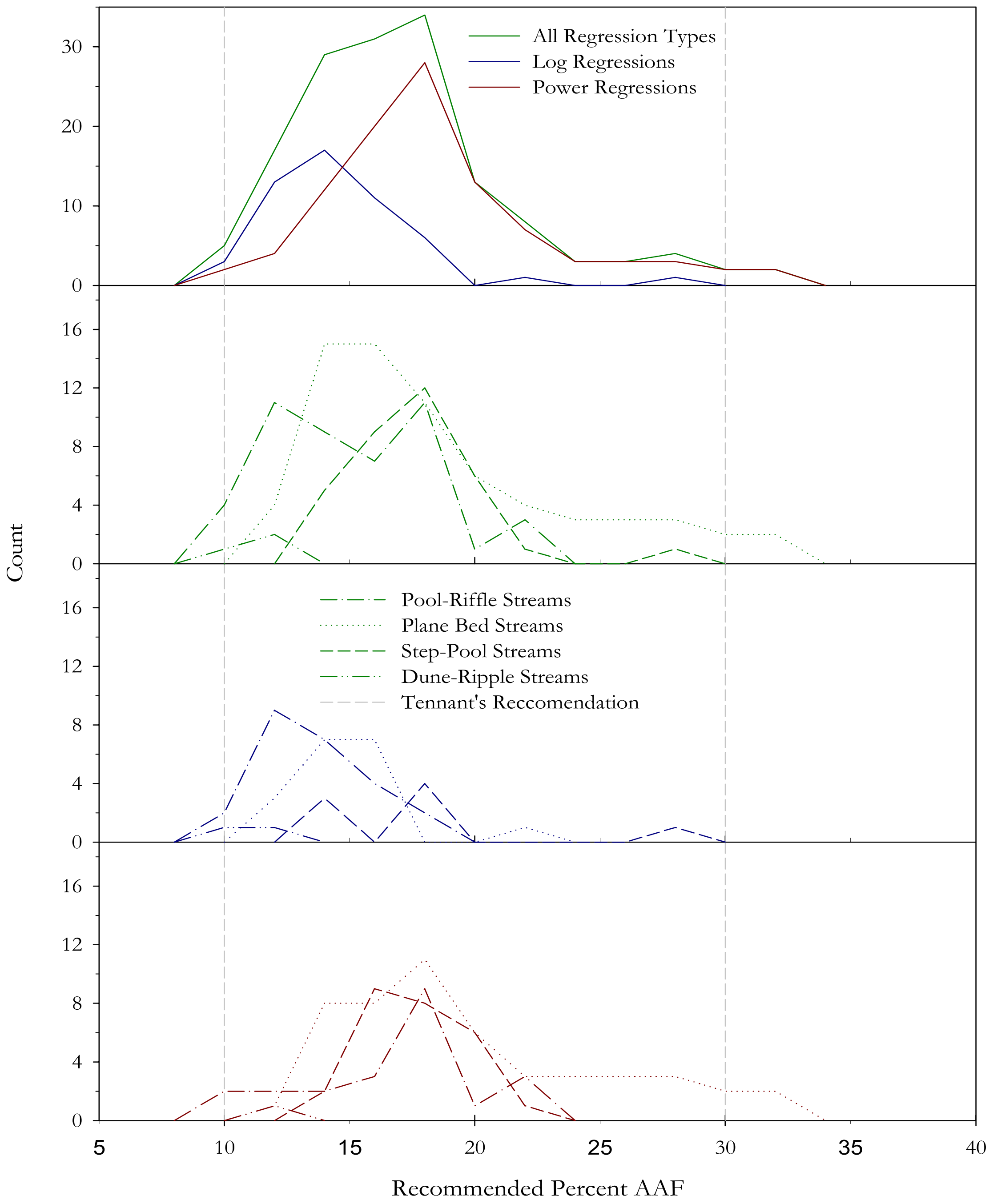

Figure 4.5 Stacked histograms showing the percent AAF recommendations from the wetted perimeter analysis, divided by regression type and stream type in comparison to Tennant's 10% and 30% AAF recommendations.

4.2.2 PHABSIM Method

The methodology comparison with the PHABSIM model is summarized in Figure 4.6 through Figure 4.8. These figures represent each of the stream segments run in PHABSIM and are from the three predominant stream types included in this study (pool-riffle West Willow Creek Colorado, step-pool Stevenson Creek Colorado, and plane bed Halfmoon Creek Colorado). The PHABSIM model was run using three habitat suitability curves (HSCs) producing three weighted usable area (WUA) curves; these curves represent juvenile and adult rainbow trout. Of the three HSC curves, one characterizes the physical habitat preferences of juvenile rainbow trout. The other two HSC curves characterize adult physical habitat preferences, divided into two stream size categories (small and medium). The two stream categories are included because the preference for rainbow trout (and probably other fish species) will change with, both, the potential habitat within the stream, and the size of the fish themselves. Larger fish can occupy a wider range of hydraulic conditions, especially velocity.

Halfmoon Creek data show that by Tennant's 30% AAF the habitat level is at or above 90% of the peak habitat flow values for all three curve sets (Figure 4.6). Discharge data were not collected at a low flow so that habitat level could not be compared to Tennant's 10% AAF value. Peak habitat levels for all three WUA curves occur at discharges at or below the 50% AAF value.

The data from Stevenson Creek, a step-pool system, show a different trend than Halfmoon Creek, a plane bed stream type. The WUA curves continue to increase at higher flows while dropping briefly around 100% AAF, where Halfmoon Creek WUA curves decreased after peaks occurred. At 10% AAF the WUA curves show between 15% and 60%

of the peak habitat flow (Figure 4.7). Additionally at 30% AAF the peak habitat flow is between 40% and 85%, showing an increase between 10% and 30% AAF (Figure 4.7).

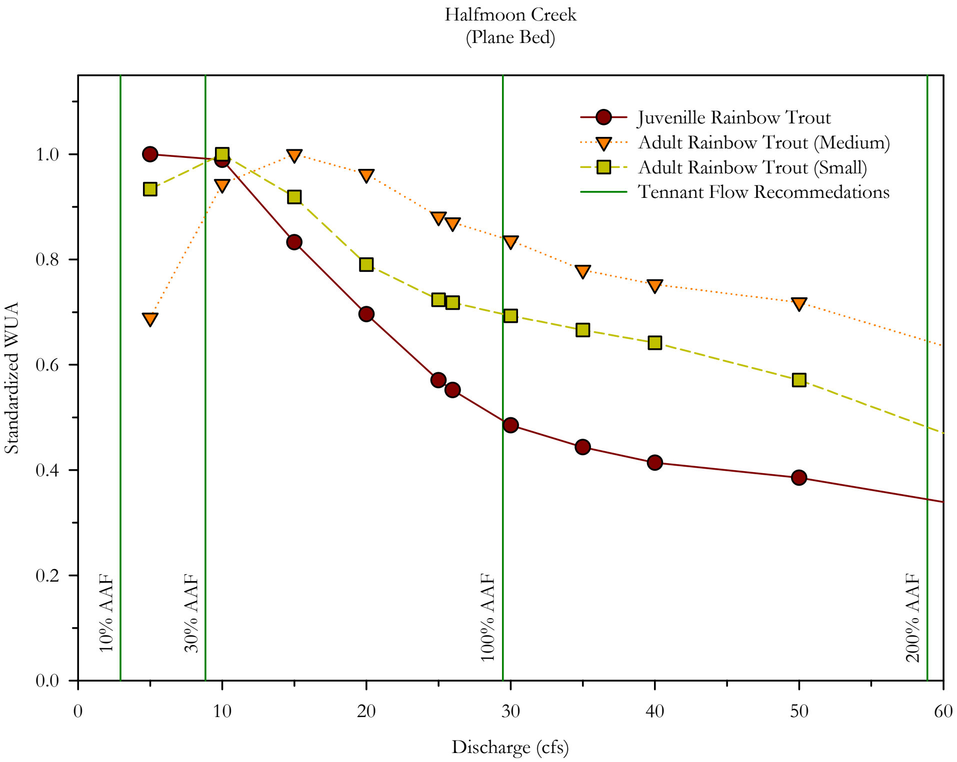

Figure 4.6 PHABSIM Weighted Usable Area curve for Halfmoon creek, CO. showing the standardized habitat curves for rainbow trout at discharges corresponding to Tennant's percent AAF recommendations

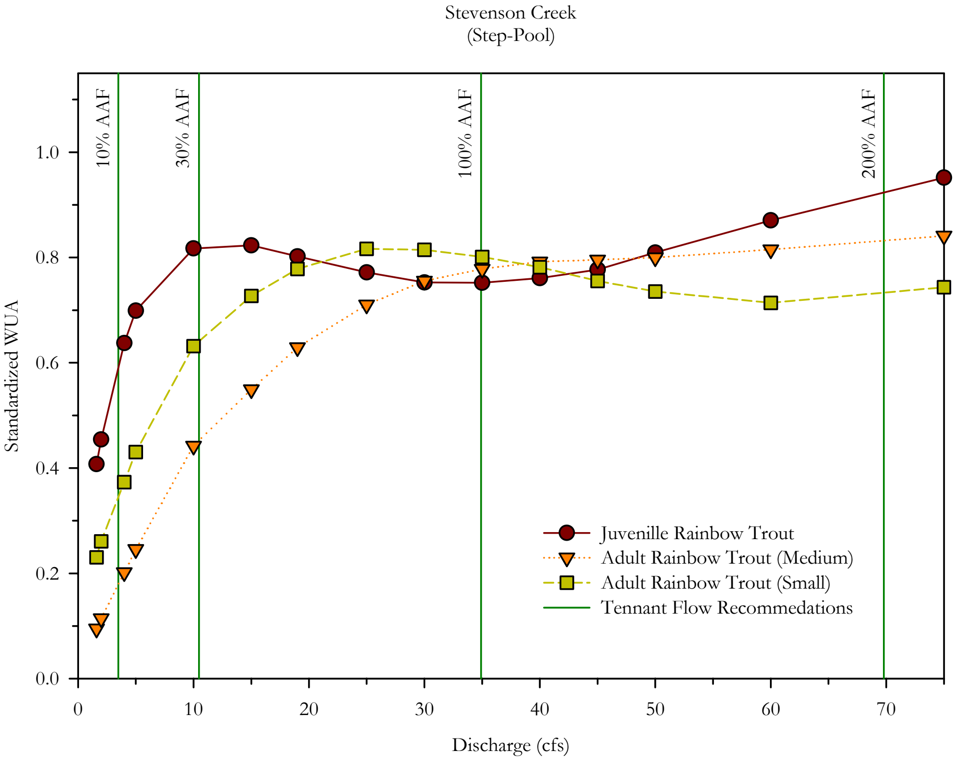

Figure 4.7 PHABSIM Weighted Usable Area curve for Stevenson creek, CO. showing the standardized habitat curves for rainbow trout at discharges corresponding to Tennant's percent AAF recommendations

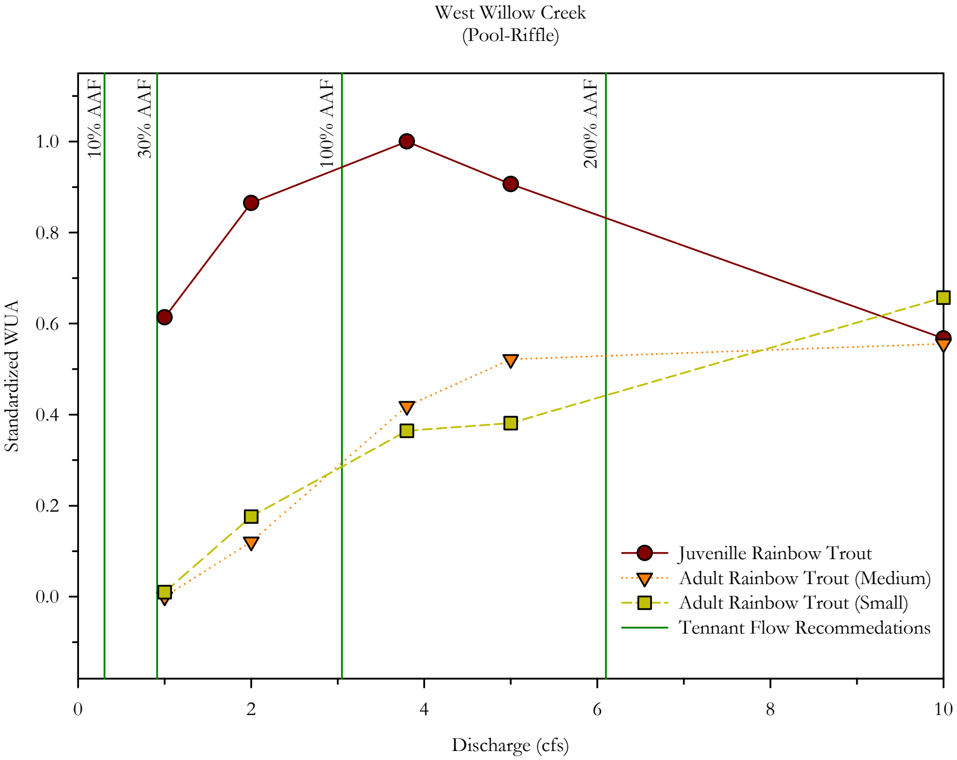

Figure 4.8 PHABSIM Weighted Usable Area curve for West Willow creek, CO. showing the standardized habitat curves for rainbow trout at discharges corresponding to Tennant's percent AAF recommendations

West Willow Creek WUA curves do not extend down to the 10% AAF flow due to the range of discharges used for the PHABSIM. The 30% flow shows a different result than the other two streams; the adult rainbow trout WUA curves show approximately 0% peak habitat flow at 30% AAF (Figure 4.8). The juvenile curve shows approximately 60% peak habitat flow at 30% AAF, illustrating a drastic contrast between flow requirements for adult and juvenile rainbow trout (Figure 4.8).

All three streams showed a common trend, that the juvenile peak habitat flow occurs at a lower discharge than the adult peak habitat flow. This is due to the juvenile life stages use of lower velocities and shallower depths. The two adult WUA curves showed similar trends within each stream along the discharge continuum. The differences tended to be in the magnitude of the percent of the peak habitat flow at any particular discharge. Tennant's results underestimated habitat needs for adult life stages in a pool-riffle stream type.

4.3 Regional Analyses

4.3.1 Stream Types

The stream type analysis results are summarized in Appendix C. One difference in the depth data was apparent. The pool-riffle stream type data did not follow the same distribution as the whole data set. The pool-riffle data were very close to Tennant's original result values, 1.00, 1.50, 2.00, and 3.00 ft. The means fell at 0.98, 1.45, 2.26, and 3.00 ft for 10%, 30%, 100%, and 200% respectively (Appendix Table C.1). The averages of the current study's pool-riffle data were similar to Tennant's results; the standard deviation and range/spread of the data are considerably larger than that of the entire dataset. Instead of having standard deviations ranging from 0.46 to 1.22 like the full data set the standard deviations were from 0.65 to 1.59. The plane bed and step-pool streams both had considerably lower mean depths and smaller standard deviations than Tennant's values. The plane bed streams had slightly higher means compared to the step-pool streams, 0.67, 0.98, 1.48, 1.90 ft, and 0.64, 0.92, 1.40, 1.78 ft respectively.

The plane bed streams have velocities that are less variation at each percent of AAF. The standard deviations and ranges are smaller than the other stream types and the velocity data as a whole. The plane bed data also fit Tennant's results better than the rest of the data set. The 30% AAF data are 1.53 ft/sec for this study and Tennant stated 1.50 ft/sec. In contrast the 200% AAF data is on average lower than Tennant's of 3.5 ft/sec at 2.98 ft/sec.

The step-pool and pool-riffle data seem to have an opposite trend from the plane bed streams. The data in these two types have a larger standard deviation than the whole data set, showing a range of velocities from 1.99 to 8.10 ft/sec and 1.45 to 7.49 ft/sec in the

200% AAF category, for step-pool and pool-riffle stream types respectively. In addition the velocities of the step-pool and pool-riffle stream types are higher than the plane bed velocities and are higher than Tennant's results, than the entire data set is.

The three main stream types did not show any obvious variation for the overall percent width trend or from each other. The step-pool streams showed a minor variation from the overall trend. The data for the 10% AAF is not as evenly distributed and resembles the 30% data because it is skewed towards the upper end or the 100% width point.

4.3.2 Ecoregions

The regional analysis results for determining ecoregion differences in the width, depth, and velocity data are summarized in Appendix D. The number of cross sections in the different ecoregions are not evenly distributed. The temperate steppe regime mountain division (TempStepRMT) contains approximately two thirds of the cross sections (97). Since the number of cross sections is so skewed towards one division the ecoregion patterns were examined on a larger scale, focusing on the marine and mediterranean divisions as being climactically different from the temperate divisions for interpreting the results from this analysis.

The 10% and 30% AAF mean depth categories did not differ by ecoregion ($p>0.05$, Appendix Table D.1). At 100% AAF the TempStepRMT division was significantly different from mediterranean regime mountain division (MedRMT, Appendix Table D.1). Additionally at 200% AAF the TempStepRMT was significantly different from the MedRMT and the marine division (MarDiv, Appendix Table D.1). Two of the ecoregion divisions were more closely correlated with Tennant's depth values: the mediterranean division (MedDiv) and the temperate desert division (TempDesDiv, Appendix Figure D.1). The

TempStepRMT data were lower than Tennant's depth values in each percent AAF category (Appendix Figure D.1).

The velocity data showed significant differences, for all of the percent AAF categories, between the mediterranean divisions (MedDiv and MedRMT) and two of the temperate divisions (TempDesDiv and TempStepRMT, Appendix Table D.1). At 100% AAF the temperate step division (TempStepDiv) is also significantly different from the mediterranean divisions (Appendix Table D.1). Additionally at 200% AAF there is a significant difference between the MarDiv and the two temperate divisions (TempDesDiv and TempStepRMT), and the MedDiv is significantly different from all four temperate divisions (Appendix Table D.1). Unlike the depth data, the velocity data only seems to follow Tennant's values for the TempDesDiv (Appendix Figure D.2). The TempStepRMT velocities have little variation within percent AAF categories and the categories are closer together than Tennant's values are (Appendix Figure D.2). The rest of the ecoregions show higher velocity values than Tennant's values (Appendix Figure D.2).

The percent width data showed fewer significant trends (Appendix Table D.1, Appendix Figure D.3). The only significant differences between ecoregions were found at lower percent AAF categories (10% and 30%) and were variations between the temperate divisions; and differences between the temperate desert regime mountain division (TempDesRMT) and other ecoregions, which compare one data point and therefore can not be considered significant (Appendix Table D.1, Figure 3.6). Each of the ecoregions somewhat fit Tennant's percent width data, which is the same trend seen in the entire dataset (Figure 4.3, Appendix Figure D.3).

4.3.3 States

The analysis of width, depth, and velocity differences between states is summarized in Appendix E. The depth data showed one set of differences. The Oregon depth data is significantly different from the Montana, Colorado, Idaho, and California data but not from the Washington data (Appendix Table E.1). The OR depth data is higher than Tennant's values, as is WA data, but the other states (MT, CO, CA, and ID) are all lower than OR and Tennant's values, except for CA which is similar to Tennant's values (Appendix Figure E.1).

The velocity data shows two sets of differences between states. First, CO is significantly different from CA, OR, and WA; second, CA is significantly different from CO, ID, and MT (Appendix Table E.1). CA, OR, and WA's data are all higher than Tennant's velocities, where ID, MT, and CO's velocities are all clustered closer together within Tennant's values (Appendix Figure E.2).

The percent of width data does not show any significant patterns despite occasional significant differences between single states (Appendix Table E.1). The width data are all somewhat close to Tennant's values, with the exception of the 30% AAF values which tend to be higher than Tennant's values (Appendix Figure E.3).

4.3.4 Hydro-Climatic Data

The hydro-climatic data regression analysis is summarized in Appendix F. The regression of the depth data and the hydro-climatic data resulted in equations that explain between about 15 and 20% of the variation in the depth data, including all three parameters (PPT, TMAX, and TMIN) even though daily average maximum temperature was the only parameter that was significant in all of the depth regressions (Appendix Table F.1). The depth data show no significant patterns except the fact that the data is clustered in the lower ranges of the environmental data (Appendix Figure F.1, Appendix Figure F.2, and Appendix Figure F.3).

The hydro-climatic regressions were able to explain between approximately 45 to 60% of the variation in the velocity data (Appendix Table F.1). At 10 and 30% AAF the regressions did not include PPT data, and at 100 and 200% AAF the PPT parameter was not significant but was included; both the TMAX and TMIN parameters were significant for all of the velocity regressions (Appendix Table F.1). The scatter plots describing these regressions were similar to the depth plots showing no real trends (Appendix Figure F.4, Appendix Figure F.5, and Appendix Figure F.6). The percent of width regressions were not significant, and the data showed no trends in the scatter plots (Appendix Figure F.7, Appendix Figure F.8, Appendix Figure F.9, and Appendix Table F.1).

4.4 Nebraska Data Comparison

The Nebraska data are summarized in Table 4.5 and Figure 4.9 through Figure 4.11. Results of hypotheses tests on the Nebraska data are summarized in Table 4.6 and Table 4.7. The depth data from Nebraska seems to better represent Tennant's depth values (Figure 4.9 through Figure 4.11). The depth data are not significantly different from Tennant's values (Table 4.6). The pool-riffle streams have a larger variability than the dune-ripple streams but both stream types seem to approximate Tennant's values well (Figure 4.12).

The velocity data do not correspond as closely to Tennant's values (Table 4.5, Figure 4.10). The velocities from Nebraska are lower than Tennant's values, which is the opposite trend of the entire dataset where the velocities were higher (Figure 4.2, Figure 4.10). The velocities are significantly different from Tennant's values except for the velocity at 100% AAF where the p value is 0.0530 (t value = -2.06, DF = 19, Table 4.6). The stream types are significantly different from each other for the velocities; the pool-riffle streams have a higher variability than the dune-ripple streams but both stream types are well below Tennant's 30, 100, and 200% AAF values and slightly higher than the 10% AAF value (Table 4.7, Figure 4.13).

The percent width at 30% AAF is the only category that is significantly different than Tennant's values (Table 4.6). As with the results for the other datasets, the Nebraska dataset indicate a significant difference between the stream types (Table 4.7). The variability within the pool-riffle stream is higher than for the other stream types (Figure 4.14). This is similar to the results for the other datasets.

Table 4.5 Summary statistics from width, depth, and velocity calculations, on the Nebraska cross sections, in comparison to Tennant's results from his 1975 study.

	Width as Percent of the Width at 100% AAF			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	60.00	65.00	100.00	110.00
Average	55.30	78.77	100.00	116.90
Standard Deviation	17.47	16.16	0.00	29.73
Minimum	28.95	43.51	100.00	101.33
Maximum	90.49	97.52	100.00	237.17
Number of Stations	20	20	20	20
	Depth (ft)			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	1.00	1.50	2.00	3.00
Average	0.90	1.36	2.09	2.70
Standard Deviation	0.32	0.47	0.73	0.90
Minimum	0.28	0.41	0.67	0.92
Maximum	1.54	2.08	3.57	4.68
Number of Stations	20	20	20	20
	Velocity (ft/sec)			
	10% AAF	30% AAF	100% AAF	200% AAF
Tennant	0.75	1.50	2.00	3.50
Average	0.88	1.21	1.81	2.32
Standard Deviation	0.27	0.35	0.41	0.48
Minimum	0.35	0.57	0.96	1.29
Maximum	1.42	2.01	2.46	2.99
Number of Stations	20	20	20	20

Table 4.6 ANOVA table of Tennant calculations showing differences between data collected in the Nebraska dataset and Tennant's original values (Tennant 1975).

Variable	Degrees of Freedom	t Value	Pr > |t|
Width 10% AAF	19	-1.20	0.2442
Width 30% AAF	19	3.81	0.0012
Width 100% AAF	19	-	-
Width 200% AAF	19	1.04	0.3126
Depth 10% AAF	19	-1.39	0.1821
Depth 30% AAF	19	-1.28	0.2153
Depth 100% AAF	19	0.56	0.5797
Depth 200% AAF	19	-1.51	0.1484
Velocity 10% AAF	19	2.13	0.0467
Velocity 30% AAF	19	-3.82	0.0012
Velocity 100% AAF	19	-2.06	0.0530
Velocity 200% AAF	19	-10.94	<0.0001

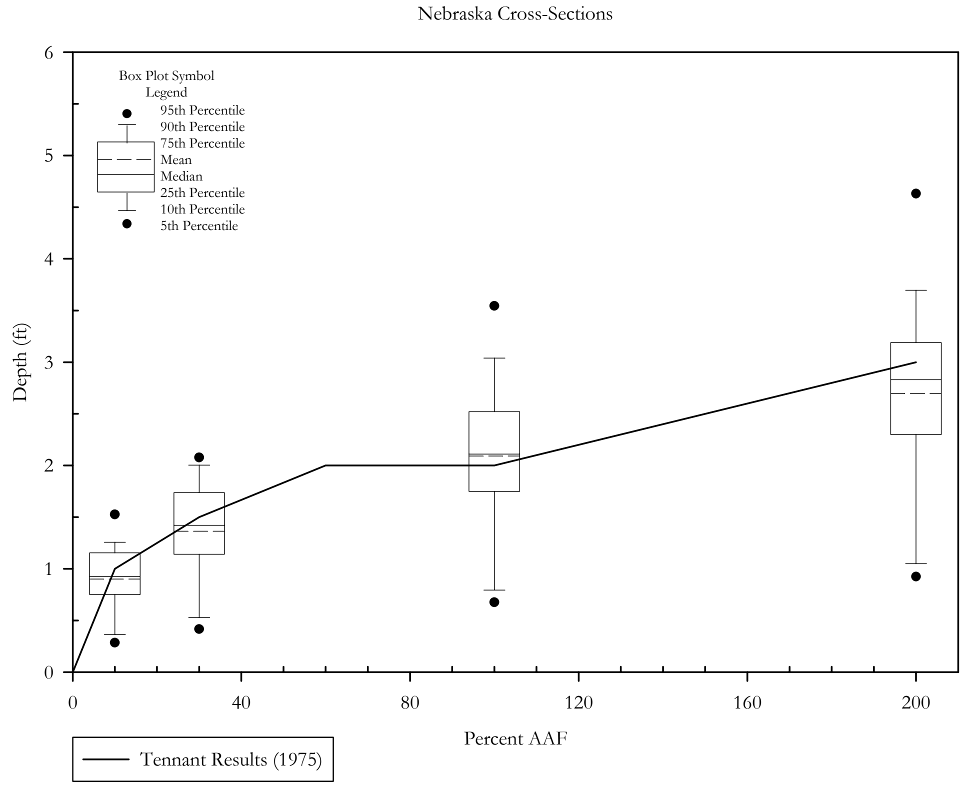

Figure 4.9 Box plot showing the Nebraska results of the depths corresponding to each %AAF being tested in the Tennant method analysis.

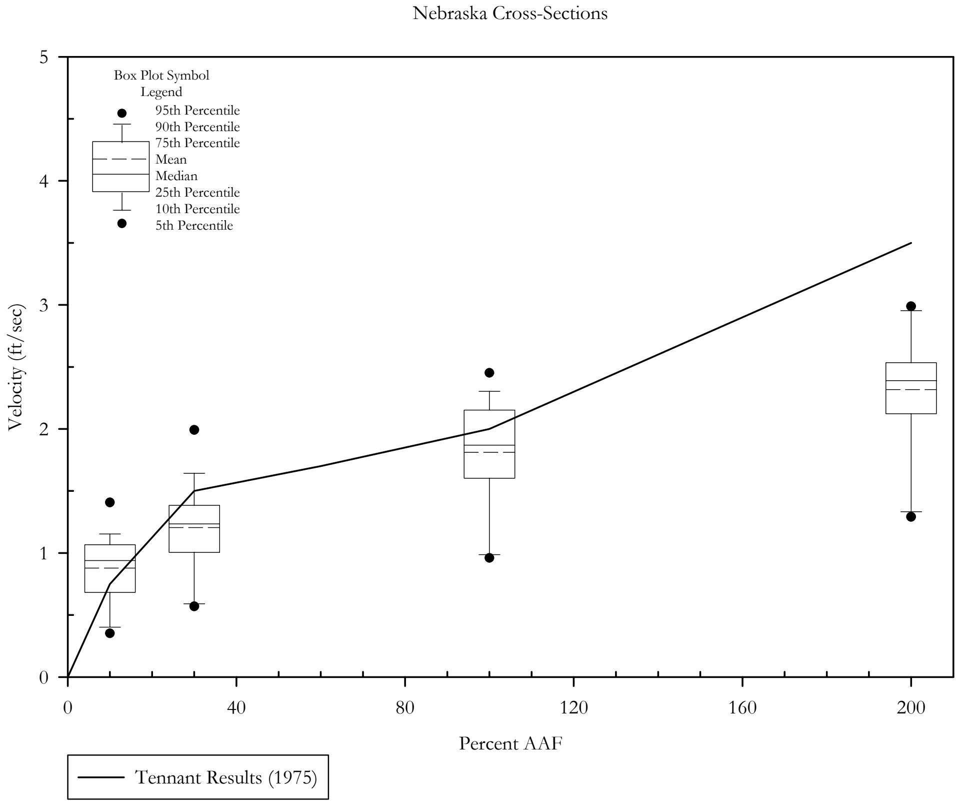

Figure 4.10 Box plot showing the Nebraska results of the velocities corresponding to each %AAF being tested in the Tennant method analysis.

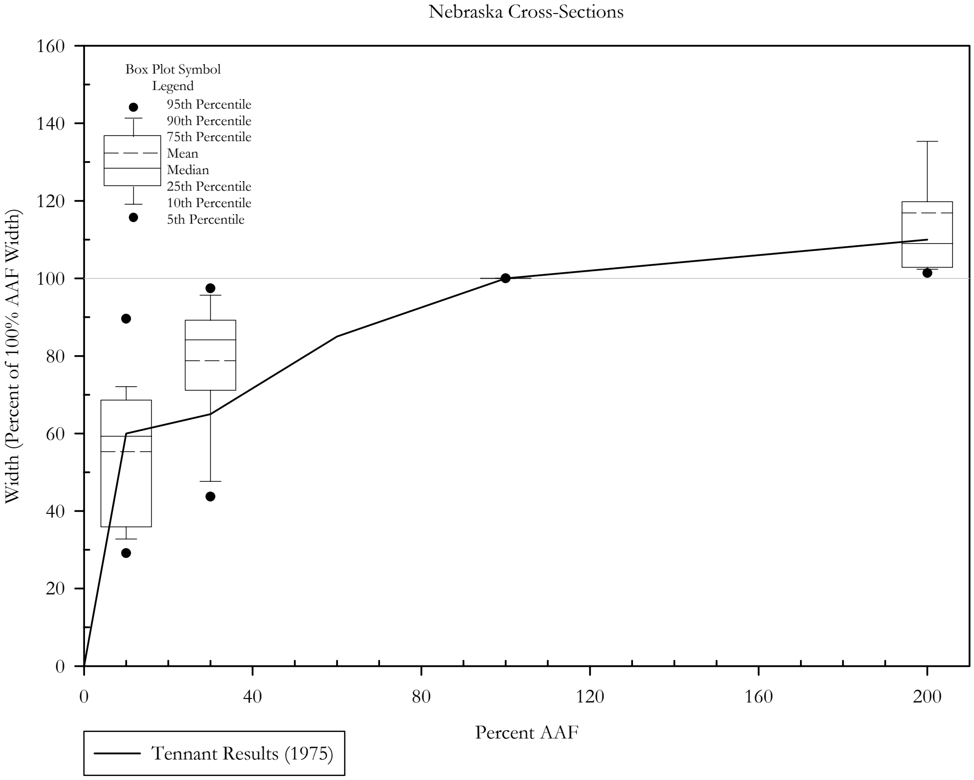

Figure 4.11 Box plot showing the Nebraska results of the widths (percent of 100% AAF width) corresponding to each %AAF being tested in the Tennant method analysis.

Table 4.7 ANOVA table of Tennant calculations showing differences between stream types for data collected in the Nebraska dataset.

Variable	Method	Variances	Degrees of Freedom	t Value	Pr > |t|
Width 10% AAF	Pooled	Equal	18	-7.42	<0.0001
Width 30% AAF	Pooled	Equal	18	-8.57	<0.0001
Width 100% AAF	-	-	-	-	-
Width 200% AAF	Satterthwaite	Unequal	8.29	-8.66	<0.0001
Depth 10% AAF	Pooled	Equal	18	-6.13	<0.0001
Depth 30% AAF	Pooled	Equal	18	-6.31	<0.0001
Depth 100% AAF	Satterthwaite	Unequal	10.7	-5.12	0.0004
Depth 200% AAF	Satterthwaite	Unequal	9.94	-6.28	<0.0001
Velocity 10% AAF	Satterthwaite	Unequal	10.6	-5.62	0.0002
Velocity 30% AAF	Satterthwaite	Unequal	9.65	-8.61	<0.0001
Velocity 100% AAF	Satterthwaite	Unequal	9.65	-9.40	<0.0001
Velocity 200% AAF	Satterthwaite	Unequal	10.2	-14.01	<0.0001

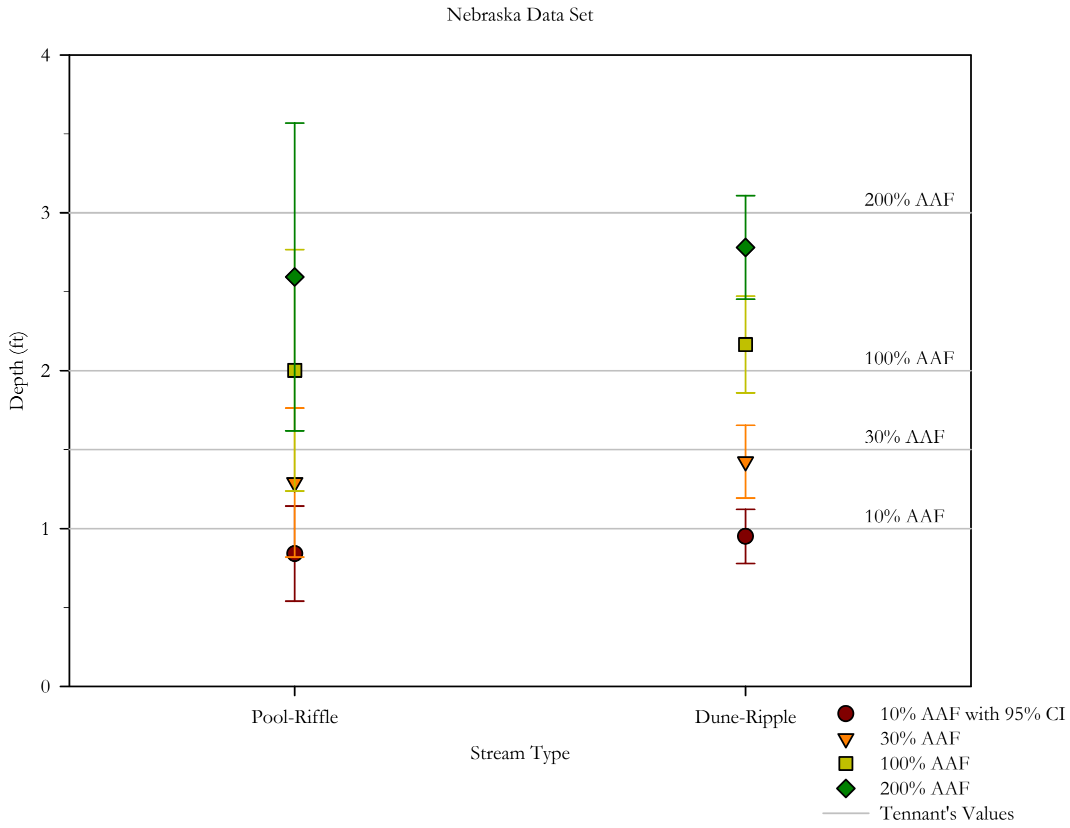

Figure 4.12 Scatter plot showing the difference between stream types in the Nebraska cross-sections, comparing the depths to Tennant's original data. Error bars show the 95% confidence intervals for the means.

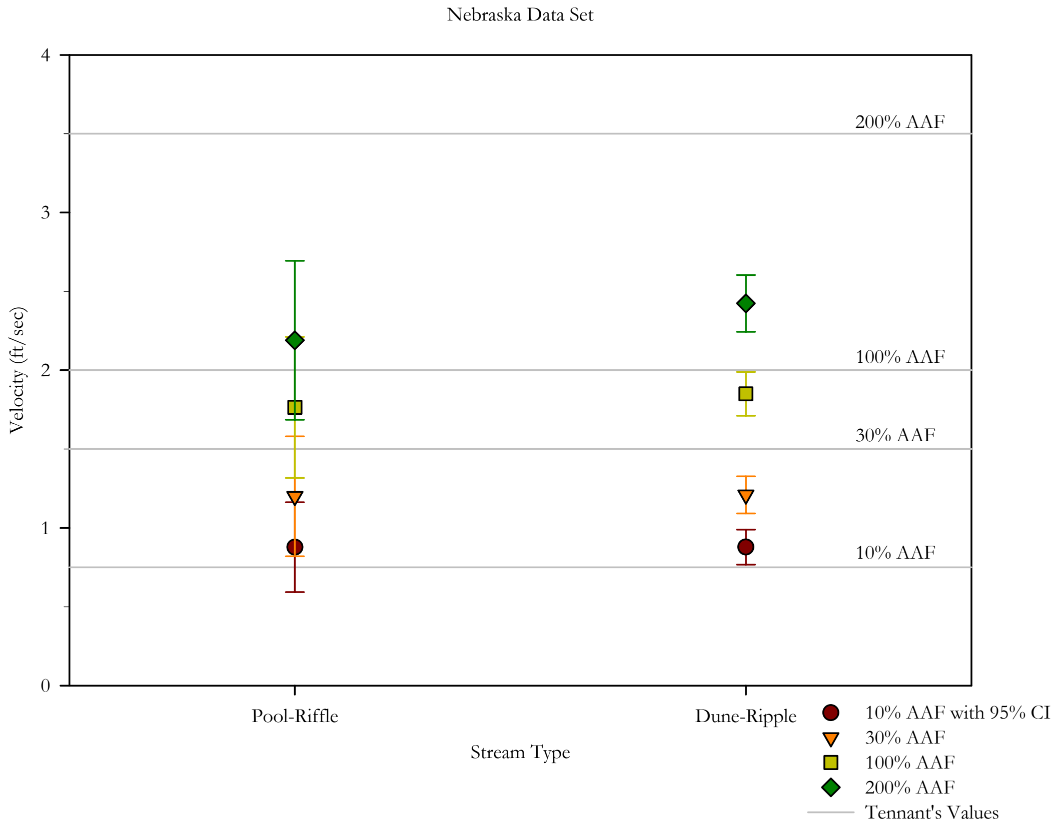

Figure 4.13 Scatter plot showing the difference between stream types in the Nebraska cross-sections, comparing the velocities to Tennant's original data. Error bars show the 95% confidence intervals for the means.

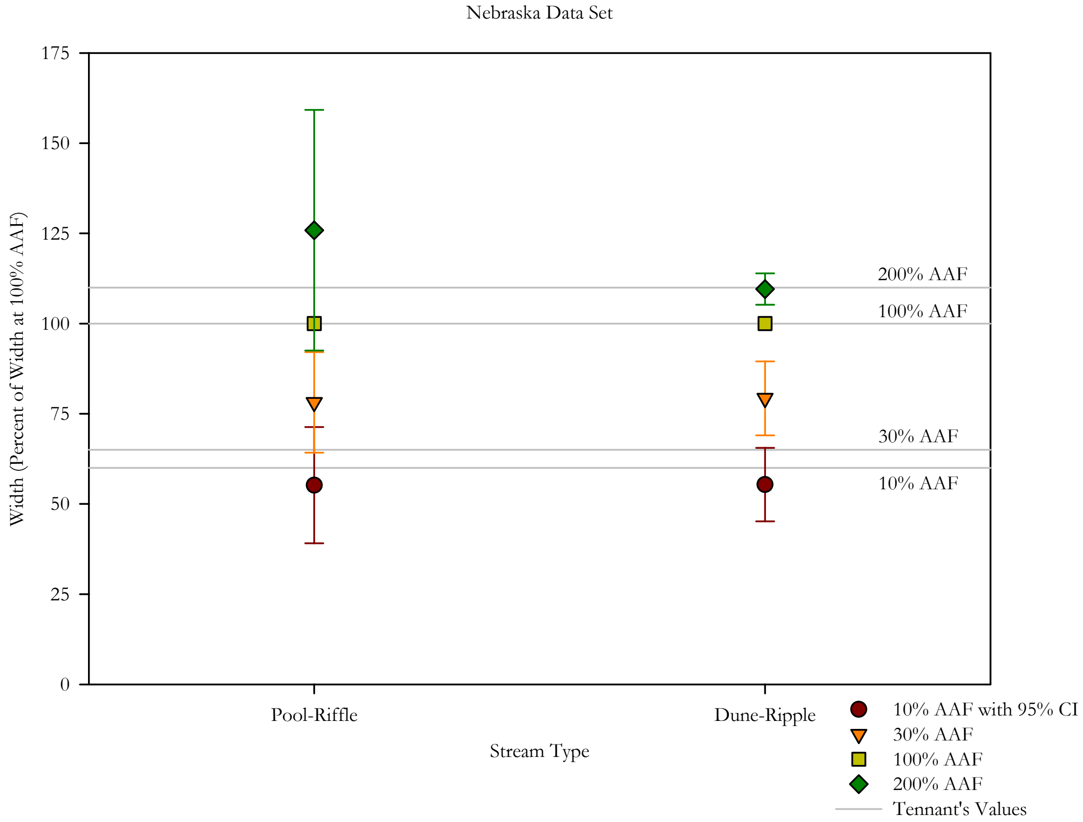

Figure 4.14 Scatter plot showing the difference between stream types in the Nebraska cross-sections, comparing the widths (percent of width at 100% AAF) to Tennant's original data. Error bars show the 95% confidence intervals for the means.

Chapter 5

5.0 Discussion

5.1 Tennant Method Calculations

5.1.1 Depth Calculations

The data in this study provides evidence that the depth data and subsequent analyses by Tennant do not necessarily represent all streams (Figure 4.1). Tennant's depths at each percent of average annual flow were significantly different than the corresponding depths in this study. Therefore, the depths that are usable by fish in each percent AAF category differ from those suggested by Tennant (1976).

This study shows that the depth of the stream is likely to be significantly lower, therefore containing less fish habitat at each percent AAF. This implies, from depths only, that Tennant's flow recommendations are not conservative for typical mountain stream types. The stream depths may be lower than what fish actually require at each habitat quality interval. The average depth in this study at 10% AAF is only 0.76 ft where as Tennant used a 1 ft depth threshold. This leaves streams almost a fourth shallower than Tennant suggested would be the case at the 10% AAF level. At 30% AAF the difference between this study and Tennant's data remains about 25 percent, 1.12 ft and 1.50 ft respectively. At 100% AAF the difference between the mean of the study data and Tennant's estimate are closer to each other. Tennant's estimate is only 14 percent higher than the study data set, 2.00 ft and 1.72 ft respectively. The difference returns to 25 percent higher for the 200% AAF category where the data shows a depth of 2.24 ft and Tennant states 3.00 ft.

Tennant's data showed greater depths at each qualitative level of fish habitat. Adult rainbow trout prefer deeper water over shallower areas for holding and resting habitat (Pert and Erman 1994) favoring depths of approximately 2.76 ft (Braaten et al. 1997). The depth of 2.76 ft falls between Tennant's 100% AAF and 200% AAF values. These depth preferences show that there is a greater amount of habitat in deeper reaches. Tennant's depth values tended to overestimate the depth of the streams in the current study. The combination of increased habitat in deeper waters and Tennant overestimating depths cause concern to be raised for the quality of habitat that is conserved at Tennant's percent AAF categories.

5.1.2 Velocity Calculations

For streams in this study, Tennant's threshold velocities were exceeded at the respective percent AAF levels. Depth can to some extent be seen as continuing to add usable habitat up to depths that are well past likely depths of streams within this study. Velocity does not follow this same trend. Fish velocity preferences for fish can be exceeded in the smaller streams used in this study. For the streams in this study the 30 to 100% AAF may cause velocities to be unsuitable for fish. Braaten (1997) found, in a study on the energetic habitat suitability for trout, that the maximum observed velocity used by rainbow trout is approximately 2.6 ft/sec. The same study found that the mean velocity used by trout was 0.66 ft/sec (point velocity), which falls below Tennant's velocity at 10% AAF. According to Tennant's criteria, 10% AAF would be considered to be poor or temporary minimum habitat for fish survival by Tennant (Tennant 1975, Braaten et al. 1997). This initial conflict of what would be considered to be "preferred" velocity for rainbow trout habitat is compounded by the velocities that were calculated in this study. Since these mean velocities for this study are higher than Tennant's in all cases (1.33 ft/sec to 0.75 ft/sec, 1.89 ft/sec to

1.5 ft/sec, 2.87 ft/sec to 2.0 ft/sec, and 3.66 ft/sec to 3.5 ft/sec, 10, 30, 100, and 200% AAF respectively), then it follows that the habitat quality and quantity could be met at lower percent AAF values then Tennant recommends.

5.1.3 Width Calculations

The width category is distinctly different from the depth and velocity categories in that it is a percent width of the width at 100% AAF not actual width. This percent width is used because Tennant used a percent width. As mentioned previously, Tennant was not specific with the percent width used in his study and consequently there is no way of knowing whether these calculations are even comparable to Tennant's data. The only anchor of the data in Tennant's original study is the 100% AAF point. Tennant stated that at 100% AAF the width was also at 100%. The current study's data set reflects that same point, which was used as a reference point. As this only creates a reference point and not comparability the data will not be discussed in this section as it was in previous sections.

The percent width at 10% AAF was not significantly different from the value stated in Tennant's work (59.85% and 60% respectively). The 30% AAF and 200% AAF values were significantly different though, both being larger than Tennant's values, meaning that the streams were wider than Tennant predicted. This means that there is potentially more usable habitat at each discharge level than Tennant would have predicted. Unfortunately this can not truly be backed up by the study data because the uncertainty of the method, for standardizing width into a percent width, is too large. Using percent width also shifts the way that the data are evaluated since it standardizes the width data so that the values ought to be more comparable across stream size, type, and other channel characteristics.

The Tennant method calculations showed some important factors that should be considered when deciding what method(s) should be used in setting instream flows (either for protection of current conditions or as a base flow portion of a hydrograph). One of the biggest factors that needs to be discussed is the fact that Tennant's velocities and depths did not adequately (significantly different at p value < 0.005) represent with the data from this study. That leads to a questioning of the validity of the specific percents used in this percent of average annual flow method, potentially requiring a shift in the percent of average annual flow that corresponds to fish habitat quality. To determine whether the percent AAF should be higher or lower than Tennant states depends on further determination of what the optimal (or minimum or what ever value of interest) velocity and depth are for whatever the target fish species is (in this case rainbow trout data was used for comparisons).

5.2 Methodology Comparisons

5.2.1 Wetted Perimeter Method

The wetted perimeter method was used to develop a flow recommendation for comparison with the Tennant method. Since the wetted perimeter method produces a single value that is then applied as the flow recommendation without any specific classification as a minimum (Gillilan and Brown 1997) or optimal (Gordon et al. 1992) flow, this study used two of Tennant's recommendation categories and compared them to the recommendation from the wetted perimeter method. The data were compared to 10% AAF and 30% AAF. The t-test to see if the mean wetted perimeter recommendation was significantly (p value < 0.005) different from both 10% AAF and 30% AAF. The data had a mean of 16.13% AAF and is consistent enough to be different from both 10 and 30 %. This means that the Tennant method and the wetted perimeter method result in different flow recommendations. This can be looked at from several perspectives. It can be evidence to support that the Tennant method does not give an accurate flow recommendation, and can be seen as evidence that the wetted perimeter method is not an accurate method. Both of these methods lack inclusion of actual habitat data at the specific sites for which they are applied. Neither method is truly calibrated to each site as a PHABSIM model would be. This means that both methods take a physical parameter of the stream that is easy and inexpensive to collect and use that parameter as a surrogate for a very complex set of requirements for multiple species, lifestages, and changes in habitat needs. The question then is whether either or both of these methods do an adequate job of representing the parameters that the method relies on. This analysis suggests that the Tennant method does produce similar results for different stream types although the results do not reproduce Tennant's physical characteristic results.

5.2.2 PHABSIM Method

The percent average annual flow data was compared to the PHABSIM standardized WUA curves to see what the potential fish habitat is in comparison to Tennant's fish habitat quality. The PHABSIM method is not going to be considered to be 'truth' in terms of fish habitat analysis because there are drawbacks to this method, as in all methods, and more importantly because this study is only able to compare a very small set of stream reaches.

The juvenile rainbow trout curve showed a noticeable trend in all three of the streams sampled. The juvenile curve reaches a peak habitat flow at lower discharges than the adult curves do. This is logical since smaller fish have lower velocity and depth preferences. This pattern is seen on West Willow Creek where the adult curves are still increasing at a level beyond 200% AAF and the juvenile curve starts to decrease at approximately 120% AAF. On Stevenson Creek, all three curves are increasing beyond the 200% AAF discharge but the initial peaks in the curves happened between 30 and 100% AAF with the juvenile curve peaking earliest. Halfmoon Creek WUA curves show the juvenile curve declining from the lowest simulated discharge with the two adult curves peaking at higher discharges than 30% AAF. These data show that juvenile rainbow trout habitat needs are likely to be met at lower discharges.

Adult rainbow trout curves peaked later for the medium stream versus the small stream curve velocity and depth preferences; this can be accounted for since the medium stream curve assumes a larger adult fish size, therefore requiring a larger stream or higher discharge. This provides evidence for using a specific HSC in determining instream flow requirements so that the PHABSIM model develops plausible results of the flow-habitat relationship.

There is considerable variation in the percent of average annual flow that corresponds to the peak habitat flow from the standardized WUA curves. This evidence suggests that it is not appropriate to apply the Tennant method regardless of setting. The PHABSIM model (like many other models) is not designed to produce a specific instream flow recommendation; therefore this comparison should not be seen as a direct comparison but instead as a view of the likely fish habitat at Tennant's flow recommendations.

5.3 Regional Analyses

5.3.1 Stream Types

For the relationship between discharge and depth data, the pool-riffle streams are significantly different from the step-pool and plane bed streams; the question then is whether there is a stream type where Tennant's values fit better. In this case, mean values by stream type differ significantly from Tennant's recommendations. But the pool-riffle data show an opposite trend where as the mean values are highly consistent with Tennant's values (Appendix Figure C.1). This could possibly show that Tennant's streams were likely to be pool-riffle but the other parameters will need to show the same trend for this to be truly supported by this study. At this point it only shows us that there is a bias somewhere in the methodology that results in a larger spread of data and larger depth values for pool-riffle streams. The plane bed and step-pool stream types had a very narrow range of variation between the 25th and 75th percentiles and a more average spread from the 5th to the 95th percentiles (Appendix Figure C.1).

The velocity data showed significant (p value < 0.005) differences between stream types like the depth data did. The plane bed stream type was significantly different from the pool-riffle and step-pool stream types. The velocity results combined with the depth stream type analysis refute the idea that Tennant was using most pool-riffle streams in his study. The velocities of the plane bed streams are the ones that are the closest to Tennant's values, with the 30% AAF velocity being very similar to Tennant's value (Appendix Figure C.2). The 200% AAF mean velocity for the plane bed streams (2.98 ft/sec) is actually lower than Tennant's velocity of 3.5 ft/sec which goes against the trend of the velocity data which is consistently above the Tennant value. The pool-riffle and step-pool stream types were not significantly different from each other or from the dune-ripple stream type. These stream types are similar to the overall pattern that the data followed. The step-pool streams have a wider range of values than the other stream types. The patterns that are emerging within each type of measurement are not continuing outside of that measurement.

The stream types were not significantly (p value < 0.005) different from each other in the percent width category. This is what would be expected from a standardized value like percent width of the width at 100% AAF. There were some less significant (p value < 0.05) trends in the percent width data. Step-pool and pool-riffle streams were different at the 30% AAF widths but this is the only place that they were somewhat different from each other. This is seen in the added variability in the step-pool streams that is not there in the pool-riffle streams (Appendix Figure C.3).

The results for the physical parameters of depth, velocity, and percent width were not consistent between the stream types. One might try to look at each individual parameter and argue that the Tennant method is better suited for one stream type versus another. The data in this study illustrate that this is not the case. In fact different stream types were favored for different parameters. Since the Tennant method relies on the combination of all of the parameters that were originally studied, the favored stream type would have to be the same for all of the parameters, and is not the case here.

5.3.2 Ecoregions

The depth data show two ecoregions that approximate Tennant's values for the physical channel characteristics of depth, velocity, and percent width, the mediterranean division and the temperate desert division (Appendix Figure D.1). This difference is not represented in the statistics, as there is not a significant difference between these two ecoregions and the other ecoregions (Appendix Table D.1). The differences that were significantly different within the ecoregions separated the temperate steppe regime mountain division from other ecoregions, which is likely because of the high number of data points in this ecoregion. Velocity data show that the temperate desert division still approximates Tennant's values well. Along with the temperate steppe regime mountain division these two ecoregions differ from the trend of velocity values that are higher than Tennant's values (Appendix Figure D.2). The velocities in the temperate steppe regime mountain division are similar (not significantly different at p value < 0.05) to the velocities in the temperate desert division except that the confidence interval is small in comparison and therefore appears to be more different from Tennant's values (Appendix Table D.1).

The percent width data do not negate any of the trends found in the depth or velocity data. The lack of support for the methodology used in determining the percent width data, the data will not be strictly used to substantiate or negate differences between ecoregions, or specific differences from Tennant's values. The temperate desert division therefore has similar values to Tennant's original dataset.

5.3.3 States

The depths from this study show California, Washington, and Oregon to be closer to Tennant's values than the other states in this study (Appendix Figure E.1). Oregon is significantly different (p value < 0.05) than Colorado, Idaho, and Montana. Therefore, streams from Oregon may better approximate Tennant's depth values except that Oregon is also significantly different from California (Appendix Table E.1).

Velocity data do not show any state to have data that approximates Tennant's values (Appendix Figure E.2). Oregon, Washington, and California have velocities that are considerably (outside of the 95% CI) higher than Tennant's values (Appendix Table E.1). Colorado, Idaho, and Montana velocities are lower (CO is significantly different from CA, OR, and WA) than Oregon, Washington, and California, but the velocities tend to be lower than Tennant's 200% AAF value and higher than Tennant's 10% AAF value (Appendix Table E.1, Appendix Figure E.2).

The percent width data for the individual states appear to be less like Tennant's values than the entire dataset (Appendix Figure E.3, Figure 4.3). Overall, none of the states seem to fit Tennant's values well for any of the parameters tested.

5.3.4 Hydro-Climatic Data

The utility of the Tennant method does not vary by hydro-climatic regime. Conversely the regressions with velocity and the hydro-climatic data are able to account for around half of the variation in the velocity data (Appendix Table F.1). Although this isn't useful in determining the relevance of Tennant's method it could be used to help predict stream velocities, to better apply a desktop instream flow methodology.

5.4 Nebraska Data Comparison

The Nebraska dataset shows that Tennant's values are closer in streams with lower gradients. The depth data is well represented by Tennant's values, but the velocities were not as close to Tennant's values. Even though the velocities at 200% AAF were not as high as Tennant's values, this dataset does allow for a confidence in the Tennant method at lower gradient (less than 1% slope) streams.

5.5 Analysis of Error - Sensitivity Analyses

Several areas of the methodology of this study were studied to determine the error introduced into the study. These areas include the original cross section data, the use of WinXSPro (specifically the use of more than one resistance equation and the potential biases in consistency), and the methodology involved in fitting equations to the data for the wetted perimeter method and the affects on the flow recommendations.

5.5.1 Cross Section Survey Density Analysis

The data for this study were acquired from multiple sources one of the potential sources of bias in the study is the methods used in the cross section profile data collection. Some of the cross section profiles were acquired from the USGS, who used the measurements for determining discharge, and therefore only surveyed the channel and took measurements in increments that produced reliable discharge data. Other sources had a much higher point density in their surveys. To run a sensitivity analysis on the number of points in the cross section, thirteen cross sections were selected and then the number of points in each cross section were reduced to ten points using three different methods. First, the original cross sections were cut down by selecting visually the breaks in slope throughout the cross section and only keeping ten points. The next method was to use a random number generator and choose ten points at random (by continuing to choose until there were ten different points selected from each cross section). Last, five of the original cross sections were reduced in number of points using a systematic approach where every other or every third point was kept to get ten points for each cross section. The percent change in area was then computed from the original cross section to the reduced cross sections using WinXSPro (Figure 5.1). This analysis shows that the cross section area is based more on a good collection method than on the number of points collected since decreasing the number of points only caused a +/- 5% change in the cross section area. Using the systematic approach may cause a slightly larger range of variability, but the data are still centered on the original cross section area unlike the random method that is skewed to a smaller area. This study will therefore assume for all analyses that the original cross sections were taken with appropriate care to either set up a systematic survey method or purposely pull out the slope breaks. This means that any error from cross section point density is considered negligible for this study.

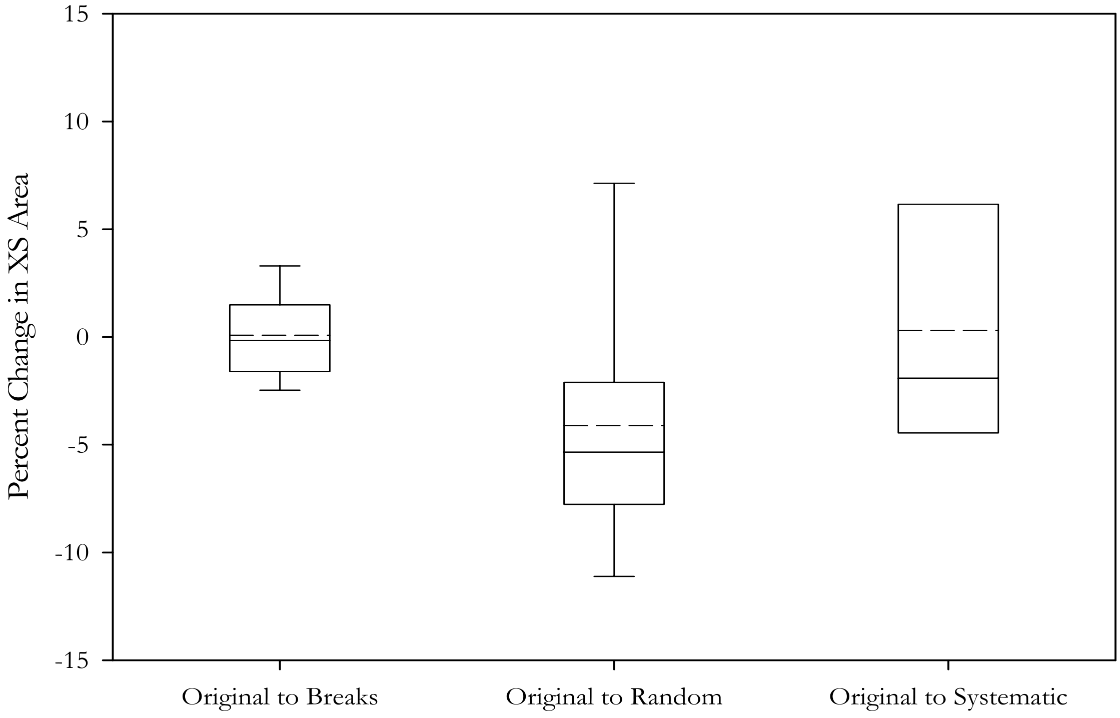

Figure 5.1 Cross section sensitivity analysis, containing 13 cross sections in Original to Breaks and Random and 5 cross sections in Original to Systematic, where final reduced cross sections only had 10 points.

5.5.2 Resistance Equation Sensitivity Analysis

Preferably this study would have chosen a particular resistance equation and used it throughout the entire analysis process. The data set was not complete enough to be able to do that. This sensitivity analysis was used to determine the bias that using several resistance equations introduced into the study. The analysis was completed by selecting cross sections that had enough data to be able to run all three resistance methods included in this study on them. There were seven cross sections included in this analysis. To evaluate the bias involved with using several equations the width, depth, and velocity were compared for the 10% AAF values (Figure 5.2). The data showed that there were no obvious biases introduced into this study by the use of several resistance equations. The velocity data at 10% AAF were all very similar in the mean value with Jarrett's equation (Jarrett 1984) having a larger range of values than the other two equations (Manning 1891, Thorne and Zevenbergen 1985). The width data for all three equations were very similar. There was slightly more variation in the depth data with Manning's n method having less variability compared to the other two methods but still all showing similar means. This analysis showed that, although using one equation would have been ideal, using three equations still allow this study to use the outputs from each method as comparable data.

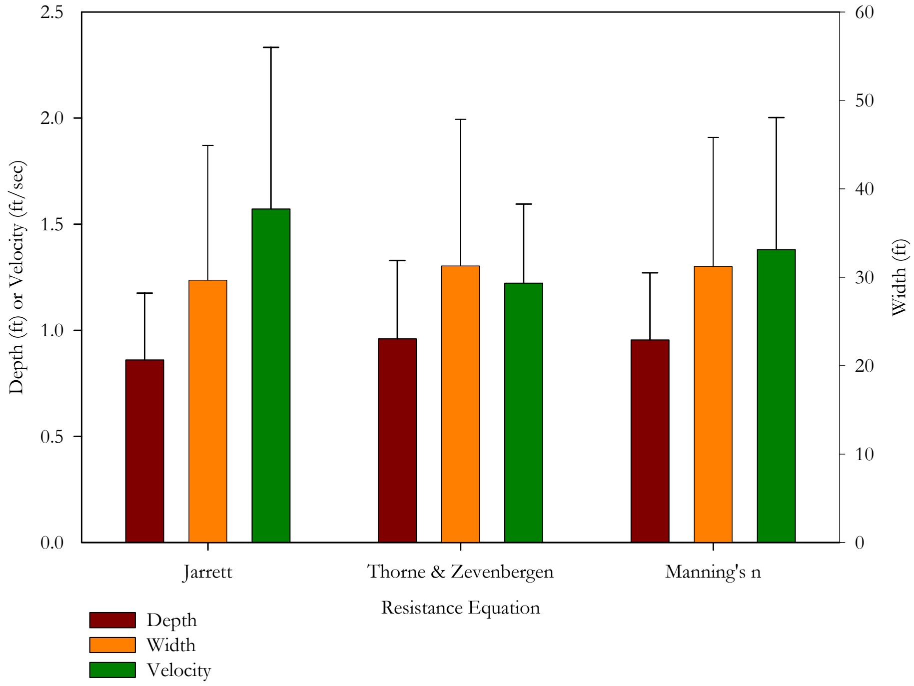

Figure 5.2 Resistance Equation Sensitivity Analysis results with 95% Confidence Interval Error Bars (Seven study sites were run using each method and the results for 10%AAF were graphed to show any biases)

5.5.3 Wetted Perimeter Method Sensitivity Analysis

To look at the validity of using the wetted perimeter method in the comparison with the Tennant method, this study looked at potential biases from the way that the wetted perimeter method was used. To do this, two sites were selected from the database; one site with an original regression with a high r square value and one site with a low value. The cross section data were degraded to show any patterns associated with the complexity of the cross section. Degradation was done by selecting every other point to form a cross section with half the points, and then selecting every other point again to form a cross section with a quarter of the points. This process tends to remove some of the complexity from the channel bed. The other part of this analysis was to look at any differences in the discharge recommendation depending on the amount of the wetted perimeter curve data that was included in the regression. This analysis showed two distinct patterns (Figure 5.3, Figure 5.4). The first is that the discharge recommendation increases as the complexity of the channel geometry increases (or the amount of the cross section included in the analysis) and secondly that the discharge recommendation increases as the amount of data used in the regression decreases. Since this study assumes that the cross section data is adequate to overcome any significant biases due to survey density, the fact that simpler channel geometries have lower discharge recommendations lend weight to the idea that channel geometry (or the surveying of that geometry) is more important in determining the discharge recommendation. Ideally the recommendation would be based on the needs of the fisheries instead. And the bias shown by the amount of the wetted perimeter curve included in the regression lends weight to not arbitrarily reducing the amount of data that the regression curve is fit to. This allows for the entire channel geometry to determine the flow recommendation instead of selecting only a portion, which might be better justified when making a minimum discharge recommendation. But the problem of determining what data to include and what not to include would still exist. For this study the entire wetted perimeter curve will be included in the regression curve fit.

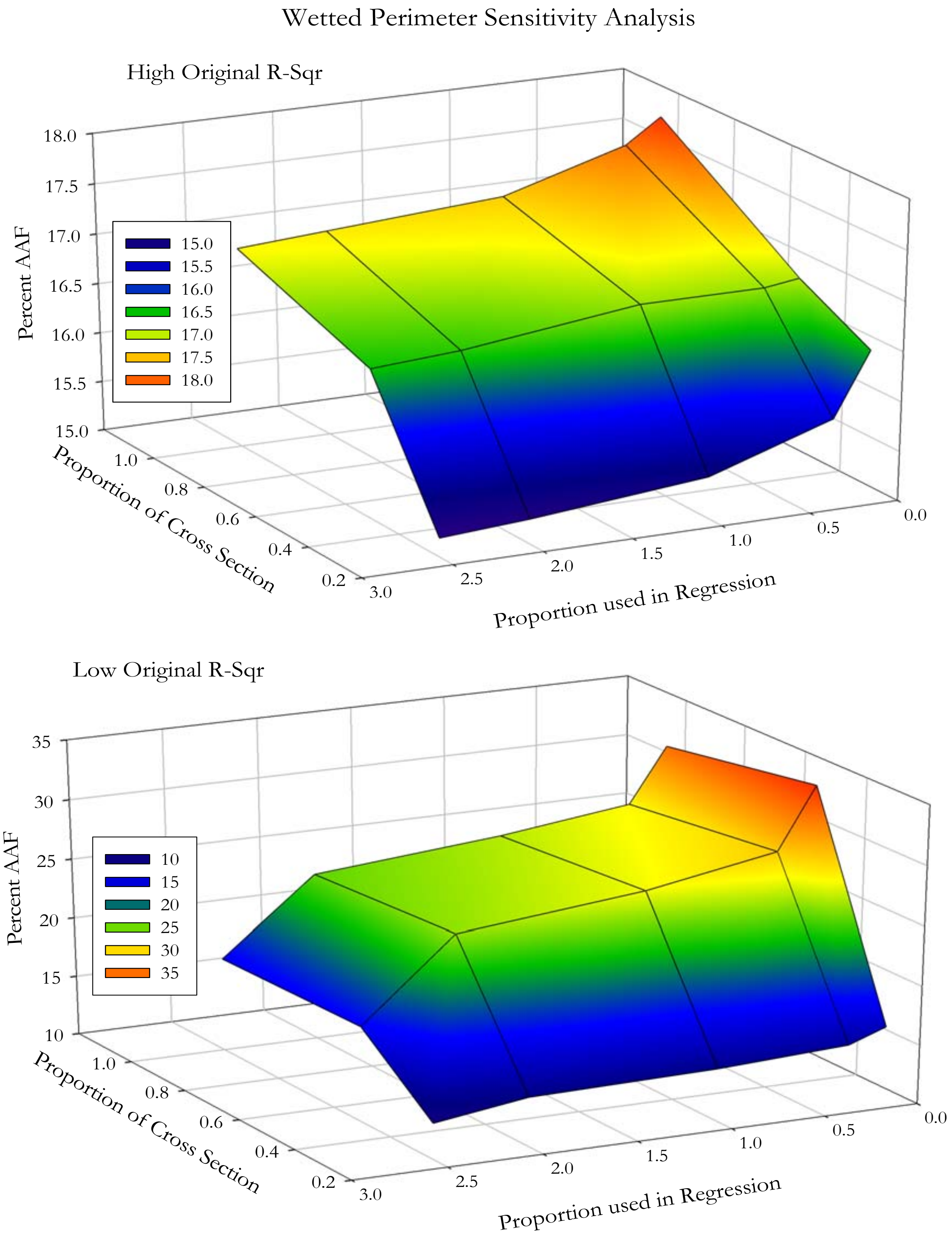

Figure 5.3 Wetted perimeter method sensitivity to the proportion of the data used in the regression and the proportion of the cross section used to generate the data.

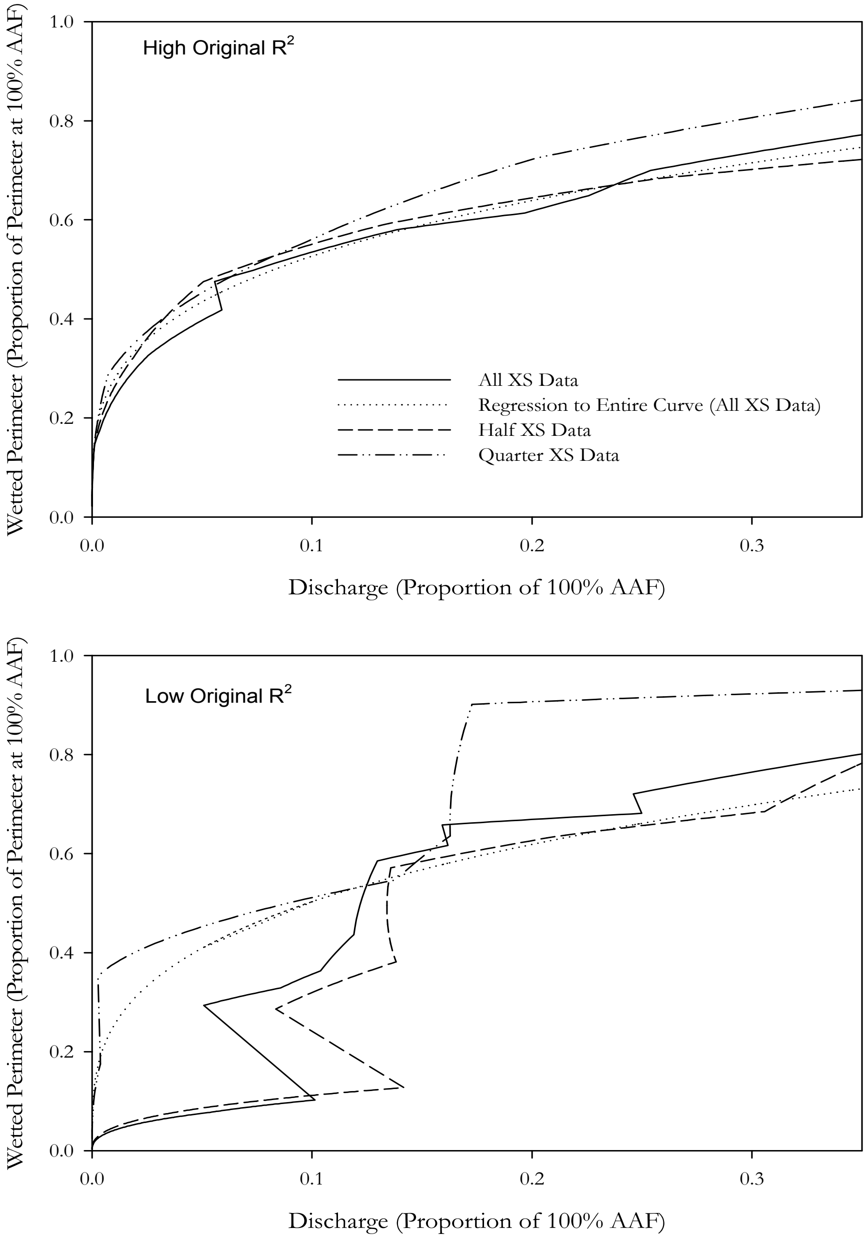

Figure 5.4 Wetted perimeter curves for different proportions of the cross section data along with the regression line that was fit to the entire curve.

5.5.4 Analysis of Relative Accuracies

This study used the results of the sensitivity analyses to reduce the possible error introduced into the study. Since the cross section data collection was not part of this study and completed by others, the data will be assumed that the data is of high quality. The determination of slope for cross sections that did not have a field determined slope is a potential source of error. This error was minimized through careful calculations for topographic maps but also presents the possibility for small error introduction. A potentially greater source of error is the use of three resistance equations in WinXSPro. This error is potentially as high as +/- 7%. Lastly the wetted perimeter methodology is the area with the largest potential for error introduction. The patterns seen in the wetted perimeter sensitivity analysis suggest a source of error around +/- 10% in the percent of average annual flow recommendation from the wetted perimeter method. Unlike the other potential sources of error, where sensitivity analyses showed visually random distribution of errors, this distinct pattern shows a certain bias. This bias is reduced best by not arbitrarily reducing the amount of the cross section used in the regression to determine the flow recommendation.

Chapter 6

6.0 Conclusions

The original data that Tennant collected in Montana, Nebraska, and Wyoming are not representative of many stream types in the western United States. The 151 cross sections in this study produced depth and velocity measurements that were statistically significantly different ($p < 0.05$) from the data Tennant collected from the 58 cross sections included in the original study. Little can be said for certain about the percent width parameter that Tennant included in his study because this study was unable to reproduce the exact method. The data in Tennant's study is not representative of the entire western U.S., so there needs to be some sort of adaptation of the Tennant method for the application of this method in locations outside of Tennant's original region. The current form of the Tennant method does not necessarily protect habitat adequately because the channel characteristics (width, depth, and velocity) that Tennant based habitat quality on are not consistent across stream types in the western U.S. The depths in this study were seen to be lower than Tennant's predicted depths; application of Tennant's method would lead to under protection of habitat. The velocities that Tennant predicted were lower than the velocities from this study. Depending on what velocities are determined to be the target for fish (whatever species the flow recommendation is targeting), the Tennant method will produce slower velocities than stated. Therefore the Tennant method needs to be adapted to the area of use so as to more accurately represent the physical parameters that will be conserved at each percent of AAF recommendation.

The wetted perimeter was compared to the Tennant method and produced significantly different ($p < 0.005$) flow recommendations than both the 10% minimum and the 30% fair ratings in Tennant's method. The wetted perimeter method is a cross section or transect method, it is considered as a method that includes more data about the specific stream in question, unlike the Tennant method that is a standard setting method that is used primarily for habitat protection. The wetted perimeter method produces a single discharge recommendation where the Tennant method provides a spectrum of recommendations depending on the quality of habitat that is trying to be preserved. This means that a direct comparison is hard to produce; especially in light of the error introduced into this method through curve fitting. The flow recommendation from the wetted perimeter method is thought to be, ideally, the preferred discharge for salmon spawning (Collings 1972). This study does not imply that the wetted perimeter method or the PHABSIM model yield better estimates of the instream flow required for fish habitat. The PHABSIM model produced peak habitat flows that were not consistent with any particular percent average annual flow. Comparisons to these two methods allows for the conclusion that the Tennant method does not necessarily produce similar habitat results in all conditions or locations.

Whether the difference between the data seen in the methodology comparisons and the data from the Tennant method calculations (of physical stream parameters) are enough to allow for an overall recommendation of either rejecting or accepting the Tennant method is unclear. This study concludes that the Tennant method should be adapted and tested in regions before being applied to a particular setting. This is already happening in some locations but is not done in all locations as it should be (Orth and Maughan 1981).

For regional applicability, this study found evidence to support applying the Tennant method in some settings. Individual stream types never produced a stream type that fit the

Tennant method better than the others. Therefore, this study concludes that there is not a difference in the applicability of the Tennant method between different stream types. The same outcome was seen when individual states were analyzed. Conversely there was a single ecoregion, temperate desert division, which reproduced Tennant's values, and therefore the Tennant method is most applicable in this ecoregion. The Nebraska data showed that the Tennant method is applicable on streams with low gradients (less than 1% slope).

6.1 Recommendations

For the Tennant method to be used as purposed in 1976, this study recommends that the method be applied with caution or modified to better represent local conditions based on further research. Future research needs to validate the physical channel characteristics (width, depth, and velocity) needed to support desired fish habitat levels. This will provide the support needed to use the Tennant method in any situation where the instream flow recommendations need to be defended.

Second, it is recommended that the Tennant method be used only for initial planning flow recommendations without serious validation within the region of use. The Tennant method does provide a general idea of the amount of water is needed to sustain a desired level of fish habitat and shows a clear progression of the needs of the fish for the quality of habitat that is desired. This function of the Tennant method is not diminished by the evidence provided in this study. The defense of any specific flow recommendation produced solely through the use of the Tennant method, outside of Tennant's study area and the characteristics validated in this study (temperate desert division streams, and low gradient streams), is diminished by the data produced in this study and therefore should be treated as potentially suspect without further validation.

Finally, this study recommends that the Tennant method not be used for restoration purposes. The Tennant method by nature lacks the ability to be used in restoration scenarios. The Tennant method relies solely on the average annual flow, any stream that has been degraded will not have an AAF that is able to sustain the habitat that is desired from a restoration stand point. Therefore, the Tennant method should be used in protection situations instead, and a more complex habitat model should be used for restoration purposes unless based on a natural hydrograph that has been validated in that particular setting for use in restoring the desired habitat.

This study has provided data to support a better idea of where and when the Tennant method is applicable and should be used. Hopefully this will allow for a better application of the Tennant method as well as other instream flow recommendation methodologies in the future.

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Appendix A Abbreviations

- AAF – Average Annual Flow
- ANOVA – Analysis of Variance
- CI – Confidence Interval
- DF – Degrees of Freedom
- Ecoregions – Bailey's Divisions
  - MarDiv – Marine Division
  - MarRMT – Marine Regime Mountains
  - MedDiv – Mediterranean Division
  - MedRMT – Mediterranean Regime Mountains
  - TempDesDiv – Temperate Desert Division
  - TempDesRMT – Temperate Desert Regime Mountains
  - TempStepDiv – Temperate Steppe Division
  - TempStepRMT – Temperate Steppe Regime Mountains
- ESRI – Environmental Systems Research Institute, Inc.
- Methodologies
  - HQI – Habitat Quality Index
  - IFIM – Instream Flow Incremental Methodology
  - MesoHABSIM – Mesohabitat Simulation (Larger Scale Habitat Model)
  - PHABSIM – Physical Habitat Simulation System
    - D50 – Diameter of the mean particle size
    - d84 – Diameter of the 84th percentile particle size
    - HABITAE – Habitat Program that creates WUA curves
    - HSC – Habitat Suitability Curve
    - MANSQ – WSL model using Manning's equation

STGQ – WSL model using the stage discharge regression

VELSIM – Velocity Model

WSL – Water Surface Level

WUA – Weighted Usable Area

R2 Cross – A One-Dimensional Hydraulic Model

RHYHABSIM – River Hydraulic and Habitat Simulation

RIMOS – River-Modeling System (Uses meteorological data not habitat preference)

RVA – Range of Variability Approach

NWIS – National Water Information System

PRISM – Parameter-elevation Regressions on Independent Slopes Model (Climatic Data)

PPT – Precipitation (Average Annual Precipitation)

TMAX – Average Daily Maximum Temperature

TMIN – Average Daily Minimum Temperature

USDOI – U.S. Department of the Interior

USFS – U.S. Forest Service

USGS – U.S. Geological Survey

WD1 – Colorado Water Division 1 Trial

WinXSPro – Windows® based Channel Cross Section Analyzer

Appendix B Site Data Tables

Appendix Table B.1 Table of information about the USGS gages used in this study

USGS Gage ID	State	Latitude	Longitude	Altitude (ft)	Drainage Area (sq mi)	USGS Gage Name	Source	# of Cross Sections	# of Peble Counts	# of Rating Curves	AAF (cfs)
06700500	CO	39.2089	-105.3036	6910	87	Goose Creek Above Cheesman Lake, CO.	WD1	3	1	0	27.39
06710500	CO	39.6530	-105.1958	5780	164	Bear Creek At Morrison, CO.	WD1	1	1	0	52.37
06712000	CO	39.3558	-104.7633	6150	169	Cherry Creek Near Franktown, CO.	WD1	1	1	1	9.53
06722500	CO	40.0908	-105.5144	9372	14	South St. Vrain Creek Near Ward, CO.	WD1	7	2	0	27.80
06725500	CO	39.9617	-105.5044	8186	36	Middle Boulder Creek At Nederland, CO.	WD1	16	1	0	54.27
06729500	CO	39.9311	-105.2958	6080	109	South Boulder Creek Near Eldorado Springs, CO.	David Merritt	6	0	2	68.88
06748600	CO	40.6469	-105.4936	7597	92	South Fork Cache La Poudre River Nr Rustic, CO.	WD1	20	5	0	62.80
07083000	CO	39.1722	-106.3892	9830	24	Halfmoon Creek Near Malta, CO.	WD1	3	1	1	29.45
07089000	CO	38.8128	-106.2222	8532	65	Cottonwood C Bl Hot Springs, Nr Buena Vista, CO.	WD1	1	0	0	55.47
10242000	UT	37.6722	-113.0347	6000	81	Coal Creek Near Cedar City, UT	USGS	1	0	0	32.92
11372000	CA	40.5132	-122.5242	673	228	Clear C Nr Igo CA	USGS	1	0	0	263.19
11376000	CA	40.3871	-122.2386	364	927	Cottonwood C Nr Cottonwood CA	USGS	2	0	0	884.94
11460400	CA	38.0269	-122.7364	100	34	Lagunitas C A Sp Taylor State Pk CA	Janine Castro	1	1	0	46.70
11460600	CA	38.0802	-122.7844	40	82	Lagunitas C Nr Pt Reyes Station CA	Janine Castro	1	1	0	93.19
11468000	CA	39.1705	-123.6681	5	303	Navarro R Nr Navarro CA	Janine Castro	1	1	1	513.85
11469000	CA	40.3132	-124.2834	60	245	Mattole R Nr Petrolia CA	USGS	1	0	1	1302.59
11475800	CA	39.8746	-123.7206	691	248	Sf Eel R A Leggett CA	Janine Castro	1	1	0	800.00
11481200	CA	41.0110	-124.0817	18	41	Little R Nr Trinidad CA	McBain and Trush	11	1	1	137.44
11481500	CA	40.9060	-123.8153	850	68	Redwood C Nr Blue Lake CA	Mary Ann Madej	1	1	1	226.65
11517500	CA	41.8229	-122.5956	2000	793	Shasta R Nr Yreka CA	USGS	1	0	1	184.51
11519500	CA	41.6407	-123.0150	2624	653	Scott R Nr Fort Jones CA	USGS	1	0	1	637.23
12010000	WA	46.3740	-123.7435	24	55	Naselle River Near Naselle, WA	Janine Castro	1	0	0	426.65
12013500	WA	46.6509	-123.6527	4	130	Willapa River Near Willapa, WA	Janine Castro	1	0	0	634.85
12020000	WA	46.6173	-123.2776	302	113	Chehalis River Near Doty, WA	Janine Castro	1	0	0	574.21
12303100	MT	48.3447	-115.6066	2866	11	Flower Creek near Libby MT	Sean Lawlor	3	1	0	26.38
12321500	ID	48.9972	-116.5691	1770	97	Boundary Creek Nr Porthill ID	USGS	1	0	0	201.32
12324590	MT	46.5197	-112.7934	4344	407	Little Blackfoot River near Garrison MT	Sean Lawlor	2	1	0	150.36
12330000	MT	46.4721	-113.2340	4750	71	Boulder Creek at Maxville MT	Sean Lawlor	2	1	0	44.62
12332000	MT	46.1845	-113.5025	5444	123	Middle Fork Rock Cr nr Philipsburg MT	Sean Lawlor	2	1	0	117.95
12335500	MT	46.7783	-112.7675	4640	116	Nevada Cr ab reservoir, nr Helmville, MT	Sean Lawlor	2	1	0	35.23
12374250	MT	47.8297	-114.6976	3000	20	Mill Cr ab Bassoo Cr nr Niarada MT	Sean Lawlor	3	1	0	8.00
12375900	MT	47.4916	-114.0268	3320	8	South Crow Creek near Ronan MT	Sean Lawlor	3	1	0	19.64
12377150	MT	47.3230	-113.9795	3460	12	Mission Cr ab Reservoir nr ST Ignatius MT	Sean Lawlor	3	1	0	48.30
12383500	MT	47.1474	-113.9743	3720	7	Big Knife Creek near Arlee MT	Sean Lawlor	3	1	0	10.21
12388400	MT	47.2663	-114.4068	3420	23	Revais Cr bl West Fork nr Dixon MT	Sean Lawlor	3	1	0	17.88
12396900	WA	48.8463	-117.2869	2557	70	Sullivan Creek Ab Outlet Cr Nr Metaline Falls, WA	Bert Wasson	1	0	0	122.62

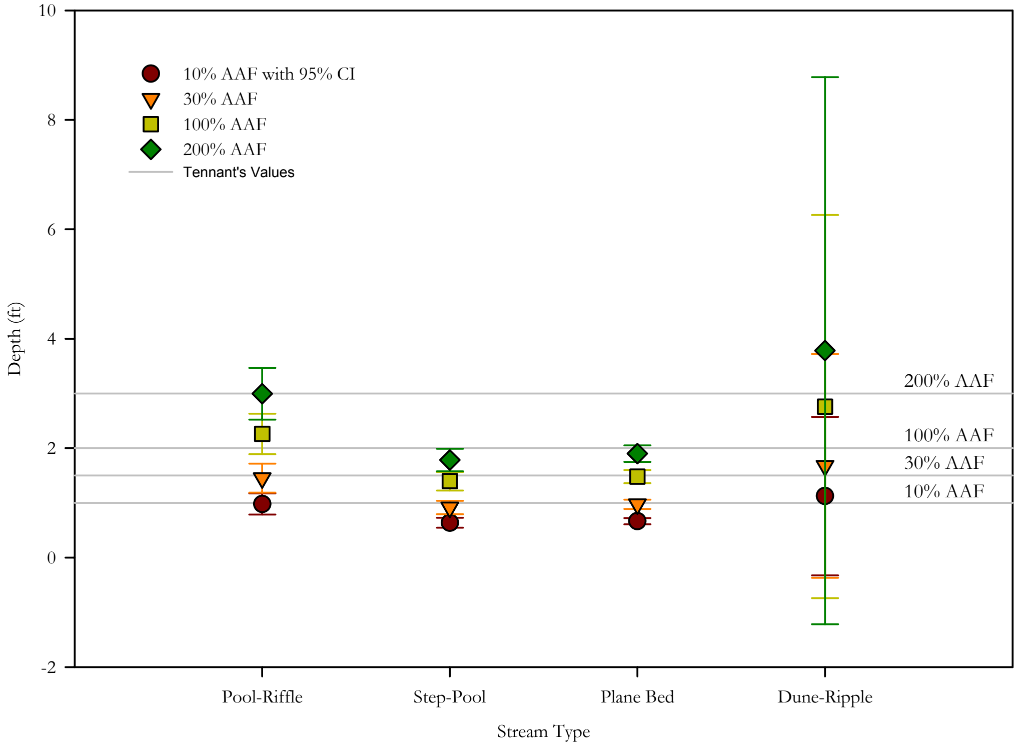
Appendix Table B.1 Continued

USGS Gage ID	State	Longitude	Latitude	Altitude (ft)	Drainage Area (sq mi)	USGS Gage Name	Source	# of Cross Sections	# of Peble Counts	# of Rating Curves	AAF (cfs)
12414900	ID	47.1763	-116.4927	2575	275	St Maries River Nr Santa ID	Janine Castro	1	0	1	353.11
13057940	ID	43.4417	-111.7283	5200	568	Willow Creek Bl Tex Creek Nr Ririe ID	USGS	2	0	1	110.14
13058520	ID	43.5764	-111.9131	4840		Willow Creek Floodway Channel Nr Ucon ID	USGS	1	0	1	69.31
13063000	ID	42.8156	-111.5058	6239	350	Blackfoot River Ab Reservoir Nr Henry ID	USGS	2	0	1	150.83
13075000	ID	42.6300	-112.2260	4160	353	Marsh Creek Nr Mccammon ID	USGS	1	0	0	83.71
13112000	ID	44.0028	-112.2208	4807	400	Camas Creek At Camas ID	USGS	1	0	0	35.50
13132500	ID	43.5822	-113.2706	5240	1410	Big Lost River Nr Arco ID	USGS	1	0	0	97.33
13132535	ID	43.5739	-112.9433	4900		Big Lost R At Lincoln Blvd Bridge Nr Atomic City	USGS	1	0	0	26.60
13200000	ID	43.6481	-115.9897	3120	399	Mores Creek Ab Robie Creek Nr Arrowrock Dam ID	Janine Castro	1	0	0	283.92
13236500	ID	44.2919	-115.6419	5181	112	Deadwood River Bl Deadwood Res Nr Lowman ID	USGS	1	0	1	230.97
13240000	ID	44.9136	-115.9972	5140	49	Lake Fork Payette River Ab Jumbo Cr Nr Mccall ID	Janine Castro	1	0	0	142.32
13265500	ID	44.2914	-116.7822	2270	288	Crane Creek At Mouth Nr Weiser ID	USGS	1	0	0	83.11
13297330	ID	44.2703	-114.5167	5700	29	Thompson Creek Nr Clayton ID	Janine Castro/USGS/ Betsy Rieffenberger	3	4	1	17.10
13297355	ID	44.2908	-114.4717	5710	79	Squaw Creek Bl Bruno Creek Nr Clayton ID	Janine Castro	1	0	0	33.68
13311000	ID	44.9057	-115.3293	6460	20	Ef Of Sf Salmon River At Stibnite ID	Janine Castro	1	0	0	23.93
13334700	WA	46.3263	-117.1527	1090	170	Asotin Creek Below Kearney Gulch Near Asotin, WA	Janine Castro	1	0	0	72.08
13337500	ID	45.8253	-115.5272	3810	261	Sf Clearwater River Nr Elk City ID	USGS	1	0	1	271.00
13339500	ID	46.3717	-116.1625	1080	243	Lolo Creek Nr Greer ID	Janine Castro	1	0	0	334.04
13342450	ID	46.4266	-116.8052	865	235	Lapwai Creek Nr Lapwai ID	Janine Castro	1	0	0	77.12
13344500	WA	46.5054	-118.0663	730	431	Tucannon River Near Starbuck, WA	Janine Castro	1	0	0	170.18
13345000	ID	46.9152	-116.9510	2455	317	Palouse River Nr Potlatch ID	USGS	1	0	1	267.38
13346800	ID	46.7318	-117.0243	2543	18	Paradise Cr At University Of Idaho At Moscow ID	Janine Castro	1	0	0	7.48
14017000	WA	46.2743	-118.2219	1150	361	Touchet River At Bolles, WA	Janine Castro	1	0	0	227.85
14018500	WA	46.0276	-118.7297	405	1657	Walla Walla River Near Touchet, WA	Janine Castro	1	0	0	570.65
14020000	OR	45.7196	-118.3233	1855	131	Umatilla River Above Meacham Creek, Nr Gibbon, OR	Janine Castro	1	0	0	226.03
14021000	OR	45.6721	-118.7928	1054	637	Umatilla River At Pendleton,Oreg	Janine Castro	1	0	1	509.68
14033500	OR	45.9029	-119.3270	330	2290	Umatilla River Near Umatilla, OR	Janine Castro	1	0	1	498.74
14038530	OR	44.4185	-118.9063	3131	386	John Day River Near John Day, OR	Janine Castro	1	0	1	201.11
14202000	OR	45.2332	-122.7501	72	479	Pudding River At Aurora, OR	Janine Castro	1	0	1	1253.31
14207500	OR	45.3507	-122.6762	86	706	Tualatin River At West Linn, OR	Janine Castro	1	0	1	1472.21
14307700	OR	42.9540	-122.8289	1240	152	Jackson Creek Nr Tiller, OR	Mikeal Jones	2	2	2	315.90
14308000	OR	42.9304	-122.9484	992	449	South Umpqua River At Tiller, OR	Janine Castro	1	0	1	1030.83
14325000	OR	42.8915	-124.0707	197	169	South Fork Coquille River At Powers, OR	Janine Castro	1	0	1	780.87
14357500	OR	42.3240	-122.8667	1343	289	Bear Creek At Medford, OR	Janine Castro	1	0	1	115.45
							Number of Stations with each	71	26	27	Avg 258.47 Min 7.48 Max 1472.21

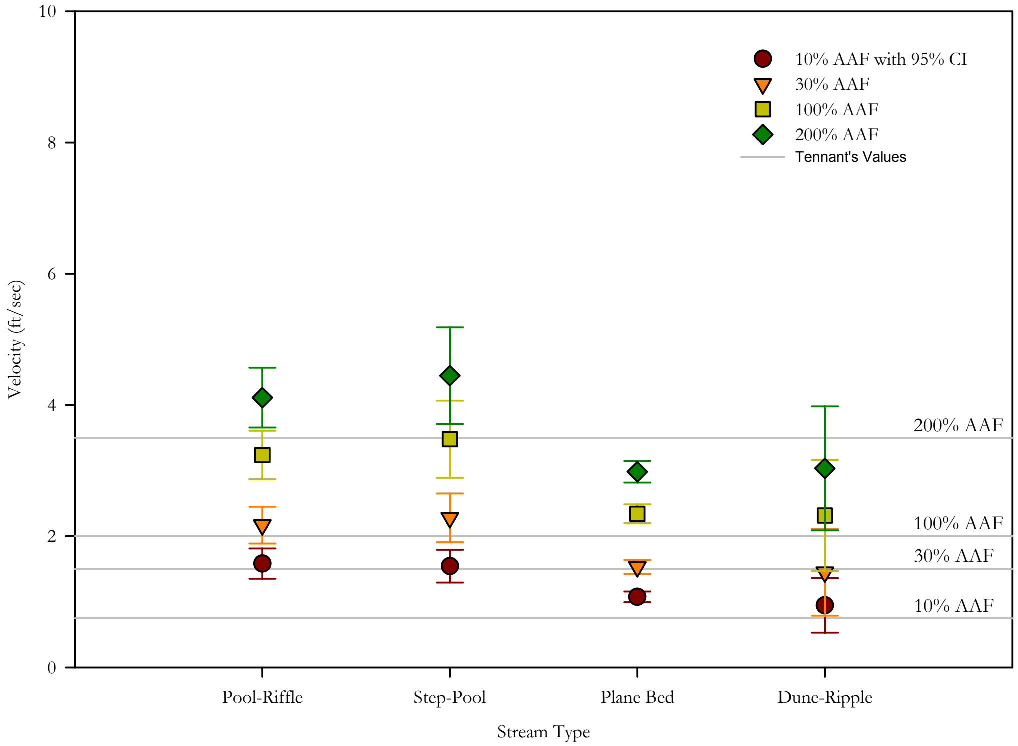
Appendix Table B.2 Table of information about the USGS gages used in Nebraska

USGS Gage ID	State	Latitude	Longitude	Altitude (ft)	Drainage Area (sq mi)	USGS Gage Name	Source	# of Cross Sections	AAF (cfs)
06453600	NE	42.8111	-98.1758	1233	812	Ponca Creek At Verdel, Nebr.	USGS	1	88.99
06466500	NE	42.7322	-97.9225	1243	440	Bazile Creek Near Niobrara, NE	USGS	1	83.39
06795500	NE	41.5261	-97.2817	1435	306	Shell Creek Near Columbus, Nebr.	USGS	1	48.77
06797500	NE	42.2686	-98.3394	1836	1400	Elkhorn River At Ewing, NE	USGS	1	193.07
06799100	NE	42.1483	-97.4786	1543	701	North Fork Elkhorn River Near Pierce, Nebr.	USGS	1	103.96
06800000	NE	41.5603	-96.5408	1212	368	Maple Creek Near Nickerson, NE	USGS	1	79.80
06803000	NE	40.6578	-96.6656	1193	167	Salt Creek At Roca, Nebr.	USGS	1	50.80
06803510	NE	40.8931	-96.6817	1115	44	Little Salt Creek Near Lincoln, Nebr.	USGS	2	14.34
06803530	NE	41.0158	-96.5442	1109	120	Rock Creek Near Ceresco, Nebr.	USGS	1	36.20
06804000	NE	41.1475	-96.5378	1110	273	Wahoo Creek At Ithaca, Nebr.	USGS	1	84.48
06806500	NE	40.7942	-95.9114	927	241	Weeping Water Creek At Union, Nebr.	USGS	1	101.34
06814500	NE	40.1569	-95.9447	944	548	North Fork Big Nemaha River At Humboldt, Nebr.	USGS	2	212.25
06835500	NE	40.2347	-100.8782	2583	2990	Frenchman Creek At Culbertson, Nebr.	USGS	1	83.51
06836500	NE	40.1458	-100.6732	2503	361	Driftwood Creek Near Mc Cook, Nebr.	USGS	1	8.82
06847500	NE	40.1317	-99.5547	1981	3840	Sappa Creek Near Stamford, Nebr.	USGS	1	42.65
06849500	NE	40.0783	-99.1686	1863	20820	Republican River Bl Harlan County Dam, Nebr.	USGS	1	208.09
06880800	NE	40.7311	-97.1775	1403	1192	West Fork Big Blue River Nr Dorchester, Nebr.	USGS	1	183.35
06883000	NE	40.3325	-98.0669	1633	984	Little Blue River Near Deweese, NE	USGS	1	144.87
							Number of Stations	18	Avg 98.26
									Min 8.82
									Max 212.25

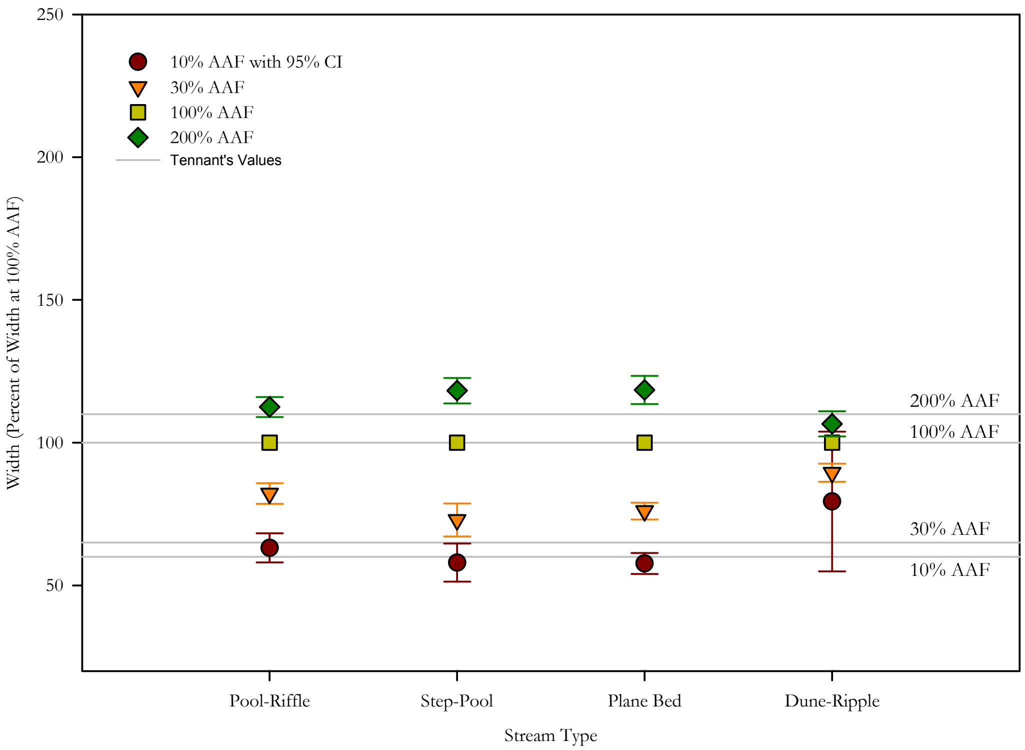
Appendix C Stream Type Tennant Analysis Results



Appendix Figure C.1 Scatter plot showing differences between stream types in comparing depths to Tennant's original data.



Appendix Figure C.2 Scatter plot showing differences between stream types in comparing velocities to Tennant's original data.

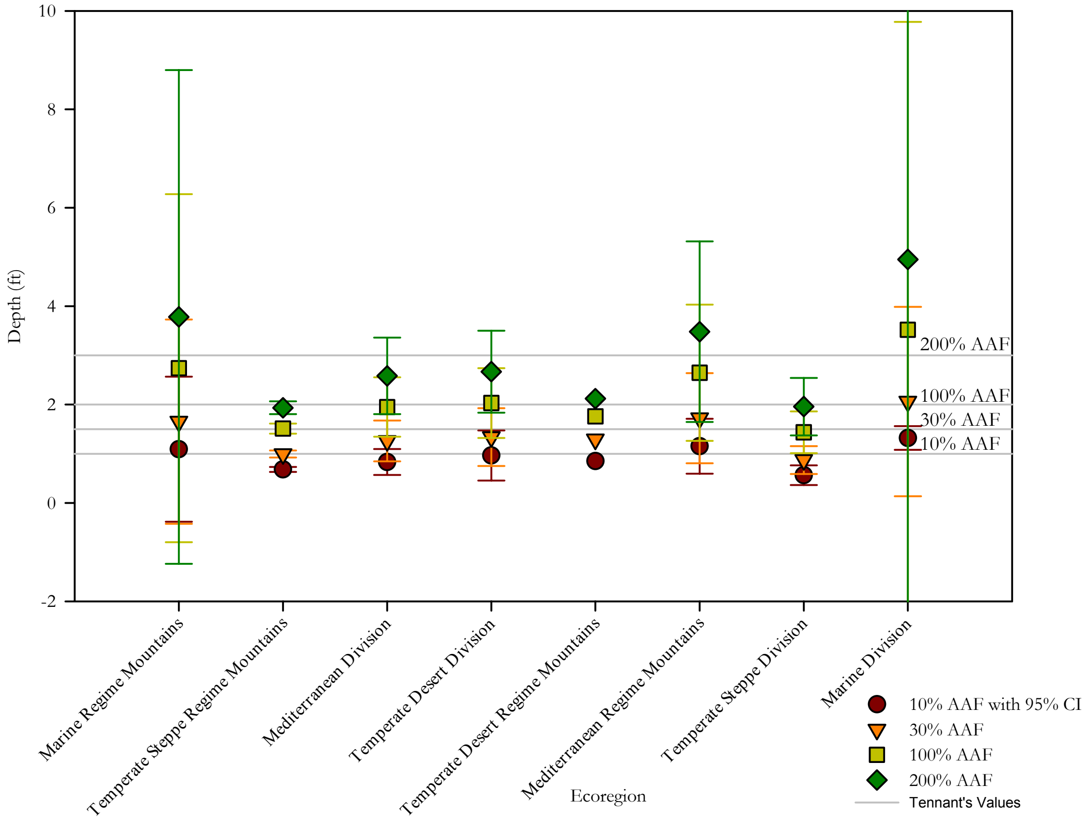


Appendix Figure C.3 Scatter plot showing differences between stream types in comparing widths (percent of width at 100% AAF) to Tennant's original data.

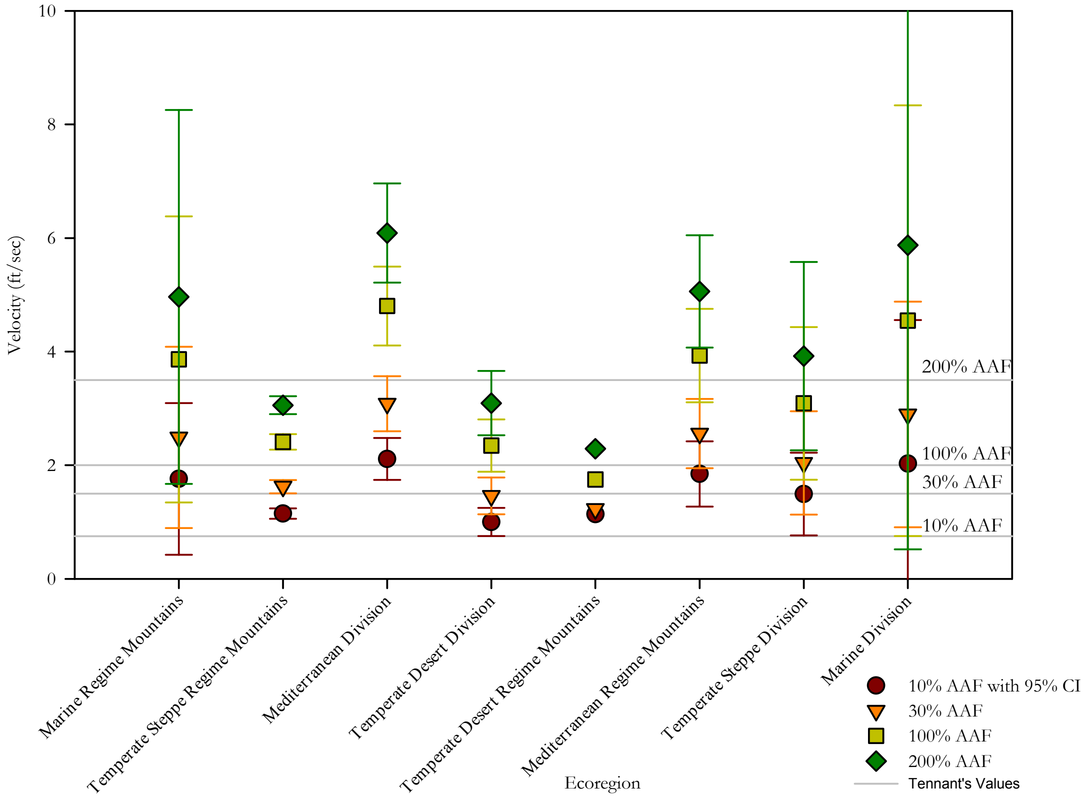
Appendix Table C.1 ANOVA table of Tennant calculations showing differences between stream types for data collected in this study. Stream types with different letters are significantly different from each other at a p value of less than 0.05.

Variable	Stream Type ANOVA				Stream Types			
	Degrees of Freedom		F Value	Pr > F	Dune-Ripple	Plane Bed	Pool-Riffle	Step-Pool
	Numerator	Denominator						
Width 10% AAF	3	147	2.09	0.1044	A	A	A	A
Width 30% AAF	3	147	4.13	0.0076	AB	AB	A	B
Width 100% AAF	-	-	-	-	-	-	-	-
Width 200% AAF	3	147	1.88	0.1351	A	A	A	A
Depth 10% AAF	3	147	5.27	0.0018	AB	A	B	A
Depth 30% AAF	3	147	6.77	0.0003	AB	A	B	A
Depth 100% AAF	3	147	10.12	<0.0001	AB	AC	B	C
Depth 200% AAF	3	147	13.15	<0.0001	A	B	A	B
Velocity 10% AAF	3	147	6.28	0.0005	AB	A	B	B
Velocity 30% AAF	3	147	7.23	0.0001	AB	A	B	B
Velocity 100% AAF	3	147	7.82	<0.0001	AB	A	B	B
Velocity 200% AAF	3	147	8.63	<0.0001	AB	A	B	B

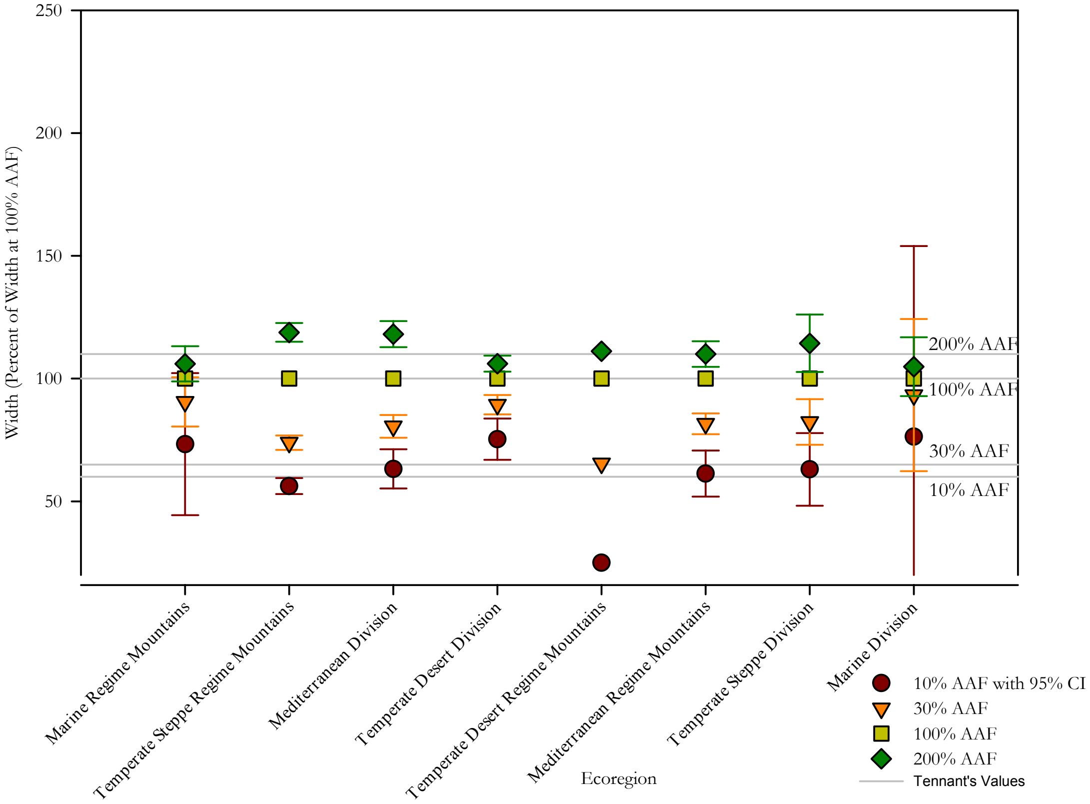
Appendix D Ecoregion Tennant Analysis Results



Appendix Figure D.1 Scatter plot showing differences between ecoregions in comparing depths to Tennant's original data.



Appendix Figure D.2 Scatter plot showing differences between ecoregions in comparing velocities to Tennant's original data.

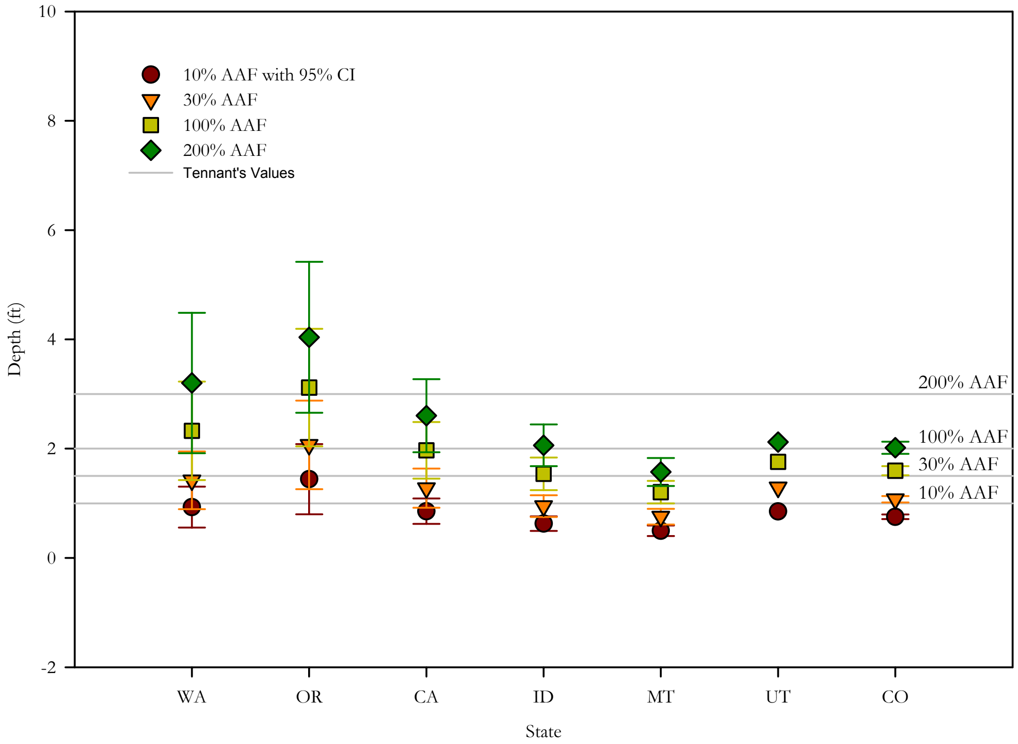


Appendix Figure D.3 Scatter plot showing differences between ecoregions in comparing widths (percent of width at 100% AAF) to Tennant's original data.

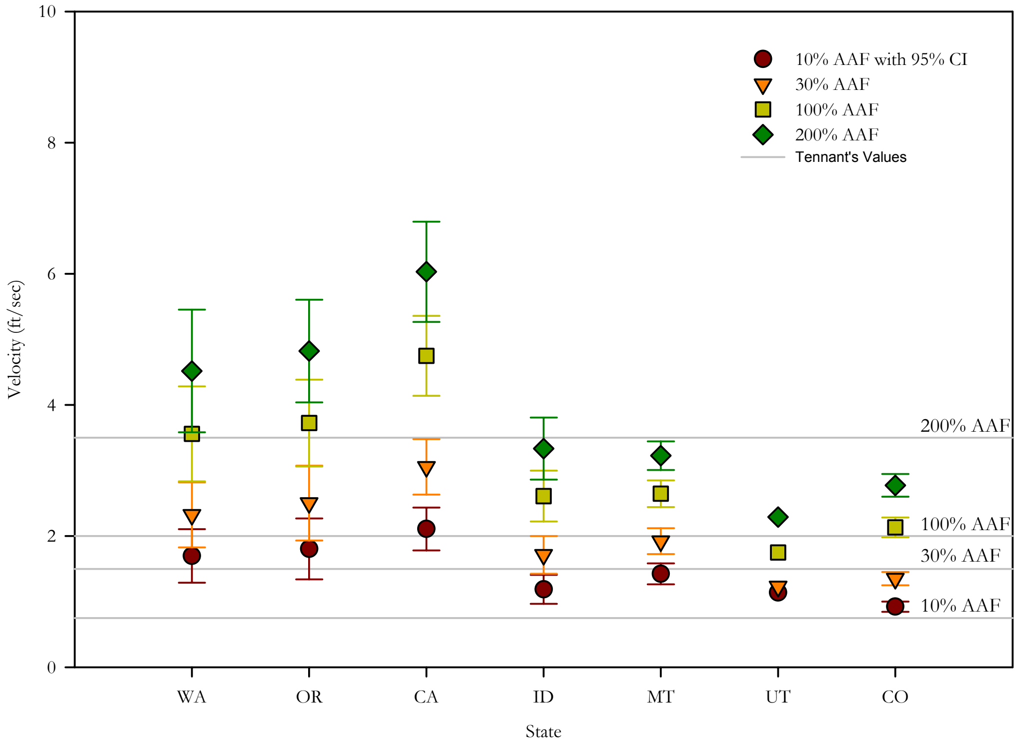
Appendix Table D.1 ANOVA table of Tennant calculations showing differences between ecoregions for data collected in this study. Ecoregions with different letters are significantly different from each other at a p value of less than 0.05. Ecoregions abbreviations are defined in Appendix A.

Variable	Ecoregion ANOVA				Ecoregion (Division)							
	Degrees of Freedom		F Value	Pr > F	MarDiv	MarRMT	MedDiv	MedRMT	TempDesRMT	TempDesDiv	TempStepRMT	TempStepDiv
	Numerator	Denominator										
Width 10% AAF	7	143	4.02	0.0005	ACD	ACD	ABC	ABC	B	C	BD	ABC
Width 30% AAF	7	143	3.73	0.0010	AB	AB	AB	AB	AB	A	B	AB
Width 100% AAF	-	-	-	-	-	-	-	-	-	-	-	-
Width 200% AAF	7	143	1.96	0.0651	A	A	A	A	A	A	A	A
Depth 10% AAF	7	143	2.36	0.0259	A	A	A	A	A	A	A	A
Depth 30% AAF	7	143	2.65	0.0132	A	A	A	A	A	A	A	A
Depth 100% AAF	7	143	3.57	0.0014	AB	AB	AB	A	AB	AB	B	AB
Depth 200% AAF	7	143	4.55	0.0001	A	AB	AB	A	AB	AB	B	AB
Velocity 10% AAF	7	143	8.09	<0.0001	AB	AB	A	A	AB	B	B	AB
Velocity 30% AAF	7	143	10.34	<0.0001	AB	AB	A	A	AB	B	B	AB
Velocity 100% AAF	7	143	14.90	<0.0001	ABC	ABC	A	AC	ABC	B	B	BC
Velocity 200% AAF	7	143	16.67	<0.0001	ABE	ABD	A	ABE	BD	CD	D	DE

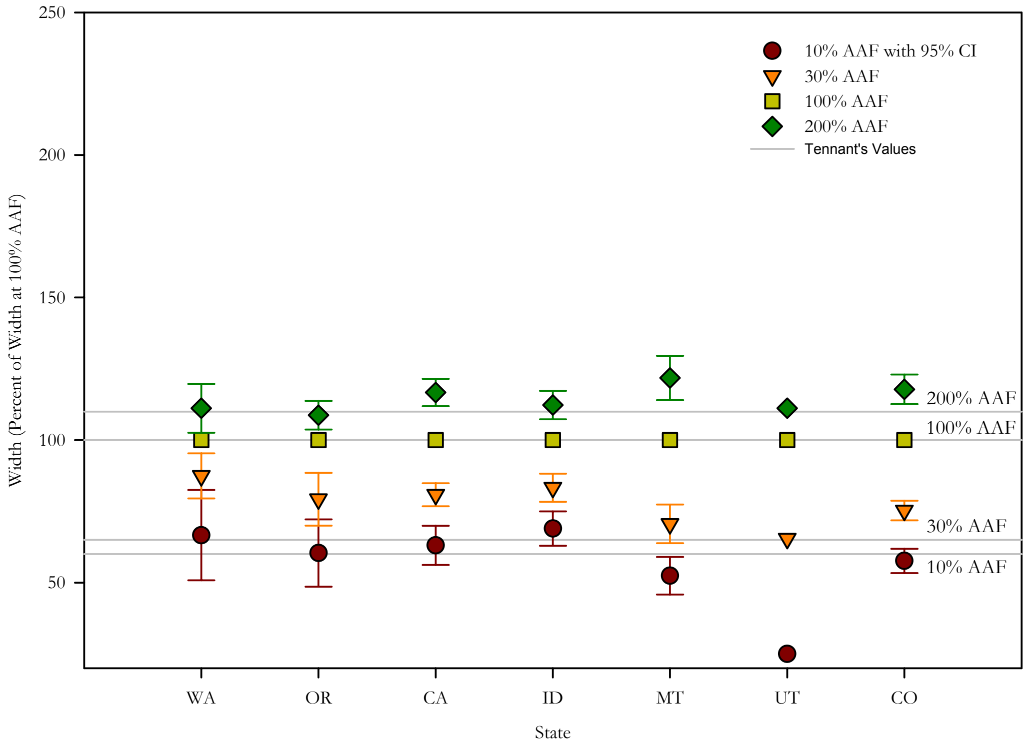
Appendix E State Tennant Analysis Results



Appendix Figure E.1 Scatter plot showing differences between states in comparing depths to Tennant's original data.



Appendix Figure E.2 Scatter plot showing differences between states in comparing velocities to Tennant’s original data.

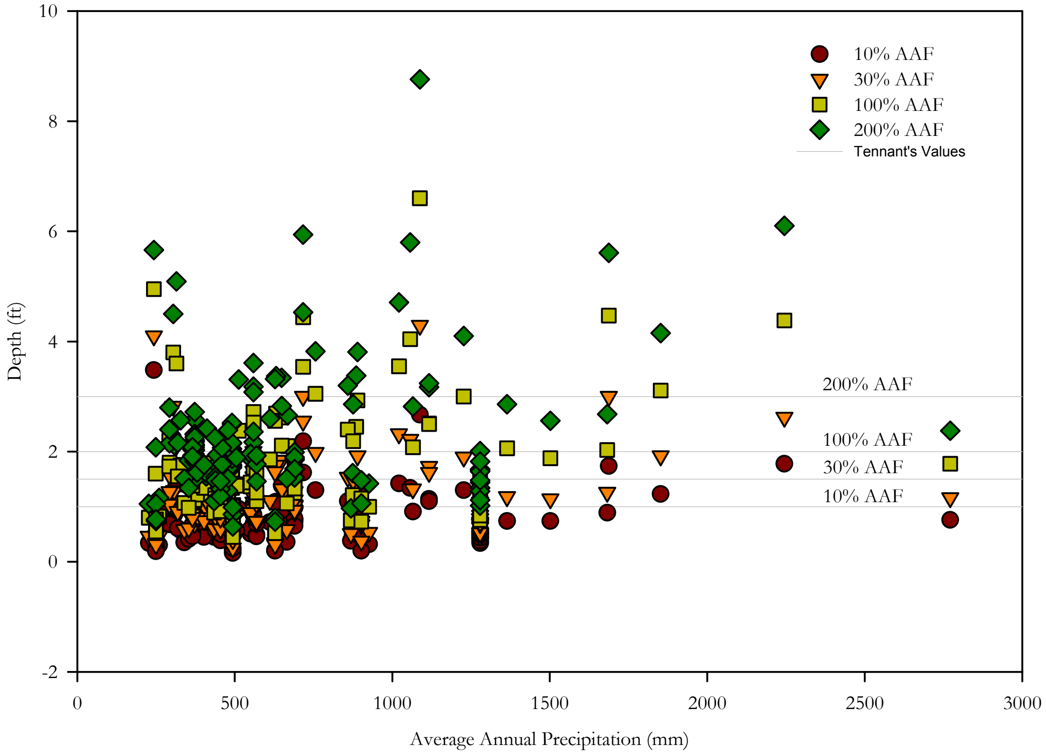


Appendix Figure E.3 Scatter plot showing differences between states in comparing widths (percent of width at 100% AAF) to Tennant's original data.

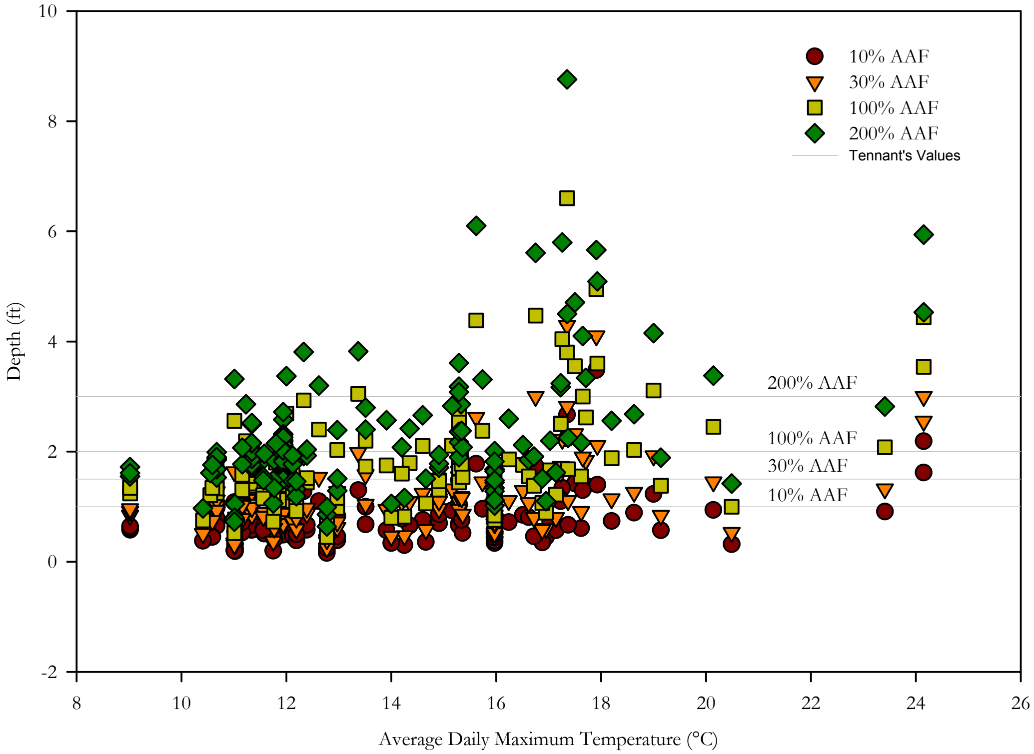
Appendix Table E.1 ANOVA table of Tennant calculations showing differences between states for data collected in this study. States with different letters are significantly different from each other at a p value of less than 0.05.

Variable	State ANOVA Degrees of Freedom Numerator	 Denominator	F Value	Pr > F	State CA	 CO	 ID	 MT	 OR	 UT	 WA
Width 10% AAF	6	144	4.02	0.0009	ABC	ABC	AC	BD	ABC	B	CD
Width 30% AAF	6	144	3.34	0.0041	ABC	ABC	AC	B	ABC	ABC	C
Width 100% AAF	-	-	-	-	-	-	-	-	-	-	-
Width 200% AAF	6	144	1.50	0.1839	A	A	A	A	A	A	A
Depth 10% AAF	6	144	8.98	<0.0001	A	A	AB	BC	D	ACD	AD
Depth 30% AAF	6	144	8.54	<0.0001	A	A	AB	BC	D	ACD	AD
Depth 100% AAF	6	144	8.70	<0.0001	A	A	AB	BC	D	ACD	AD
Depth 200% AAF	6	144	9.10	<0.0001	A	A	AB	BC	D	ACD	AD
Velocity 10% AAF	6	144	18.75	<0.0001	A	B	BC	CD	AD	ABC	AC
Velocity 30% AAF	6	144	20.47	<0.0001	A	B	BC	CD	AD	ABC	AC
Velocity 100% AAF	6	144	24.53	<0.0001	A	B	BC	CD	AE	BDE	ACD
Velocity 200% AAF	6	144	26.19	<0.0001	A	B	BC	BCD	AE	BCE	ADE

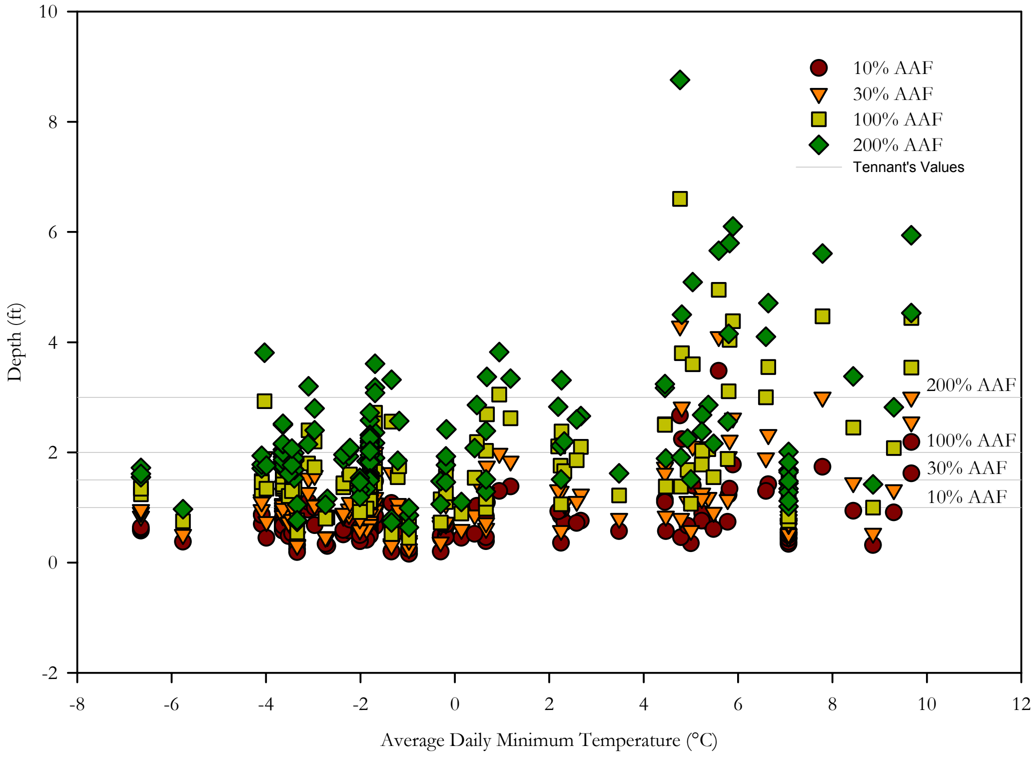
Appendix F Hydro-Climatic Tennant Analysis Results



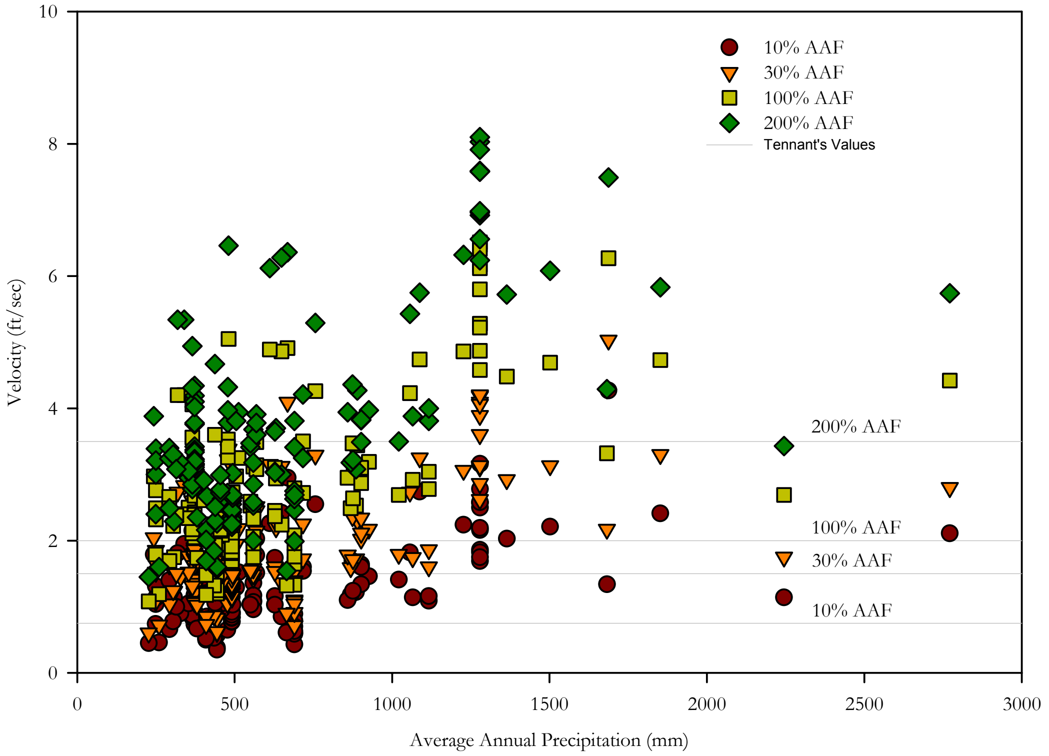
Appendix Figure F.1 Scatter plot showing differences with average annual precipitation (PRISM database) in comparing depths to Tennant's original data.



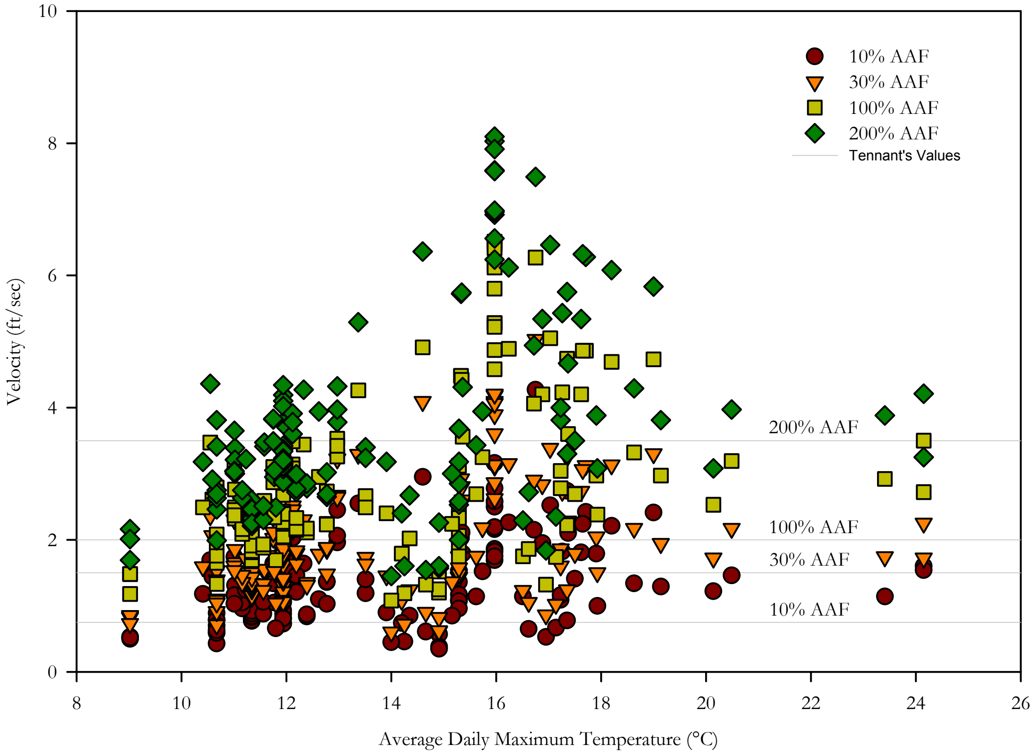
Appendix Figure F.2 Scatter plot showing differences with average daily maximum temperature (PRISM database) in comparing depths to Tennant's original data.



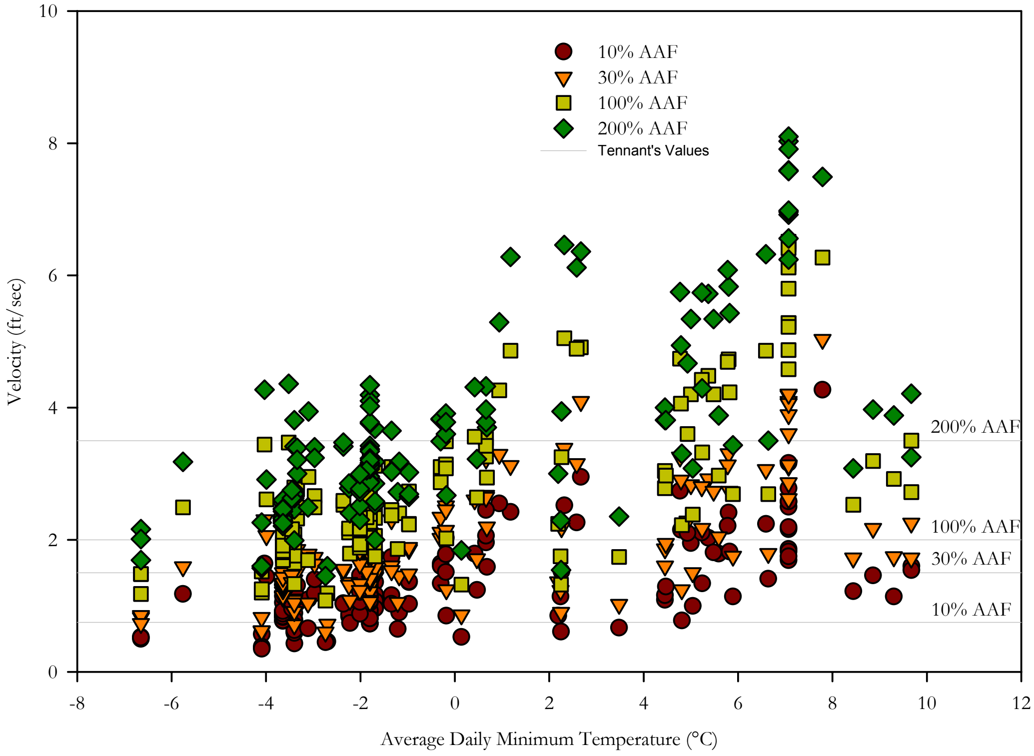
Appendix Figure F.3 Scatter plot showing differences with average minimum temperature (PRISM database) in comparing depths to Tennant's original data.



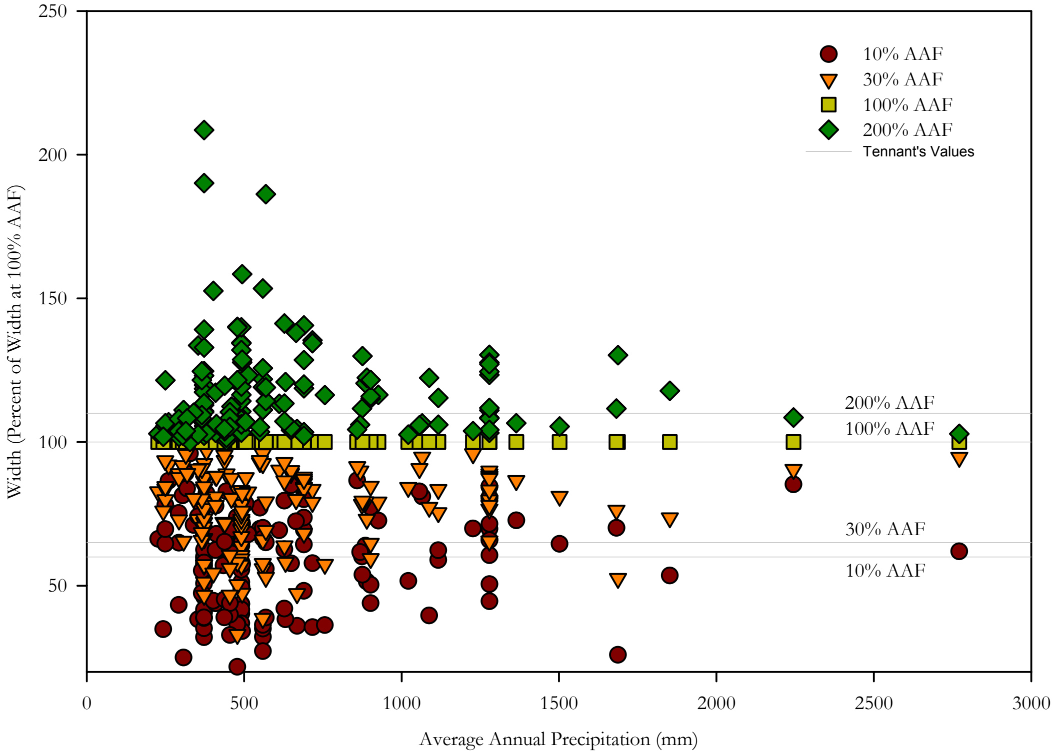
Appendix Figure F.4 Scatter plot showing differences with average annual precipitation (PRISM database) in comparing velocities to Tennant's original data.



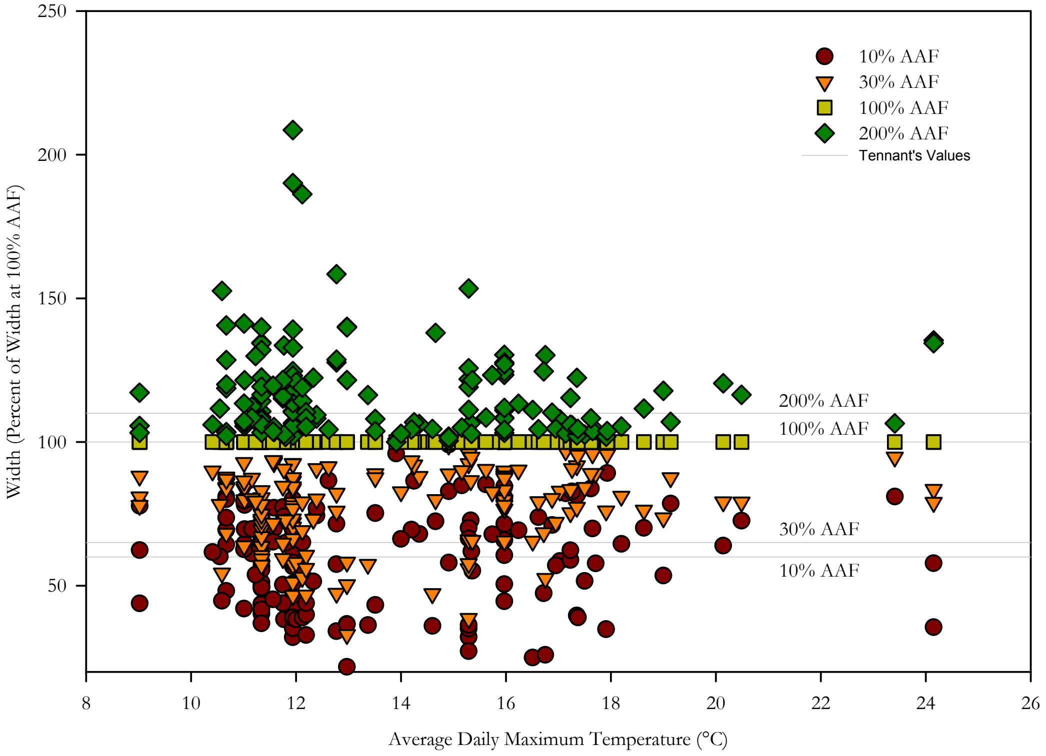
Appendix Figure F.5 Scatter plot showing differences with average daily maximum temperature (PRISM database) in comparing velocities to Tennant's original data.



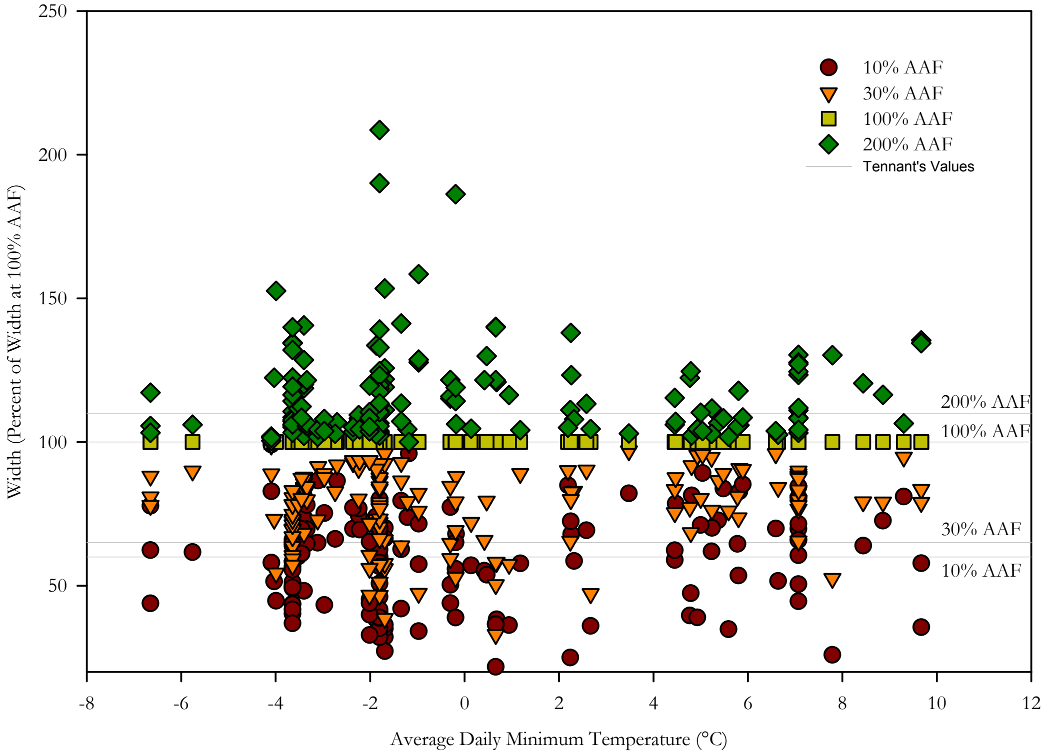
Appendix Figure F.6 Scatter plot showing differences with average minimum temperature (PRISM database) in comparing velocities to Tennant's original data.



Appendix Figure F.7 Scatter plot showing differences with average annual precipitation (PRISM database) in comparing widths (percent of width at 100% AAF) to Tennant's original data.



Appendix Figure F.8 Scatter plot showing differences with average daily maximum temperature (PRISM database) in comparing widths (percent of width at 100% AAF) to Tennant's original data.



Appendix Figure F.9 Scatter plot showing differences with average daily minimum temperature (PRISM database) in comparing widths (percent of width at 100% AAF) to Tennant's original data.

Appendix Table F.1 ANOVA table showing the regression of hydro-climatic data and the results from the Tennant calculations. The regression with the highest adjusted r-square was used to calculate the p values for the individual parameter(s).

			PRISM Regressions		
Variable	F Value	Pr > F	Adjusted R-Square	Parameter(s)	Pr > |t|
Width 10% AAF	1.87	0.1731	0.0058	PPT	0.1731
Width 30% AAF	2.42	0.0681	0.0277	PPT, TMAX, TMIN	0.2112, 0.0337, 0.1741
Width 100% AAF	-	-	-	-	-
Width 200% AAF	1.76	0.1570	0.0150	PPT, TMAX, TMIN	0.2803, 0.0252, 0.0468
Depth 10% AAF	9.62	<0.0001	0.1470	PPT, TMAX, TMIN	0.0692, <0.0001, 0.0085
Depth 30% AAF	10.09	<0.0001	0.1538	PPT, TMAX, TMIN	0.0794, <0.0001, 0.0213
Depth 100% AAF	12.06	<0.0001	0.1812	PPT, TMAX, TMIN	0.0739, <0.0001, 0.0505
Depth 200% AAF	14.40	<0.0001	0.2113	PPT, TMAX, TMIN	0.0633, <0.0001, 0.0735
Velocity 10% AAF	66.93	<0.0001	0.4678	TMAX, TMIN	<0.0001, <0.0001
Velocity 30% AAF	86.60	<0.0001	0.5330	TMAX, TMIN	<0.0001, <0.0001
Velocity 100% AAF	73.16	<0.0001	0.5907	PPT, TMAX, TMIN	0.1319, <0.0001, <0.0001
Velocity 200% AAF	77.36	<0.0001	0.6043	PPT, TMAX, TMIN	0.0653, <0.0001, <0.0001

Appendix G Full Site Analysis Walkthrough

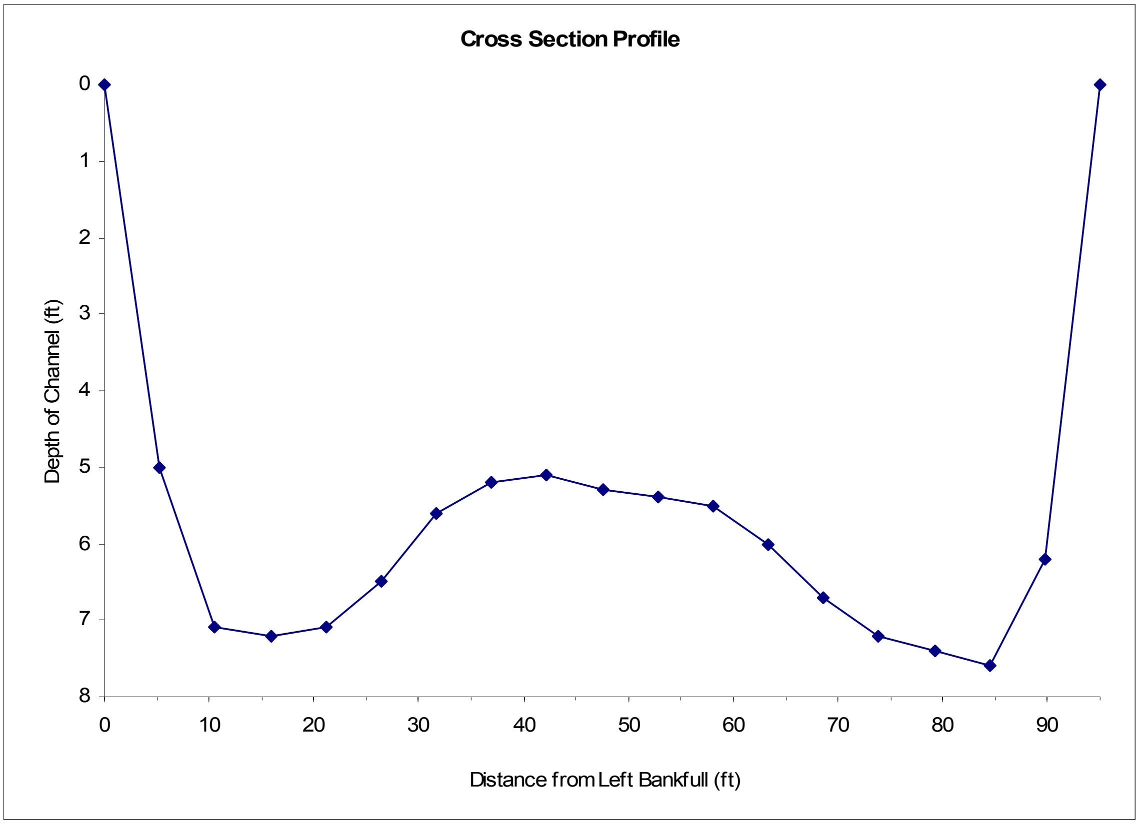
A Day in the Life of Site 11468000

This appendix is meant to be a way to understand the process that was gone through for each site to produce the results for this study's analyses. The walkthrough is designed as a step by step display of what each step looks like along with brief narratives; the overview and importance of each step is covered in the methods section. Appendix G is meant as a supplemental reference when the methods seem intangible.

Raw cross section data are entered into columns in excel™ (Appendix Table G.1) and then the data are graphed in excel™ (Appendix Figure G.1).

Appendix Table G.1

X	Y
0.00	0
5.28	5
10.56	7.1
15.83	7.2
21.11	7.1
26.39	6.5
31.67	5.6
36.94	5.2
42.22	5.1
47.50	5.3
52.78	5.4
58.06	5.5
63.33	6
68.61	6.7
73.89	7.2
79.17	7.4
84.44	7.6
89.72	6.2
95.00	0

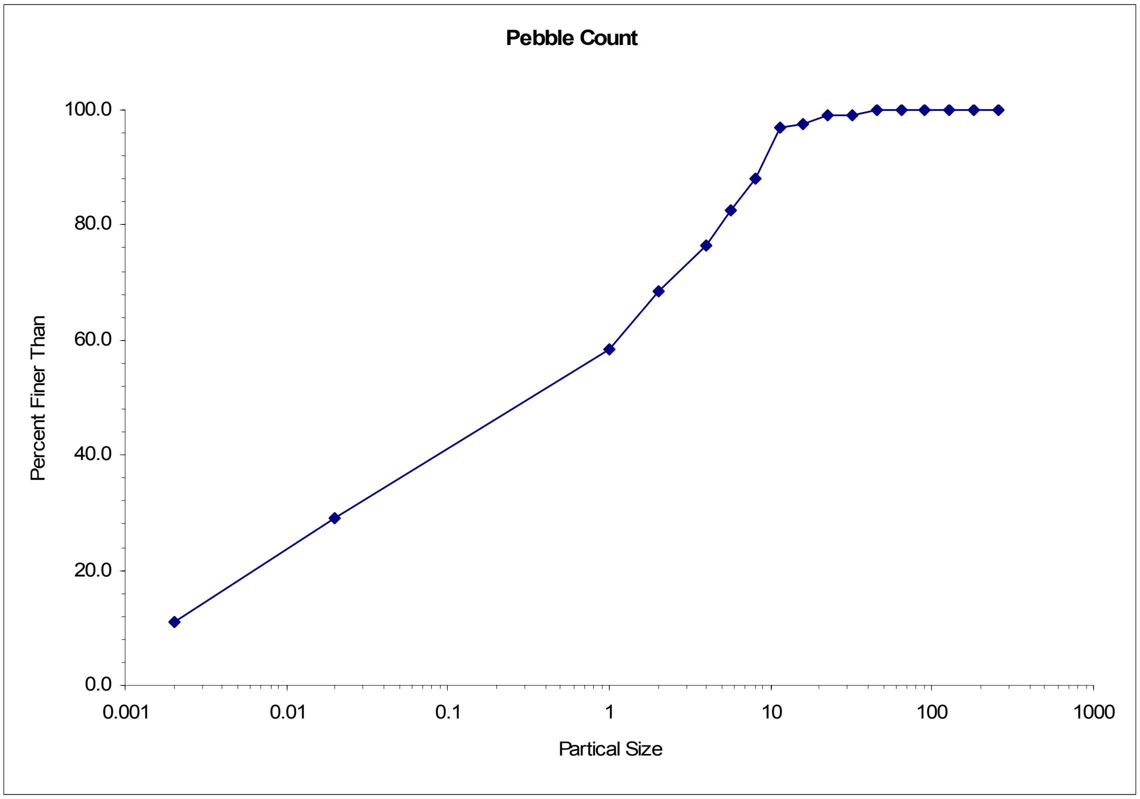


Appendix Figure G.1

Any pebble count data are entered into an excel™ worksheet (Appendix Table G.2). Raw data for columns titled 'mm' (pebble diameter size class in millimeters) and '#' (number of pebbles/samples in that size class) are used to calculate the sum of the number of samples, that is then used to calculate the "%' column which is the '#' value divided by the sum. The 'Cum %' column is calculated by adding the "%' value to the previous 'Cum %' value. And then is plotted (Appendix Figure G.2) using excel™.

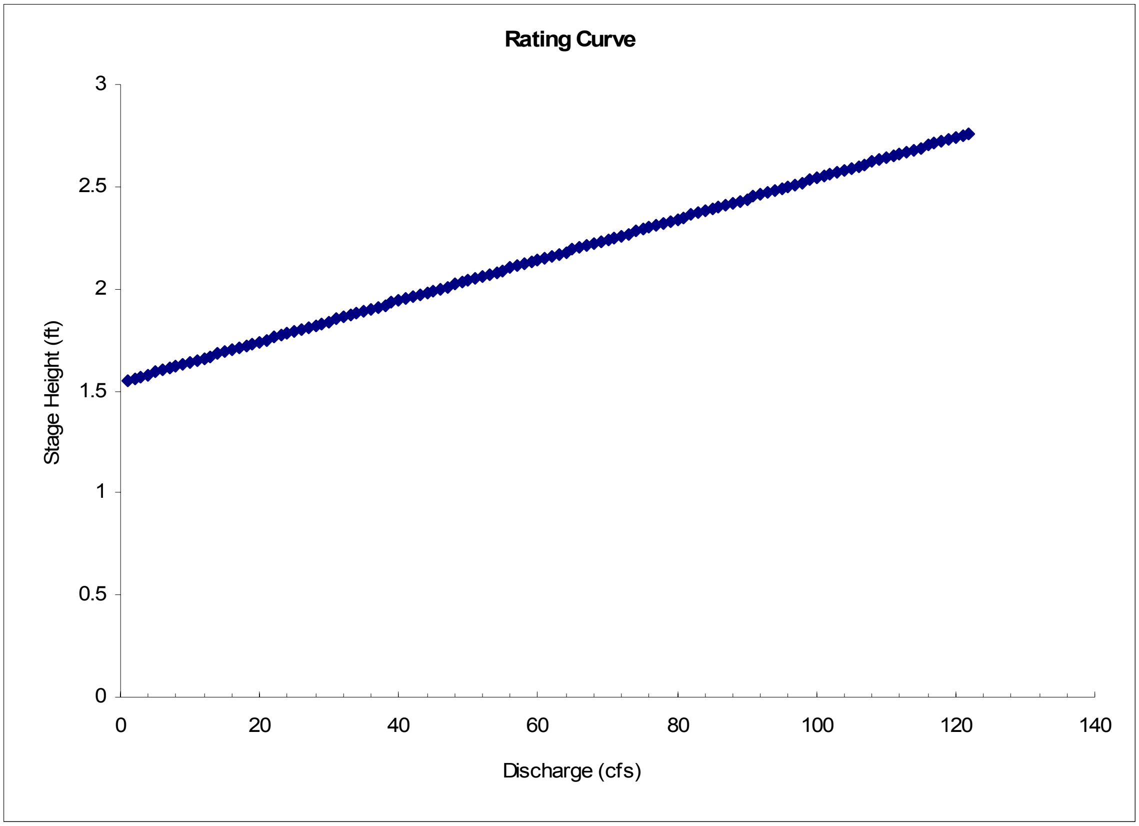
Appendix Table G.2

mm	#	%	Cum %
0.002	14	11.0	11.0
0.02	23	18.1	29.1
1	37	29.1	58.3
2	13	10.2	68.5
4	10	7.9	76.4
5.6	8	6.3	82.7
8	7	5.5	88.2
11.3	11	8.7	96.9
16	1	0.8	97.6
22.6	2	1.6	99.2
32	0	0.0	99.2
45	1	0.8	100.0
64	0	0.0	100.0
90	0	0.0	100.0
128	0	0.0	100.0
180	0	0.0	100.0
256	0	0.0	100.0
	127		



Appendix Figure G.2

Rating curve data, either from the USGS NWIS database (USGS 2005) or the cross section source is plotted in excel™ if available (Appendix Figure G.3).



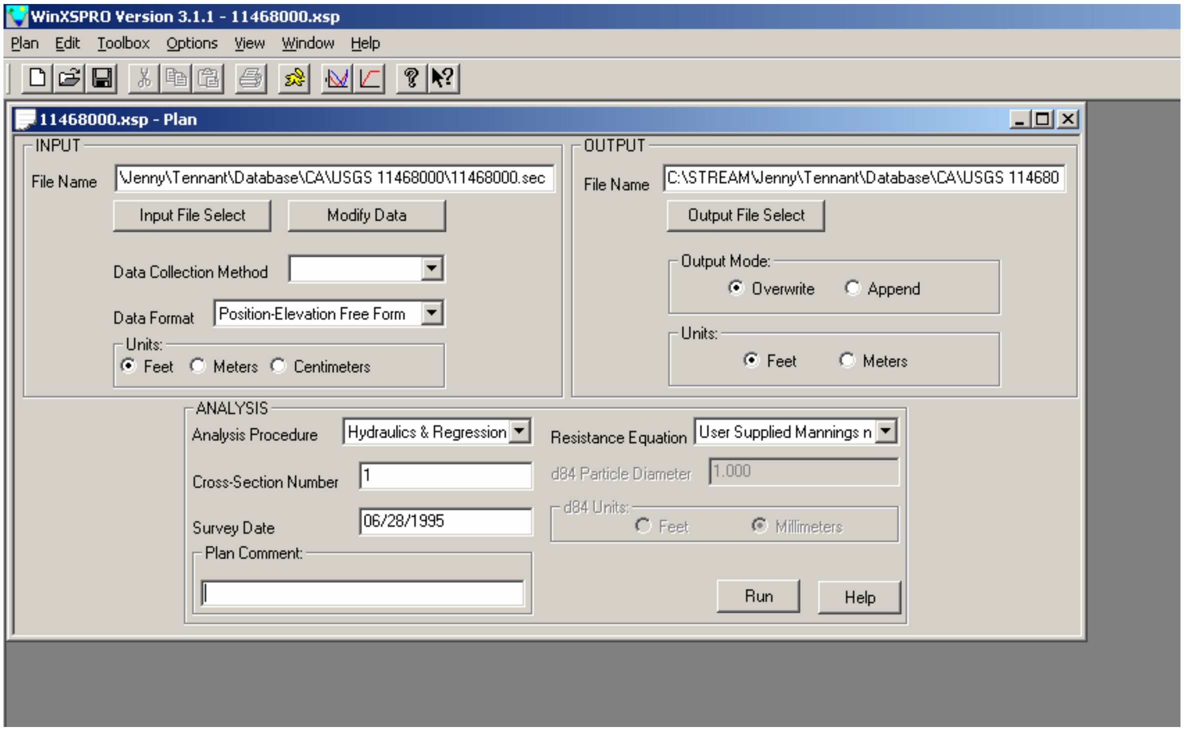
Appendix Figure G.3

The text output of the calendar year statistics from the NWIS database (USGS 2005) is opened/imported into excel™ (Appendix Table G.3). The average of the 'mean_va' column is calculated. This average is then multiplied by the added proportion numbers to calculate the percent AAF values used in the rest of the analyses.

Appendix Table G.3

```
#
#
# US Geological Survey, Water Resources Data
# retrieved: 2005-08-03 10:19:56 EDT
#
# This file contains Calendar Year Streamflow Statistics
#
# This file includes the following columns:
#
#
# agency_cd  agency code
# site_no    USGS site number
# year_nu    Calendar year for value
# mean_va    annual-mean value in cubic-feet per-second.
#            if there is not complete record
#            for a year this field is blank
#
#
# Sites in this file include:
# USGS 11468000 NAVARRO R NR NAVARRO CA
#
#
agency_cd site_no      year_nu     mean_va
5s        15s          4s          12n
USGS      11468000        1951         664
USGS      11468000        1952         643
USGS      11468000        1953         506
USGS      11468000        1954         566
USGS      11468000        1955         497
USGS      11468000        1956         570
USGS      11468000        1957         421
USGS      11468000        1958         857
USGS      11468000        1959         313
USGS      11468000        1960         414
USGS      11468000        1961         324
USGS      11468000        1962         417
USGS      11468000        1963         503
USGS      11468000        1964         552
USGS      11468000        1965         464
USGS      11468000        1966         449
USGS      11468000        1967         490
USGS      11468000        1968         432
USGS      11468000        1969         792
USGS      11468000        1970         810
USGS      11468000        1971         351
USGS      11468000        1972         222
USGS      11468000        1973         858
USGS      11468000        1974         796
USGS      11468000        1975         587
USGS      11468000        1976         102
USGS      11468000        1977         122
USGS      11468000        1978         709
USGS      11468000        1979         374
USGS      11468000        1980         514
USGS      11468000        1981         585
USGS      11468000        1982         875
USGS      11468000        1983        1495
USGS      11468000        1984         305
USGS      11468000        1985         181
USGS      11468000        1986         650
USGS      11468000        1987         312
USGS      11468000        1988         190
USGS      11468000        1989         239
USGS      11468000        1990         140
USGS      11468000        1991         193
USGS      11468000        1992         383
USGS      11468000        1993         615
USGS      11468000        1994         159
USGS      11468000        1995        1142
USGS      11468000        1996         742
USGS      11468000        1997         476
USGS      11468000        1998        1010
USGS      11468000        1999         527
USGS      11468000        2000         393
USGS      11468000        2001         341
USGS      11468000        2002         472
USGS      11468000        2003         490
                                  513.8491                 0.1   51.38491
                                                           0.3   154.1547
                                                             1   513.8491
                                                             2   1027.698
```

The cross section data from Appendix Table G.1 is then saved as a text file without any column headings or graphs, just the x and y data points. The file is then changed so that it has a .sec file extension. This gets the data ready to be entered into WinXSPro. Then, after starting WinXSPro, a new plan is started and saved. The cross section that is exported is opened in the input section of the plan window (Screen Shot G.1), and is confirmed to have a horizontal tape (or adjusted if needed). Next the output file is named and a location for it is chosen. The analysis section is filled in according to the site being processed, the survey date is entered along with a cross section number if needed, and the resistance equation is chosen depending on the data available at that site (in this case the data included a Manning's n value so the user supplied Manning's n equation is used). Then the site is 'run'.



INPUT

File Name: \Jenny\Tennant\Database\CA\USGS 11468000\11468000.sec

Data Collection Method:

Data Format: Position-Elevation Free Form

Units: ● Feet ○ Meters ○ Centimeters

OUTPUT

File Name: C:\STREAM\Jenny\Tennant\Database\CA\USGS 114680

Output Mode: ● Overwrite ○ Append

Units: ● Feet ○ Meters

ANALYSIS

Analysis Procedure: Hydraulics & Regression

Cross-Section Number: 1

Survey Date: 06/28/1995

Plan Comment:

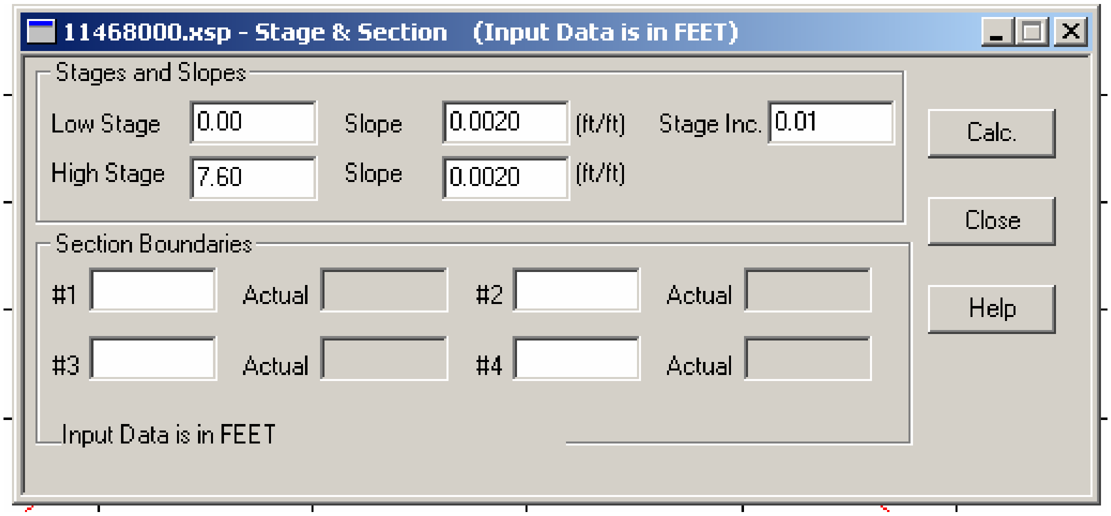
Resistance Equation: User Supplied Mannings n

d84 Particle Diameter: 1.000

d84 Units: ○ Feet ● Millimeters

Screen Shot G.1

The next window (Screen Shot G.2) allows the user to choose the stage range and increment for the analysis and is where the slope is input. For this study the low stage was always 0.00 and the high stage was where the cross section data ended even though WinXSPro will extrapolate past that point using vertical banks beyond the data. The stage increment was generally between 0.01 and 0.03 depending on how many stage increments would be calculated since the program had a limit around a thousand increments.



11468000.xsp - Stage & Section (Input Data is in FEET)

Stages and Slopes

Low Stage 0.00 Slope 0.0020 (ft/ft) Stage Inc. 0.01

High Stage 7.60 Slope 0.0020 (ft/ft)

Section Boundaries

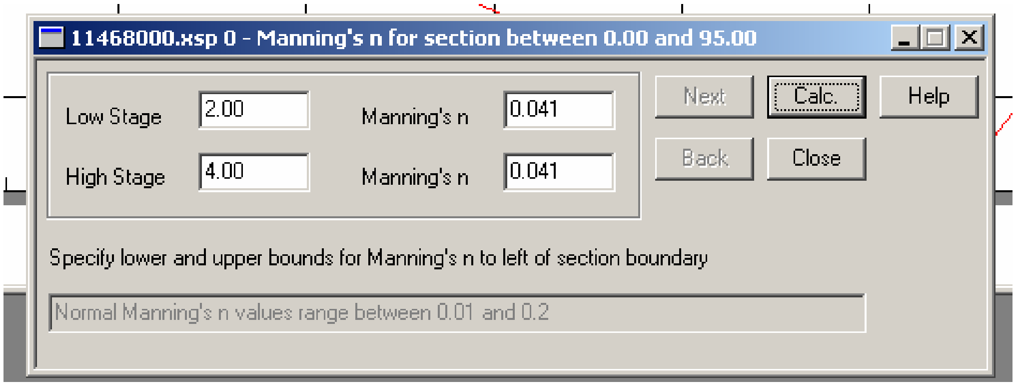
#1 Actual #2 Actual

#3 Actual #4 Actual

Input Data is in FEET

Screen Shot G.2

Since the user defined Manning's n was chosen for this site, the next window (Screen Shot G.3) is used to input the n value(s).



11468000.xsp 0 - Manning's n for section between 0.00 and 95.00

Low Stage 2.00 Manning's n 0.041

High Stage 4.00 Manning's n 0.041

Specify lower and upper bounds for Manning's n to left of section boundary

Normal Manning's n values range between 0.01 and 0.2

Screen Shot G.3

WinXSPro then does all of the calculations, resulting in an output table with all of the information that is produced (Appendix Table G.4). The data for the Tennant calculations are pulled directly from this table. The discharge (column 'Q') that is closest to the percent AAF discharges (Appendix Table G.3) is used as the stage increment for that percent AAF value. The depth ('STAGE') and velocity ('VAVG') are taken directly from the table. The width is determined by taking the value for the table (column 'WIDTH') and dividing it by the bankfull width and multiplying the resulting proportion by one hundred to determine the percent width.

Appendix Table G.4

```
********************************WinXSPRO**********************************
C:\STREAM\Jenny\Tennant\Database\CA\USGS 11468000\11468000.out
Input File:       C:\STREAM\Jenny\Tennant\Database\CA\USGS 11468000\11468000.sec
Run Date:          10/21/05
```

Analysis Procedure: Hydraulics & Regression
Cross Section Number: 1
Survey Date: 06/28/1995

Subsections/Dividing positions

Resistance Method: Manning's n

SECTION	A
Low Stage n	0.041
High Stage n	0.041

Unadjusted horizontal distances used

STAGE (ft)	#SEC	AREA (sq ft)	PERIM (ft)	WIDTH (ft)	R (ft)	DHYD (ft)	SLOPE (ft/ft)	n	VAVG (ft/s)	Q (cfs)	SHEAR (psf)
0.01	T	0.00	0.30	0.30	0.00	0.01	0.0020	0.041	0.05	0.00	0.00
0.02	T	0.01	0.61	0.60	0.01	0.01	0.0020	0.041	0.08	0.00	0.00
0.03	T	0.01	0.91	0.90	0.01	0.02	0.0020	0.041	0.10	0.00	0.00
0.04	T	0.02	1.21	1.20	0.02	0.02	0.0020	0.041	0.12	0.00	0.00
0.05	T	0.04	1.51	1.51	0.02	0.03	0.0020	0.041	0.14	0.01	0.00
0.06	T	0.05	1.82	1.81	0.03	0.03	0.0020	0.041	0.16	0.01	0.00
0.07	T	0.07	2.12	2.11	0.03	0.04	0.0020	0.041	0.17	0.01	0.00
0.08	T	0.10	2.42	2.41	0.04	0.04	0.0020	0.041	0.19	0.02	0.00
0.09	T	0.12	2.72	2.71	0.04	0.05	0.0020	0.041	0.20	0.03	0.01
0.10	T	0.15	3.03	3.01	0.05	0.05	0.0020	0.041	0.22	0.03	0.01
0.11	T	0.18	3.33	3.31	0.05	0.06	0.0020	0.041	0.23	0.04	0.01
0.12	T	0.22	3.63	3.61	0.06	0.06	0.0020	0.041	0.25	0.05	0.01
0.13	T	0.25	3.94	3.92	0.06	0.07	0.0020	0.041	0.26	0.07	0.01
0.14	T	0.30	4.24	4.22	0.07	0.07	0.0020	0.041	0.28	0.08	0.01
0.15	T	0.34	4.54	4.52	0.07	0.08	0.0020	0.041	0.29	0.10	0.01
0.16	T	0.39	4.84	4.82	0.08	0.08	0.0020	0.041	0.30	0.12	0.01
0.17	T	0.44	5.15	5.12	0.08	0.09	0.0020	0.041	0.31	0.14	0.01
0.18	T	0.49	5.45	5.42	0.09	0.09	0.0020	0.041	0.33	0.16	0.01
0.19	T	0.54	5.75	5.72	0.09	0.10	0.0020	0.041	0.34	0.18	0.01
0.20	T	0.60	6.05	6.02	0.10	0.10	0.0020	0.041	0.35	0.21	0.01
0.21	T	0.66	6.36	6.33	0.10	0.10	0.0020	0.041	0.36	0.24	0.01
0.22	T	0.73	6.66	6.63	0.11	0.11	0.0020	0.041	0.37	0.27	0.01
0.23	T	0.80	6.96	6.93	0.11	0.11	0.0020	0.041	0.38	0.31	0.01
0.24	T	0.87	7.27	7.23	0.12	0.12	0.0020	0.041	0.39	0.34	0.01
0.25	T	0.94	7.57	7.53	0.12	0.12	0.0020	0.041	0.40	0.38	0.02
0.26	T	1.02	7.87	7.83	0.13	0.13	0.0020	0.041	0.42	0.42	0.02
0.27	T	1.10	8.18	8.14	0.13	0.13	0.0020	0.041	0.43	0.47	0.02
0.28	T	1.18	8.48	8.44	0.14	0.14	0.0020	0.041	0.44	0.52	0.02
0.29	T	1.27	8.78	8.74	0.14	0.14	0.0020	0.041	0.45	0.57	0.02
0.30	T	1.36	9.09	9.04	0.15	0.15	0.0020	0.041	0.46	0.62	0.02
0.31	T	1.45	9.39	9.34	0.15	0.15	0.0020	0.041	0.47	0.68	0.02
0.32	T	1.54	9.69	9.65	0.16	0.16	0.0020	0.041	0.48	0.74	0.02
0.33	T	1.64	10.00	9.95	0.16	0.16	0.0020	0.041	0.49	0.80	0.02
0.34	T	1.74	10.30	10.25	0.17	0.17	0.0020	0.041	0.50	0.87	0.02
0.35	T	1.85	10.60	10.55	0.17	0.17	0.0020	0.041	0.51	0.94	0.02
0.36	T	1.95	10.91	10.85	0.18	0.18	0.0020	0.041	0.52	1.01	0.02
0.37	T	2.06	11.21	11.15	0.18	0.18	0.0020	0.041	0.53	1.08	0.02
0.38	T	2.18	11.51	11.46	0.19	0.19	0.0020	0.041	0.54	1.16	0.02
0.39	T	2.29	11.82	11.76	0.19	0.19	0.0020	0.041	0.54	1.25	0.02
0.40	T	2.41	12.12	12.06	0.20	0.20	0.0020	0.041	0.55	1.34	0.02
0.41	T	2.54	13.32	13.26	0.19	0.19	0.0020	0.041	0.54	1.37	0.02
0.42	T	2.68	14.52	14.46	0.18	0.19	0.0020	0.041	0.53	1.41	0.02
0.43	T	2.83	15.72	15.65	0.18	0.18	0.0020	0.041	0.52	1.46	0.02
0.44	T	2.99	16.92	16.85	0.18	0.18	0.0020	0.041	0.51	1.53	0.02
0.45	T	3.16	18.12	18.05	0.17	0.18	0.0020	0.041	0.51	1.61	0.02
0.46	T	3.35	19.32	19.25	0.17	0.17	0.0020	0.041	0.51	1.69	0.02
0.47	T	3.55	20.52	20.45	0.17	0.17	0.0020	0.041	0.50	1.79	0.02
0.48	T	3.76	21.72	21.65	0.17	0.17	0.0020	0.041	0.50	1.90	0.02
0.49	T	3.98	22.92	22.84	0.17	0.17	0.0020	0.041	0.51	2.01	0.02
0.50	T	4.22	24.12	24.04	0.17	0.18	0.0020	0.041	0.51	2.14	0.02

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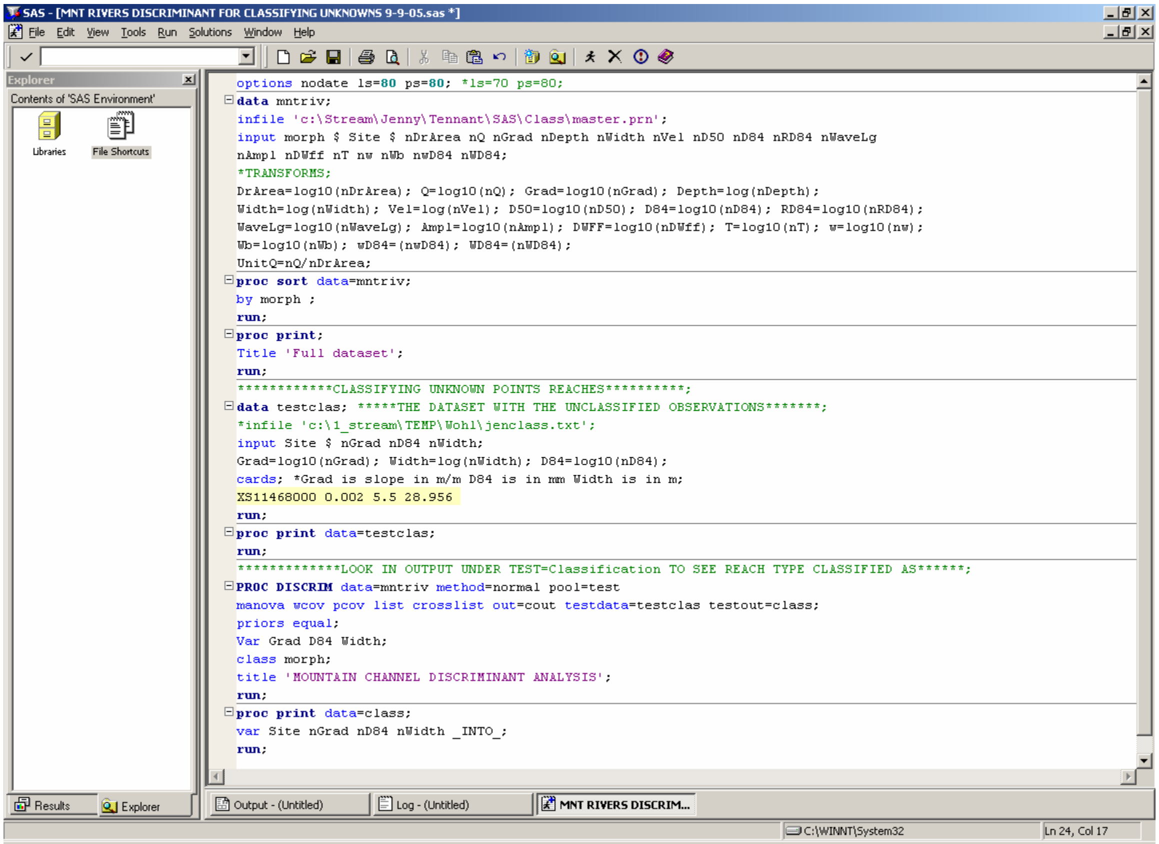
 7.00   T   503.30   99.01   93.86   5.08   5.36   0.0020   0.041   4.80   2418.21   0.63
 7.01   T   504.24   99.04   93.87   5.09   5.37   0.0020   0.041   4.81   2425.28   0.64
 7.02   T   505.18   99.07   93.89   5.10   5.38   0.0020   0.041   4.81   2432.36   0.64
 7.03   T   506.12   99.10   93.91   5.11   5.39   0.0020   0.041   4.82   2439.44   0.64
 7.04   T   507.05   99.13   93.93   5.12   5.40   0.0020   0.041   4.82   2446.54   0.64
 7.05   T   507.99   99.15   93.95   5.12   5.41   0.0020   0.041   4.83   2453.64   0.64
 7.06   T   508.93   99.18   93.97   5.13   5.42   0.0020   0.041   4.84   2460.75   0.64
 7.07   T   509.87   99.21   93.99   5.14   5.42   0.0020   0.041   4.84   2467.87   0.64
 7.08   T   510.81   99.24   94.01   5.15   5.43   0.0020   0.041   4.85   2474.99   0.64
 7.09   T   511.75   99.26   94.03   5.16   5.44   0.0020   0.041   4.85   2482.13   0.64
 7.10   T   512.69   99.29   94.05   5.16   5.45   0.0020   0.041   4.86   2489.27   0.64
 7.11   T   513.63   99.32   94.07   5.17   5.46   0.0020   0.041   4.86   2496.43   0.65
 7.12   T   514.58   99.35   94.08   5.18   5.47   0.0020   0.041   4.87   2503.59   0.65
 7.13   T   515.52   99.37   94.10   5.19   5.48   0.0020   0.041   4.87   2510.75   0.65
 7.14   T   516.46   99.40   94.12   5.20   5.49   0.0020   0.041   4.88   2517.93   0.65
 7.15   T   517.40   99.43   94.14   5.20   5.50   0.0020   0.041   4.88   2525.11   0.65
 7.16   T   518.34   99.46   94.16   5.21   5.50   0.0020   0.041   4.89   2532.31   0.65
 7.17   T   519.28   99.49   94.18   5.22   5.51   0.0020   0.041   4.89   2539.51   0.65
 7.18   T   520.22   99.51   94.20   5.23   5.52   0.0020   0.041   4.90   2546.72   0.65
 7.19   T   521.17   99.54   94.22   5.24   5.53   0.0020   0.041   4.90   2553.94   0.65
 7.20   T   522.11   99.57   94.24   5.24   5.54   0.0020   0.041   4.91   2561.16   0.65
 7.21   T   523.05   99.60   94.26   5.25   5.55   0.0020   0.041   4.91   2568.40   0.66
 7.22   T   523.99   99.62   94.28   5.26   5.56   0.0020   0.041   4.92   2575.64   0.66
 7.23   T   524.94   99.65   94.29   5.27   5.57   0.0020   0.041   4.92   2582.89   0.66
 7.24   T   525.88   99.68   94.31   5.28   5.58   0.0020   0.041   4.93   2590.15   0.66
 7.25   T   526.82   99.71   94.33   5.28   5.58   0.0020   0.041   4.93   2597.41   0.66
 7.26   T   527.77   99.73   94.35   5.29   5.59   0.0020   0.041   4.94   2604.69   0.66
 7.27   T   528.71   99.76   94.37   5.30   5.60   0.0020   0.041   4.94   2611.97   0.66
 7.28   T   529.65   99.79   94.39   5.31   5.61   0.0020   0.041   4.95   2619.26   0.66
 7.29   T   530.60   99.82   94.41   5.32   5.62   0.0020   0.041   4.95   2626.56   0.66
 7.30   T   531.54   99.85   94.43   5.32   5.63   0.0020   0.041   4.96   2633.87   0.66
 7.31   T   532.49   99.87   94.45   5.33   5.64   0.0020   0.041   4.96   2641.19   0.67
 7.32   T   533.43   99.90   94.47   5.34   5.65   0.0020   0.041   4.97   2648.51   0.67
 7.33   T   534.38   99.93   94.49   5.35   5.66   0.0020   0.041   4.97   2655.84   0.67
 7.34   T   535.32   99.96   94.50   5.36   5.66   0.0020   0.041   4.97   2663.18   0.67
 7.35   T   536.27   99.98   94.52   5.36   5.67   0.0020   0.041   4.98   2670.53   0.67
 7.36   T   537.21   100.01  94.54   5.37   5.68   0.0020   0.041   4.98   2677.89   0.67
 7.37   T   538.16   100.04  94.56   5.38   5.69   0.0020   0.041   4.99   2685.25   0.67
 7.38   T   539.10   100.07  94.58   5.39   5.70   0.0020   0.041   4.99   2692.62   0.67
 7.39   T   540.05   100.09  94.60   5.40   5.71   0.0020   0.041   5.00   2700.00   0.67
 7.40   T   540.99   100.12  94.62   5.40   5.72   0.0020   0.041   5.00   2707.39   0.67
 7.41   T   541.94   100.15  94.64   5.41   5.73   0.0020   0.041   5.01   2714.79   0.68
 7.42   T   542.89   100.18  94.66   5.42   5.74   0.0020   0.041   5.01   2722.20   0.68
 7.43   T   543.83   100.21  94.68   5.43   5.74   0.0020   0.041   5.02   2729.61   0.68
 7.44   T   544.78   100.23  94.69   5.44   5.75   0.0020   0.041   5.02   2737.03   0.68
 7.45   T   545.73   100.26  94.71   5.44   5.76   0.0020   0.041   5.03   2744.46   0.68
 7.46   T   546.67   100.29  94.73   5.45   5.77   0.0020   0.041   5.03   2751.90   0.68
 7.47   T   547.62   100.32  94.75   5.46   5.78   0.0020   0.041   5.04   2759.34   0.68
 7.48   T   548.57   100.34  94.77   5.47   5.79   0.0020   0.041   5.04   2766.80   0.68
 7.49   T   549.52   100.37  94.79   5.47   5.80   0.0020   0.041   5.05   2774.26   0.68
 7.50   T   550.47   100.40  94.81   5.48   5.81   0.0020   0.041   5.05   2781.73   0.68
 7.51   T   551.41   100.43  94.83   5.49   5.81   0.0020   0.041   5.06   2789.21   0.69
 7.52   T   552.36   100.45  94.85   5.50   5.82   0.0020   0.041   5.06   2796.69   0.69
 7.53   T   553.31   100.48  94.87   5.51   5.83   0.0020   0.041   5.07   2804.19   0.69
 7.54   T   554.26   100.51  94.89   5.51   5.84   0.0020   0.041   5.07   2811.69   0.69
 7.55   T   555.21   100.54  94.90   5.52   5.85   0.0020   0.041   5.08   2819.20   0.69
 7.56   T   556.16   100.57  94.92   5.53   5.86   0.0020   0.041   5.08   2826.72   0.69
 7.57   T   557.11   100.59  94.94   5.54   5.87   0.0020   0.041   5.09   2834.24   0.69
 7.58   T   558.06   100.62  94.96   5.55   5.88   0.0020   0.041   5.09   2841.78   0.69
 7.59   T   559.01   100.65  94.98   5.55   5.89   0.0020   0.041   5.10   2849.32   0.69

STAGE    ALPHA    FROUDE
 0.01   1.000000   0.118045
 0.02   1.000000   0.132502
 0.03   1.000000   0.141765
 0.04   1.000000   0.148728
 0.05   1.000000   0.154363
```

```
 0.06   1.000000    0.159126
 0.07   1.000000    0.163267
 0.08   1.000000    0.166941
 0.09   1.000000    0.170251
 0.10   1.000000    0.173267
 0.11   1.000000    0.176041
 0.12   1.000000    0.178613
 0.13   1.000000    0.181012
 0.14   1.000000    0.183261
 0.15   1.000000    0.185381
.
.
 1.25   1.000000    0.268127
 1.26   1.000000    0.268541
 1.27   1.000000    0.268950
 1.28   1.000000    0.269356
 1.29   1.000000    0.269757
 1.30   1.000000    0.270154
 1.31   1.000000    0.270548
 1.32   1.000000    0.270937
 1.33   1.000000    0.271323
 1.34   1.000000    0.271705
 1.35   1.000000    0.272084
 1.36   1.000000    0.272459
 1.37   1.000000    0.272831
 1.38   1.000000    0.273199
 1.39   1.000000    0.273564
 1.40   1.000000    0.273925
 1.41   1.000000    0.274299
 1.42   1.000000    0.274668
 1.43   1.000000    0.275035
 1.44   1.000000    0.275398
 1.45   1.000000    0.275757
 1.46   1.000000    0.276113
 1.47   1.000000    0.276466
 1.48   1.000000    0.276816
 1.49   1.000000    0.277162
 1.50   1.000000    0.277506

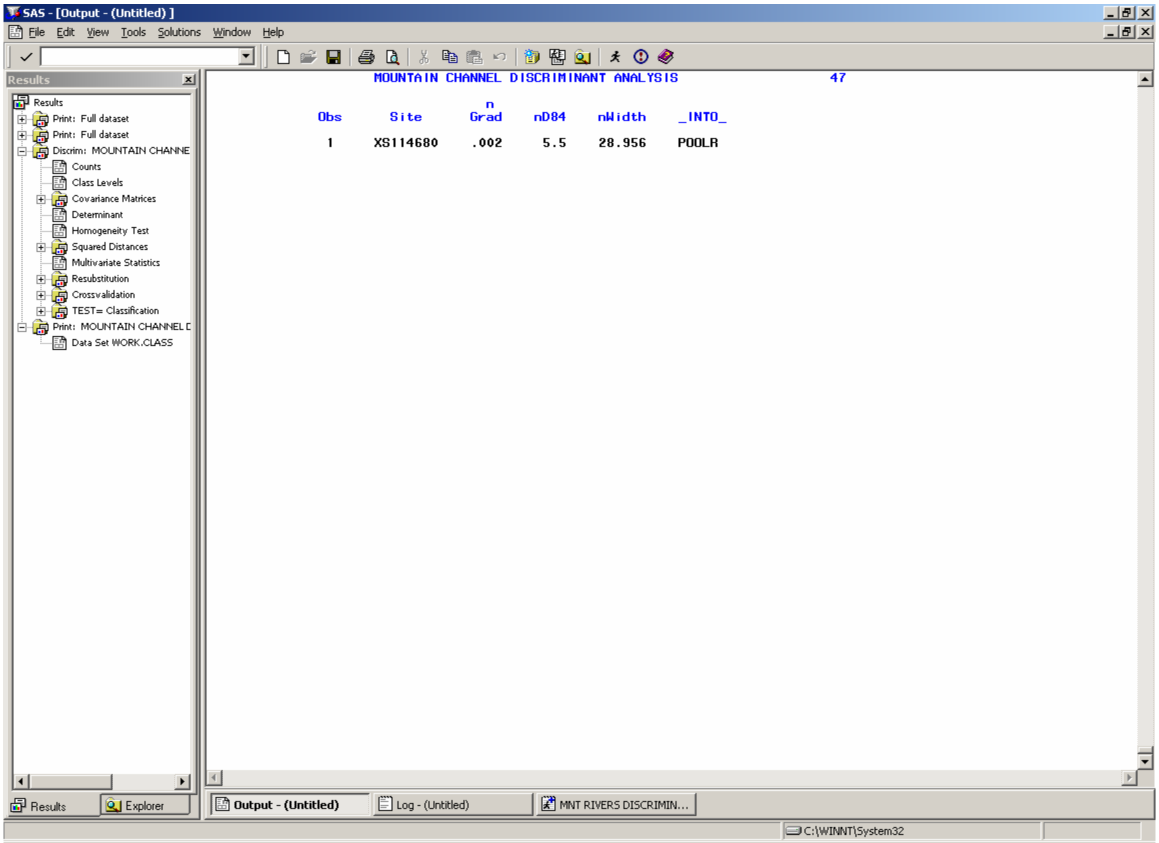
 Q = aR^b    a=75.746742  b=2.294978  r^2=0.988250  n=759
 Q = aZ^b    a=73.395042  b=0.531  r^2=0.435554  n=759
```

The next step in the analyses process is to classify the stream. The discriminant analysis (Screen Shot G.4) is used with all of the streams for consistency (Wohl and Merritt 2005). Streams that were classified in the field were used to check the analysis. The discriminant analysis is opened in SAS® and the specific stream data are input in the card section (highlighted yellow). The analysis is then run, and the stream classification is taken from the output (Screen Shot G.5).



```
options nodate ls=80 ps=80; *ls=70 ps=80;
data mntriv;
infile 'c:\Stream\Jenny\Tennant\SAS\Class\master.prn';
input morph $ Site $ nDrArea nQ nGrad nDepth nWidth nVel nD50 nD84 nRD84 nWaveLg
nAmpl nDWff nT nw nWb nwD84 nWD84;
*TRANSFORMS;
DrArea=log10(nDrArea); Q=log10(nQ); Grad=log10(nGrad); Depth=log(nDepth);
Width=log(nWidth); Vel=log(nVel); D50=log10(nD50); D84=log10(nD84); RD84=log10(nRD84);
WaveLg=log10(nWaveLg); Ampl=log10(nAmpl); DWFF=log10(nDWff); T=log10(nT); w=log10(nw);
Wb=log10(nWb); wD84=(nwD84); WD84=(nWD84);
UnitQ=nQ/nDrArea;
proc sort data=mntriv;
by morph ;
run;
proc print;
Title 'Full dataset';
run;
************CLASSIFYING UNKNOWN POINTS REACHES**********;
data testclas; *****THE DATASET WITH THE UNCLASSIFIED OBSERVATIONS*******;
*infile 'c:\1_stream\TEMP\Wohl\jenclass.txt';
input Site $ nGrad nD84 nWidth;
Grad=log10(nGrad); Width=log(nWidth); D84=log10(nD84);
cards; *Grad is slope in m/m D84 is in mm Width is in m;
XS11468000 0.002 5.5 28.956
run;
proc print data=testclas;
run;
*************LOOK IN OUTPUT UNDER TEST=Classification TO SEE REACH TYPE CLASSIFIED AS******;
PROC DISCRIM data=mntriv method=normal pool=test
manova wcov pcov list crosslist out=cout testdata=testclas testout=class;
priors equal;
Var Grad D84 Width;
class morph;
title 'MOUNTAIN CHANNEL DISCRIMINANT ANALYSIS';
run;
proc print data=class;
var Site nGrad nD84 nWidth _INTO_;
run;
```

Screen Shot G.4



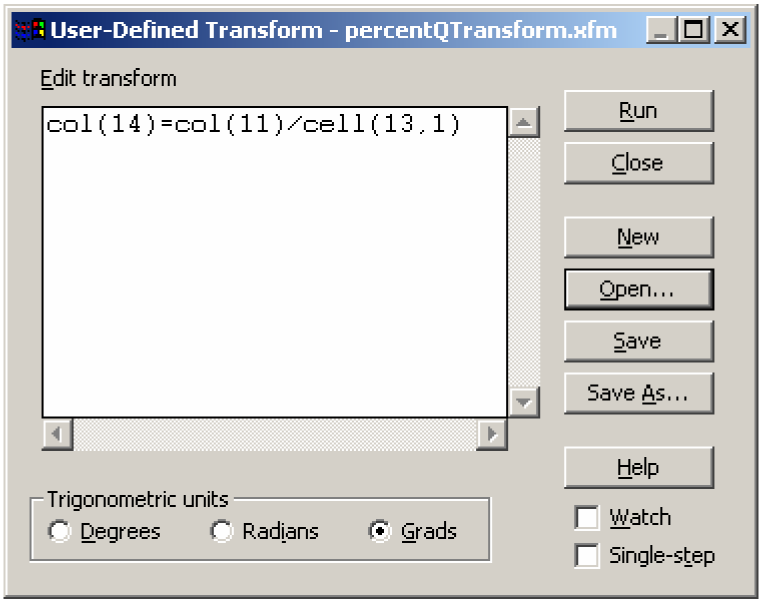
```
                 MOUNTAIN CHANNEL DISCRIMINANT ANALYSIS                47

                          n
     Obs      Site      Grad     nD84     nWidth    _INTO_

       1    XS114680    .002      5.5     28.956    POOLR
```

Screen Shot G.5

The data from the WinXSPro output (Appendix Table G.4) is imported into excel™ and then copied into SigmaPlot® for the wetted perimeter method comparison analysis. Once the data are in SigmaPlot® the first calculation is the percent Q and percent P_w columns. These are calculated through dividing the discharge column by the average annual flow and the wetted perimeter by the corresponding wetted perimeter value for the discharge at the average annual flow (Screen Shot G.6, Screen Shot G.7). These columns are plotted to determine the raw data curve (Appendix Figure G.4). The raw data curve is selected and then the regression wizard is run; looking at both the log and the power regression and choosing the regression type with the highest R^2 value.



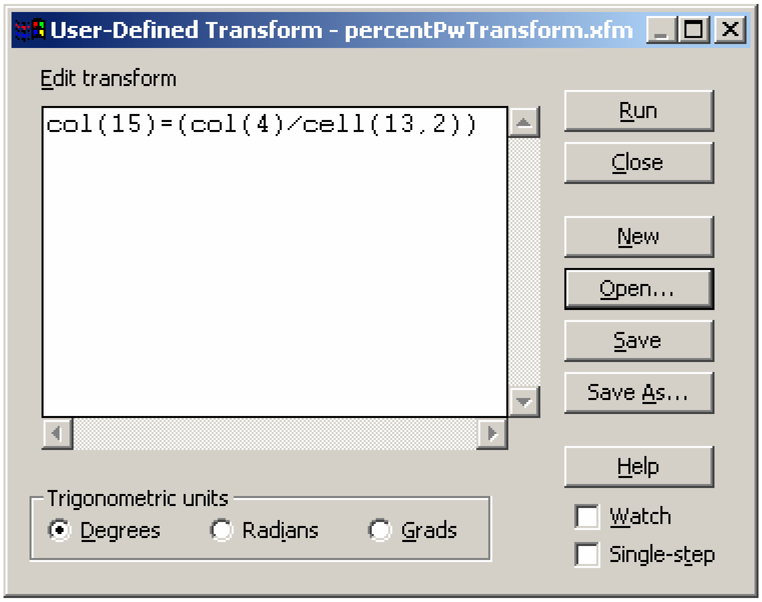
```
col(14)=col(11)/cell(13,1)
```

○ Degrees ○ Radians ● Grads

☐ Watch

☐ Single-step

Screen Shot G.6



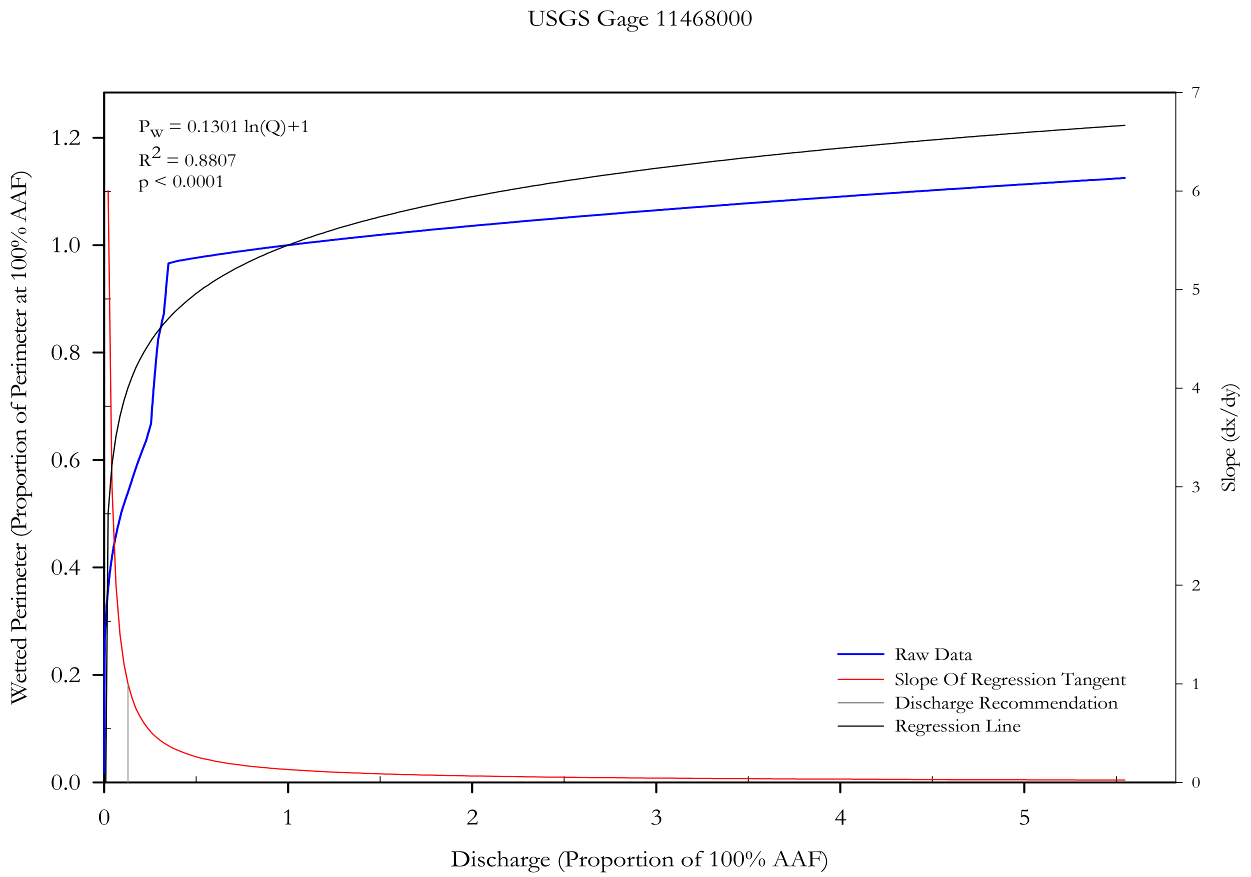
```
col(15)=(col(4)/cell(13,2))
```

● Degrees ○ Radians ○ Grads

☐ Watch

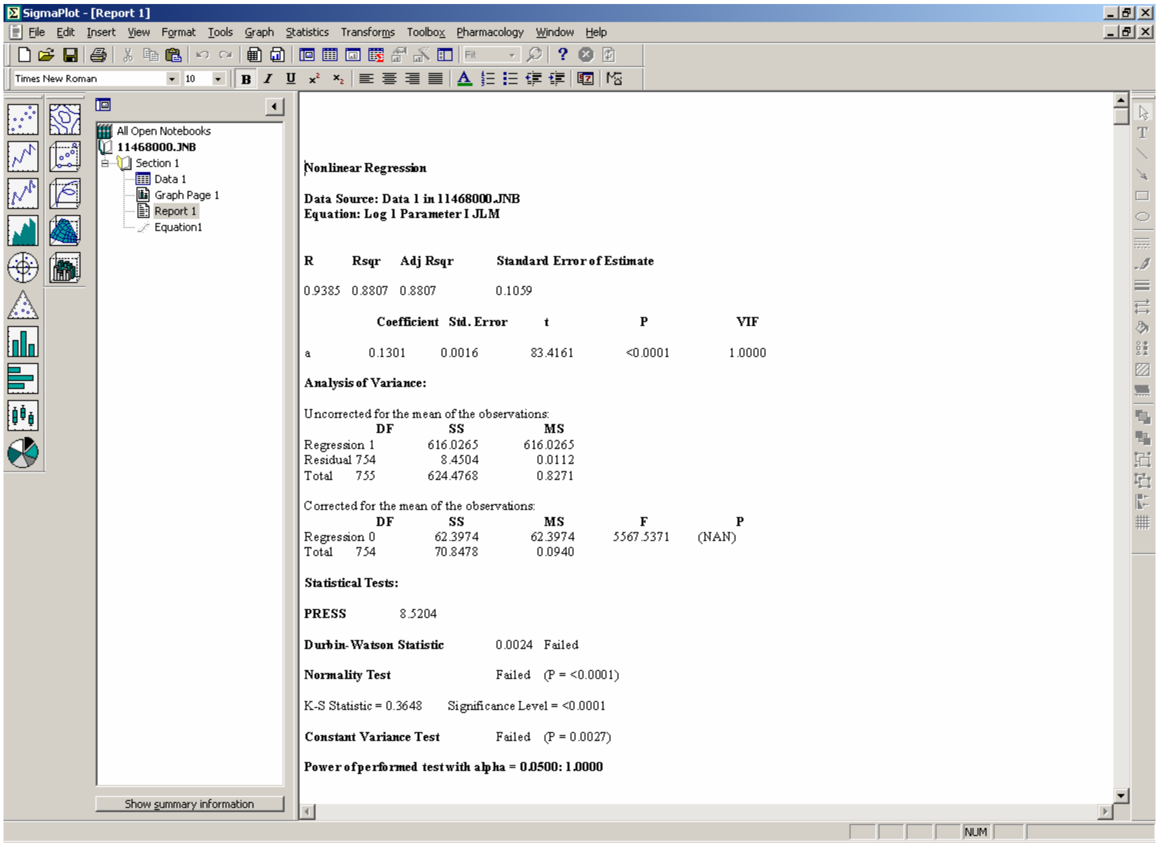
☐ Single-step

Screen Shot G.7



Appendix Figure G.4

The regression line data are then read off of the report that is produced (Screen Shot G.8). SigmaPlot® is then used to run the rest of the wetted perimeter analysis. The slope of the regression line is calculated using either a function for power regressions or one for log regressions (Screen Shot G.9). The dx/dy slope line is also plotted on the graph with the wetted perimeter curve (Appendix Figure G.1). The percent of the AAF, which is calculated by finding the spot on the dx/dy line that equals one, and then is plotted showing the discharge recommendation from this method (Screen Shot G.10, Appendix Figure G.4).



```
Nonlinear Regression

Data Source: Data 1 in 11468000.JNB
Equation: Log 1 Parameter I JLM

R        Rsqr     Adj Rsqr       Standard Error of Estimate

0.9385   0.8807   0.8807         0.1059

                Coefficient   Std. Error        t              P              VIF

a               0.1301        0.0016           83.4161        <0.0001        1.0000

Analysis of Variance:

Uncorrected for the mean of the observations:
               DF            SS             MS
Regression 1              616.0265       616.0265
Residual 754                8.4504         0.0112
Total      755            624.4768         0.8271

Corrected for the mean of the observations:
               DF            SS             MS              F              P
Regression 0               62.3974        62.3974      5567.5371        (NAN)
Total      754             70.8478         0.0940

Statistical Tests:

PRESS            8.5204

Durbin-Watson Statistic        0.0024   Failed

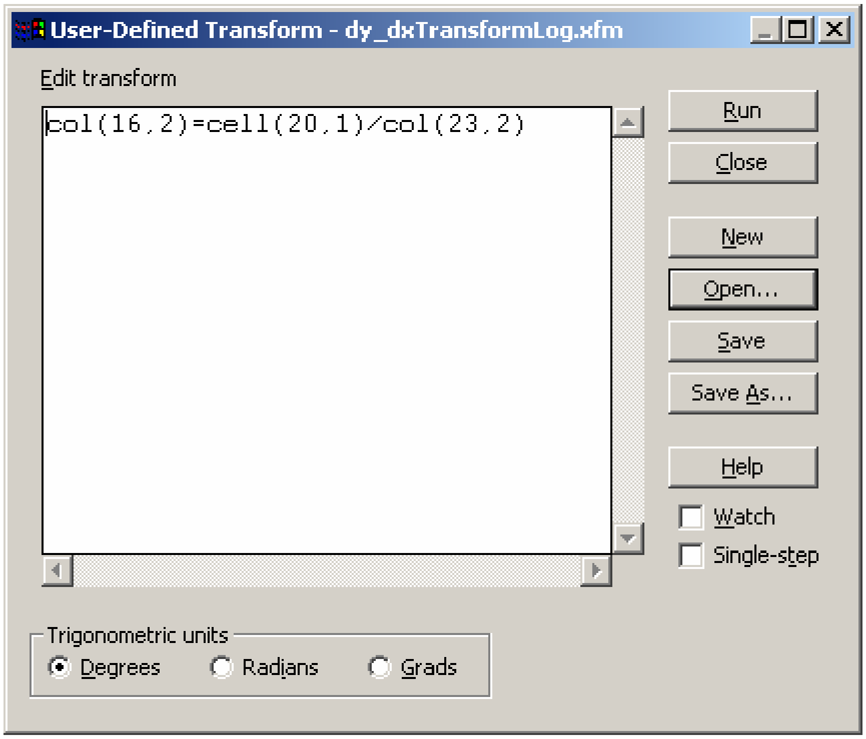
Normality Test                 Failed   (P = <0.0001)

K-S Statistic = 0.3648     Significance Level = <0.0001

Constant Variance Test         Failed   (P = 0.0027)

Power of performed test with alpha = 0.0500: 1.0000
```

Screen Shot G.8

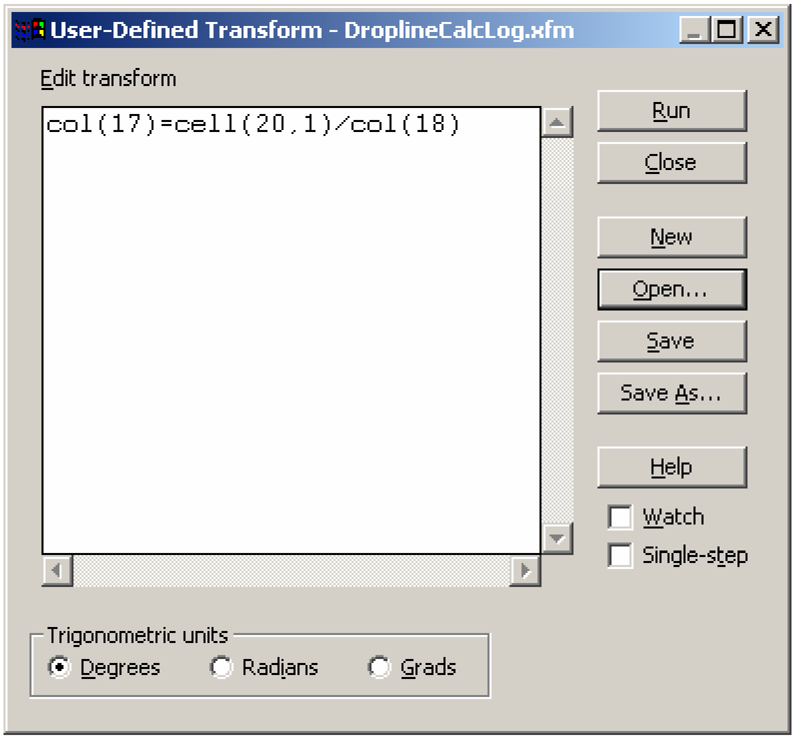


```
col(16,2)=cell(20,1)/col(23,2)
```

☐ Watch
☐ Single-step

Trigonometric units
● Degrees ○ Radians ○ Grads

Screen Shot G.9

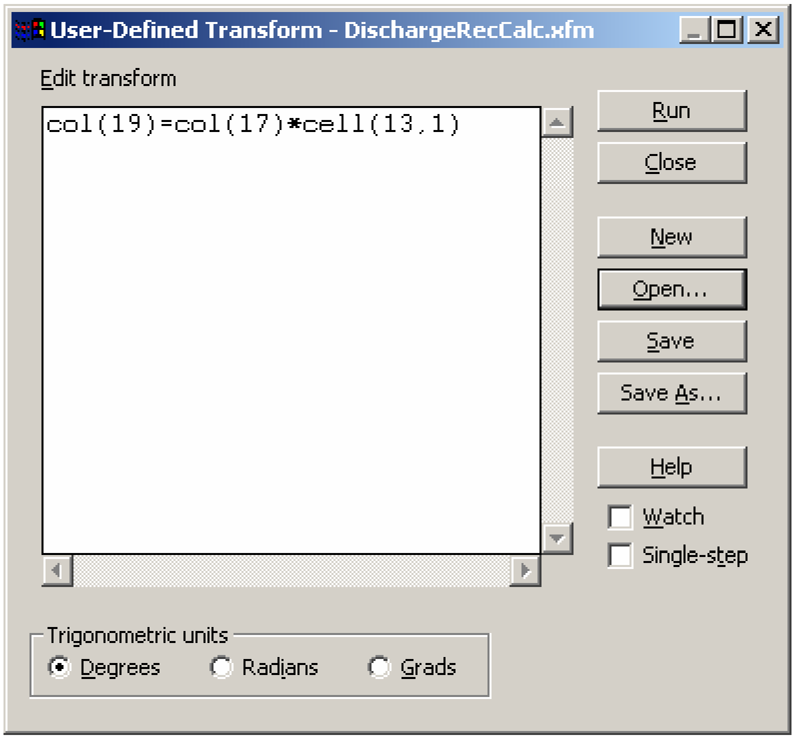


```
col(17)=cell(20,1)/col(18)
```

● Degrees ○ Radians ○ Grads

Screen Shot G.10

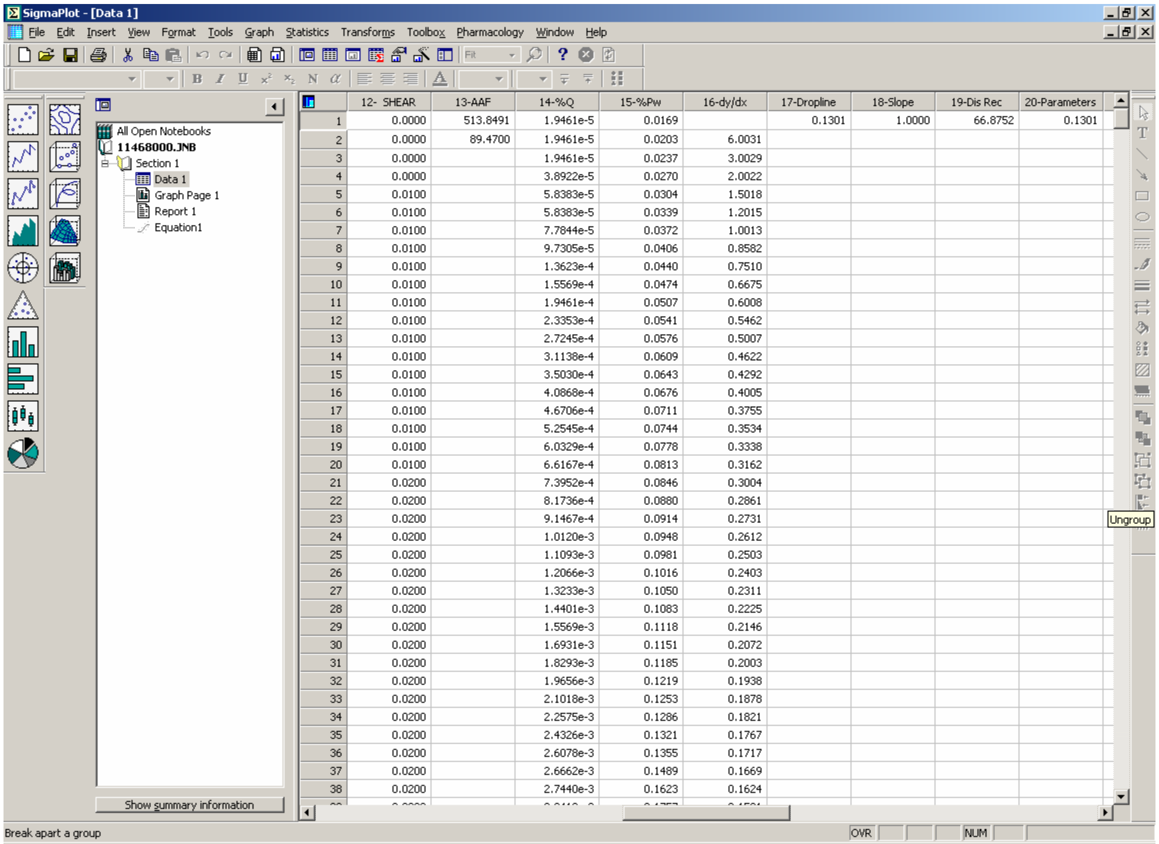
The discharge is calculated from the percent AAF recommendation (Screen Shot G.11), and is recorded along with the rest of the data from SigmaPlot® (Screen Shot G.12) into excel™ in rows for each of the cross sections and compiled for the final analyses.



```
col(19)=col(17)*cell(13,1)
```

Trigonometric units: ● Degrees ○ Radians ○ Grads

Screen Shot G.11



	12- SHEAR	13-AAF	14-%Q	15-%Pw	16-dy/dx	17-Dropline	18-Slope	19-Dis Rec	20-Parameters
1	0.0000	513.8491	1.9461e-5	0.0169		0.1301	1.0000	66.8752	0.1301
2	0.0000	89.4700	1.9461e-5	0.0203	6.0031				
3	0.0000		1.9461e-5	0.0237	3.0029				
4	0.0000		3.8922e-5	0.0270	2.0022				
5	0.0100		5.8383e-5	0.0304	1.5018				
6	0.0100		5.8383e-5	0.0339	1.2015				
7	0.0100		7.7844e-5	0.0372	1.0013				
8	0.0100		9.7305e-5	0.0406	0.8582				
9	0.0100		1.3623e-4	0.0440	0.7510				
10	0.0100		1.5569e-4	0.0474	0.6675				
11	0.0100		1.9461e-4	0.0507	0.6008				
12	0.0100		2.3353e-4	0.0541	0.5462				
13	0.0100		2.7245e-4	0.0576	0.5007				
14	0.0100		3.1138e-4	0.0609	0.4622				
15	0.0100		3.5030e-4	0.0643	0.4292				
16	0.0100		4.0868e-4	0.0676	0.4005				
17	0.0100		4.6706e-4	0.0711	0.3755				
18	0.0100		5.2545e-4	0.0744	0.3534				
19	0.0100		6.0329e-4	0.0778	0.3338				
20	0.0100		6.6167e-4	0.0813	0.3162				
21	0.0200		7.3952e-4	0.0846	0.3004				
22	0.0200		8.1736e-4	0.0880	0.2861				
23	0.0200		9.1467e-4	0.0914	0.2731				
24	0.0200		1.0120e-3	0.0948	0.2612				
25	0.0200		1.1093e-3	0.0981	0.2503				
26	0.0200		1.2066e-3	0.1016	0.2403				
27	0.0200		1.3233e-3	0.1050	0.2311				
28	0.0200		1.4401e-3	0.1083	0.2225				
29	0.0200		1.5569e-3	0.1118	0.2146				
30	0.0200		1.6931e-3	0.1151	0.2072				
31	0.0200		1.8293e-3	0.1185	0.2003				
32	0.0200		1.9656e-3	0.1219	0.1938				
33	0.0200		2.1018e-3	0.1253	0.1878				
34	0.0200		2.2575e-3	0.1286	0.1821				
35	0.0200		2.4326e-3	0.1321	0.1767				
36	0.0200		2.6078e-3	0.1355	0.1717				
37	0.0200		2.6662e-3	0.1489	0.1669				
38	0.0200		2.7440e-3	0.1623	0.1624				

Break apart a group

Screen Shot G.12