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Step-Pool Morphology of a Wilderness Headwater Stream of the Buffalo River, Arkansas

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STEP-POOL MORPHOLOGY OF A WILDERNESS HEADWATER STREAM OF THE BUFFALO RIVER, ARKANSAS.

A Thesis

Presented to

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In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Science

By

Aaron Michael Nickolotsky

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Geography, Geology, and Planning

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ABSTRACT

Step-pool and cascade morphology reflect the geological and climatic factors affecting channels in mountain watersheds. This study uses longitudinal and cross-section surveys of a headwater stream in the Boston Mountains of the Ozarks Plateau region in northwest Arkansas to describe channel form and develop quantitative models for comparisons with other regions. The Bowers Hollow Creek watershed (3.5 km^2) is located within the boundaries of the Forest Service's Upper Buffalo Wilderness Area. Step-pool morphology varies with the influence of lithology and sediment supply in the Boston Mountains. However, step height and wavelength relationships are generally similar to other regions. Distribution of step-pool forms occurred throughout the watershed. The study area exhibited on average reach slopes of 0.105 m/m, widths of 6.10 m, crest particle sizes of 440 mm, step height of 0.87 m, and step wavelength of 6.62 m. The mean step steepness for the watershed was 0.13, while the mean reach step length to height ratio was 9:1. Step height and steepness values can vary by >30% according to measurement method. Thus, comparisons of step height-based relationships among different studies may be problematic unless a standardized method is selected to define step height.

KEYWORDS: Step-pool, Geomorphology, River, Mountain, Stream, Buffalo River

This abstract is approved as to form and content

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF TABLES

Chapter 4

Chapter 5

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

LIST OF FIGURES (cont.)

CHAPTER 1

INTRODUCTION

Steep headwater streams located in mountainous environments are the beginnings of entire fluvial systems. These low order streams influence the sediment budget downstream in the fluvial system as well as the geomorphology based on the inference of the sediment from headwater streams directly into the main stem of the larger system. The geometry of the channel must be studied in order to conceptualize how mountainous headwater streams cope with erosional processes. Through understanding the form and function of the features comprising the bed of the channel, steps and pools for example, we can better comprehend why steep headwater streams are not primarily flumes which flush discharge and sediment through the immediate system.

Due to the harsh environment in which step-pools are found, there is an incomplete understanding of how step-pools fit into the broader context of the overall fluvial system. This gap in the knowledge of step-pools is important for three reasons: (i) step-pools are a dominating feature in headwater and mountainous streams, and mountains cover a large portion of the earth's surface, (ii) in order to obtain a clear picture of the fluvial system, headwater and mountainous streams; which are the beginning of larger streams, are comprised of step-pools, and produce large quantities of sediment and water, must be better understood, and (iii) as populations move further into mountainous environments, the more knowledge we have concerning step-pool streams the better we can manage the development and restoration of these areas (Chin, 2003). This is especially true in northwest Arkansas, where there are increases in populations into environmentally

sensitive areas, yet there has been little or no research done on the headwater streams of the rivers in the Boston Mountains.

The research completed for this study took place in the Bowers Hollow watershed located in the upper 10% of the Buffalo National River watershed (Figure 1.1). The mouth of Bowers Hollow Creek is approximately seven miles downstream of the forming of the Buffalo River at the confluence of Big Buffalo Creek and Reeves Creek. Due to the rugged topography, this area produces streams which exhibit step-pool bedforms, waterfall features, and other geomorphic characteristics found in steep mountain streams. The Bowers Hollow watershed is fully contained on public lands supervised by the U. S. Forest Service, therefore fieldworkers had complete access of the entire study area watershed.

Step-pool characteristics are difficult to quantify due to their limitations of sampling logistics and high degree of variation in form. The spatial distributions of step-pool features reflect the influence of lithology, hydraulic regime, slope, and sediment supply in the watershed (Wooldridge and Hickin, 2002, Rathburn and Wohl, 2003, and Montgomery and Buffington, 1997). Nevertheless the amount of knowledge concerning step-pool morphology is lacking in comparison with riffle-pool literature (Chin, 2005). As human activities move further into mountainous regions, a better understanding of step-pool morphology will be needed to responsibly cope with management and restoration issues (Lenzi, 2002). Three of the most important and commonly studied geomorphic variables of step-pool channels are step height, wavelength, and slope (Chin,

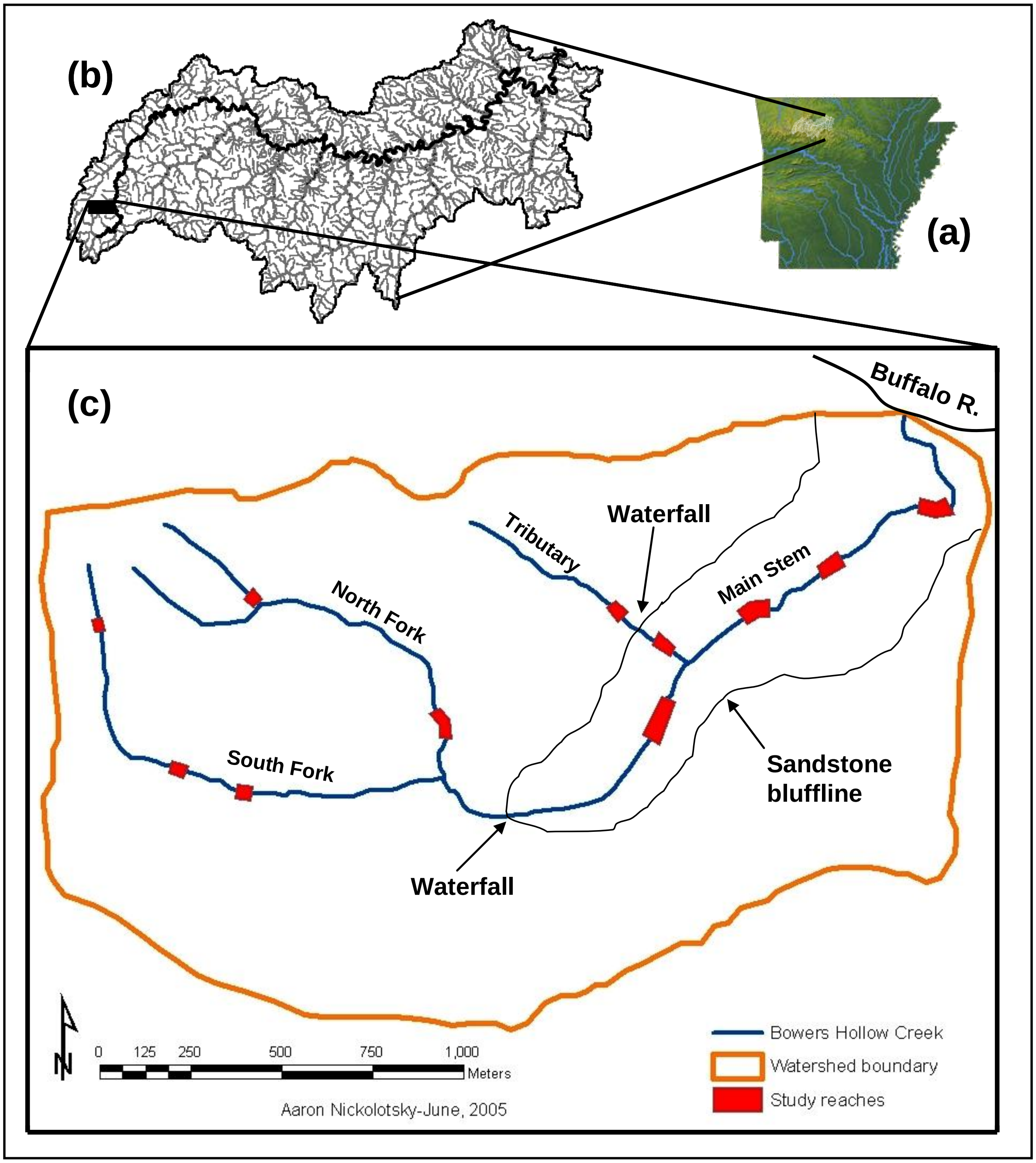

Figure 1.1 (a) Location of Buffalo River watershed within confines of Arkansas, (b) location of study area in Buffalo River watershed, and (c) study reaches in Bowers Hollow Creek watershed

1999, and Zimmermann and Church, 2001) (Figure 1.2). Empirical relationships and reach comparisons of these variables have shown potential for developing geomorphic models of step-pool evolution and behavior in mountain areas can be applied to models for use in management and restoration (Chartrand and Whiting, 2000, and Lenzi, 2002).

The longitudinal profile of a step-pool stream consists of a repetition of steps and pools to create a profile similar to a staircase (Zimmermann and Church, 2001) (Figure 1.3). The steps defined in this paper consist of cobbles, boulders, and bedrock forms which span the width of the channel to create a natural step in the stream (Chin, 1999). The step creates a vertical drop which dissipates the energy of the water, thus minimizing the effects of erosional forces on the morphology of the stream (Chin, 1998). These steps are the geomorphic feature most often studied in mountain streams. They are a potential window to understanding the sediment supply, both directly through transport and indirectly through bank stabilization through erosion control. Pools are collectors of this

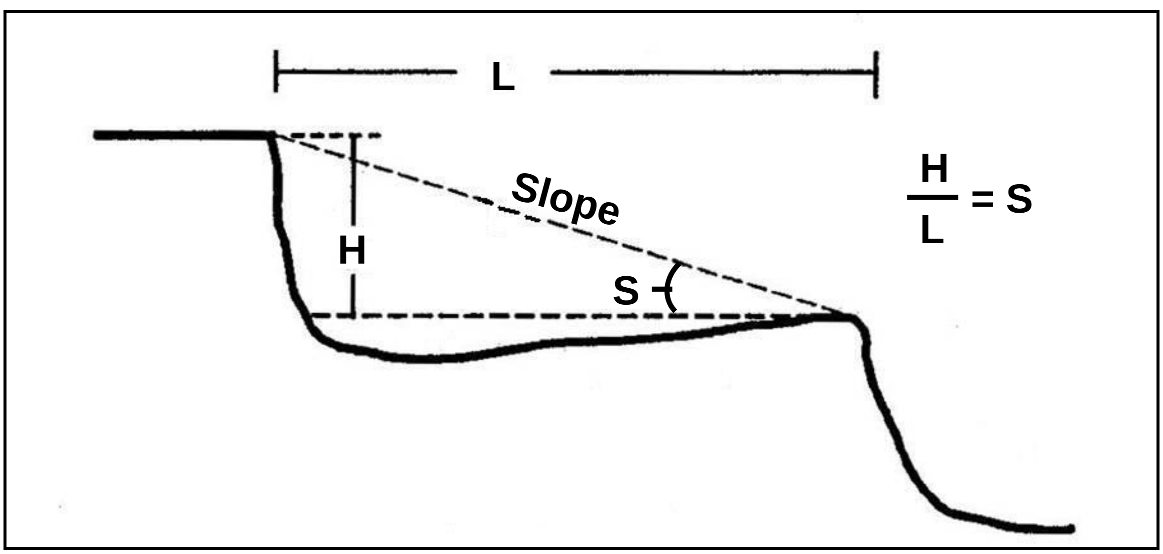

Figure 1.2 Longitudinal profile of a step-pool form with key measurements (Duckson and Duckson, 2001)

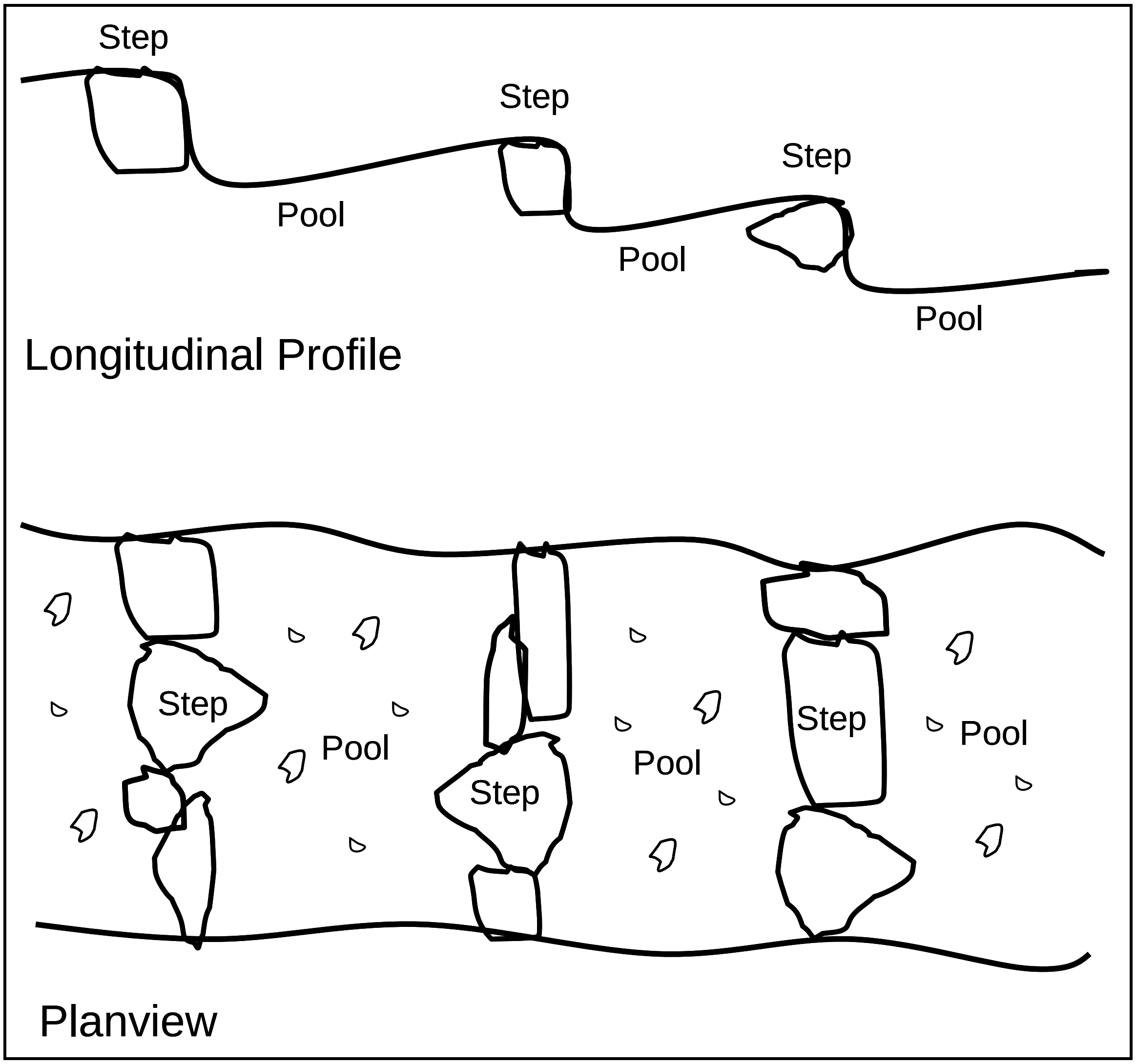

Figure 1.3 Schematics of a natural step-pool sequence (Lenzi, 2002)

turbulent water where tumbling flow and recovery eddies reduce the flow's kinetic energy (Chin, 2003). Therefore streams which exhibit step-pool morphology are most efficient at low flow conditions, when the water level has not exceeded the bounds of the active width. The step-pool form is a dynamic which is developed for long term energy dissipation, with the capability to withstand, to a certain threshold, the increased discharge and velocities associated with storm events. Floods produce enough energy to assist the bedform in the formation and evolution of step-pool sequences.

Step-pool forms need a high gradient or slope to produce the amount of velocity necessary in the formation of step-pool sequences. This can be found in steep mountain streams which are strongly associated with hillslopes that provide sources of sediment (Knighton, 1998) and channel gradients which exceed 5% (Wohl, 1997; Gomi et al. 2003). The sediment in step-pool streams varies in size, but step form is generally influenced by relatively larger sized clasts, since headwater streams generally transport larger sediments than downstream sections of the river (Wohl, 2000).

Step-pool morphology is traditionally described by measures of step height and wavelength. Wavelength is the longitudinal measure of importance, similar to riffle spacing, when examining mountain streams. Step height is the vertical measure used when studying mountain streams and is the distance from step crest to the pool below. When step height is divided by wavelength (H/L) the step steepness (S) is produced (Abrahams et al., 1995, and Wohl, 2000) (Figure 1.2). Inversely, when the step wavelength is divided by height, the wavelength to height ratio is produced. Zimmermann and Church (2001) mention minor variation in the measurement of step heights (Zimmermann and Church, 2001). Most studies do not discuss variation in the

different measurement methods used when comparisons of different studies are used. However, variability may exist in the measurement methods pertaining to step height and wavelength and thus hinder the organization of an encompassing step-pool data set (Figure 1.2).

Study Objectives

The purpose of this study is to characterize and quantify step-pool morphology of Bowers Hollow Creek in the Boston Mountains of Arkansas (Figure 1.1). The objectives of this study are to: (i) characterize the spatial distribution of step-pool reaches within an Ozark headwater watershed, (ii) describe the geomorphic relationships involving step height, step wavelength, active width, drainage area, slope, and particle size, (iii) evaluate the influence of three common measures of height and length used in the literature for geomorphic analyses, and (iv) evaluate the influence of channel substrate type on these geomorphic relationships.

Very little is known about mountainous headwater streams in the Midwest. However, the geologic nature of the Ozarks Plateau produces headwater streams which exhibit the mountain bedforms of steps and pools (Figure 1.4). This is the first study on step-pools in the Ozarks looking at a river catchment that heads on a plateau surface with base level controlled by the Buffalo River. Few studies, with the exception of Gomi et al. (2003) which studied headwaters streams of Southeast Alaska, have examined step-pool reaches across very small drainage areas. Through understanding the sediment transport of

Figure 1.4 Typical step-pool sequence from study area

headwater streams, the river continuum concept can be used to examine the influence of headwater stream sediment into the larger order streams. Fluvial systems exhibit a continuum of form which infers that processes upstream effect morphology downstream (Rosgen, 1996). Therefore data from this study can be applicable to multiple scientific disciplines, such as biology and geomorphology, and by managers concerned with the protection of aquatic species and habitats.

CHAPTER 2

STEP-POOL FORMATION AND FUNCTION

Step-pool morphology reflects the geological and climatic factors affecting channels in mountain watersheds. This study will use longitudinal and cross-section field surveys of a headwater stream in the Boston Mountains of the Ozarks Plateau region in northwest Arkansas to describe channel form and develop quantitative models for comparisons with other regions. Channel form of steep mountain streams is usually dominated by step-pool morphology (Chin, 2005).

The characteristics found in step-pool streams can be organized following classifications. Montgomery and Buffington (1997) introduced a scheme for channel reach classification which included step-pool, cascade, planebed and bedrock categories. Zimmermann and Church (2001) presented the categories of step-step and rapids which Gomi et al. (2003) combined with the categories presented by Montgomery and Buffington (1997) to create a modified classification scheme (Figure 2.1). The classification of channel reach type in Bowers Hollow watershed will follow a modified scheme which will be discussed later.

Work done on step-pool formations has shown them to occur in streams with a gradient which ranging from 0.02 to 2.0 (Grant, Swanson, and Wolman, 1990). Once this range of slope has been exceeded, cascade morphology influences the bedform (Figure 2.1). So higher slopes will create cascade features in the longitudinal profile, while lower

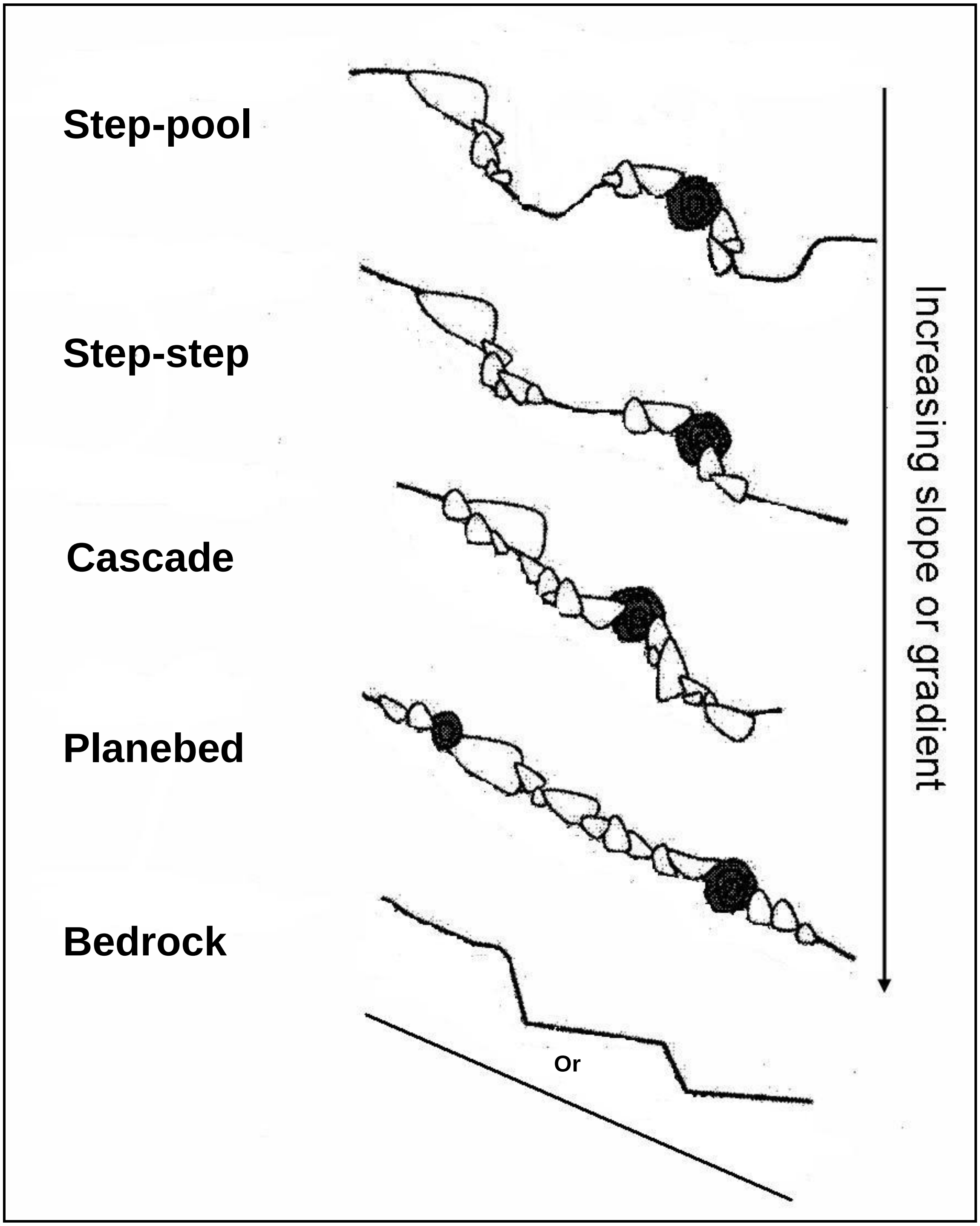

Figure 2.1 Profiles of channel types in mountainous areas (Gomi, 2003)

slopes will create planebeds (more laminar flows which show up as straighter lines without peaks and valleys in the profile). These planebeds do not exhibit stream-wide accumulations of boulders and gravel (Montgomery and Buffington, 1997).

Step-pool sequences can still be found in higher gradient channels, yet the pools are generally deeper and more developed according to lithology (Gomi, et al., 2003). Therefore as the slope increases so does the step height (there is conflict between workers concerning this), while the wavelength decreases as the slope increases (Wohl and Grodek, 1994; Chartrand and Whiting, 2000). This may not show the true picture since slope is related to other stream variables. In bedrock channels with lower gradient there is more of a chance that gravel and boulders will accumulate to form transverse ribs, which are the foundations for steps (Duckson and Duckson, 2001). In bedrock channels with a higher gradient the sediment supply is usually flushed through the bedrock section. This dynamic is similar to a flume without any chance for a step to from.

Step-pools are bedform structures which accomplish their job of energy dissipation best in low flow situations (Chin, 1998). The size of particles found within steps varies greatly ranging from sand/silt particles trapped in crevices between gravel to boulders which are larger than the depth of flow. The step is designed to produce a vertical drop into a recovery pool which in turn reduces the forces contained within the flow (Heede, 1981). Therefore levels of stream discharge, which are lower than the maximum height of the active width or lower work best in this scheme to dissipate the energy of the flow (Figure 2.2). The two types of energy dissipation involved with step-pools are potential energy dissipation and kinetic energy dissipation (Chin, 2003). Potential energy dissipation involves the vertical drop associated with the step, while kinetic energy

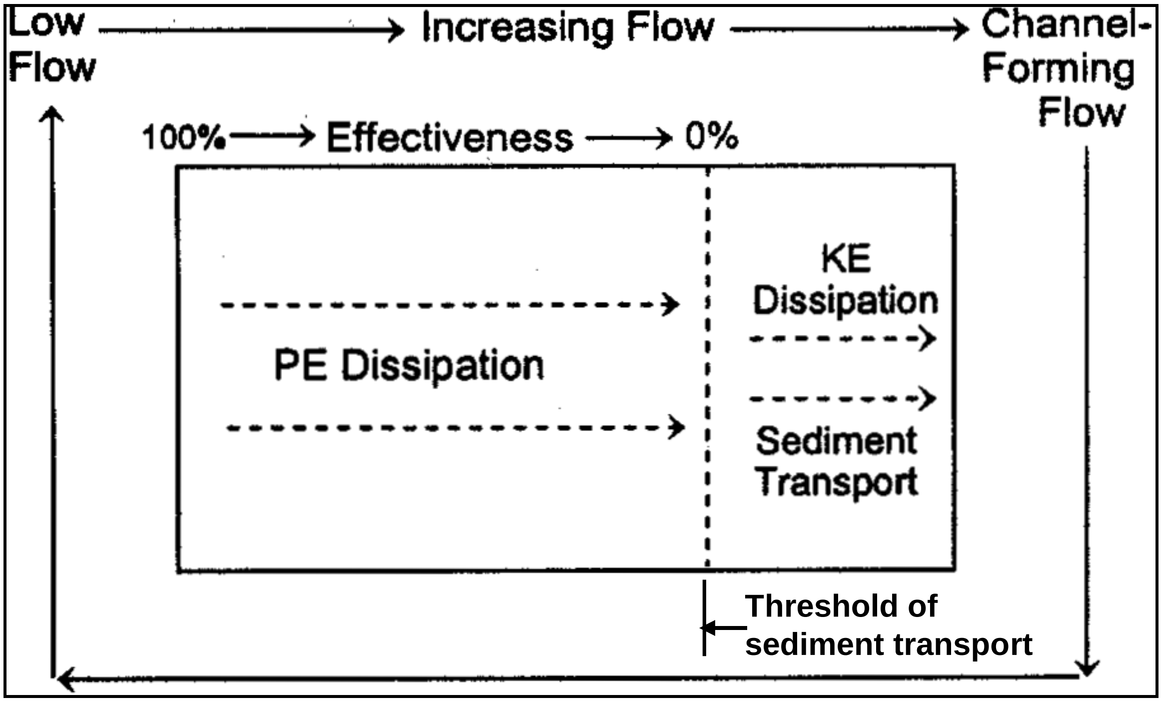

Figure 2.2 Model showing energy dissipation effectiveness of low flows (Chin, 2003)

dissipation involves the roughness of the channel and substrate (Chin, 2003). As levels of discharge increase the overall effect of the step is greatly diminished due to the reduction in both vertical drop and the influence of substrate resistance (Lee and Ferguson, 2002) (Figure 2.2).

The actual formation of these steps is debatable due to the harsh environment in which they are located. Step-pool streams are generally located in mountainous areas which are rugged in terrain and present the researcher with unique logistical problems involving accessibility (Chin, 2005). These steps are generally formed during high discharge, low frequency flood events (Whittaker and Jaeggi, 1982). These high discharge levels can be estimated through hydraulic reconstructions using measurements taken at low flow conditions (Lenzi, 2002) (Figure 2.3). Figure 2.3 represents a complete fluvial cycle of a step-pool sequence. The model shows the low flow form of step-pools to be the central

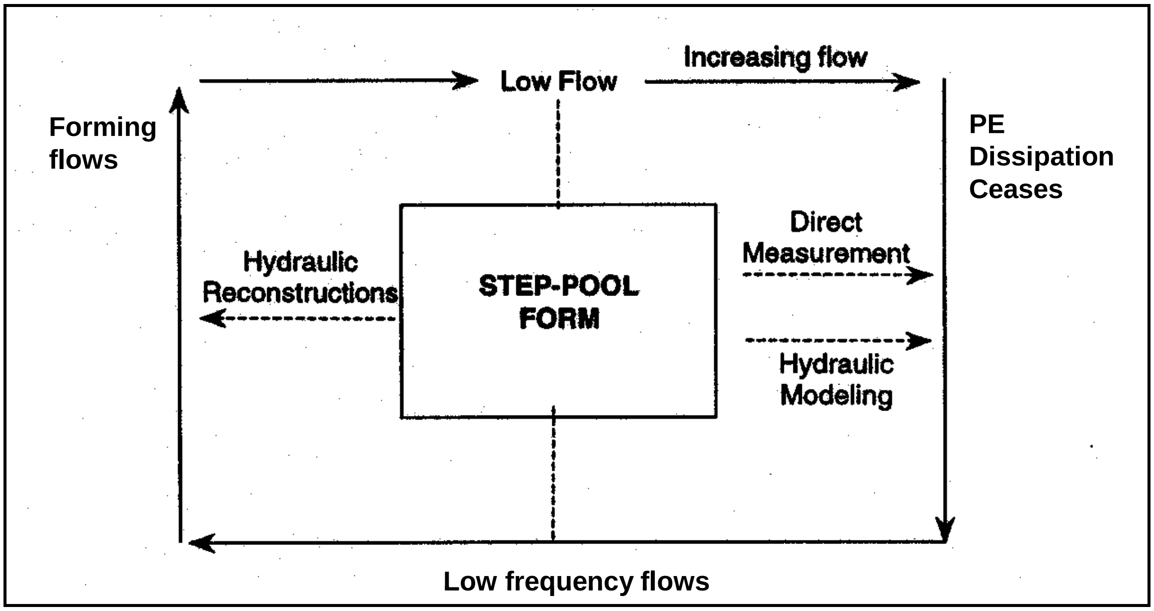

Figure 2.3 Model showing evolution of the step-pool fluvial system (Chin, 2003)

member in the understanding of step-pool form with hydraulic reconstructions used to investigate channel-forming flow and direct measurement and modeling used to investigate energy dissipation (Chin, 2003). Capturing high discharge events are difficult to capture in the field, much less finding a way in order to study the transport and deposition of the large boulders and sediment under the water. Therefore modeling and working backwards through reconstructions are used during investigations.

Case Study Of Step-pool Morphology

Regional Overview. Chin (1998, 1999, 2003) has set some of the precedents concerning step-pools through her studies in the Santa Monica Mountains of southern California. Chin’s studies concern geomorphology, stability, structure, and significance of step-pools (Chin, 1998, 1999, 2003). Wooldridge and Hickin (2002) used four analytical techniques

to study the morphology of Mosquito Creek in British Columbia. Their study proves the merits of certain methods when measuring steps in mountain streams. Gomi and et. al., (2003) studied 15 streams in southeast Alaska in order to find out the characteristics of steps in headwater streams. Their analysis concerns how fluvial and colluvial processes dominate and influence the structure of the reach, as well as how woody debris can influence the bed forms.

A study by Lee and Ferguson (2002) incorporates velocity and flow resistance into the scheme of step-pools. They conclude that step pools are unique in that flow resistance is not only affected by shear drag, but also by form drag attributed to the pressure differences around large boulders or other forms in the step. This helps in understanding the idea of the step being most efficient at dispersing energy during lower flows. Zimmermann and Church (2001) also concentrate on this aspect, but deal with the stability of non-cohesive bed materials, which predominate in steps, during flood conditions.

Duckson and Duckson (2001) have formulated some relationships between pool-shape and size variables attributed to steps and pools found along Soda Creek in Oregon. This study is interesting because of the use of lithology in their analysis of their data. Grant's (1995) study of valley floors in the western Cascades of Oregon is important due to his conclusion that mountain streams are strongly controlled by bedrock, hillslope, and tributary stream processes. Wohl's (1994, 2004) studies of sediment in mountain streams is valuable to understanding the role that erosion, transport, and deposition plays in controlling channel form. Her study areas include the Christopher Creek drainage in

Arizona, the Grey River in New Zealand, the Agua Fria River basin in Arizona, and the Arkansas River and North Fork Cache la Poudre River in Colorado.

There are specialty areas of study involved with step-pool research. For example, the Wooldridge and Hickin (2002) study, used two separate longitudinal surveys and four distinct techniques to delineate the step-pool bedforms. The preliminary survey sampled every large bedform feature and a second survey used rod intervals of 0.6 meters to measure the bed elevation. From these surveys 55 step-pool and cascade forms were delineated. The data collected from each bedform included wavelength, height-measured the same as Chin (1989), and bedform steepness-height/wavelength. The wavelength measurements were scaled to the width of the channel (measured across the crest of the step) in order for the data to be compared with other published works. This scaling involves dividing the wavelength by the width of the channel. (Wooldridge and Hicken, 2002).

The Duckson and Duckson (2001) study located the steps and pools through the use of longitudinal profiles. At each step-pool three measurements were taken; the height of the step-“the distance between the lowest outlet elevation of the upstream edge to the pool elevation created by the lowest step outlet on the downstream pool edge”, pool length, and pool depth. Each individual pool was extensively surveyed in order to obtain pool outlines, plan, and profile. From this the pool area could be accurately estimated. Each transect throughout the reach was set at an interval of 1 to 1.5 active channel widths. Grain size was calculated from the average of the five largest stones at each step being used as an approximation of the D90. The study also included the variables of slope (as a

percentage), step steepness (height/length), and pool length factor (length/height) (Duckson and Duckson, 2001).

Geomorphic Classifications. Due to workers using visual identification techniques there is some subjective nature to classifying step-pools (Wooldridge and Hickin, 2002). There are characteristics which distinguish between step-pool, step-step, cascade, rapids, and bedrock morphology (Gomi and et. al. 2003) (Figure 2.1). These characteristics are based on the dominant morphological features such as cascade, riffle, or rapid as proposed by Zimmermann and Church (2001). Wooldridge and Hickin (2002) distinguishes steps from cascades by "(i) the degree of structuring and arrangement of grains, (ii) the extent to which structures spanned the channel, and (iii) the nature of pool development". This study will use the classification scheme proposed by Chin (1999) which defines steps as "accumulations of cobbles and boulders that are transverse to the channel, they are separated by finer sediments that define pools". The study of Bowers Hollow Creek will include bedrock and colluvial block steps with alluvial steps in the analysis of steps and step-pool reaches.

Sediment size and material composition are related in that both are influenced by either alluvial, colluvial, or bedrock processes. Sediment size corresponds to an axis measurement of particles comprising a step or pool, while material composition corresponds to the make up of the bed substrate and bank materials (Rosgen, 1996). Some workers have observed significant relationships between step height and sediment size--as the sediment size becomes larger, so does the step height (Wohl, Madsen and Mcdonald, 1997, Chatrand and Whiting, 2000). This makes sense since steps are

accumulations of sediment. However, other workers have concluded that as particle size decreases downstream so does step height (Zimmermann and Church, 2001). In areas, such as Bowers Hollow Creek, where colluvial blocks are mixed with alluvium and bedrock there is conflict to this notion since larger sediment is dispersed in the middle, rather than the very upper portion of the watershed, from exposed sandstone and shale strata. However, the general theory is that sediment size decreases downstream, as does step height (Chin, 2005).

The material which makes up the bank and bed of the channel also influences the longitudinal profile of the stream (Duckson and Duckson, 2001). This can be seen by looking at the differences between bedrock dominated channels, colluvial block dominated channels, and alluvial channels (Montgomery and Buffington, 1997). Alluvial deposition may occur in low slope bedrock channels, whereas high slope bedrock channels tend to have larger velocities which flush the sediment straight through. The bedrock material also plays a part in how the profile looks. Some bedrock, like shale, will allow downcutting into the bed to create slides or troughs in the channel similar to the inner gorge found in Bowers Hollow (Rosgen, 1996) (Figure 2.4). Other bedrock, like sandstone or granite, will create waterfalls and undercut ledges, which creates a continuous vertical drop in the profile of the reach (Duckson and Duckson, 2001). The presence of colluvial blocks also affects the profile by generally creating higher steps and shorter wavelengths. Alluvial channels allow for the most uniform step-pool sequences to be created. If alluvial channels have adequate sediment and slope, then the most uniform form of step-pool sequences can be naturally formed. It is these step-pool bedforms in alluvial channels that are studied the most (Chin, 2005).

Figure 2.4 Inner gorge located in steepest part of the hollow

Step-Pool Measurements. The methods for measuring the characteristics of step-pool reaches for my study will be referenced from three previous studies: (i) Chin's (1999) study of the morphologic structure of step-pools in the Santa Monica Mountains, California, (ii) Chartrand and Whiting's (2000) study of step-pool and cascade morphology on streams throughout Idaho, and (iii) the Zimmermann and Church's (2001)

work on Shatford Creek in British Columbia. These three methods constitute measurement practices for step height and step wavelength which have been used during recent research.

Chin (1999) uses the reach paradigm in her work to assess her study area and the averages for the measurement of steps in the reach were used in her study. It seems that studying individual steps did not provide adequate information for analysis. The measurements taken for each step within a reach were: longitudinal profile, the active channel width measured at the crest of each step, b-axis measurements of the five largest particles in each step (this should approximate the D84) , wavelength (pool to pool distance), step-pool spacing (measured in units of channel width), and height (measured by using a "perpendicular distance between the crest and an imaginary line connecting the troughs of the step-pool unit"). For each reach additional data used included drainage area, slope, channel width, and length (Chin, 1999).

Geomorphic Analysis. The analysis of each of these studies is unique in their regard to their modeling. Chin (1999) and Chartrand and Whiting (2000) show variations of step wavelength, step height, and channel width with drainage area, as well as step wavelength and step height with channel width. They also plots relationships between step wavelength and slope, step wavelength and particle size, step height and particle size, critical discharge and observed wavelength, step-pool spacing and slope, and step height and slope. The average wavelength to height ratio was approximately 10:1 (Chin, 1999) and 8:1 (Chatrand and Whiting, 2000). The analyses used by Wooldridge and Hickin (2002) include; bedform wavelength frequency distributions, regression model of

wavelength as a function of height, downstream trends in height and grain size, and wavelength as a function of grain size.

The Duckson and Duckson (2001) study is unique in that they use lithology as a component of their analyses. The lithology is divided into three classes; andesite, dacite, and basalt pools. For each class of lithology their evaluation involved graphic and regression analysis of step height and slope, pool length and slope, pool depth and slope, height-length ration (steepness) and slope, length-height (size) and slope, H/L ratios on slope by rock type and pool class, and L/H ratios on slope by rock type and pool class (Duckson and Duckson, 2001).

The Zimmermann and Church study examined the velocity and shear stress involved with step-pool morphology based on Shields and other methods (Zimmermann and Church, 2001). This was studied in order to explain the stability and movement of step bedforms. They also examined the geometric relationships of step-pool with other variables similar to Chin and Chartrand and Whiting. The unique component of the Zimmermann and Church study involves the use of the variance in the measured parameters rather than averages of the parameters as most other studies use. This was used to investigate the random effects concerning the formation of step-pool sequences.

Summary

This study is the first study to evaluate the channel characteristics and step-pool forms in headwater streams in the most rugged portion of the Ozarks Plateau. Since there is limited knowledge pertaining to step-pools, especially in the case of the formation of

these step-pools and cascades, my data will help filling in some of the gaps. This will be done through using the preferred or standard, measuring methods and surveying techniques found in the literature. Further, the results of this study will be compared with data from other regions (most notably the Santa Monica Mountains in California, Shatford Creek in British Columbia, and streams throughout Idaho. Through this comparison analysis, a hypothesis can be formed as to whether or not a mountainous, step-pool stream from the Ozarks behaves geomorphically similar to other region's step-pool streams and to published data and results. This assists in filling in the gaps of knowledge in complete, mountainous, fluvial systems, which in turn would lead to more responsible management practices when encountering development and restoration in mountainous environments.

The results of step-pool morphology in the Bowers Hollow watershed exhibit similar characteristics found within recent literature. The step height and wavelength relationships were quite strong. However when step height and wavelength were correlated to other reach variables (width, sediment size, and drainage area) they did not have as strong of a relationship found by other workers (Chin, 1999 and Chatrand and Whiting, 2000).

Step-pool mountain streams provide the necessary means for riparian, aquatic, and biologic habitats (Chin, 2005). Therefore it is beneficial for scientists and managers to understand step-pool systems. Step-pool morphology has also been used in stream restoration. Through bioengineering techniques, the step-pool form has been used to act as low check dams and as bank and substrate stabilizer (Lenzi, 2002). The data obtained

from this study could be useful as reference material for stream restoration projects in the area.

CHAPTER 3

STUDY AREA

Region

Location/Physiography. This study describes channel form using longitudinal and cross-section field surveys of a 2nd order headwater stream, Bowers Hollow Creek watershed (3.5 km^2), in the Boston Mountains of the Ozarks Plateau region in northwest Arkansas (fig. 1.). The study watershed is located within the boundaries of the Forest Service-maintained Upper Buffalo Wilderness Area which was established by Congress in 1975. The Upper Buffalo Wilderness Area actually has two parts (one Forest Service maintained and one National Park Service maintained) which total more than 13,000 acres.

This area has some of the most rugged terrain found in the Midwest (Figure 3.1). The Boston Mountains in this area have a maximum elevation of 2561 feet, or 780.6 meters, located at an abandoned fire tower approximately 3 kilometers from the study area. The elevation of the Buffalo River in this area is approximately 1350 feet, or 411.5 meters. This topography lends itself well to hillslope processes which are rare to find in other areas of the Midwest. This drastic terrain coupled with hillslope processes creates an environment suitable for the development of step-pool formations (Figure 3.2).

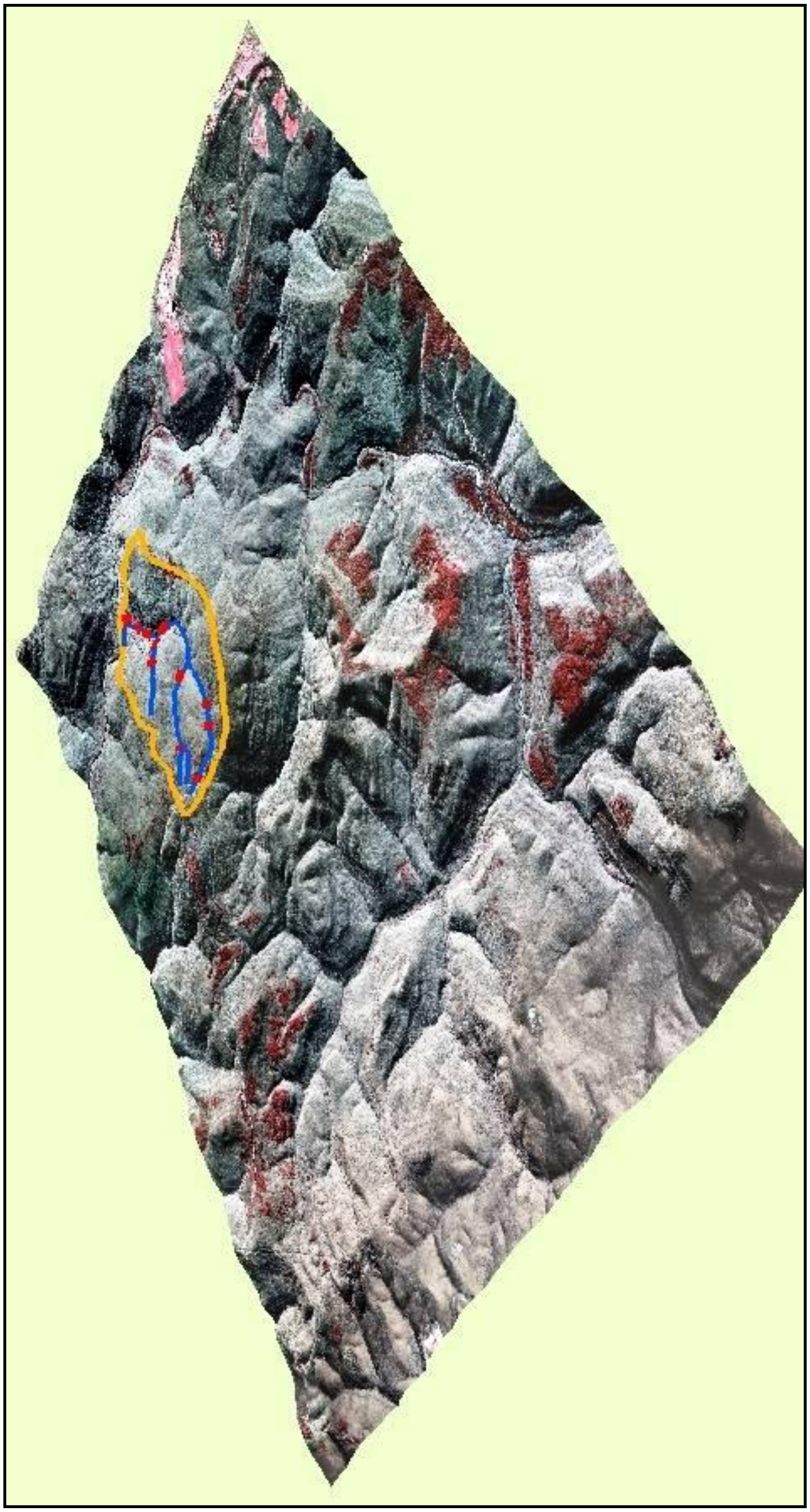

Figure 3.1 Image showing location of study watershed within Upper Buffalo Wilderness Area topography

Geology/Soils. The geology of the area is generally composed of Pennsylvanian shales, siltstones, and sandstones (McFarland, 1998). The Boston Mountains are the highest section of the Ozark Plateaus region located at the southern end of the Ozarks. The Ozark Plateau region is formed through uplifting processes occurring along faults. The surface rock of the Boston Mountains is a Paleozoic formation known as the Atoka Formation (McFarland, 1998). The Atoka formation "is a sequence of marine, mostly tan to gray silty sandstones and grayish-black shales" (McFarland, 1998).

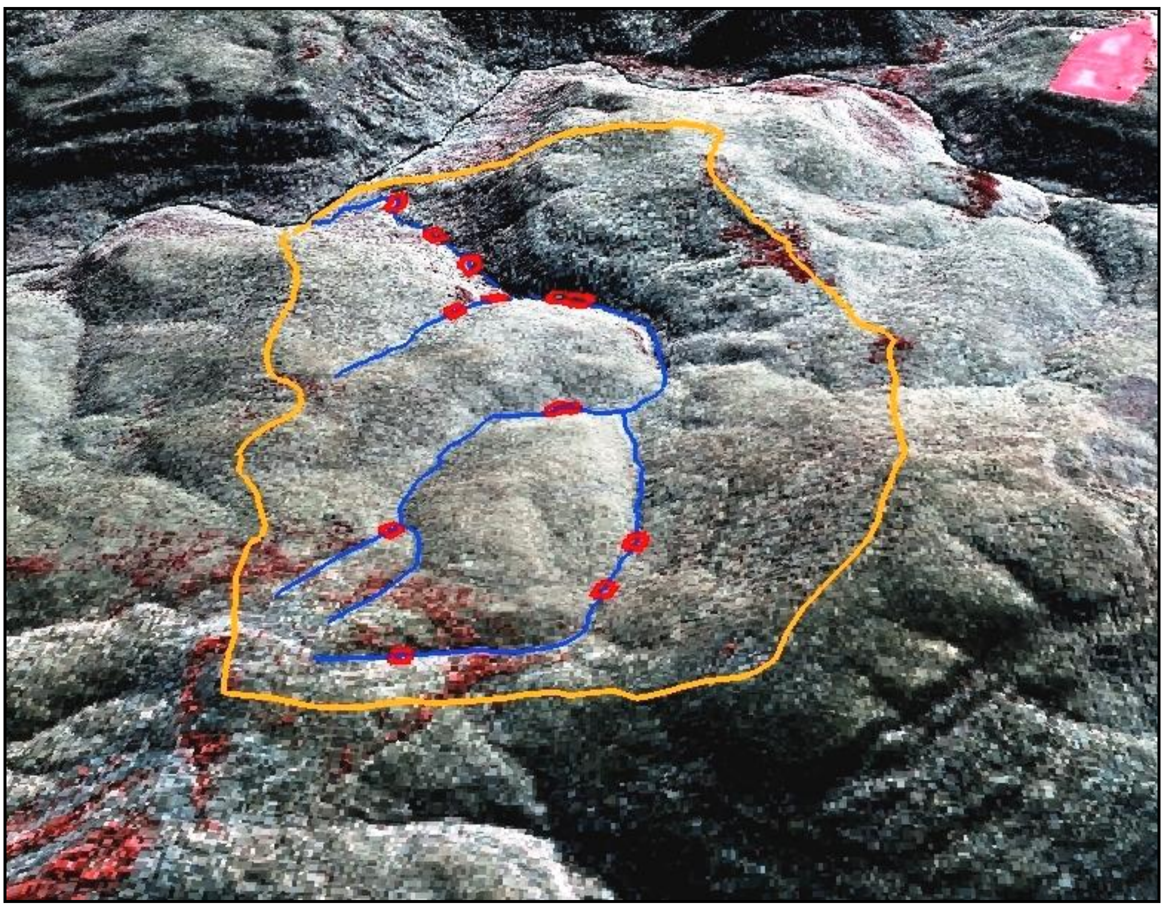

Figure 3.2 3-D terrain image showing the topography of the study area

Climate/Hydrology. Bowers Hollow Creek is located in a four-season humid climate. The nearest flow gage to the study area watershed is located at the Boxley bridge (Highway 21) on the main stem of the Buffalo River. This gage is approximately 14.5 kilometers downstream from the confluence of Bowers Hollow Creek and the Buffalo River. The area surrounding the gage is typical of a low-gradient riffle-pool stream. The gage area is engulfed by willow thickets and long shallow pools for two miles upstream of the gage.

The flow gage at Boxley has been in operation since May, 1993. The record between May, 1993 to July, 1996 and October, 1998 to April, 2004 has a mean annual flow of 3.0 cubic meters per second. The Buffalo River drainage area is 148.7 km^2 at the gage and the channel slope is approxiamately 0.001. The discharge amounts and geomorphic characteristics found at the gage vary considerably from the upstream study area.

The largest event which occurred at the gage within the last two years occurred in May of 2004 and produced around 17,000 cubic feet per second (cfs), or 481.4 cubic meters per second (cms) (Figure 3.3). The second largest event occurred during January of 2005 and produced a peak flow of around 12,000 cfs, or 339.8 cms.

Vegetation/Land Use. The ridge tops and bottomlands of the Upper Buffalo area were farmed by homesteaders until around the 1930's, some farming is still occurring at the present time. Located in these same areas were native shortleaf pine and cedars. Hardwoods, hickories and oaks, along with beech and magnolias comprised the main canopy. Smaller dogwoods and maples made up the mid-canopy while creepers and poison ivy formed the undergrowth.

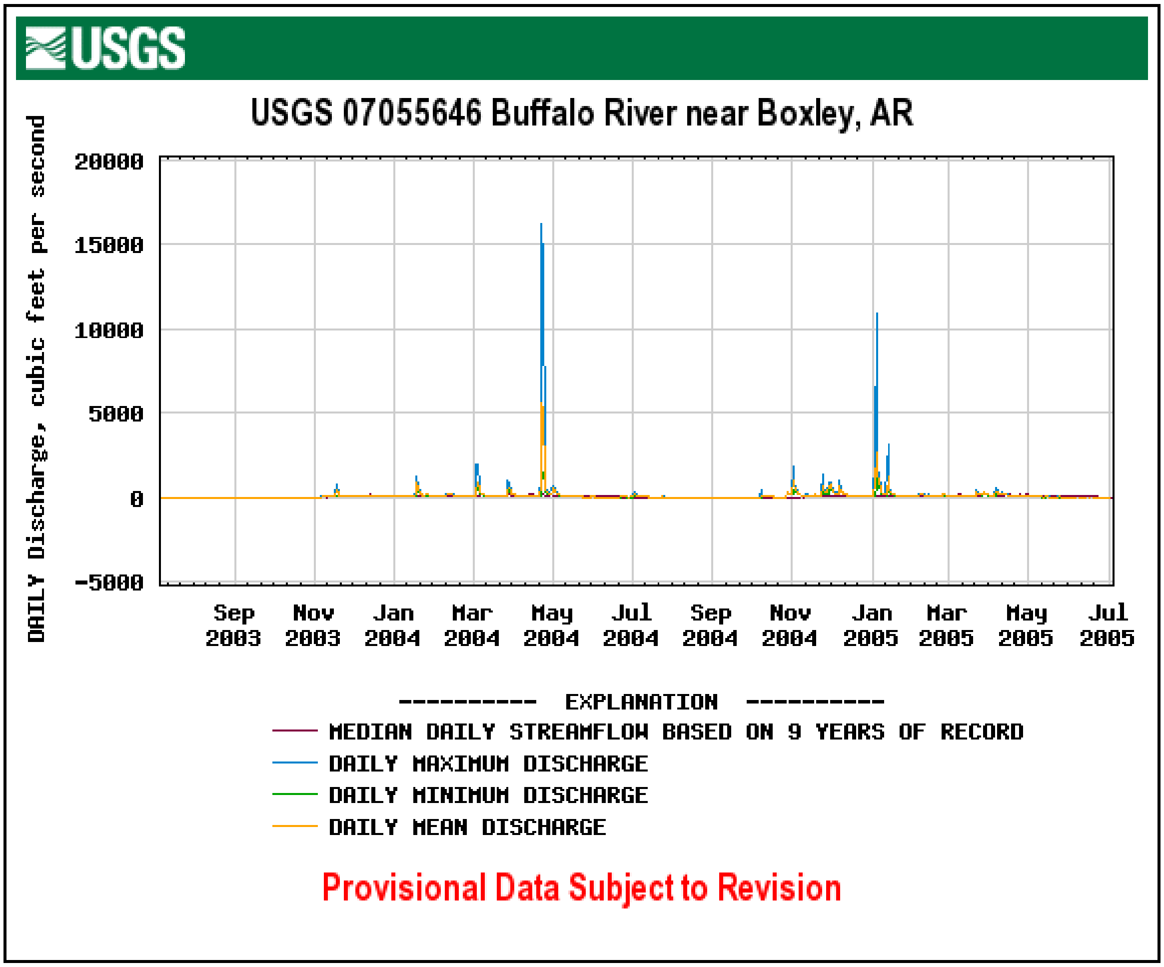

Figure 3.3 Hydrograph showing discharge for two-year period at USGS Boxley gage, notice the peaks where highest discharge amounts occurred

Previous to 1975 the land use of this area included timber harvesting from the late 1800s to the late 1960s and agriculture from two small homesteads until the early 1970s. Recreation has been the prominent land use since 1975 with backpacking and hiking being the dominant activities. Sporadic farming has occurred in the area since homesteaders first arrived. The upper reaches of surrounding watersheds have recent (fall of 2004) timber harvesting activity which has taken place. This activity could have

substantial effects on the step-pool morphology of the streams. The influx of additional sediment from timber harvesting may place the sediment budget of surrounding streams in a state out of equilibrium. The question on how fast a step-pool stream can recover from a disturbance like timber harvesting was not addressed with this study. Therefore Bower Hollow Creek was selected in order to obtain measurements from naturally forming step-pool channels in a relatively undisturbed catchment.

Bowers Hollow Watershed

The length of the main stem of Bowers Hollow Creek is 3.6 kilometers and it flows from 713 meters above sea level to 415 meters above sea level at the confluence with the Buffalo River. An important geologic feature of the watershed is a horizontal layer of resistant sandstone that forms an obvious bluff line that outcrops about halfway down the main stem near 550 meters above sea level. This bluff line affects the geomorphology of Bowers Hollow Creek at two locations: (i) a 17 meter high waterfall at the point of the hollow (Figure 3.4) and (ii) a 15 meter high waterfall at the point where the bluff and the tributary intersect (Figure 3.5).

Until the study stream reaches the lip of the bluffline, it is predominately an alluvial channel which flows over the Plateau surface. There are occasional thin strata of shale and sandstone bedrock located above the bluff line which provide ample slope and sediment supply of step-forming clasts for step-pool morphology in the region above the bluffline. It is in these headwater sections of the watershed which provide the most

Figure 3.4 17 meter waterfall located at intersection of the main stem and the dominant bluff line.

uniform step-pool sequences. When the stream encounters the sandstone bluff line its characteristics change dramatically. Approximately 200 meters upstream of the bluff line the main stem of the stream encounters the bedrock cap which produces the bluff line feature. From this point to the lip of the waterfall, the stream is very shallow, laminar, and fast flowing with no step being apparent. This section of the stream is similar to a

Figure 3.5 15 meter high waterfall at the point where the bluff and the tributary intersect

sidewalk with faster moving water being exhibited due to the lack of shear stress over the smooth bedrock surface.

Within the confines of the hollow are bedrock sections of sandstone and shale, large colluvial blocks (some the size of houses) which have been deposited in the channel through hillslope processes originating at the bluff line, and alluvial deposits of boulders,

cobble, gravel, and silt. The largest feature found within the hollow proper is an inner gorge cut through shale bedrock. This gorge produces a steep bedrock slide (approximately 50 meter in length) and the largest pool found in the study area (Figure 2.4). The velocity of the stream during a storm event is tremendous as it plunges through this gorge. This is apparent through the rock shards found embedded in the upstream side of a log wedge in the slide (Figure 3.6). The effects caused by the substrate and processes which occur in the hollow are unclear. In general the bedrock and colluvial blocks were found in steeper sections of the stream compared to lower gradient sections which produced more organized step-pool sequences. The steps found in the steeper sections were generally less proliferate and uniform than the lower gradient sections.

Figure 3.6 Embedded shale fragment in log

CHAPTER 4

METHODOLOGY

Initial Classification

An initial classification of channel form throughout the watershed was performed following a modified classification based on classifications used by Montgomery and Buffington (1997), Gomi et al. (2003), and Zimmermann and Church (2001). Twenty-eight segments were delineated by visually assessing the streams and classifying the dominate form as: (i) step-pool (10 segments), (ii) cascade (7 segments), or (iii) plane bed (11 segments) (Figure 4.1). This initial classification was used in the watershed to become familiar with the watershed morphology and to identify step-pool reaches and select sample reaches for this study (Table 1). From this classification, 11 sample reaches showed distinct uniformity of step-pool sequences and were chosen throughout the Bower's Hollow Creek watershed. These reaches were selected in order to achieve an appropriate analysis of step-pool reaches over a wide range of drainage areas, from 0.05 to 3.44 km^2. Six of the reaches were located above the dominant bluff with five reaches located below the bluff (Figure 4.2). The average reach length was 79 meters with the maximum length being 164 meters and the minimum length being 44 meters. A total of 131 step-pool sequences were measured with 84 above the bluff and 47 below the bluff.

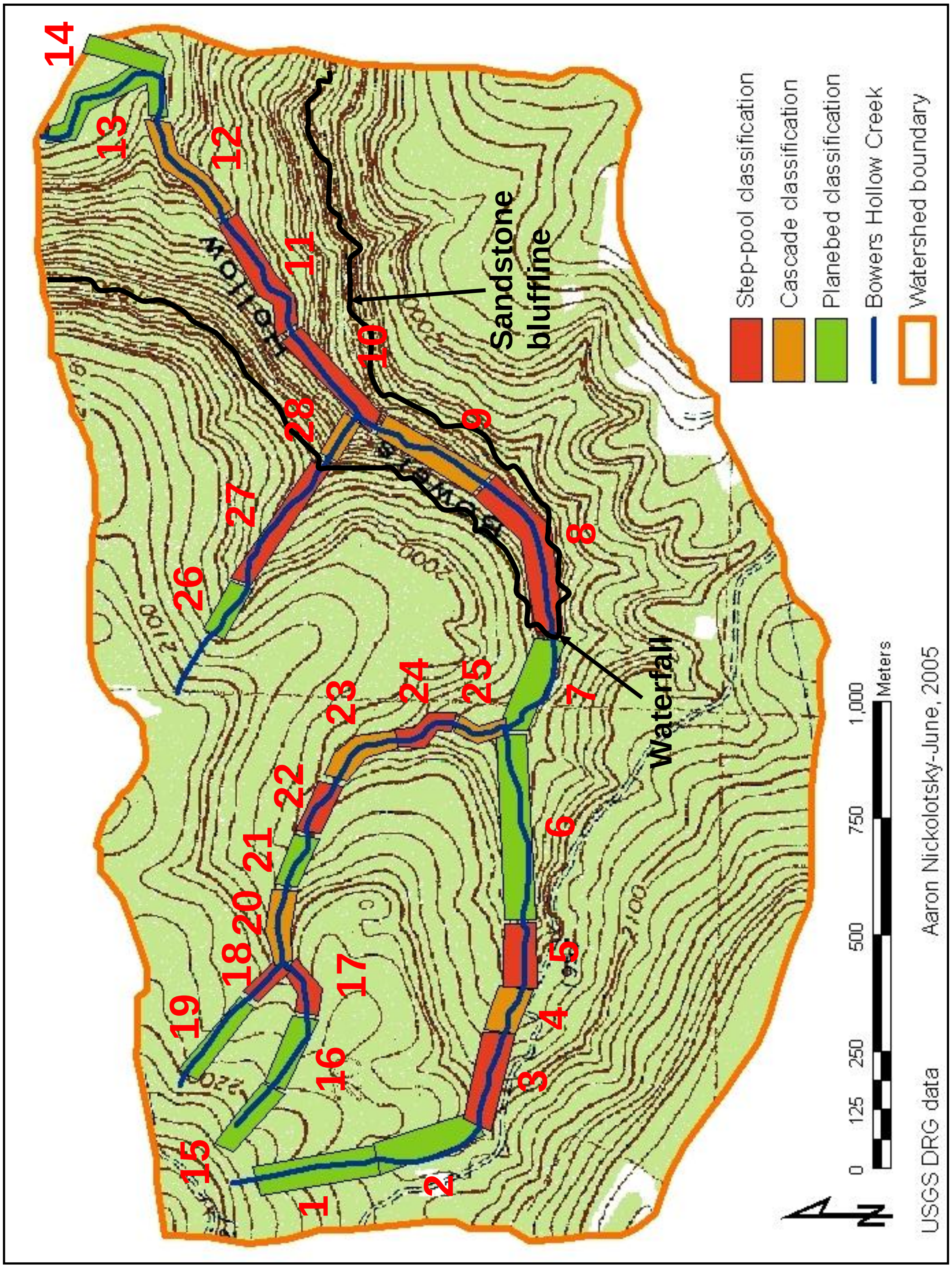

Figure 4.1 Map of initial classification (USGS Fallsville quadrangle)

This study used mean values of the entire sample reach to evaluate step-pool morphology as previous workers have done (Chin, 1999, Duckson and Duckson, 2001, and Wooldridge and Hickin, 2002). The entire sample mean was used for geomorphic and comparative analysis found in the results section of this paper. Also used for analysis of the Bowers Hollow Creek data is a stratified mean based on the division among alluvial, colluvial, and bedrock features. In this study, bedrock features are predominately exposed capstones, alluvial features consist of cobbles and boulders deposited through fluvial action, and colluvial features are considered large blocks of bedrock deposited by hillslope processes from the dominant bluffline.

Table 1: Initial classification characteristics

Segment #	Length (m)	Est. Width (m)	Field Notes
1	267	0.5-1.5	Alluvial planebed, mini step-pool sequences
2	248	1.5-2.0	Alluvial planebed, bedrock, couple of smaller step-pools
3	225	2.0	Step-pool morphology, exposed sections of bedrock
4	107	2.0-2.5	Cascade morphology, exposed bedrock, medium boulders
5	145	2.5	Step-pool morphology, exposed sections of bedrock
6	421	2.5-3.0	Planebed, meandering, some step-pools
7	239	3.0-4.0	Planebed, meandering, laminar flow over bedrock
8	389	5.0	Bedrock controlled step-pool morphology, sluice, cascades
9	264	6.0	Cascade morphology, large sluice, very large boulders, rough
10	298	4.0-5.0	Step-pool morphology, smaller steps than previous segment
11	306	6.0-7.0	Step-pool morphology, medium steps and cascades
12	259	5.0-6.0	Cascade morphology, very large steps, blocks, and cascades
13	468	4.0-5.0	Planebed, enters Buffalo floodplain, silt, gravel, and cobble
14	177	1.0-1.5	Planebed, low gradient spring offshoot from main channel
15	168	0.5	Alluvial planebed, very small occasional step
16	154	1.0-1.5	Alluvial planebed, laminar flow, very shallow, hardly any pools
17	121	1.5-2.0	Step-pool morphology, exposed bedrock step-pools/step-steps
18	92	2.0	Step-pool morphology, bedrock steps with alluvium interspersed
19	201	1.0-1.5	Alluvial planebed, occasional small steps and pools
20	145	2.0-2.5	Cascade morphology, bedrock step-steps and cascades
21	108	2.5	Alluvial planebed, stream braiding occuring with step forms
22	115	3.0	Step-pool morphology, good forms, small boulders
23	169	3.0-3.5	Cascade morphology, braiding occuring over flatter sections
24	133	3.0-3.5	Step-pool morphology, very good forms, cobble, boulders
25	101	3.5	Cascade morphology, braided channel at beginning of segment
26	148	0.5	Alluvial planebed, switches to cobbles and boulders
27	329	1.5	Step-pool morphology, bedrock at start and end of section-good
28	133	3.0	Cascade, large boulders and blocks, step-steps

Figure 4.2 Main stem of Bowers Hollow Creek at the lip of the dominant sandstone bluff line

Geographical Information System Data Study

Several different types of software were used to examine the spatial characteristics of Bowers Hollow Creek. Geographic Information System technology was used most often in creating initial maps for fieldwork purposes and final maps for presentation. ESRI ArcMap 9.0 was the software package used for this purpose. Global Positioning System technology was used to collect points in the field. Once the GPS points were obtained, they were transferred into a GIS database for creation of spatially accurate figures.

Additional software used for analysis included ENVI 8.1 (remote sensing software), GS+ (statistical software), and Excel. Excel proved crucial for organizing and analyzing

data. The remote sensing software helped in understanding the topography of the area through the use of DEM's to examine the attributes of the watershed, such as direction of flow and elevation changes. The GS+ software was used in conjunction with the raw survey data to create three dimensional models and two dimensional contour models of the surveyed reaches.

Field Research

Reach Surveys. Channel surveys using a total station and data logger were used to obtain geomorphic measurements at 11 reaches found throughout the watershed (Figure 4.3). Survey points (Figure 4.4) were taken at the (i) crest of the step at 5 points across the channel width, (ii) the base of the step at 1 point in the thalweg, and (iii) the deepest part of the pool at 5 points across the channel width. Additional points were taken in the thalweg to facilitate a more accurate longitudinal profile (Figure 4.5).

The methods for measuring the step height and the step wavelength of step-pool features for this study were referenced from three previous studies: (i) Chin's (1999) study of the morphologic structure of step-pools in the Santa Monica Mountains, California, (ii) Chartrand and Whiting's (2002) study of step-pool and cascade morphology in Idaho streams, and (iii) the Zimmerman and Church (2001) study on Shatford Creek in British Columbia (Figure 4.6). The three different measurements were implemented for each sequence in this study. The Chin method uses a line connecting the deepest point of the pools to measure the wavelength and a perpendicular line drawn

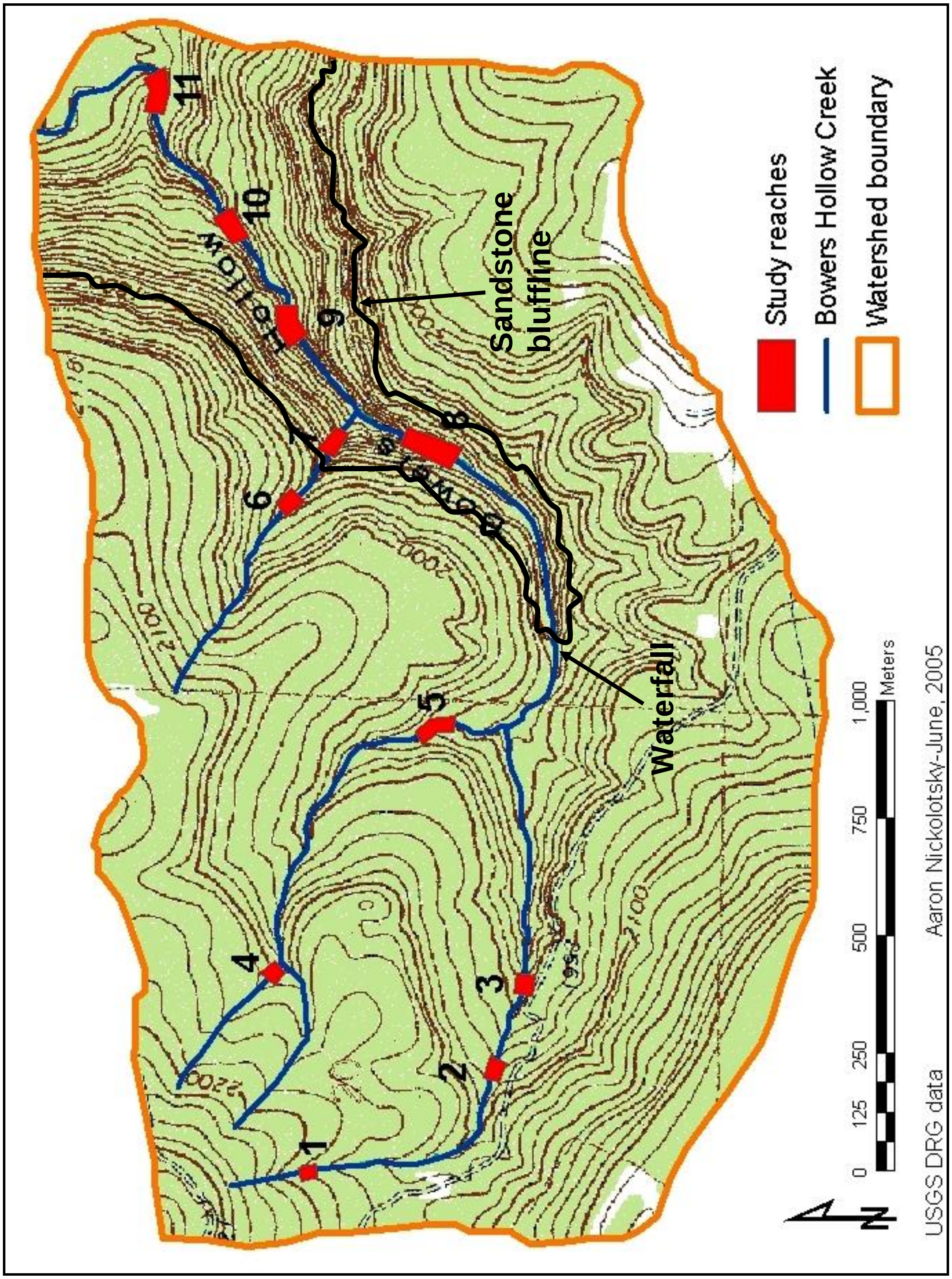

Figure 4.3 Map of study area showing reaches (USGS Fallsville quadrangle)

Figure 4.4 Location of survey points in a step-pool sequence

Figure 4.5 Total station survey taking place at reach 8 colluvial step

from the wavelength line to the crest of the step to measure the step height (Figure 4.6). The Chartrand method and Zimmermann method both use a line drawn from crest to crest to measure the wavelength, but Chartrand uses the horizontal distance while Zimmermann uses the slope distance between the crest (Figure 4.6). In addition, Chartrand uses the crest of the step and the deepest point in the downstream pool to measure the step height (Figure 4.6), while the Zimmermann method uses the crest of the step and the base of the step to measure step height (Figure 4.6). The mean value of the

three measurements for step height and wavelength will be used to analyze the geomorphic characteristics of reaches within the Bowers Hollow Creek watershed.

Sediment Sampling. Particle clast size measurements were taken at every step using a modified Wolman pebble count (Wolman, 1969). The five largest particles of the step were visually selected and the b-axis of each particle was measured using a folding meter stick (Figure 4.7) (Rosgen, 1996). Steps are accumulations of larger-sized clasts while

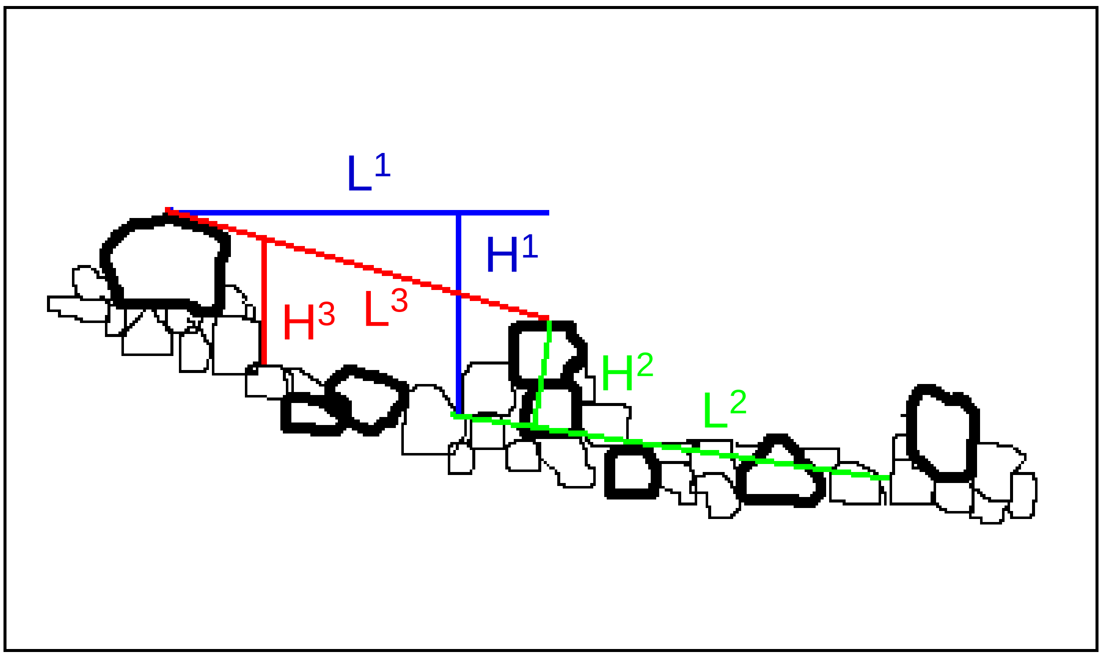

Figure 4.6 Schematic of step-pool sequence with different measurement methods used in the study. H^1 is height measurement and L^1 is length measurement used by Chartrand and Whiting (2000), H^2 is height measurement and L^2 is length measurement used by Chin (1999), H^3 is the height measurement and L^3 is the length measurement used by Zimmermann and Church (2001)

pools typically accumulate finer sediment, therefore the average of these five clasts should approximate the D_{90} of the reach (Chin, 1999). Sediment was measured in order to examine the relationship of sediment size to step height and wavelength. Throughout the study the measuring of sediment was done by three different people using the same methods.

However, since selecting the five largest particles is somewhat of a subjective process, there could be error associated with this data. Field workers were informed not to measure bedrock outcroppings or very large colluvial blocks. This was done to reduce

Figure 4.7 Measurement of the b-axis of a sediment sample

the number of immovable sediment features in the sample. The investigators were instructed to find the five largest particles comprising a step which could be moved by a 50-100 year storm event rather than focusing on house and car sized blocks which could only be moved by >100 storm event discharges.

Data Processing

Survey Data Reduction. Foresight DMX software was used to reduce raw survey data for geomorphic analysis (Figure 4.8). The measurements included width of the step crest, step height and wavelength, and longitudinal profile. The active width of the channel was measured across the crest of the step (Chin, 1999). The longitudinal profiles were

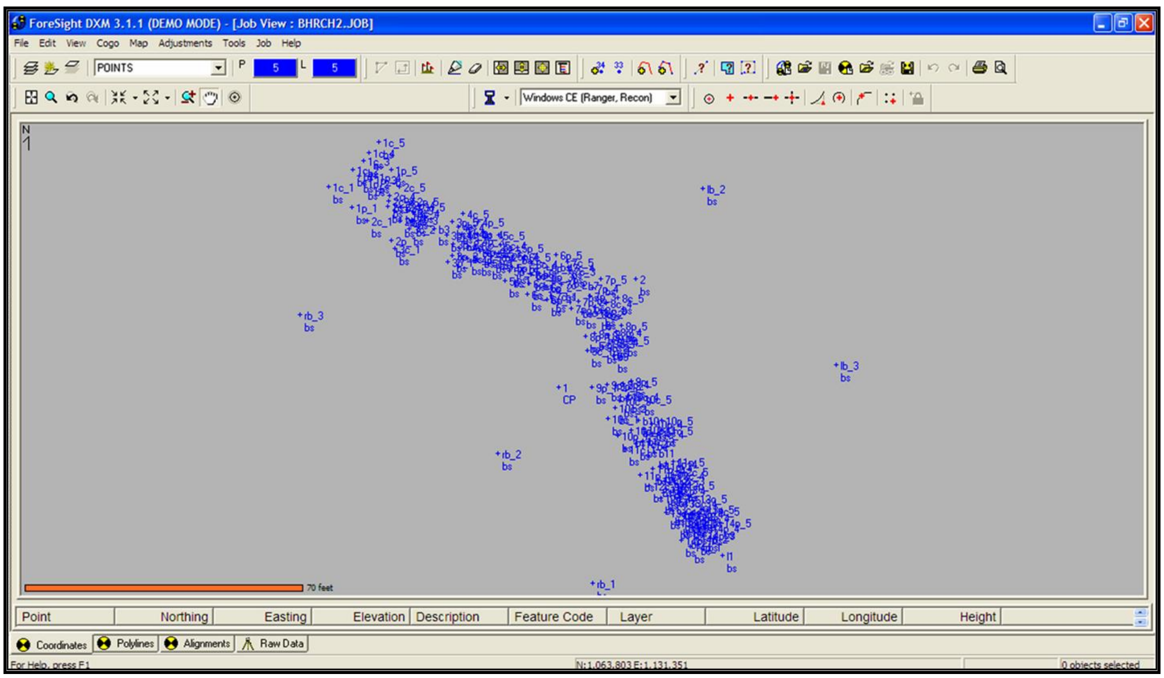

Figure 4.8 Full view of reach survey data points from reach 2 in TDS Foresight DXM software

created using the deepest point in the step crest cross-section and the deepest point of the pool cross-section. Step height and step wavelength measurements, using three different methods, were generated using these longitudinal points of the step crest and pool. Through the use of the Foresight software, and the proper placement of points during surveying, I was able to obtain measurements from all three different measurement methods. This can be done in the surveying software by collecting measurements from one point to another. Once the points have been selected the software produces measurements for the space between those points. The primary measurements included horizontal distance, slope distance, and elevation change (Figure 4.9).

Reach and Watershed Analysis. Few studies have looked at step-pool morphology that involved channel types which did not include alluvium substrates (Duckson and Duckson, 2001). Therefore this study has used a stratified mean for analysis which is based on the categories of alluvial, colluvial, and bedrock. Within each reach the steps were delineated based on these categories. Cataloguing each step type allowed for analysis based on one channel type (Appendix A).

Sub-reach variation found within individual reaches can be eliminated by removing certain step types from the reach data. This study removed the bedrock and colluvial channel types from all reach data sets in order to analyze the alluvial steps which were measured. This was done in order to achieve a better understanding of the size of the sediment in relationship to step height and wavelength.

Data from the Bowers Hollow watershed was analyzed using Microsoft Excel software and GS+ statistical software. Simple linear regression statistics, coefficients of

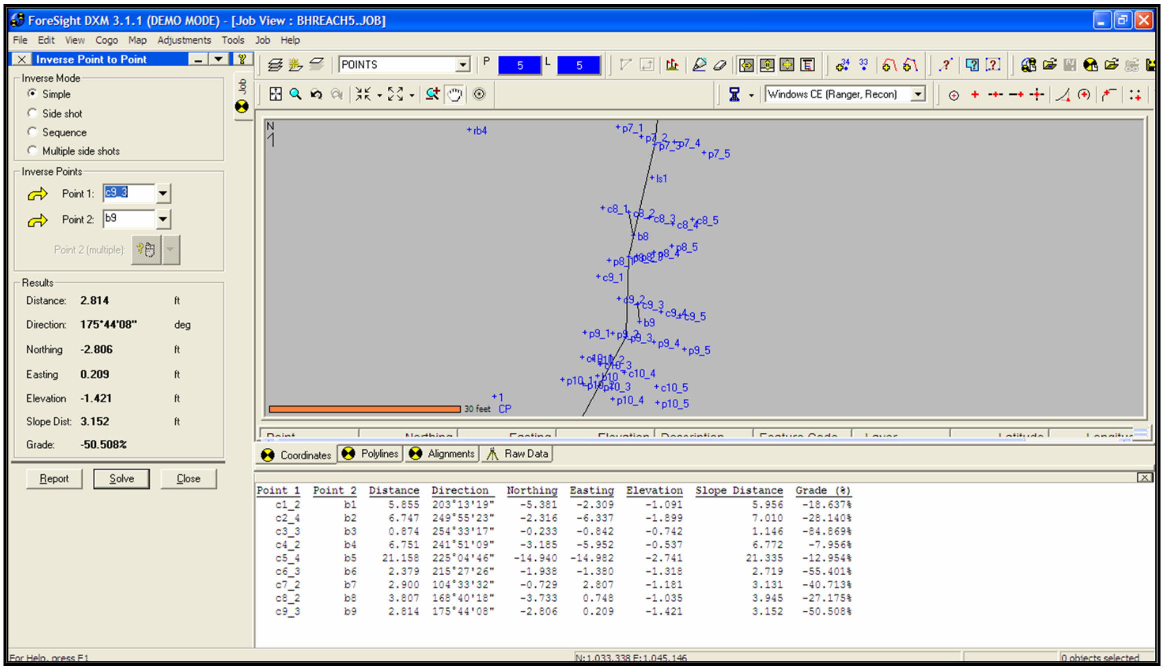

Figure 4.9 Focused view measurements in TDS Foresight DMX software derived from reach 2 survey points

determination and coefficients of variation, could be achieved through Excel. This software could also produce graphs, plots, and longitudinal profiles for visual interpretation of relationships. GS+ helped in the visualization of individual reach surveys through the creating of interpolated surfaces and contour models (Appendix C).

CHAPTER 5

RESULTS AND DISCUSSION

Channel and Sediment Data

The mean slope of the sample reaches is 0.105 (m/m) with a range from 0.046 (m/m) to 0.302 (m/m) (Table 2). Reach 7, with the maximum slope of 0.302 (m/m) is interesting because of its mid-basin location within the drainage network. This reach is located on the bluff wall of the main stem valley and is influenced by the deposition of large colluvial blocks supplied by the retreat of the sandstone scarp. The active width of all the sample reaches averaged 6.1 meters, ranging from 1.2 meters to 11.4 meters (Figure 5.1). For the most part, the width increases as the drainage area increases. The mean particle size of all the reaches was 440 mm, with a minimum of 171 mm and a maximum of 679 mm (Figure 5.2). The largest step forming clasts were found at reach 8

Table 2: Reach characteristics

Reach ID	Drainage Area (km^2)	Length (m)	Slope (m/m)	Active Width (m)*	Particle Size (mm)*
1	0.05	45	0.060	1.17	171
2	0.25	49	0.109	3.14	410
3	0.45	44	0.136	4.56	554
4	0.07	54	0.148	3.40	463
5	0.49	102	0.063	5.56	562
6	0.19	49	0.093	3.54	389
7	0.28	65	0.302	7.33	427
8	2.24	164	0.095	11.35	679
9	2.79	95	0.057	8.25	423
10	3.16	91	0.046	9.27	370
11	3.41	112	0.048	9.55	387
All-Av	3.44	79	0.105	6.10	440

* Means of the reach

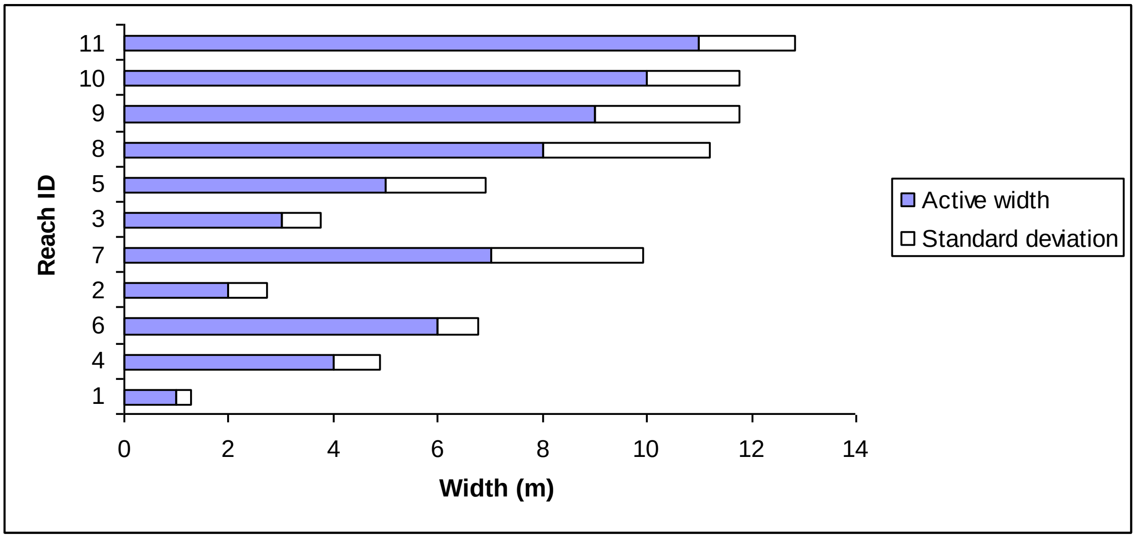

Figure 5.1 Mean active width and standard deviation for each sample reach (drainage area decreasing from top to bottom)

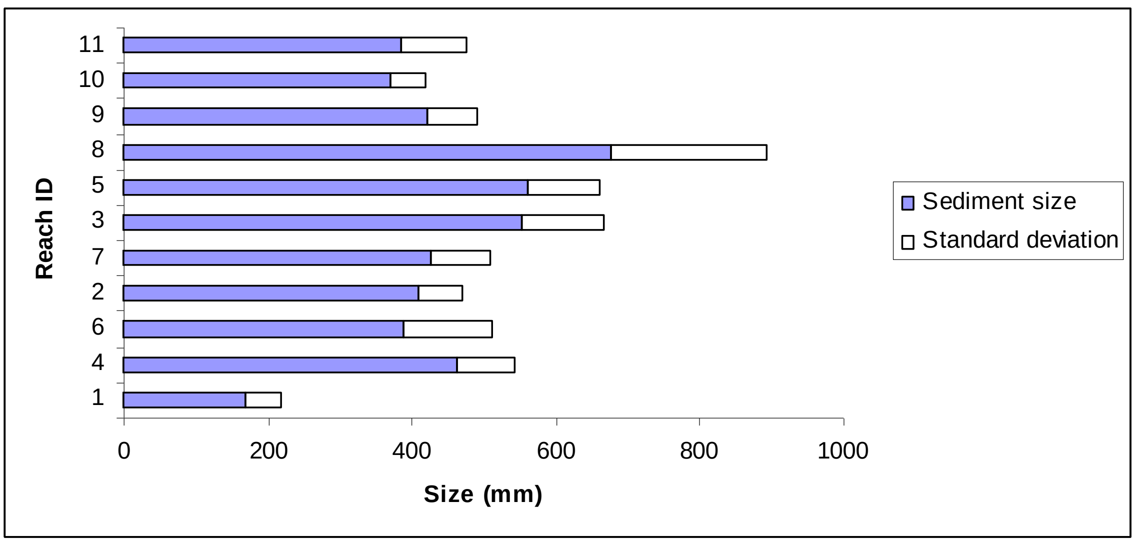

Figure 5.2 Mean sediment size and standard deviation for each sample reach (drainage area decreasing from top to bottom)

which had the largest step height and active width within this study (Table 2). Upstream and downstream portions of the reach were influenced by slab failure of sandstone strata overlaying erodible shale units. The channel flows over large colluvial blocks which form atypically large steps. Steps had formed in the less steep middle third of the profile using keystones, larger-sized clasts to which smaller clasts interlock with to create channel wide accumulations (Chin, 1999).

Analysis of the relationship between sediment size and step height and length produced surprising results. Both average step height (r^2=0.14) and wavelength (r^2=0.25) correlated poorly to the average of the five largest particles found in the steps which were surveyed (Figures 5.3 and 5.4). Logically, step particle size should correlate with step height since it is these particles which form the step (Chin, 2005). One reason for this poor correlation between step height and particle size may be the instructions given to field workers for measuring the size of the five largest particles. Field workers were instructed not to measure bedrock outcroppings or large colluvial blocks. This could attribute to the poor correlation since these bedrock outcroppings and large colluvial blocks controlled the step height at these locations. The poor relationship between wavelength and sediment size has also been found by other workers (Wohl and Grodek, 1994). This lack of correlation could be attributed to imperfect morphological adjustments in step-pool sequences, channel variables being inconsistent within the watershed, and sample size (Chin, 2005). Therefore a stratified analysis of sediment correlations and relationships of strictly alluvial step-pool sequences is discussed further in this paper.

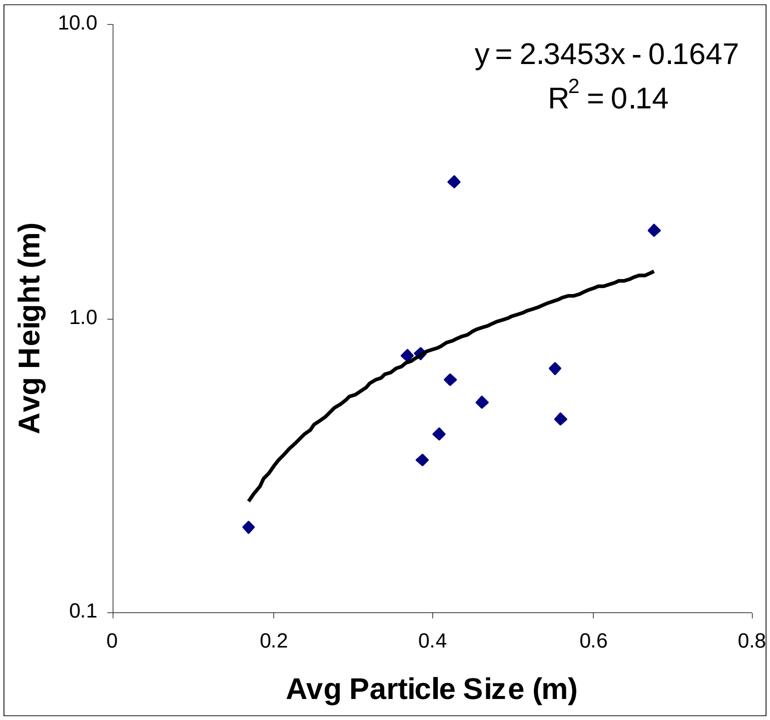

Figure 5.3 Average step height to average particle size (logged axis)

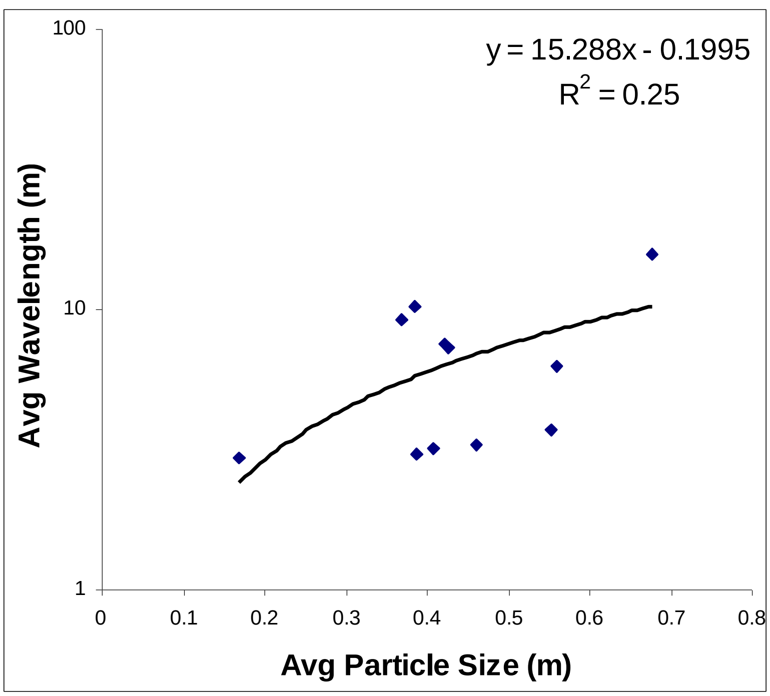

Figure 5.4 Average step wavelength to average particle size (logged axis)

By observing the change in channel characteristics above and below the dominating sandstone bluffline, three groupings of reaches can be established (Figure 4.3). In the first group, reaches 1 through 6 are all located above the bluff line in alluvium-dominated channels with the occasional bedrock outcropping where typically steps have heights with low magnitude and similar lengths (Figure 5.5). The step-pool sequences found in reach 4 show the best uniformity of sequences within the study (Appendix B). Two groups of sequences show very similar uniformity before and after a bedrock-controlled feature. Further studies of these channels could show how quickly step-pool sequences can recovery to a quasi-equilibrium state of uniformity below abrupt changes in resistance or sediment supply.

In the second group, reaches 7 and 8 are located immediately below the retreating caprock sandstone. These channels are dominated by the accumulation large colluvial blocks with exposed strata of shale being present. Both of these reaches are the first surveyed reach below the waterfalls associated with the bluff, reach 7 on the tributary and reach 8 on the main stem. The steepest reach (7) studied provided a longitudinal profile with large drops and fairly shallow pools (Figure 5.5 and Appendix B). This is indicative of a reach which was dominated with large "car and bus" size colluvial blocks.

In the third group, reaches 9 and 10 are located on the main stem downstream of the bluff line in mixed, colluvial and alluvial, bedrock-controlled channels. The less steep, alluvium-dominated reaches 9, 10, and 11 exhibited much larger wavelength and deeper pools in comparison to the step heights. Reach 11 is unique in that it is located where Bowers Hollow Creek plunges into the floodplain of the Buffalo River. Reach 11 presented an interesting profile as it flowed from the last steep section of the channel onto

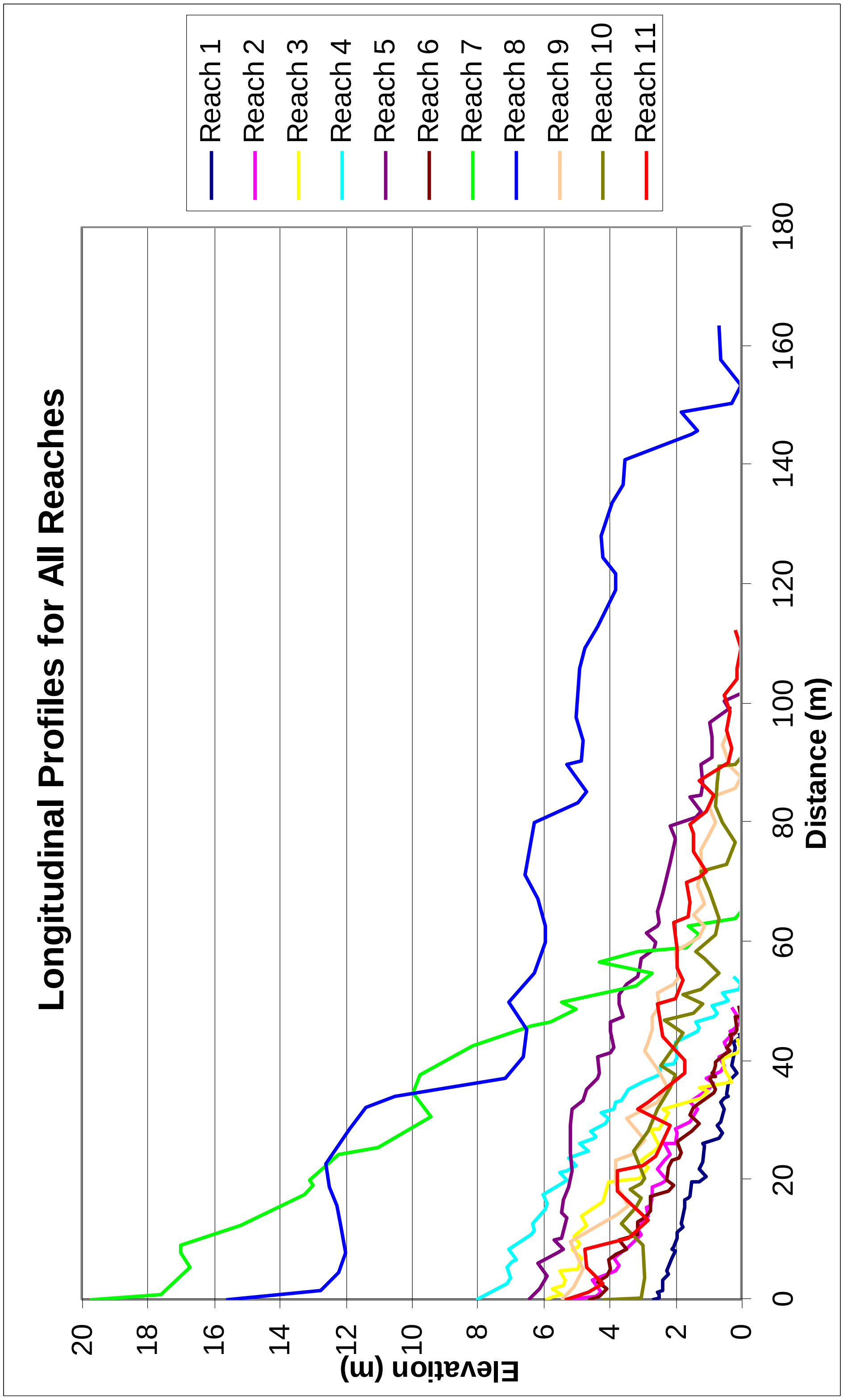

Figure 5.5 Longitudinal profiles for all reaches

the floodplain of the Buffalo River (Figure 5.5 and Appendix B). The first third of the profile is fairly steep with larger sequences as the channel reaches the edge of the floodplain. As the channel enters the floodplain the slope lessens and the sequences are reduced in size. The slope is minimal in the last portion of the profile as the channel is fully on the floodplain. Step-pool features consistently occur throughout the reach, however adjusting to decreasing slope due to base level control.

Geomorphic Relationships

Step wavelength correlations with reach variables presented mixed relationships (Figure 5.6). The best wavelength correlation was with width (r^2=0.87). Other studies have shown similar strong correlations and have used a wavelength/width ratio in their analysis. The wavelength is approximately 1.1 channels widths in Bowers Hollow Creek. This is smaller than most of the other studies: Chartrand and Whiting (2000) had a value of 0.6 to 1, Bowman (1977) had a value of 1.4, Chin (1989) had a value of 1.9, and Whittaker (1987) had a value of 2.7. The next best correlation was between wavelength and drainage area (Figure 5.6-c). The modest correlation (r^2=0.53) could be skewed by the two clusters of data points at either end of the trendline. This gap in sampled drainage areas between 0.49 km^2 and 2.24 km^2 is related to the lack of step-pool channel due to the waterfall on the main stem and the lower gradient, exposed bedrock and plane bed dominated sections both upstream and downstream of this break in the channel slope and bedrock-control. The correlation with particle size produced a weak relationship (r^2=0.25). There was no relationship between wavelength and slope (r^2=0.01).

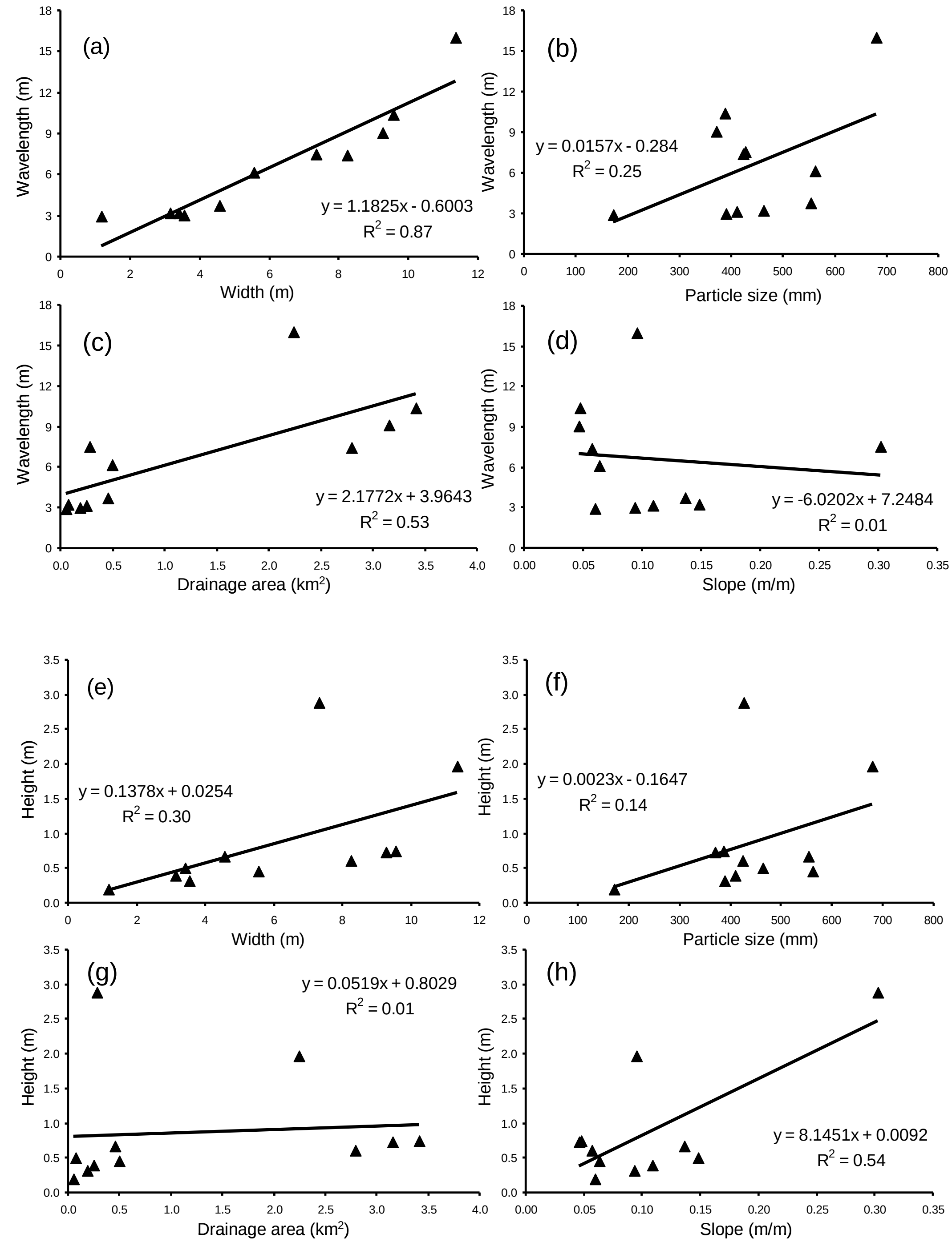

Figure 5.6 Geomorphic relationships between (a) wavelength and width, (b) wavelength and particle size, (c) wavelength and drainage area, (d) wavelength and slope, (e) height and width, (f) height and particle size, (g) height and drainage area, and (h) height and slope.

Height correlations with reach variables (Figure 5.6) were not as strong as the wavelength correlations. The best height correlation was with slope (r^2=0.54). This result goes counter to the findings of Chartrand and Whiting (2000) and Grant et al. (1990), yet is in agreement with Chin (1999) and Wohl and Grodek (1994). Correlations with width (r^2=0.30) and particle size (r^2=0.14) exhibited weak relationships. There was no relationship between step height and drainage area (r^2=0.01).

Sub-Reach Substrate Stratification

Within the individual reaches were varying types of channels. Sub-reaches with bedrock and colluvial channel steps found within a reach were removed from the dataset in order to observe the characteristics of alluvial steps (Table 3). Alluvial steps dominate the dataset from Bowers Hollow watershed. There were 12 bedrock steps and 28 colluvial steps removed from the dataset, which left 90 alluvial steps to be analyzed.

Table 3: Reach characteristics for alluvial step-pool sequences

	Crest Attributes		Mean of All Methods		
Reach	Active Width (m)	D_{90} (m)	Height (m)	Wavelength (m)	H/L
1	1.17	0.17	0.19	2.88	0.07
2	2.85	0.39	0.26	2.78	0.10
3	4.05	0.59	0.37	2.77	0.15
4	3.27	0.46	0.46	2.55	0.18
5	5.59	0.57	0.40	4.53	0.10
6	3.54	0.39	0.32	2.95	0.11
7					
8	10.95	0.71	0.89	11.99	0.09
9	9.22	0.41	0.49	6.28	0.08
10	9.99	0.38	0.63	7.02	0.11
11	8.90	0.35	0.50	9.28	0.06
All-Av	5.95	0.44	0.45	5.30	0.10

The remaining alluvial steps were averaged within their respectful reaches. Many of the reaches were transformed after the stratification. Reach 7 was completely eliminated since it contained only bedrock and colluvial steps and reach 8 was reduced to 3 step-pool sequences (Table 3). Reaches 1 and 6 remained unaffected by the stratification procedure.

When the larger step-pool sequences were removed from the dataset the average for all the reaches in the watershed decreased in active width, step height, and wavelength (Table 3). The stratified mean method also produced a lower mean step steepness (H/L) of 0.10, compared to 0.13 for the entire dataset. The mean reach step length to height ratio for the reduced dataset was 11.5:1, compared to 9:1 for the entire dataset.

The particle size remained the same from the original dataset to the stratified dataset. However, the correlation between sediment size and step height improved in the stratified dataset (r^2 from 0.14 to 0.40) and the correlation between sediment size and step wavelength became poorer (r^2 from 0.25 to 0.14) (Figure 5.7 and 5.8). The improvement in the relationship between sediment size and step height confirms the notion aforementioned which concerns the measurement methods used for measuring the particle size of steps.

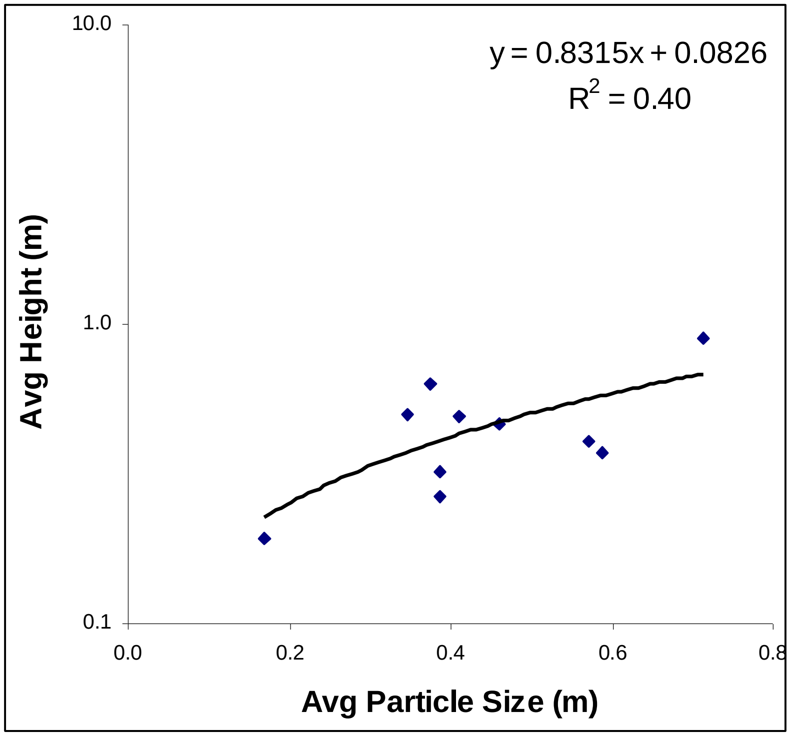

Figure 5.7 Average height to average particle size for alluvial steps (logged axis)

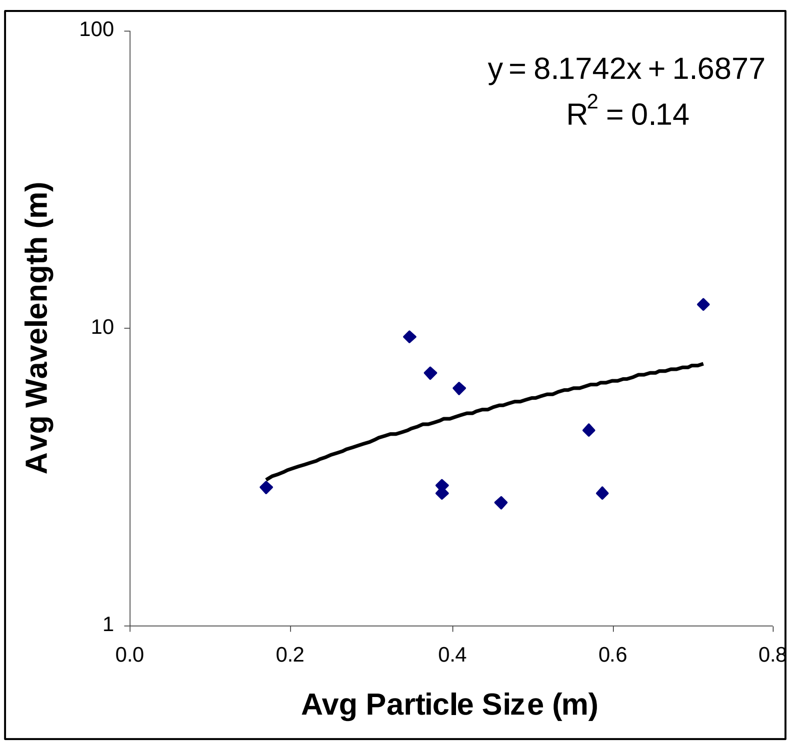

Figure 5.8 Average wavelength to average particle size for alluvial steps (logged axis)

Height/Length Analysis

Regional Comparisons. The mean step steepness for the study area was 0.13, ranging from 0.07 at reaches 1, 5, and 11 to 0.39 at reach 7. The three different methods of calculating step steepness all show excellent correlations between H/L and slope (r^2=0.99 to 0.95) for Bowers Hollow Creek (Figure 5.9). The other regions displayed poorer correlations between step steepness and slope, Idaho streams had an r^2 of 0.13 (Chartrand and Whiting, 2000), Cold Creek and Big Sycamore Creek in California had an average r^2 of 0.53 (Chin, 1999), and Shatford Creek in British Columbia had an r^2 of 0.76 (Zimmermann and Church, 2001). Data points from Bowers Hollow Creek plot lower than the points from the other regions, yet the slopes of the trendlines are all fairly similar. The best fit for the Bowers Hollow Creek data comes from the British Columbia data set.

The mean reach step length to height ratio for the Bowers Hollow Creek study area was 9:1 with the maximum ratio being 15:1 and the minimum ratio being 2:1 (reach 7). This compares well with data presented by other workers for various regions: British Columbia, 5:1 to 9:1 (Wooldridge and Hickin, 2002); Idaho, 8:1 (Chartrand and Whiting, 2000); British Columbia, 8:1 (Zimmermann and Church, 2001); and California, 10:1 (Chin, 1999).

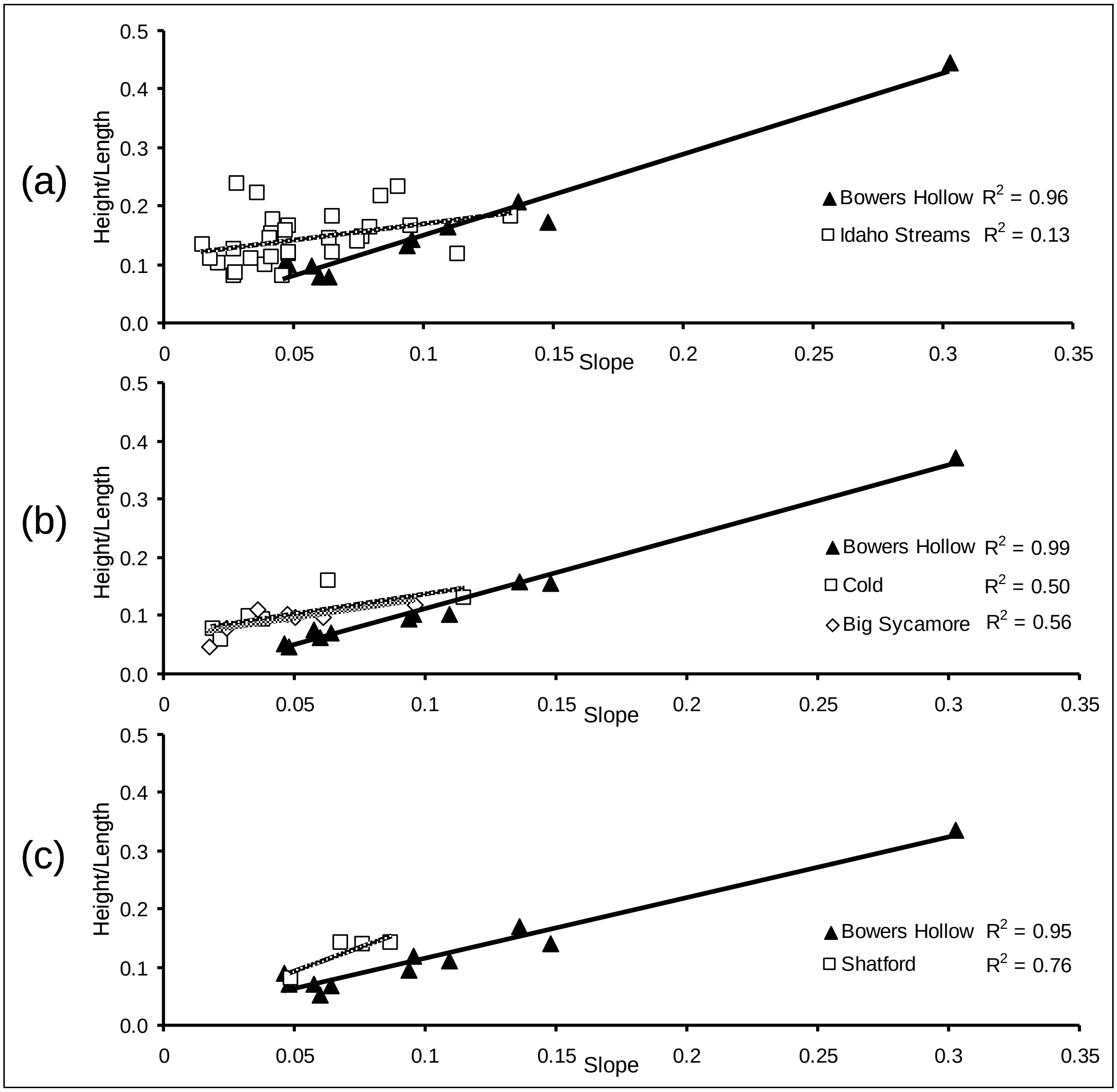

Figure 5.9 Variation of H/L with reach slope, Bowers Hollow Creek compared to (a) Idaho streams from Chartrand and Whiting (2000), (b) Cold Creek and Big Sycamore Creek in California from Chin (1999), and (c) Shatford Creek in British Columbia from Zimmermann and Church (2001)

Variability in the Measurement Methods. Variability in the values of channel variables is evident among the three different step steepness measurement methods available in the literature (Chatrand and Whiting, 2000, Chin, 1999 and Zimmermann and Church, 2001) (Table 4). This can be seen in the difference of coefficients of determination and relationships of the variables for the different methods used to measure step height and wavelength for Bowers Hollow Creek (Figure 5.10). Table 4 shows this variation in greater detail with the mean step height and wavelength values for each reach and measurement method used. The greatest disparity shown for height was in reach 7 with a difference between maximum and minimum values being 0.63 meters. The greatest disparity shown for wavelength was in reach 5 with a difference between maximum and minimum values of the different measurement methods being 1.23 meters.

Table 4: Measurements for step height and wavelength by different methods (means)

	Chartrand and Whiting Method[a]		Chin Method[b]		Zimmermann and Church Method[c]		Mean of All Methods	
Reach ID	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)
1	0.24	2.91	0.19	3.00	0.15	2.92	0.19	2.94
2	0.52	3.16	0.33	3.17	0.36	3.19	0.40	3.17
3	0.76	3.67	0.62	3.86	0.64	3.73	0.67	3.75
4	0.57	3.24	0.50	3.17	0.47	3.29	0.51	3.23
5	0.50	6.26	0.42	5.86	0.44	6.33	0.45	6.15
6	0.40	3.01	0.29	3.03	0.29	3.03	0.33	3.02
7	3.26	7.28	2.79	7.49	2.63	7.84	2.89	7.54
8	2.26	15.59	1.75	16.71	1.89	15.76	1.97	16.02
9	0.73	7.44	0.57	7.44	0.54	7.46	0.62	7.45
10	0.90	9.06	0.49	9.11	0.82	9.08	0.74	9.08
11	1.01	10.10	0.52	10.94	0.73	10.15	0.75	10.40
All-Av	1.01	6.52	0.77	6.71	0.81	6.62	0.87	6.62

[a]Measurement methods after Chartrand and Whiting (2000)
[b]Measurement methods after Chin (1999)
[c]Measurement methods after Zimmermann and Church (2001)

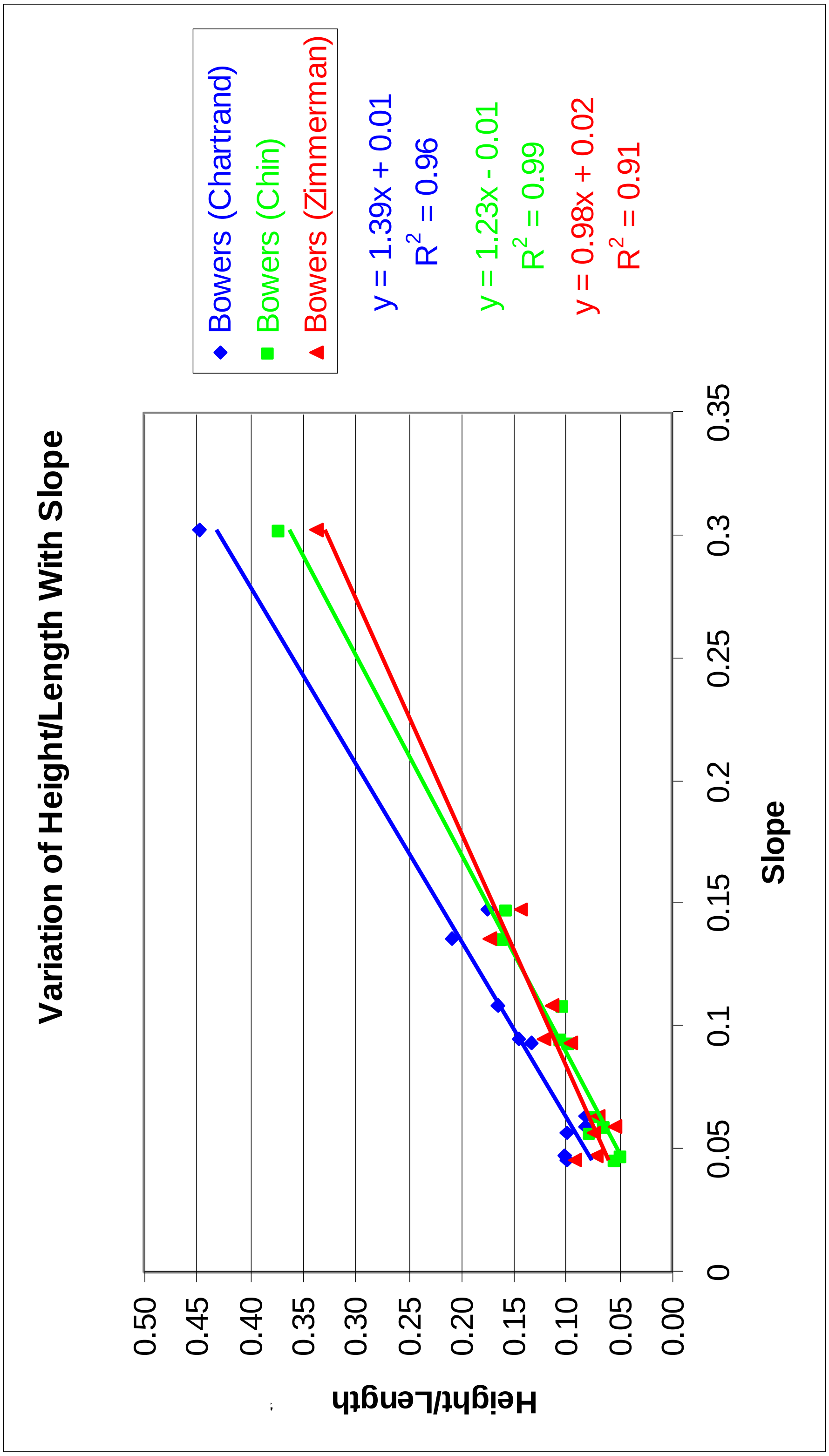

Figure 5.10 Variation of height/length with slope

Variability in the different methods is made apparent in Figure 5.11. The circled regions represent one reach location plotted using each of the three methods. The three individual data points within the circles show the reach-scale variability of the use of different measurement methods. As the wavelength increases, so does the amount of disparity between the different method points: the absolute error increases with wavelength. This can be explained by the methods of that measurement. Both Chartrand and Whiting (2000) and Zimmermann and Church (2001) measure the wavelength using the identical points on the crest features. However, Chartrand and Whiting (2000) use the horizontal distance measurement (Figure 4.6-L^1) compared to the slope distance measurement (Figure 4.6-L^3) used by Zimmermann and Church (2001). Therefore when measuring the same bedform the mean wavelength is always slightly higher for the Zimmermann and Church measurements when compared to the Chartrand and Whiting measurement method, as seen in Table 4.

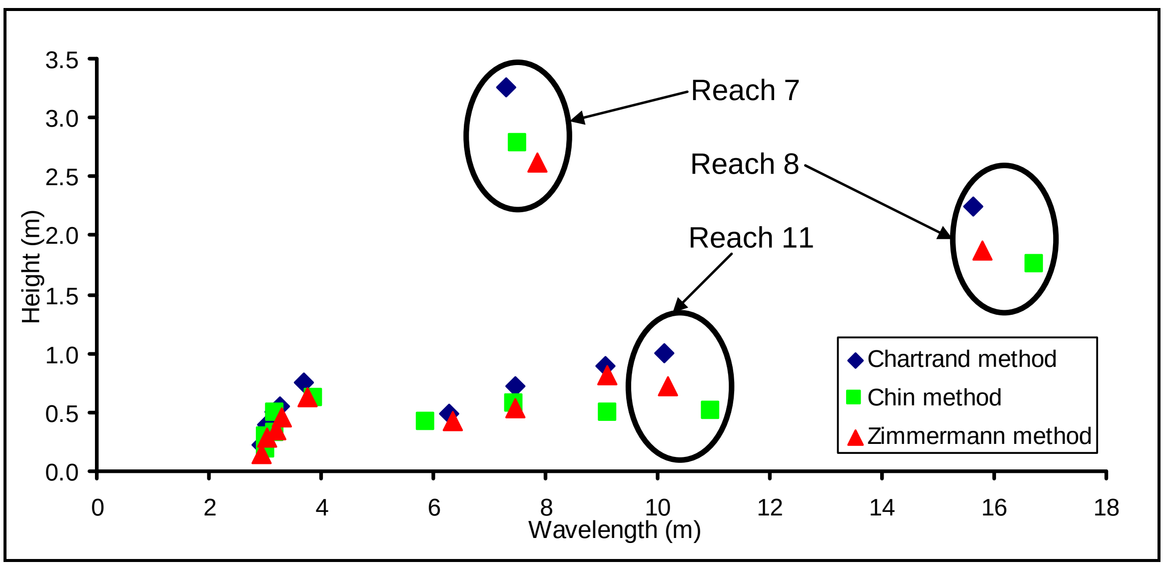

Figure 5.11 Height correlated to wavelength, circled regions represent reach mean of all three methods

An analysis of variance was done in order to examine the statistical differences between height and wavelength measurement methods. This was a model of all the sites combined. The ANOVA was done with the significance level set at 0.95. We can observe a p-value of 0.77 for the different height measurements and a p-value of 0.99 for the different wavelength measurements (Table 5). Therefore, there was no significant difference found between the three methods used to measure height. However, there is significant difference between the three measurements used for wavelength.

Variability can be seen again in the simple coefficient of determination matrixes found in Table 6. There is certain variation found within the relationships of height with wavelength, height with width, and wavelength with width. The greatest disparity between the methods in this analysis took place in the height with wavelength relationship. The difference between the maximum and minimum r^2 values for this relationship was 0.15.

Table 5: Analysis of variance tables

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.371006414	2	0.185503207	0.272681	0.763202	3.31583
Within Groups	20.40879533	30	0.680293178			
Total	20.77980174	32				

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.194805683	2	0.097402841	0.005766	0.994252	3.31583
Within Groups	506.8026052	30	16.89342017			
Total	506.9974109	32				

Table 6: Correlation matrixes

Coefficent of determination for Chartrand method			
	Wavelength	Height	Width
Wavelength	1.000	0.343	0.879
Height		1.000	0.329
Width			1.000
Coefficient of determination for Chin method			
	Wavelength	Height	Width
Wavelength	1.000	0.242	0.861
Height		1.000	0.221
Width			1.000
Coefficient of determination for Zimmermann method			
	Wavelength	Height	Width
Wavelength	1.000	0.395	0.879
Height		1.000	0.342
Width			1.000

Most of the variability shown in the different measurements methods can be attributed to the measurement of height (Table 7). This is different than what the ANOVA displayed because further variability analysis looked exclusively at data from individual sites. The average coefficient of variation (Cv%) for step height values from the three different methods is 18 % in comparison to the low 2.2 Cv% of wavelength measurements. This high Cv% is also carried over to the step steepness (H/L). Step steepness variability increases slightly to 19%. This increase in Cv% can be seen in all the reaches except reach 5, where the Cv% decreases from 9% to 8%. This slight decrease is likely due to rounding up in the data reduction and analysis. Nevertheless, average errors in step steepness can exceed 30% depending on the method of calculation used.

Table 7: Composite of step height and wavelength values from three methods

	Height (m)		Wavelength (m)		H/L (m/m)	
Reach ID	Mean	CV%	Mean	CV%	Mean	CV%
1	0.19	21	2.94	1.8	0.07	22
2	0.40	26	3.17	0.4	0.13	26
3	0.67	12	3.75	2.7	0.18	14
4	0.51	10	3.23	1.8	0.16	10
5	0.45	9	6.15	4.1	0.07	8
6	0.33	19	3.02	0.4	0.11	20
7	2.89	11	7.54	3.8	0.39	15
8	1.97	13	16.02	3.8	0.12	16
9	0.62	17	7.45	0.1	0.08	17
10	0.74	29	9.08	0.3	0.08	30
11	0.75	33	10.40	4.5	0.07	36
All-Av	0.87	18	6.62	2.2	0.13	19

CHAPTER 6

CONCLUSIONS

This study describes the step-pool characteristics of a very small watershed in the Boston Mountains of northwest Arkansas. Step-pool sequences show reach-scale variability which is affected by the geology of the area. In particular, a sandstone bluff line and large colluvial block accumulations found in the middle and lower portions of the watershed cause abrupt changes in the channel profile. Channel morphology is affected both upstream and downstream of the bluff line, below which forms a series of waterfall features.

The major conclusions of this study involve distribution of step-pool forms, morphological properties, empirical relationships, and analysis of different measurement methods.

(1) Step-pool forms occurred throughout the watershed. Colluvial blocks and bedrock were found at and below the predominate bluffline, as well as other smaller exposed strata of sandstone and shale. Therefore, sections of Bowers Hollow Creek which contained the necessary slope and were located below these exposed strata exhibited step-pool channel formations.

(2) The morphological properties of Bowers Hollow watershed (3.44 km^2) measured at the 11 reaches examined during this study were; average slope (0.105 m/m), average active width (6.10 m), average particle size (440 mm), average step height (0.87 m), and average step wavelength (6.62 m).

(3) The mean step steepness for the Bowers Hollow watershed was 0.13, ranging from 0.07 to 0.39. The mean reach step length to height ratio for the study area was 9:1, ranging from 2:1 to 15:1. The stratified mean method containing only alluvial step-pool sequences produced a lower mean step steepness (H/L) of 0.10. The mean reach step length to height ratio for the reduced dataset was 11.5:1. All of these relationships compare well with findings from recent studies. The best fit for the Bowers Hollow Creek data comes from the British Columbia data set (Zimmermann and Church, 2001).

(4) The variability found in the measurement methods used for step height averaged 18 Cv%, ranging from 9% to 33%. The variability found in the measurement methods used for step wavelength averaged 2.2 Cv%, ranging from 0.1% to 4.5%. Therefore most of the variability is attributed to the difference in the methods used to measure the variable of step height.

The characteristics of step-pool sequences, step steepness, and length/height ratio in the Bowers Hollow watershed were found to be similar to those found in other regions throughout North America. This study also found variability among the three different measurement methods used by Chin (1999) in California, Chartrand and Whiting (2000) in Idaho, and Zimmermann and Church (2001) in British Columbia. The Cv% for step height was much larger than that for wavelength suggesting that efforts to standardize step height measurements would be beneficial. This study shows that errors of more than 30% can occur due to the step steepness measure used, thus making comparisons among different studies problematic. Finally, there were differences observed in step-pool

characteristics between the entire dataset and the stratified dataset containing strictly alluvial channel type step-pool sequences.

Future research is needed on the interaction of sediment size and distribution of colluvial block accumulations with step-pool forms and channel evolution in the Boston Mountains. Areas within the field of step-pool morphology which need to be studied more include the formation of step-pool sequences and the influence of waterfalls and bluff lines on the morphology of the stream. Development of a standard measurement method for step height and length and the formation of a global step-pool datatset which has been calibrated to understand the variations in different measurement methods for step height and step wavelength would be useful for comparative analysis.

The formation of step-pool forms has been studied using laboratory methods and flume experiments, yet there is little known about how they form naturally. This is due to step-pool morphology being located in remote, rugged terrain, as well as steps forming during low frequency storm events. It is extremely difficult to catch one of these step-forming events in the field and there are many logistics and safety issues associated with swollen streams. Methods should evolve to encompass the study of these events in a natural environment.

There is little known about waterfalls and their related bluff lines as they influence channel morphology. There are influences and ramifications associated with these features which need to be studied and quantified. These affects are apparent both upstream and downstream of the bluffline. The equilibrium of the stream and the recovery rate (or distance) before the stream retains equilibrium are aspects of the

channel which need to be understood in order to fully explain the evolution of step-pool bedforms.

A standard measurement method for step height and length would assist in developing a global dataset of step-pool characteristics. This standard method and global dataset would be helpful in creating a model for step-pool morphology characteristics in a variety of environments. The dataset would have to be calibrated to even out the variations in measurement methods used by various workers. This dataset could also be organized in a manner to better explain step-pool characteristics in various lithologies. Through an organized modeling of a global step-pool dataset, one could better predict step heights and wavelengths for a variety of restoration and engineering purposes.

Figure 6.1 Sign on road to access point for the Upper Buffalo Wilderness Area

As development continues to encroach into more mountainous areas, we should examine what is known concerning the impacts on streams from this encroachment on the environment. This knowledge concerns the understanding of the equilibrium associated with step-pool mountain streams, as well as comprehending the complex and dynamic forms of step-pool sequences. The value of step-pools morphology has recently been applied to stream restoration projects involving check dams and fish ladders. However their full potential has yet to be realized in the self-sustaining stream design and management. With understanding based on field work and scientific analysis we can efficiently manage mountainous areas for anthropomorphic purposes and for the wellbeing of the stream.

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APPENDIX A

RAW DATA

Individual Feature Measurements for Step Height and Wavelength

	Chartrand and Whiting Method[a]		Chin Method[b]		Zimmermann and Church Method[c]		Mean of All Methods	
Crest ID	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)
1c1	0.2009	1.3112	0.1143	1.6971	0.1783	1.3183	0.1645	1.4422
1c2	0.1795	2.0861	0.1408	1.3411	0.1585	2.0958	0.1596	1.8410
1c3	0.1183	1.5392	0.2408	3.8173	0.0850	1.5414	0.1480	2.2993
1c4	0.2780	3.4092	0.0747	2.2266	0.1905	3.4141	0.1811	3.0166
1c5	0.1704	2.5173	0.1387	1.5539	0.0622	2.5237	0.1237	2.1983
1c6	0.1295	5.4294	0.2082	5.1929	0.0561	5.4334	0.1313	5.3519
1c7	0.1295	2.9063	0.5258	3.3421	0.0927	2.9127	0.2493	3.0537
1c8	0.4606	2.2049	0.0539	4.9204	0.2390	2.2177	0.2512	3.1143
1c9	0.1679	4.0971	0.5624	2.0970	0.1167	4.0990	0.2823	3.4310
1c10	0.6087	3.0358	0.0223	4.0374	0.4532	3.0629	0.3614	3.3787
1c11	0.2249	3.9688	0.1262	1.9132	0.1259	3.9700	0.1590	3.2840
1c12	0.2466	2.9160	0.2704	3.9587	0.1494	2.9252	0.2221	3.2666
1c13	0.2868	3.0373	0.0576	4.0767	0.1359	3.0398	0.1601	3.3846
1c14	0.1094	3.4936	0.1640	1.8934	0.0701	3.4939	0.1145	2.9603
1c15	0.2243	1.7209	0.0000	0.0000	0.1875	1.7291	0.1373	1.1500
1Average	0.2357	2.9116	0.1929	3.0048	0.1534	2.9185	0.1940	2.9450
2c1	1.1000	3.3915	0.5730	4.0133	0.9333	3.4936	0.8688	3.6328
2c2	0.8342	2.2964	0.6410	4.4498	0.6995	2.3890	0.7249	3.0451
2c3	0.8166	4.8987	0.2460	1.9257	0.4578	4.9512	0.5068	3.9252
2c4	0.3447	2.1113	0.0945	3.3187	0.1423	2.1266	0.1939	2.5189
2c5	0.1865	3.2059	0.4368	2.7188	0.1356	3.2123	0.2530	3.0457
2c6	0.4234	2.9742	0.1058	3.6460	0.2438	2.9785	0.2577	3.1996
2c7	0.3694	3.8859	0.2365	3.7908	0.2280	3.8923	0.2780	3.8563
2c8	0.3825	2.5338	0.5688	3.9145	0.2902	2.5521	0.4138	3.0001
2c9	0.6456	4.5470	0.5054	3.9679	0.4545	4.5711	0.5351	4.3620
2c10	0.6806	3.5857	0.3539	3.1117	0.5221	3.6140	0.5189	3.4371
2c11	0.5825	3.7634	0.1146	1.8529	0.4337	3.7847	0.3769	3.1336
2c12	0.2963	1.8184	0.1231	2.4893	0.1439	1.8239	0.1878	2.0439
2c13	0.2798	1.6374	0.2393	2.0513	0.1841	1.6474	0.2344	1.7787
2c14	0.3377	3.6113	0.0000	0.0000	0.1390	3.6125	0.1589	2.4079
2Average	0.5200	3.1615	0.3260	3.1731	0.3577	3.1892	0.4012	3.1746
3c1	0.5392	1.5834	0.0597	1.9772	0.2719	1.6051	0.2903	1.7219
3c2	0.3362	3.0346	0.5459	3.6981	0.2886	3.0425	0.3902	3.2584
3c3	0.6614	2.6612	0.0628	2.0169	0.5435	2.6862	0.4226	2.4548
3c4	0.2320	5.3425	2.0507	9.0020	0.1658	5.3480	0.8162	6.5642
3c5	2.0358	8.0449	0.3688	3.6670	1.8001	8.2528	1.4016	6.6549
3c6	0.5648	4.3660	0.2615	5.1664	0.4054	4.3733	0.4106	4.6352
3c7	0.5742	2.6923	1.2098	3.2796	0.3021	2.7206	0.6954	2.8975
3c8	1.3920	2.9273	0.4633	3.4863	1.1689	3.1364	1.0081	3.1833
3c9	0.7291	3.3558	0.5176	2.4890	0.9757	3.4247	0.7408	3.0899
3c10	0.5633	2.6700	0.0000	0.0000	0.4566	2.7063	0.3400	1.7921
3Average	0.7628	3.6678	0.6156	3.8647	0.6379	3.7296	0.6721	3.7540
4c1	1.0598	5.1014	0.1448	2.9495	0.9162	5.1859	0.7069	4.4123
4c2	0.2728	2.3083	0.5432	4.0919	0.1530	2.3092	0.3230	2.9031
4c3	0.7273	3.4378	0.3871	4.2693	0.6233	3.5043	0.5792	3.7372
4c4	0.4353	5.0630	0.5944	3.6692	0.3734	5.0743	0.4677	4.6022
4c5	0.6888	3.3196	0.2746	2.7063	0.5663	3.3558	0.5099	3.1272

[a]Measurement methods after Chartrand and Whiting (2000)

[b]Measurement methods after Chin (1999)

[c]Measurement methods after Zimmermann and Church (2001)

Individual Feature Measurements for Step Height and Wavelength (continued)

	Chartrand and Whiting Method[a]		Chin Method[b]		Zimmermann and Church Method[c]		Mean of All Methods	
Crest ID	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)
4c6	0.4700	2.3549	0.3889	2.2004	0.2411	2.3689	0.3667	2.3080
4c7	0.6029	1.9471	0.2551	2.0208	0.4423	1.9745	0.4334	1.9808
4c8	0.5297	1.8532	0.3606	1.6938	0.4767	1.8879	0.4557	1.8116
4c9	0.5297	2.4759	0.2073	2.8069	0.4462	2.4945	0.3944	2.5924
4c10	0.4349	7.0714	1.8767	6.8888	0.3859	7.3061	0.8992	7.0887
4c11	0.4746	3.7234	0.6800	4.3083	0.3676	3.7469	0.5074	3.9262
4c12	0.7379	2.9471	0.5215	2.2607	0.6544	3.0160	0.6379	2.7413
4c13	0.6197	2.4091	0.3542	2.0781	0.5221	2.4561	0.4987	2.3144
4c14	0.4959	1.7907	0.3816	2.4421	0.3795	1.8212	0.4190	2.0180
4c15	0.4060	2.8115	0.0000	0.0000	0.5044	2.8319	0.3035	1.8811
4Average	0.5657	3.2410	0.4978	3.1704	0.4702	3.2889	0.5112	3.2334
5c1	0.5636	5.9442	0.4819	3.9795	0.3325	5.9521	0.4593	5.2919
5c2	0.7333	3.5698	0.1030	5.1770	0.5788	3.6018	0.4717	4.1162
5c3	0.3554	6.6099	0.1759	7.2692	0.2262	6.6151	0.2525	6.8314
5c4	0.2688	7.9449	0.8513	10.4687	0.1637	8.5944	0.4279	9.0027
5c5	0.8995	9.2836	0.4328	4.1438	0.8355	9.3196	0.7226	7.5823
5c6	0.5136	5.8122	0.1338	6.2600	0.4017	5.8275	0.3497	5.9666
5c7	0.2295	5.3660	0.6504	5.5346	0.3600	3.5908	0.4133	4.8305
5c8	0.4157	4.1956	0.4883	3.8627	0.3155	4.2172	0.4065	4.0918
5c9	0.4770	3.5406	0.1113	2.6828	0.4237	3.5448	0.3373	3.2561
5c10	0.4161	16.2455	1.2299	17.1410	0.3206	18.2455	0.6555	17.2107
5c11	0.9211	4.9009	0.0762	4.2227	0.7971	4.9353	0.5981	4.6863
5c12	0.4148	5.4175	0.2490	6.3462	0.3798	5.4303	0.3479	5.7314
5c13	0.2905	5.2508	0.5127	2.7526	0.3231	5.2575	0.3754	4.4203
5c14	0.5389	3.4967	0.3868	2.1641	0.6011	3.5250	0.5089	3.0619
5c15	0.4804	0.0000	0.0000	0.0000	0.4804	6.3326	0.3202	2.1109
5Average	0.5012	6.2556	0.4202	5.8575	0.4360	6.3326	0.4525	6.1486
6c1	0.5261	2.8435	0.0978	2.7950	0.3149	2.8560	0.3129	2.8315
6c2	0.3560	3.0706	0.5166	2.4881	0.2825	3.0870	0.3851	2.8819
6c3	0.5557	2.3915	0.3338	3.6101	0.2502	2.4171	0.3799	2.8062
6c4	0.5380	2.9398	0.3621	2.3119	0.5377	2.9846	0.4792	2.7454
6c5	0.3844	4.2068	0.7361	3.9642	0.2237	4.2276	0.4481	4.1329
6c6	0.7047	5.4898	0.2054	5.3584	0.5331	5.5912	0.4811	5.4798
6c7	0.2883	3.0123	0.5541	4.6452	0.2301	3.0166	0.3575	3.5580
6c8	0.6812	5.2865	0.4944	5.7101	0.4572	5.3096	0.5443	5.4354
6c9	0.6815	4.7537	0.0034	2.2823	0.6160	4.7811	0.4336	3.9390
6c10	0.1649	0.8355	0.0351	1.5545	0.0866	0.8391	0.0955	1.0764
6c11	0.1210	2.0202	0.3962	2.2394	0.0527	2.0217	0.1900	2.0938
6c12	0.4386	1.9391	0.0533	1.6801	0.3139	1.9681	0.2686	1.8624
6c13	0.1554	1.6100	0.1807	1.3999	0.0911	1.6136	0.1424	1.5412
6c14	0.2243	2.7722	0.1119	2.3153	0.1865	2.7779	0.1742	2.6218
6c15	0.1548	1.9093	0.0000	0.0000	0.1548	1.9108	0.1032	1.2734
6Average	0.3983	3.0054	0.2915	3.0253	0.2887	3.0268	0.3262	3.0192
7c1	2.9980	7.9586	3.7749	11.5345	2.1488	8.4192	2.9739	9.3041
7c2	4.0267	9.0050	3.5564	4.2672	3.7405	9.8091	3.7745	7.6938
7c3	3.6936	10.2379	4.3696	14.3960	2.0885	10.7695	3.3839	11.8011
7c4	4.7214	10.3534	2.3497	6.0344	3.9993	11.2209	3.6901	9.2029

[a]Measurement methods after Chartrand and Whiting (2000)

[b]Measurement methods after Chin (1999)

[c]Measurement methods after Zimmermann and Church (2001)

Individual Feature Measurements for Step Height and Wavelength (continued)

	Chartrand and Whiting Method[a]		Chin Method[b]		Zimmermann and Church Method[c]		Mean of All Methods	
Crest ID	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)	Height (m)	Wavelength (m)
7c5	2.7453	5.8866	1.4182	4.9402	2.2357	5.9924	2.1331	5.6064
7c6	3.0437	5.1679	1.2576	3.7969	2.6441	5.8375	2.3152	4.9341
7c7	1.5868	2.3793	0.0000	0.0000	1.5868	2.8596	1.0579	1.7463
7Average	3.2594	7.2841	2.7878	7.4949	2.6348	7.8440	2.8940	7.5410
8c1	3.6265	20.4673	5.5068	29.6427	2.8831	20.6862	4.0055	23.5987
8c2	6.1326	20.7986	0.5200	14.0888	5.4873	21.5402	4.0466	18.8092
8c3	1.0500	20.8273	1.2908	18.8842	0.7379	20.8468	1.0263	20.1861
8c4	1.5725	4.7476	0.1417	8.2055	1.3064	4.8478	1.0069	5.9336
8c5	0.4502	6.9379	1.0193	15.6356	0.4176	6.9421	0.6290	9.8385
8c6	1.2314	29.2492	2.4725	23.2703	0.6724	29.2867	1.4588	27.2687
8c7	2.2238	7.4548	1.3155	7.2366	2.0800	7.6523	1.8731	7.4479
8c8	1.8120	14.2460	0.0000	0.0000	1.5319	14.2909	1.1147	9.5123
8Average	2.2624	15.5911	1.7524	16.7091	1.8896	15.7616	1.9681	16.0206
9c1	0.6453	9.4598	1.3771	10.5534	0.3691	9.4637	0.7972	9.8256
9c2	1.7441	13.1344	0.5157	10.6342	1.3902	13.2036	1.2167	12.3241
9c3	0.9114	6.9354	0.6306	8.4981	0.5319	6.9443	0.6913	7.4593
9c4	1.1942	10.4449	0.4225	7.8605	0.9007	10.4589	0.8391	9.5881
9c5	0.2268	4.3141	0.2362	3.9862	0.1344	4.3190	0.1991	4.2064
9c6	0.2576	4.1163	0.5547	4.7829	0.1990	4.1197	0.3371	4.3396
9c7	0.6480	6.3505	0.7806	8.3924	0.5194	6.3764	0.6493	7.0398
9c8	0.8544	5.9939	0.0375	3.4409	0.6974	6.0195	0.5297	5.1514
9c9	0.2633	7.2067	0.3981	9.1775	0.2890	7.2097	0.3168	7.8647
9c10	0.4526	5.8509	0.7513	7.0985	0.2371	5.8610	0.4804	6.2701
9c11	0.8614	8.0385	0.0000	0.0000	0.7044	8.0440	0.5219	5.3608
9Average	0.7326	7.4405	0.5704	7.4425	0.5430	7.4564	0.6153	7.4464
10c1	1.3064	12.6751	0.7379	12.6602	1.1829	12.6879	1.0757	12.6744
10c2	0.6069	5.2416	0.1049	2.6152	0.4252	5.2477	0.3790	4.3682
10c3	0.4584	6.2338	0.9345	16.7872	0.3539	6.2350	0.5823	9.7520
10c4	1.2689	13.2210	0.2344	6.9866	1.0826	13.2454	0.8620	11.1510
10c5	0.6986	5.7232	0.5706	3.2577	0.4377	5.7244	0.5690	4.9018
10c6	1.1494	3.5326	0.5270	4.8869	0.8812	3.5780	0.8525	3.9992
10c7	1.1073	6.0847	0.6425	8.9325	0.5410	6.0972	0.7636	7.0381
10c8	0.6824	12.1804	0.5328	11.7345	0.6181	12.1813	0.6111	12.0321
10c9	1.0641	16.6854	0.1490	14.1567	0.7669	16.6942	0.6600	15.8454
10c10	0.6639	0.0000	0.0000	0.0000	0.4993	0.0000	0.3877	0.0000
10Average	0.9006	9.0642	0.4926	9.1130	0.6789	9.0768	0.6907	9.0847
11c1	1.1790	6.4883	1.3615	10.0252	0.7099	6.8504	1.0835	7.7879
11c2	1.9218	12.0841	0.6654	15.1412	1.3137	12.1265	1.3003	13.1173
11c3	1.5743	9.6978	0.4599	6.6635	0.7282	9.7167	0.9208	8.6927
11c4	1.4268	15.0538	0.4090	15.0608	1.4268	15.0641	1.0875	15.0596
11c5	0.7644	13.1716	0.2652	12.8885	0.5529	13.1829	0.5275	13.0810
11c6	0.4871	6.1649	0.4694	4.9905	0.4179	6.1768	0.4581	5.7774
11c7	0.5767	9.3525	0.2399	10.6942	0.3658	9.3528	0.3941	9.7998
11c8	0.7282	5.4587	0.5465	7.0427	0.5215	5.4654	0.5987	5.9889
11c9	1.0007	13.5471	0.2630	15.9569	0.8711	13.5703	0.7116	14.3581
11c10	0.4730	10.0115	0.0000	0.0000	0.3795	10.0160	0.2842	6.6758
11Average	1.0132	10.1030	0.5200	10.9404	0.7287	10.1522	0.7540	10.3985

[a]Measurement methods after Chartrand and Whiting (2000)

[b]Measurement methods after Chin (1999)

[c]Measurement methods after Zimmermann and Church (2001)

Individual Feature Attributes

Crest ID	Crest Attributes			
	Substate Type	Active Width (m)	D_{90} (m)	H/L
1c1	Alluvial	0.8900	0.1440	0.1141
1c2	Alluvial	1.0244	0.1760	0.0867
1c3	Alluvial	1.2387	0.1220	0.0644
1c4	Alluvial	1.0400	0.1380	0.0600
1c5	Alluvial	0.9083	0.1580	0.0563
1c6	Alluvial	1.3003	0.1200	0.0245
1c7	Alluvial	1.1555	0.1340	0.0816
1c8	Alluvial	0.9769	0.1140	0.0806
1c9	Alluvial	1.6450	0.1460	0.0823
1c10	Alluvial	1.7666	0.2220	0.1070
1c11	Alluvial	0.9559	0.2220	0.0484
1c12	Alluvial	1.2485	0.2520	0.0680
1c13	Alluvial	0.9156	0.1860	0.0473
1c14	Alluvial	1.0317	0.2620	0.0387
1c15	Alluvial	1.4088	0.1710	0.1194
1Average	Alluvial	1.1671	0.1710	0.0659
2c1	Bedrock	5.1837	0.4640	0.2391
2c2	Colluvial	3.6320	0.4540	0.2381
2c3	Colluvial	3.7372	0.4420	0.1291
2c4	Alluvial	3.4519	0.4700	0.0770
2c5	Alluvial	2.2942	0.3980	0.0831
2c6	Alluvial	2.9020	0.3760	0.0805
2c7	Alluvial	2.9008	0.2860	0.0721
2c8	Alluvial	2.9185	0.3100	0.1379
2c9	Colluvial	2.8560	0.4620	0.1227
2c10	Colluvial	2.9282	0.4180	0.1510
2c11	Alluvial	3.1952	0.4040	0.1203
2c12	Alluvial	2.4101	0.4940	0.0919
2c13	Alluvial	2.5411	0.3700	0.1318
2c14	Alluvial	3.0142	0.3920	0.0660
2Average	Alluvial	3.1404	0.4100	0.1264
3c1	Alluvial	4.6628	0.4960	0.1686
3c2	Alluvial	3.6542	0.4580	0.1198
3c3	Alluvial	3.4135	0.5140	0.1721
3c4	Colluvial	4.5744	0.4580	0.1243
3c5	Colluvial	5.6303	0.4840	0.2106
3c6	Alluvial	4.1776	0.6740	0.0886
3c7	Colluvial	5.5681	0.5260	0.2400
3c8	Colluvial	4.3705	0.4940	0.3167
3c9	Colluvial	5.2246	0.6280	0.2397
3c10	Alluvial	4.3282	0.8060	0.1897
3Average	Colluvial	4.5604	0.5540	0.1790
4c1	Alluvial	2.5000	0.5520	0.1602
4c2	Alluvial	3.0288	0.3740	0.1113
4c3	Bedrock	3.2736	0.5360	0.1550
4c4	Bedrock	2.9224	0.4320	0.1016
4c5	Alluvial	1.9699	0.3240	0.1631

Individual Feature Attributes (continued)

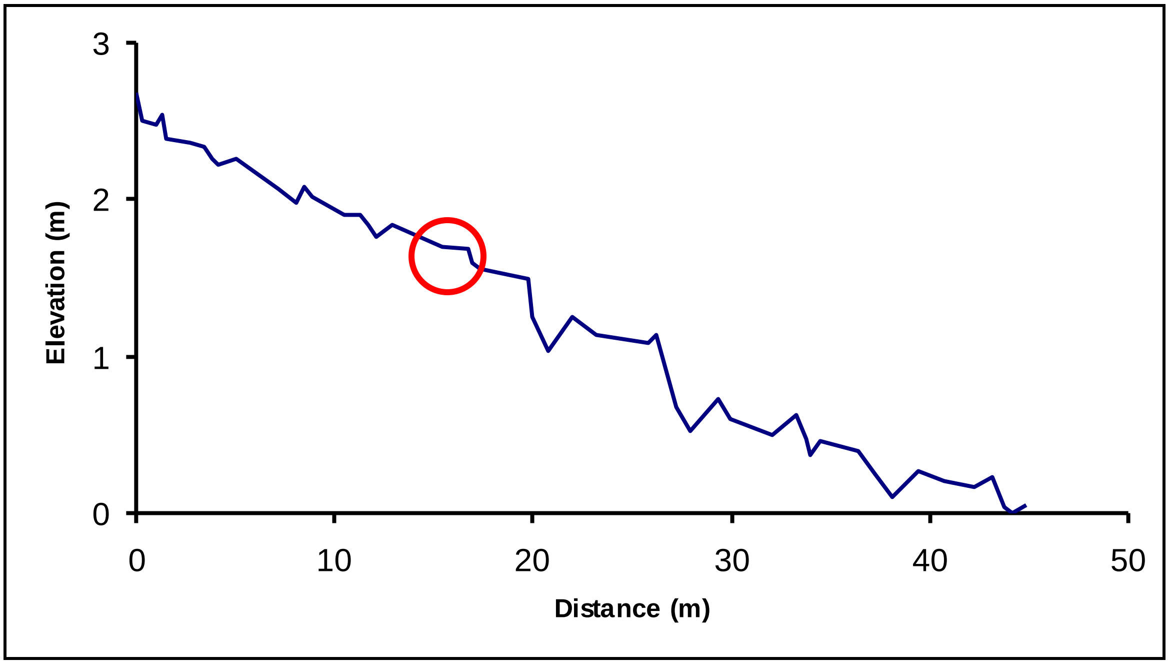
	Crest Attributes			
Crest ID	Substate Type	Active Width (m)	D_{90} (m)	H/L
4c6	Alluvial	1.7194	0.3840	0.1589
4c7	Alluvial	3.7753	0.4140	0.2188
4c8	Alluvial	3.4561	0.5580	0.2515
4c9	Alluvial	3.6564	0.4940	0.1521
4c10	Bedrock	4.4839	0.4100	0.1268
4c11	Bedrock	4.3577	0.4760	0.1292
4c12	Alluvial	4.0444	0.5000	0.2327
4c13	Alluvial	2.8855	0.6200	0.2155
4c14	Alluvial	4.1904	0.4240	0.2076
4c15	Alluvial	4.7180	0.4440	0.1613
4Average	Alluvial	3.3988	0.4628	0.1581
5c1	Alluvial	5.1658	0.6420	0.0868
5c2	Alluvial	5.0021	0.3080	0.1146
5c3	Alluvial	4.1541	0.5720	0.0370
5c4	Bedrock	5.0892	0.5000	0.0475
5c5	Bedrock	7.3829	0.5800	0.0953
5c6	Alluvial	3.6997	0.5320	0.0586
5c7	Alluvial	3.5844	0.4740	0.0856
5c8	Alluvial	4.3090	0.5480	0.0993
5c9	Alluvial	4.3404	0.5580	0.1036
5c10	Bedrock	3.8319	0.4880	0.0381
5c11	Alluvial	7.1390	0.7200	0.1276
5c12	Alluvial	4.4446	0.5440	0.0607
5c13	Alluvial	6.8489	0.6780	0.0849
5c14	Alluvial	9.7112	0.6660	0.1662
5c15	Alluvial	8.6807	0.6240	0.1517
5Average	Alluvial	5.5589	0.5623	0.0736
6c1	Alluvial	3.2918	0.5140	0.1105
6c2	Alluvial	3.5765	0.3620	0.1336
6c3	Alluvial	3.9859	0.5400	0.1354
6c4	Alluvial	4.2977	0.3130	0.1746
6c5	Alluvial	4.2821	0.3830	0.1084
6c6	Alluvial	4.7049	0.5240	0.0878
6c7	Alluvial	2.7734	0.2820	0.1005
6c8	Alluvial	4.7857	0.6240	0.1001
6c9	Alluvial	3.9718	0.5320	0.1101
6c10	Alluvial	3.1620	0.3240	0.0887
6c11	Alluvial	2.9578	0.2850	0.0907
6c12	Alluvial	2.3314	0.2860	0.1442
6c13	Alluvial	2.3335	0.2770	0.0924
6c14	Alluvial	3.4814	0.2380	0.0665
6c15	Alluvial	3.1766	0.3510	0.0811
6Average	Alluvial	3.5408	0.3890	0.1080
7c1	Bedrock	6.2966	0.3720	0.3196
7c2	Bedrock	8.4990	0.3720	0.4906
7c3	Colluvial	9.1382	0.5980	0.2867
7c4	Colluvial	11.5794	0.3920	0.4010

Individual Feature Attributes

Crest ID	Crest Attributes			
	Substate Type	Active Width (m)	D_{90} (m)	H/L
7c5	Colluvial	8.1613	0.3660	0.3805
7c6	Colluvial	4.7552	0.4420	0.4692
7c7	Colluvial	2.8773	0.4460	0.6058
7Average	Colluvial	7.3296	0.4269	0.3838
8c1	Bedrock	11.4251	0.3440	0.1697
8c2	Colluvial	16.9697	1.1080	0.2151
8c3	Alluvial	11.2611	0.7200	0.0508
8c4	Alluvial	10.1590	0.7260	0.1697
8c5	Alluvial	11.4300	0.6980	0.0639
8c6	Colluvial	13.6886	0.7000	0.0535
8c7	Colluvial	10.1407	0.5470	0.2515
8c8	Colluvial	5.7525	0.5860	0.1172
8Average	Colluvial	11.3533	0.6786	0.1228
9c1	Colluvial	4.6296	0.4520	0.0811
9c2	Colluvial	7.1863	0.4780	0.0987
9c3	Alluvial	6.4935	0.3520	0.0927
9c4	Alluvial	9.2446	0.4760	0.0875
9c5	Alluvial	7.6599	0.4240	0.0473
9c6	Alluvial	6.2850	0.3800	0.0777
9c7	Colluvial	5.1761	0.4380	0.0922
9c8	Alluvial	8.9669	0.4100	0.1028
9c9	Alluvial	13.1826	0.2760	0.0403
9c10	Alluvial	12.6455	0.5260	0.0766
9c11	Alluvial	9.2549	0.4420	0.0974
9Average	Alluvial	8.2477	0.4231	0.0826
10c1	Colluvial	6.8787	0.3420	0.0849
10c2	Alluvial	9.5180	0.2820	0.0868
10c3	Alluvial	10.4104	0.3640	0.0597
10c4	Colluvial	11.6903	0.3980	0.0773
10c5	Alluvial	9.6606	0.4320	0.1161
10c6	Alluvial	10.7567	0.3820	0.2132
10c7	Alluvial	10.7902	0.4540	0.1085
10c8	Alluvial	8.7868	0.3400	0.0508
10c9	Colluvial	7.5758	0.3240	0.0417
10c10	Bedrock	6.6050	0.3860	0.3120
10Average	Alluvial	9.2673	0.3704	0.0760
11c1	Colluvial	10.5772	0.5200	0.1391
11c2	Colluvial	10.7796	0.3600	0.0991
11c3	Colluvial	9.5018	0.5600	0.1059
11c4	Colluvial	11.2618	0.3380	0.0722
11c5	Alluvial	8.8880	0.3340	0.0403
11c6	Alluvial	10.8826	0.3840	0.0793
11c7	Alluvial	5.6022	0.2880	0.0402
11c8	Alluvial	10.0145	0.3560	0.1000
11c9	Alluvial	10.7149	0.4240	0.0496
11c10	Alluvial	7.3240	0.3020	0.0426
11Average	Alluvial	9.5547	0.3866	0.0725

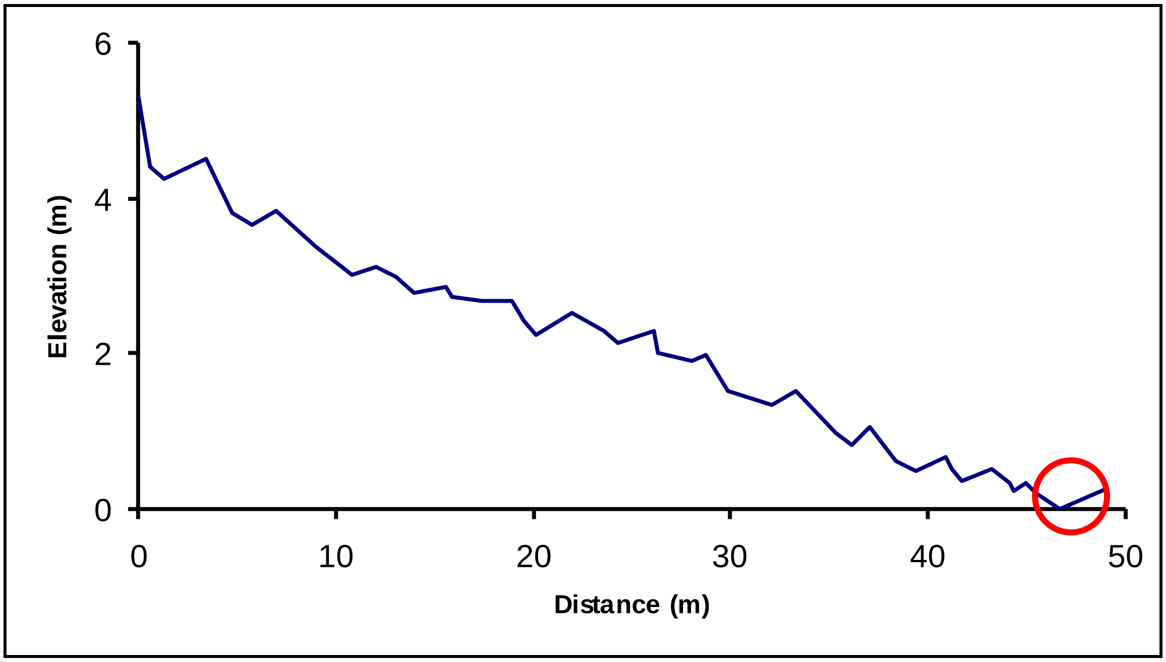
APPENDIX B

REACH PHOTOS AND LONGITUDINAL PROFILES



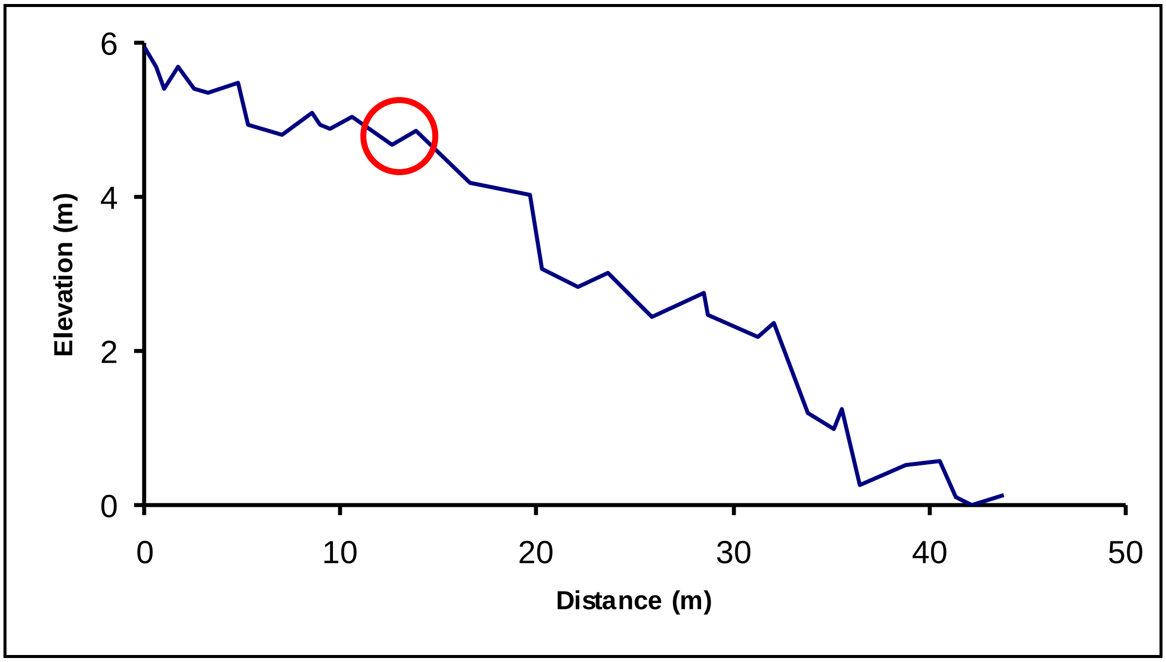
Longitudinal profile of Reach 1

Looking upstream from red circle



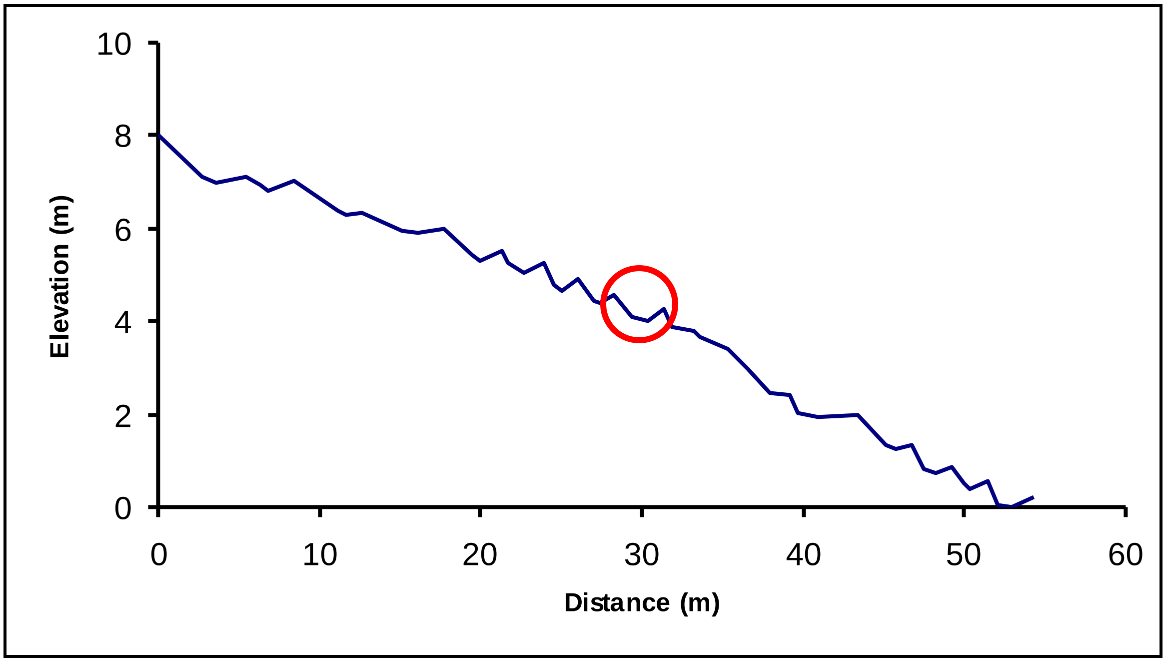
Longitudinal profile of Reach 2

Looking upstream from red circle



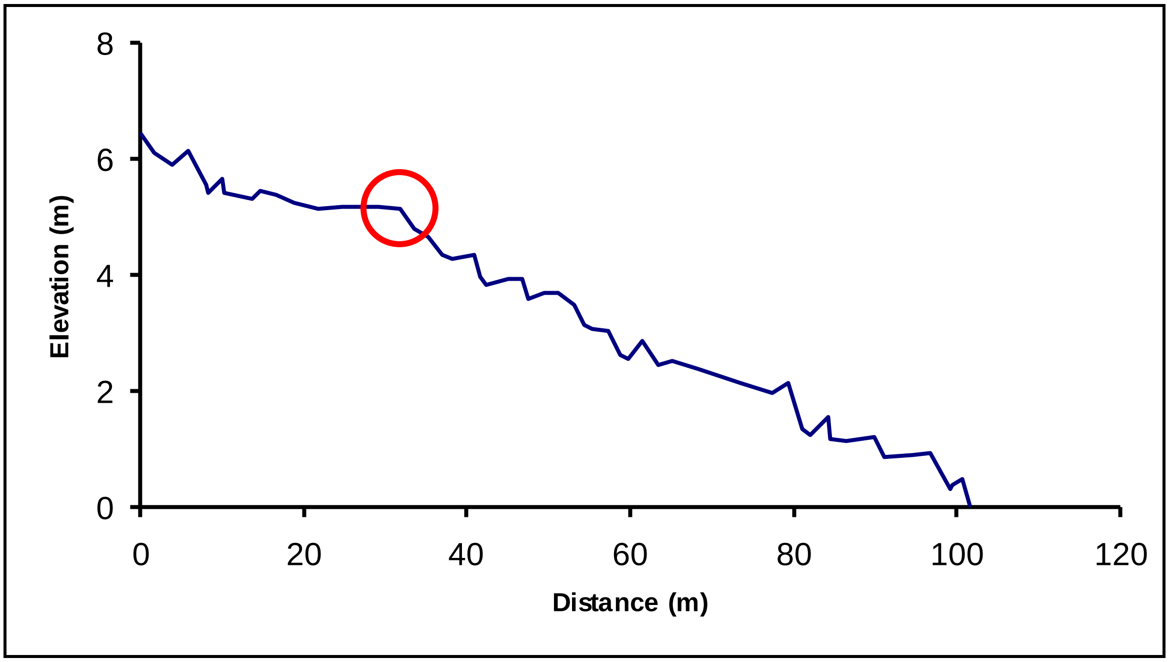
Longitudinal profile of Reach 3

Looking upstream from red circle



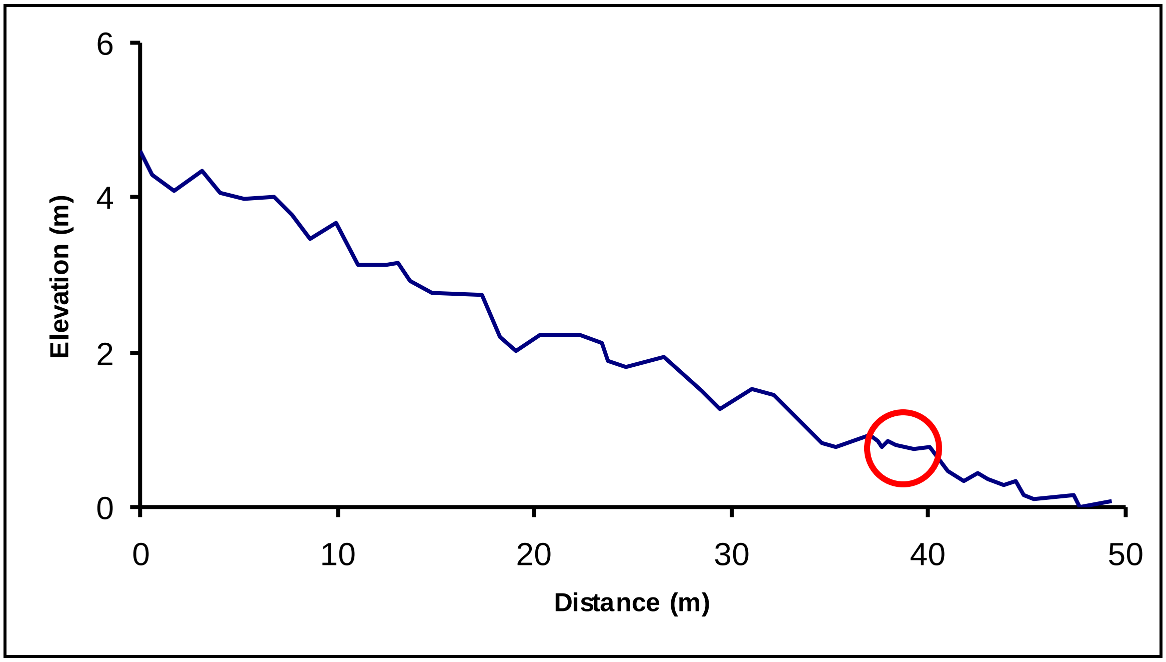
Longitudinal profile of Reach 4

Looking upstream from red circle



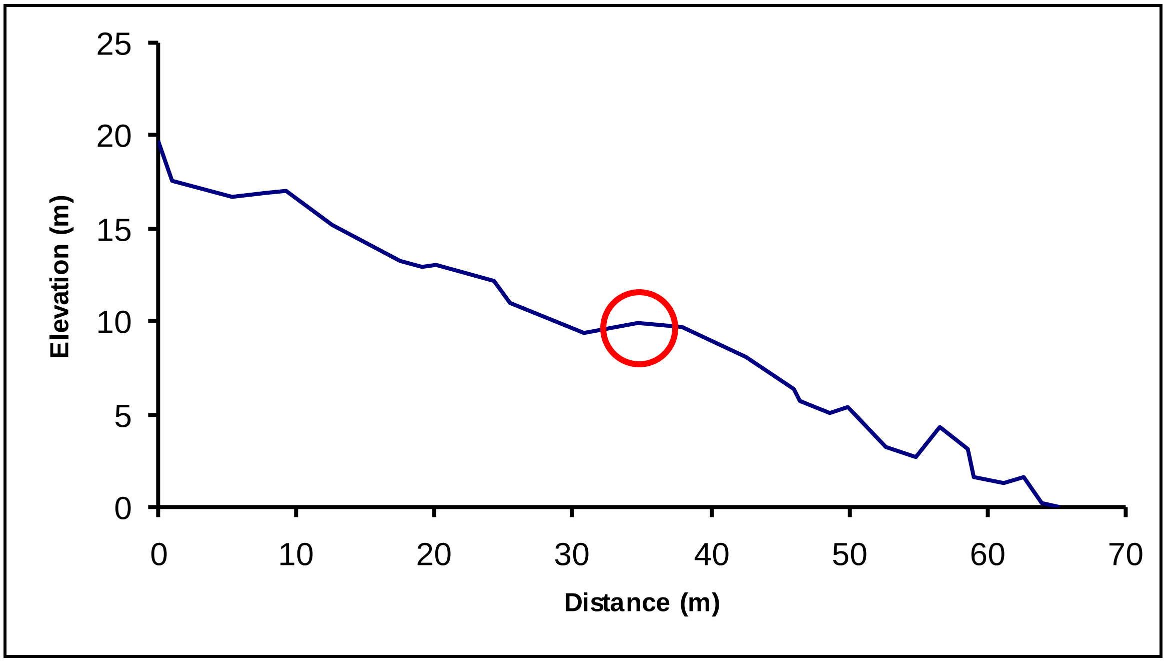
Longitudinal profile of Reach 5

Looking downstream from red circle



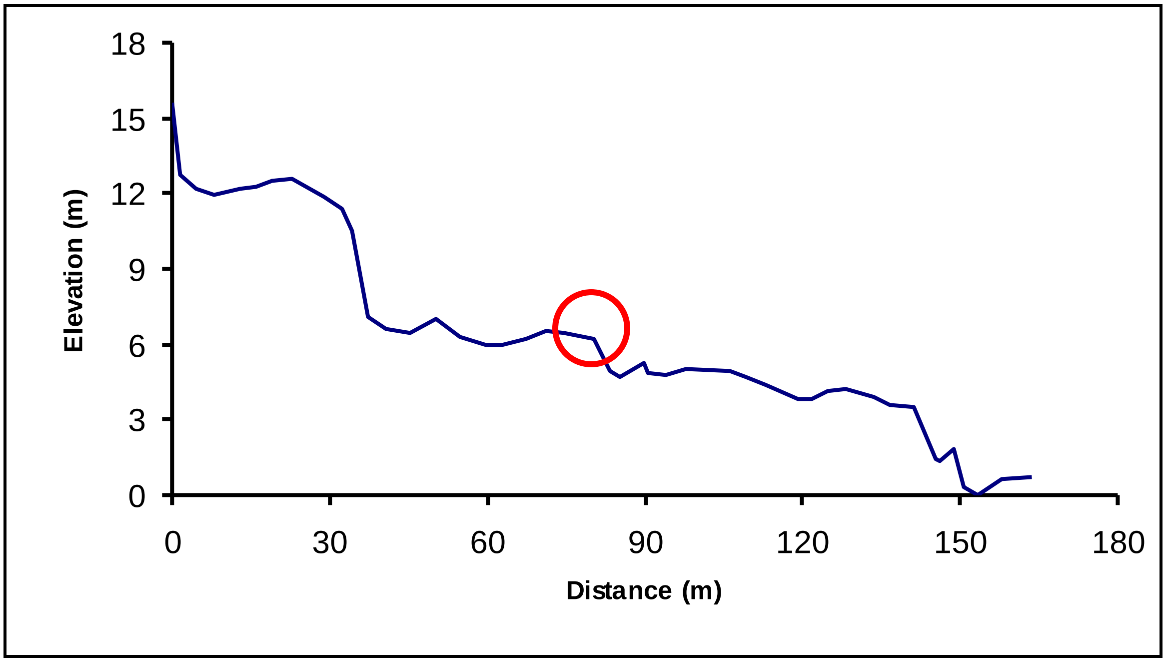
Longitudianl profile of Reach 6

Looking upstream from red circle



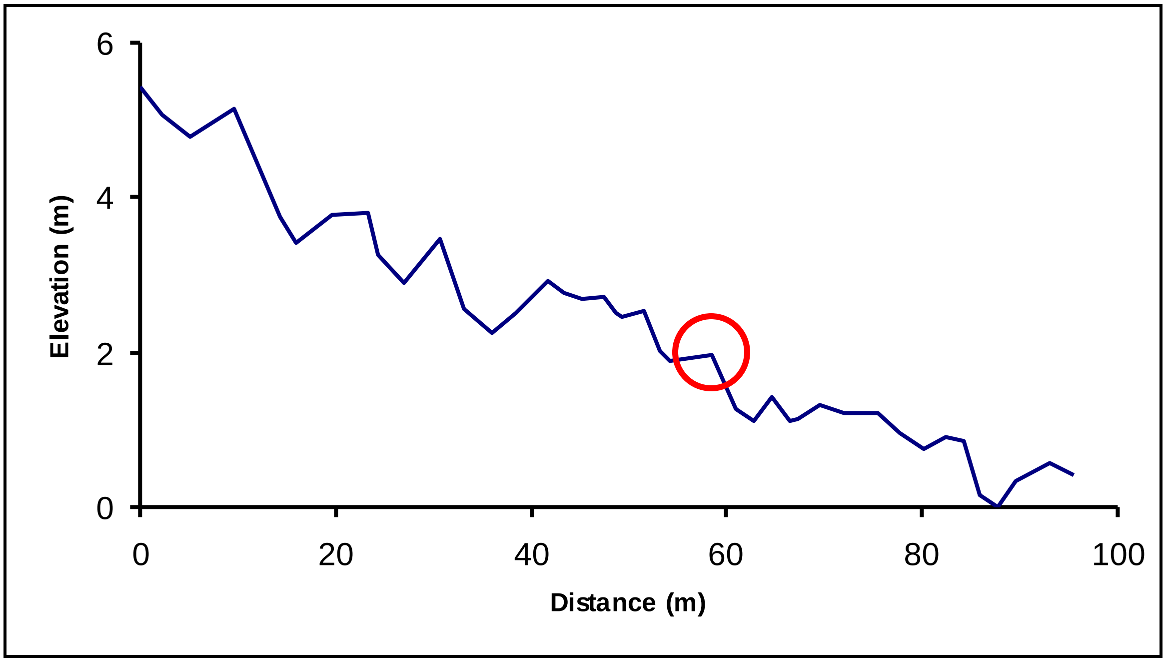
Longitudinal profile of Reach 7

Looking across the stream (towards right bank) from red circle



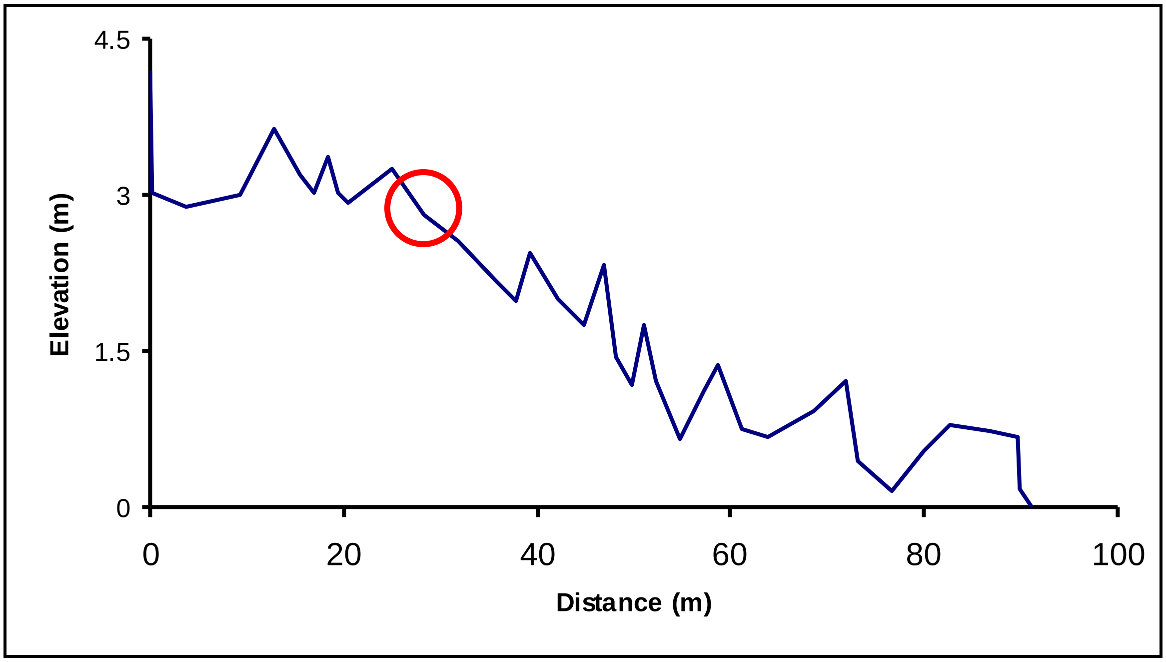
Longitudinal profile of Reach 8

Looking upstream from red circle

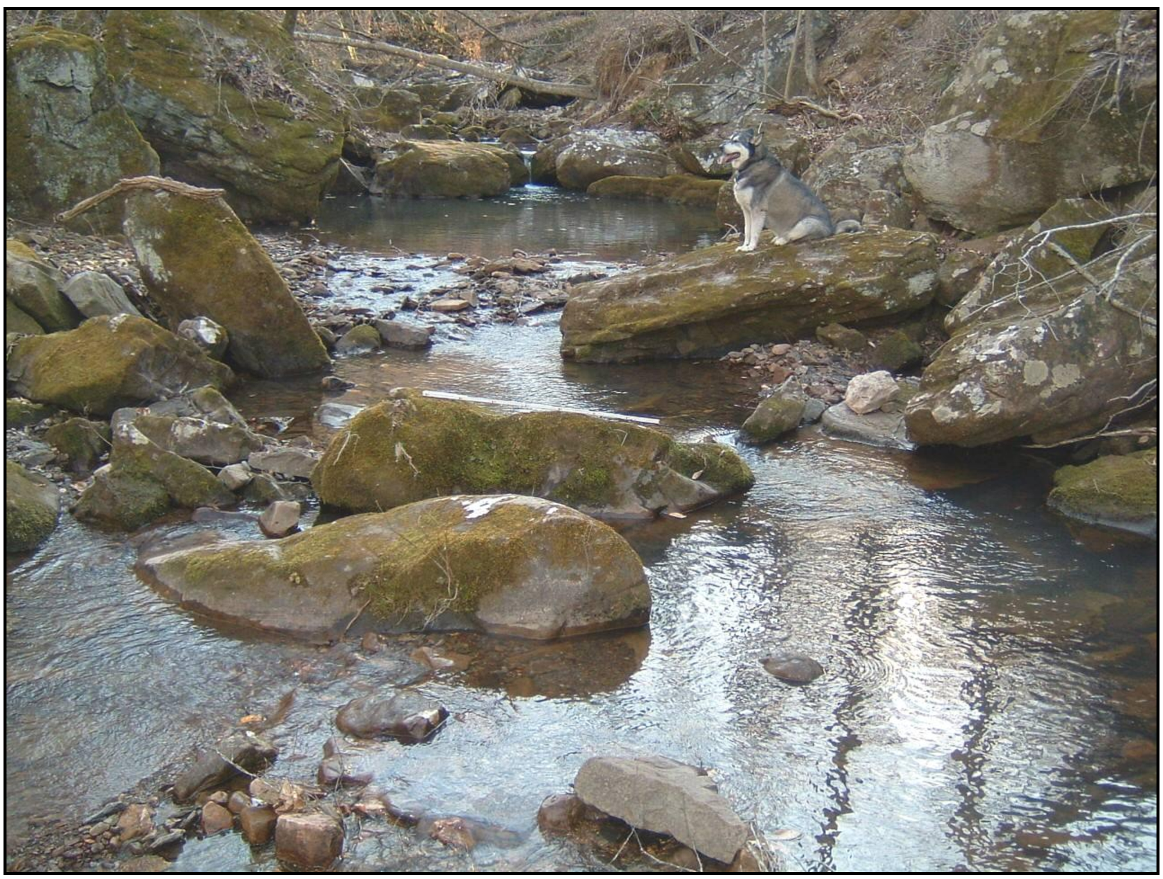


Longitudinal profile of Reach 9

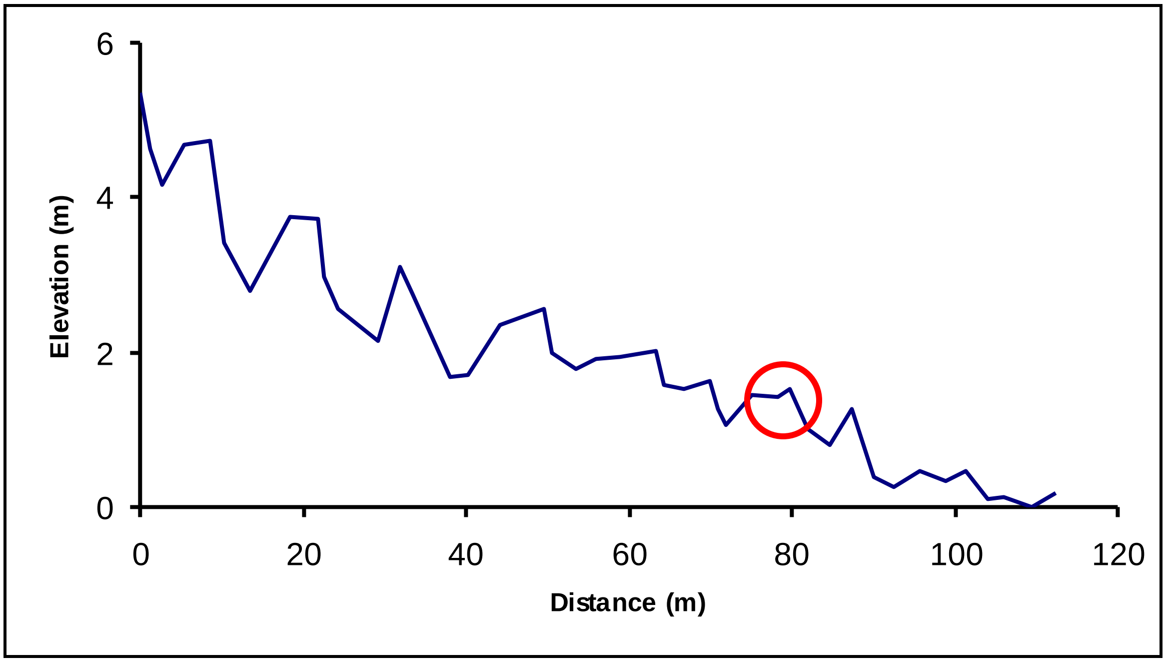
Looking upstream from red circle



Longitudinal profile of Reach 10



Looking upstream from red circle

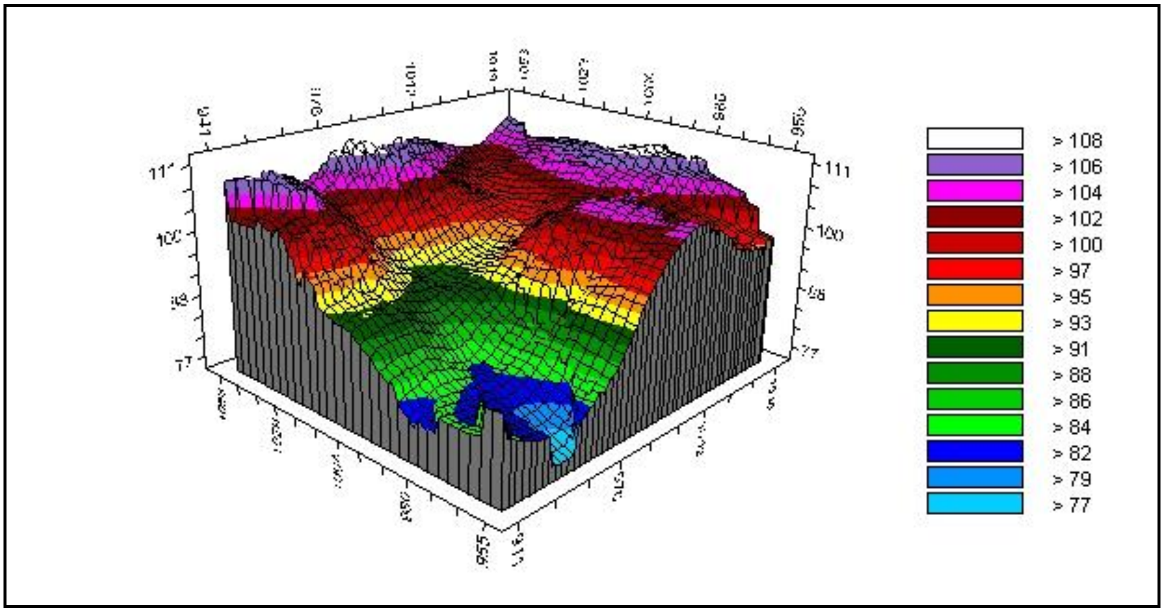


Longitudinal profile of Reach 11

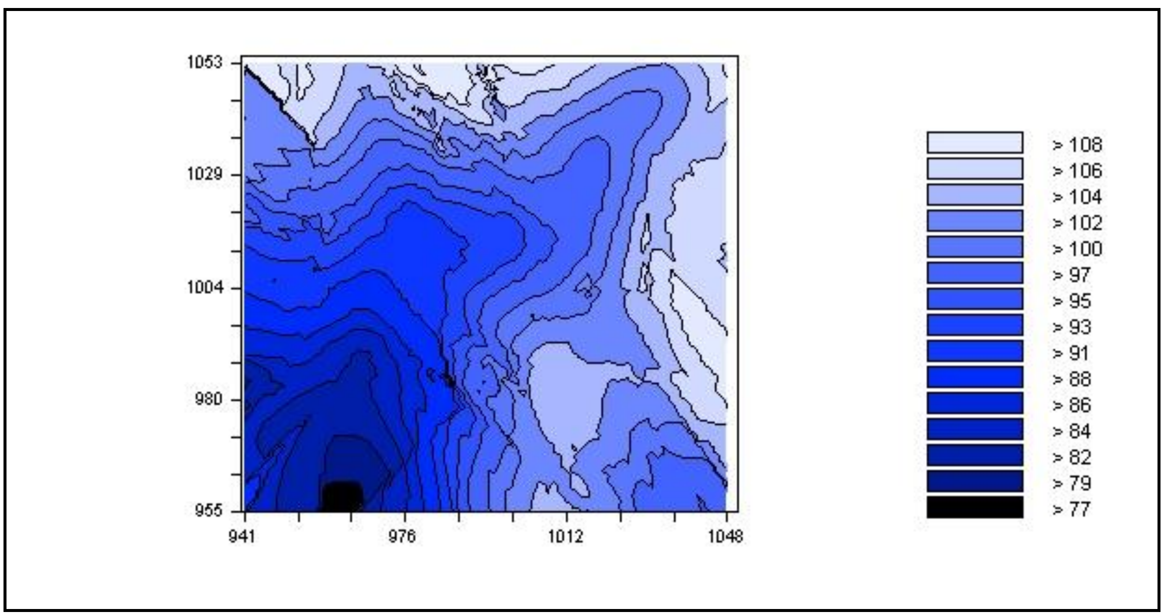
Looking upstream from red circle

APPENDIX C

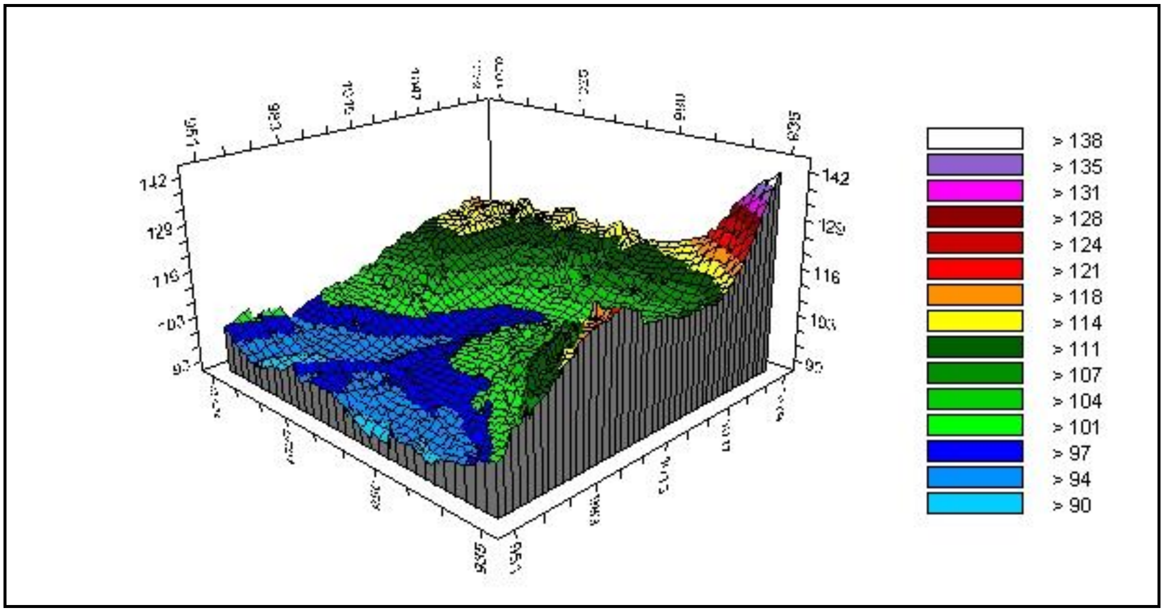
REACH CONTOUR AND 3-D IMAGING



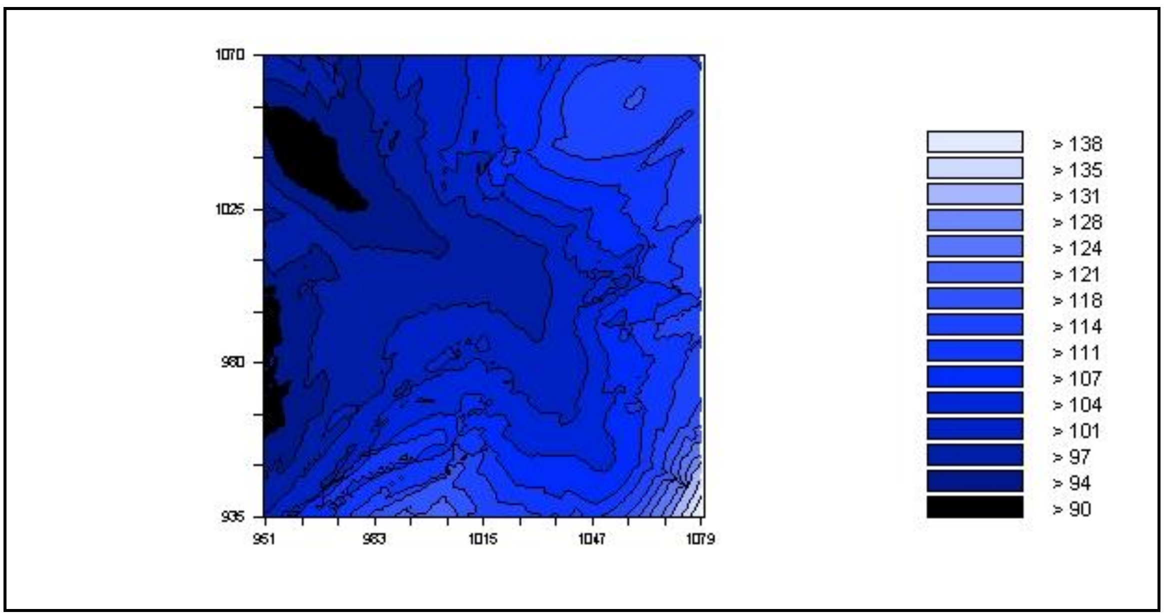
Interpolated surface from Reach 1 survey



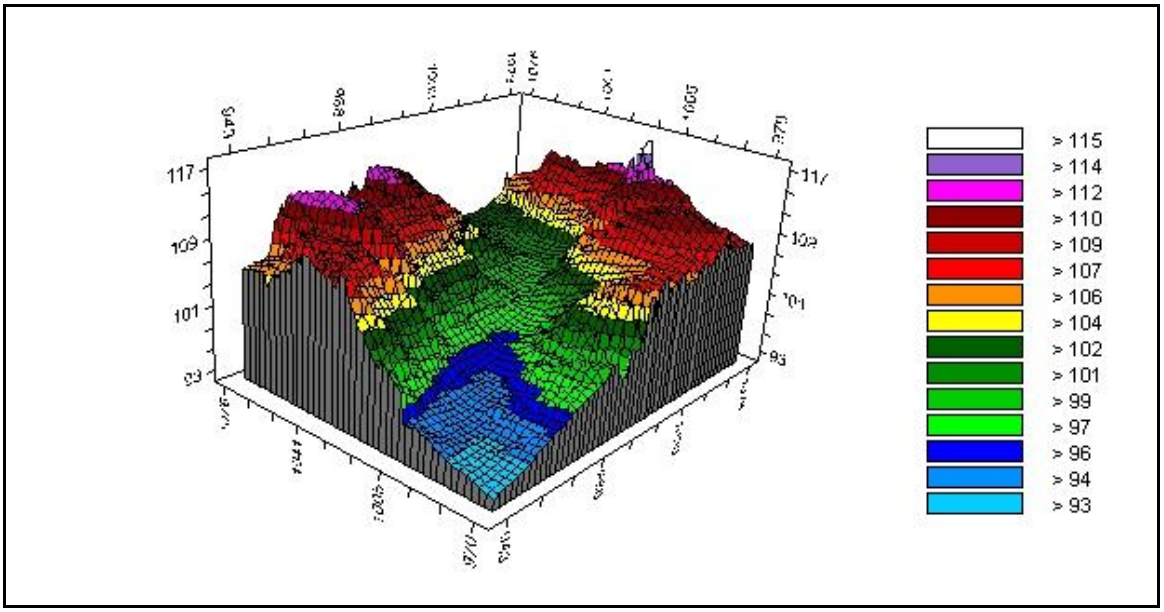
Digital contour model from Reach 1 survey



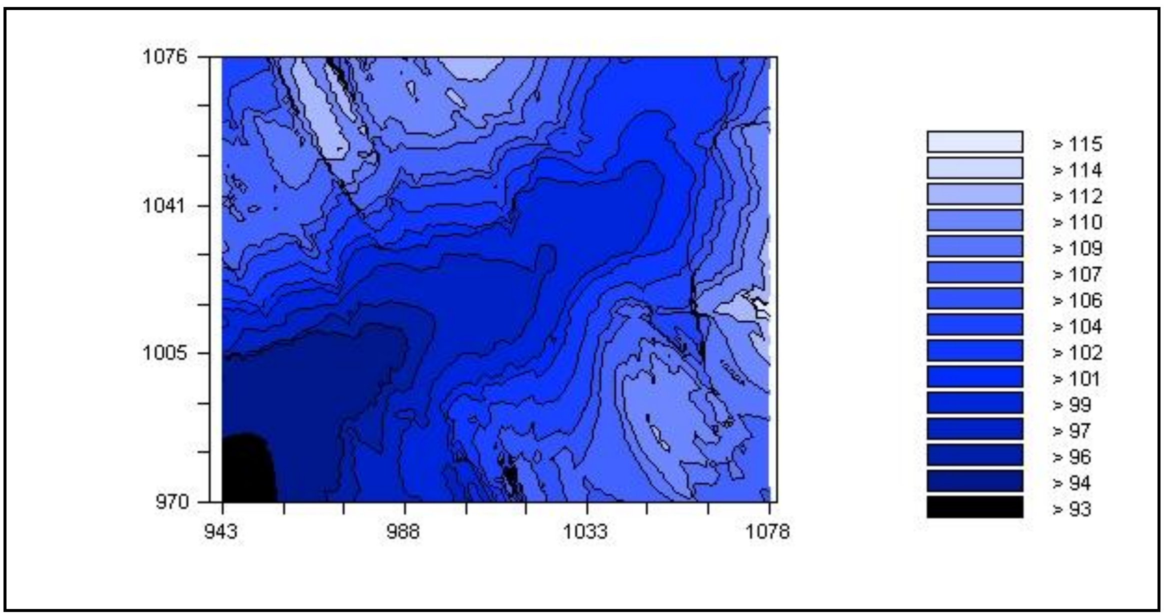
Interpolated surface from Reach 2 survey



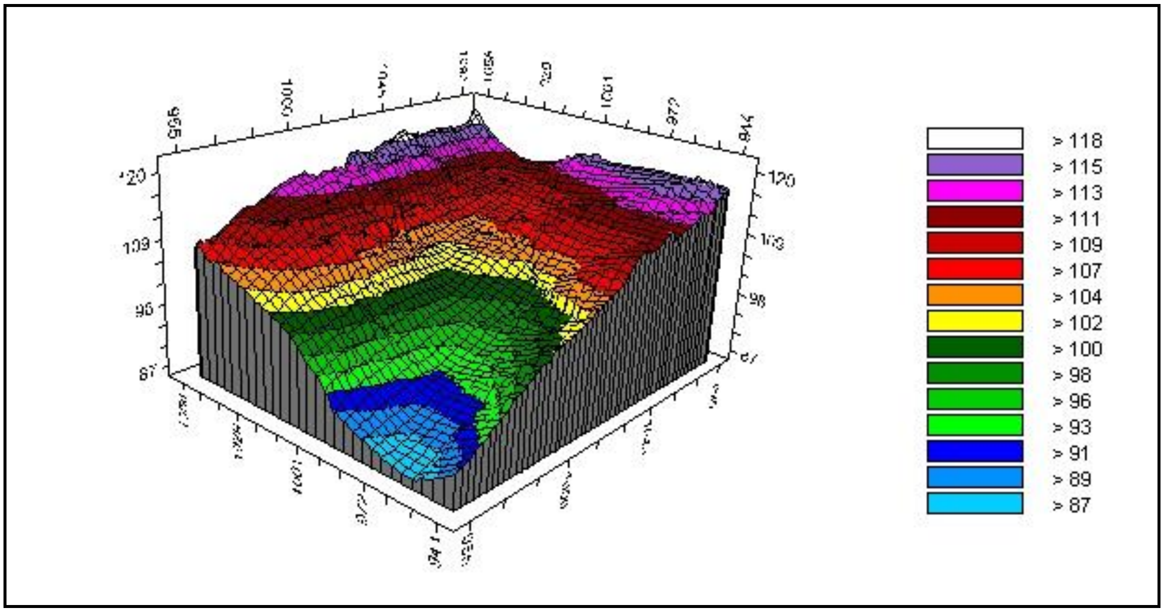
Digital contour model from Reach 2 survey



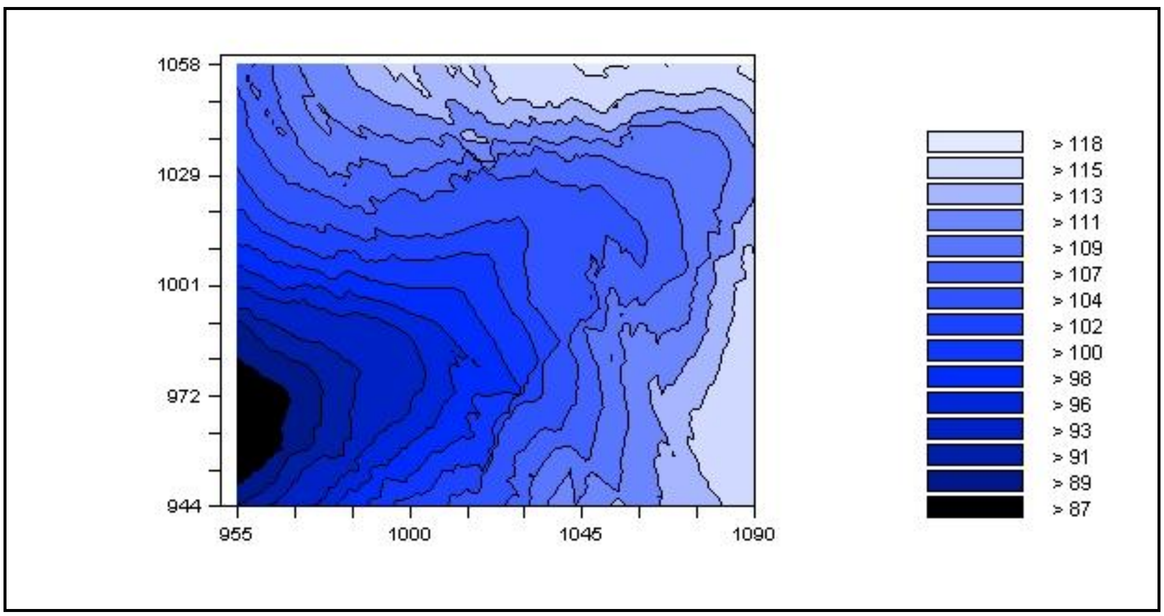
Interpolated surface from Reach 3 survey



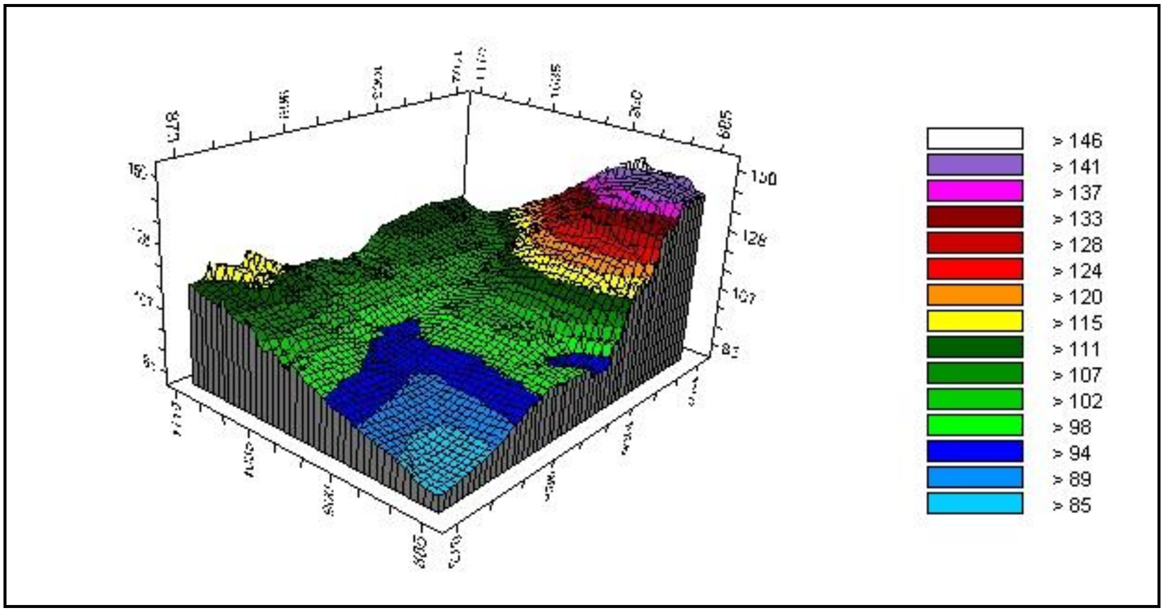
Digital contour model from Reach 3 survey



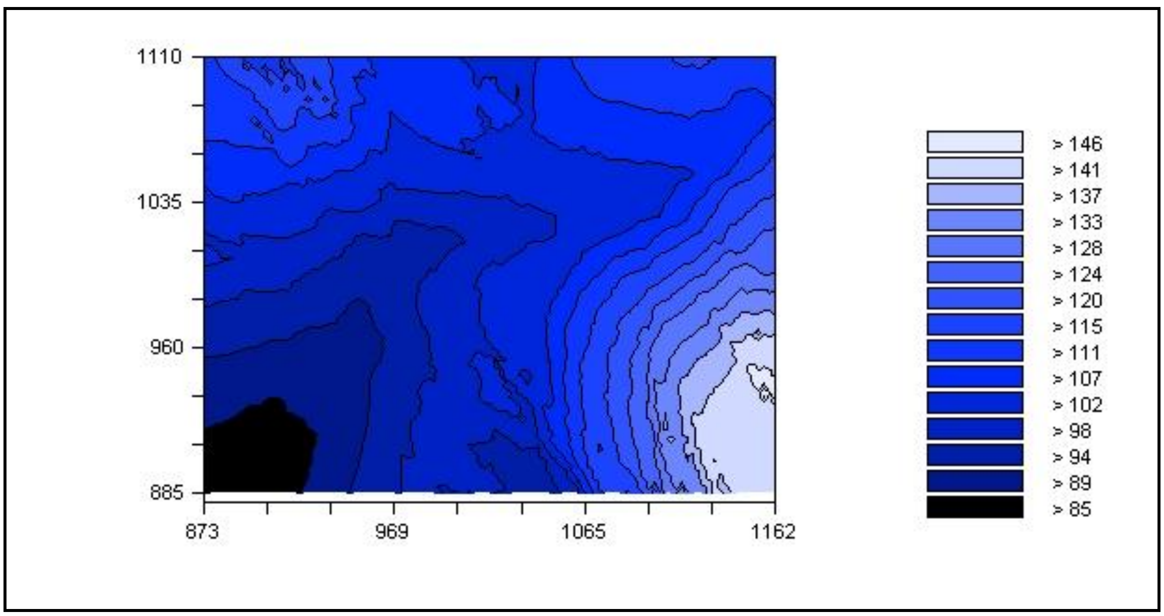
Interpolated surface from Reach 4 survey



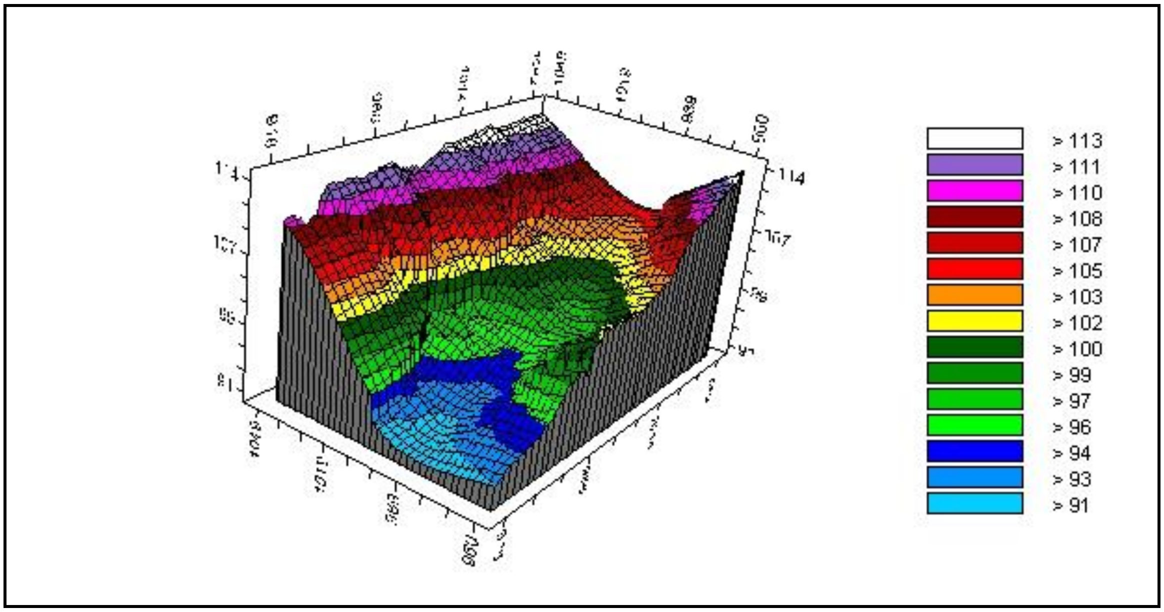
Digital contour model from Reach 4 survey



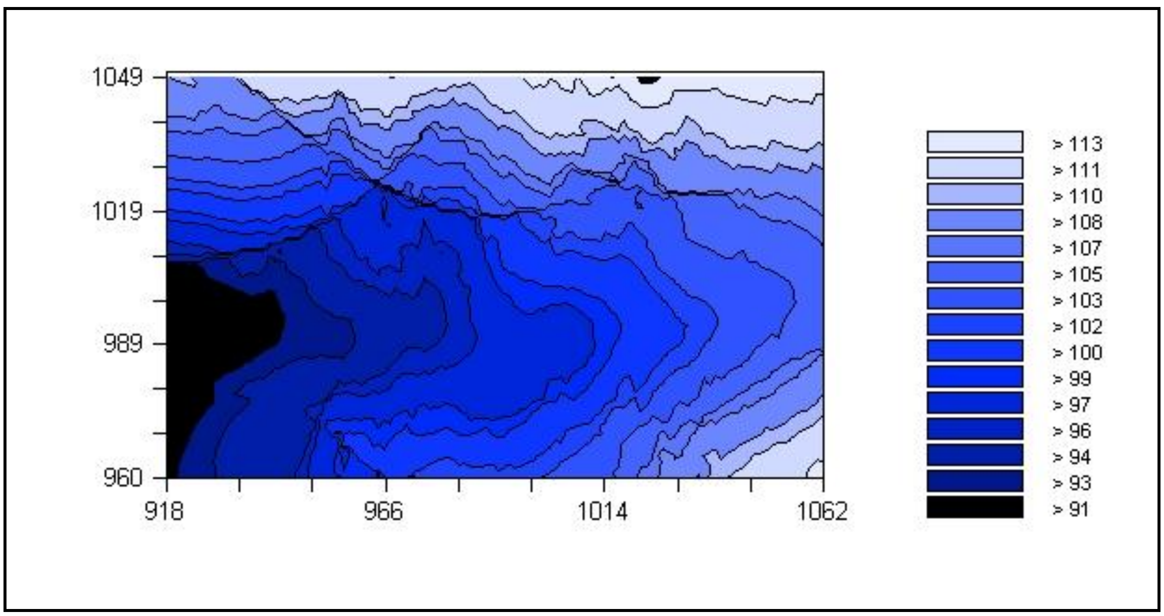
Interpolated surface from Reach 5 survey



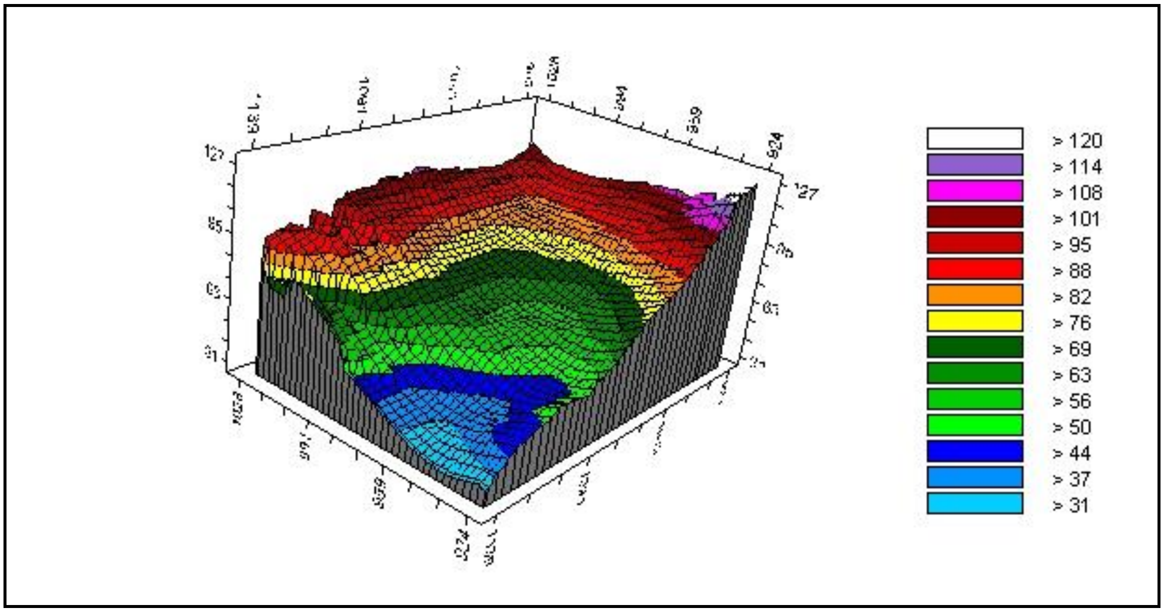
Digital contour model from Reach 5 survey



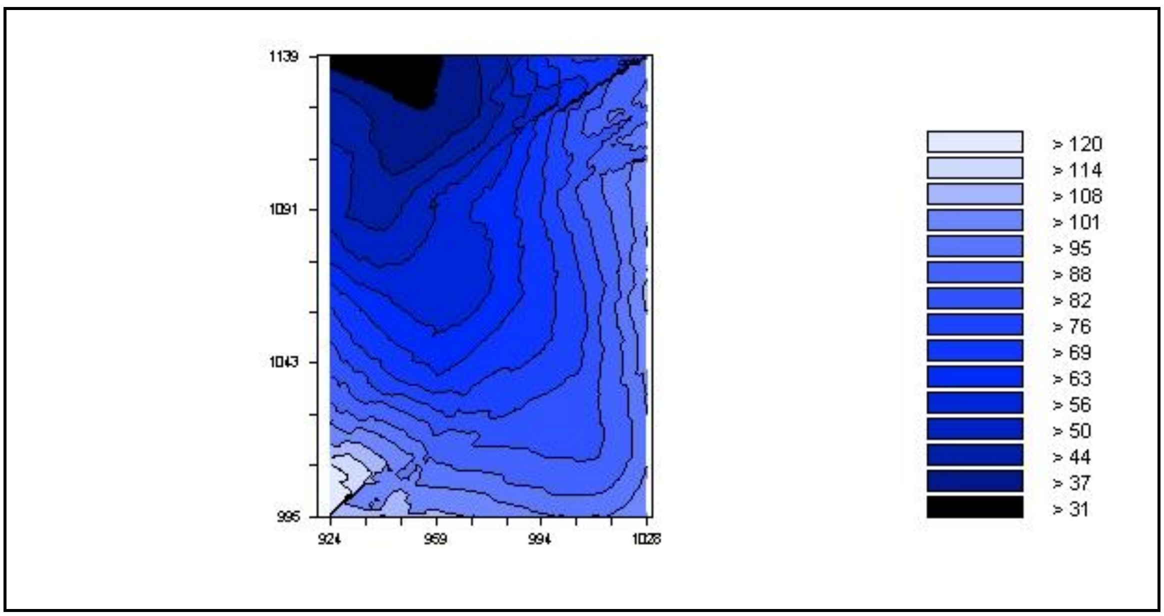
Interpolated surface from Reach 6 survey



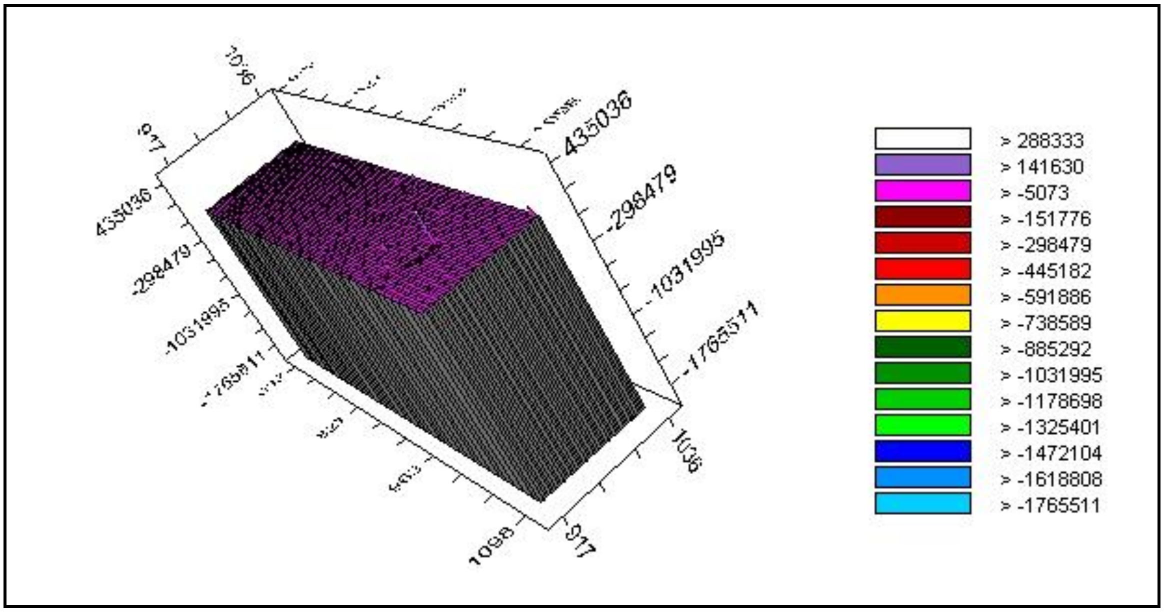
Digital contour model from Reach 6 survey



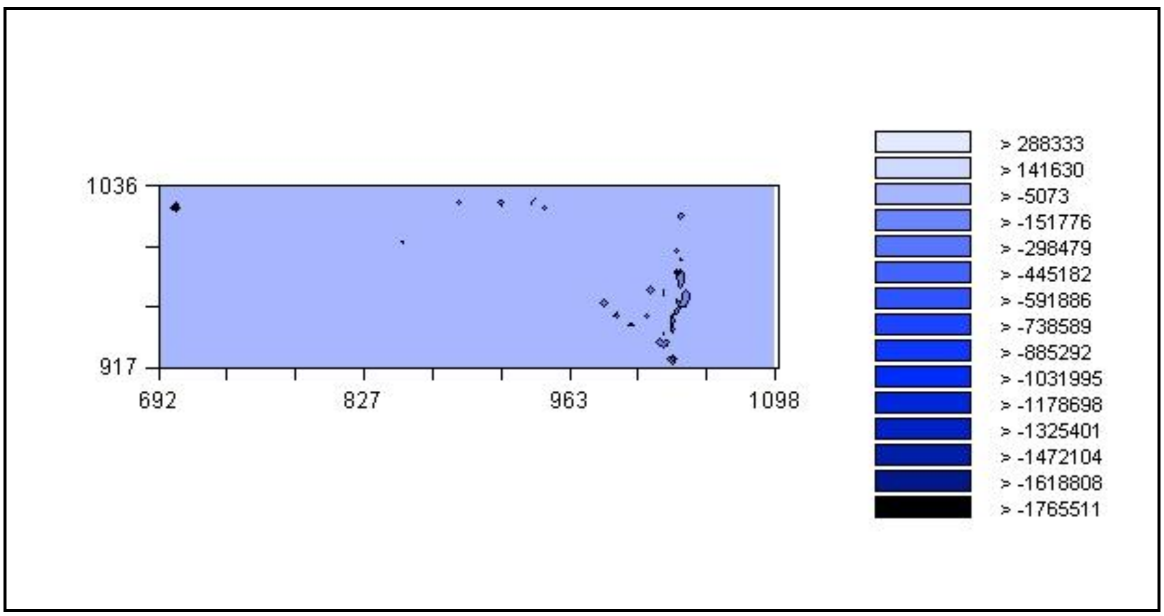
Interpolated surface from Reach 7 survey



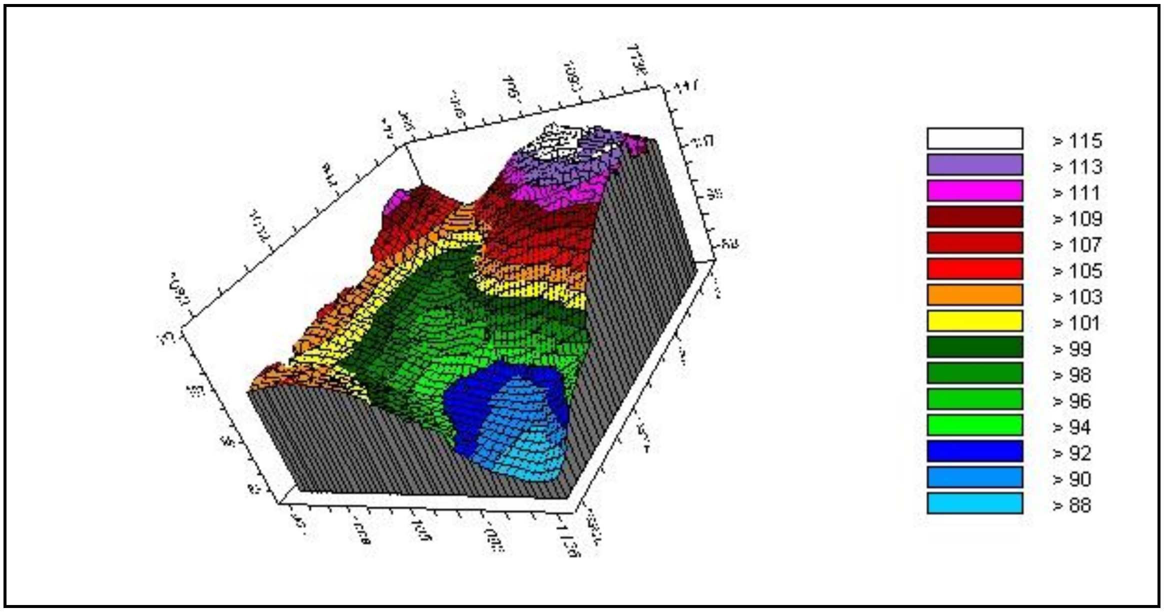
Digital contour model from Reach 7 survey



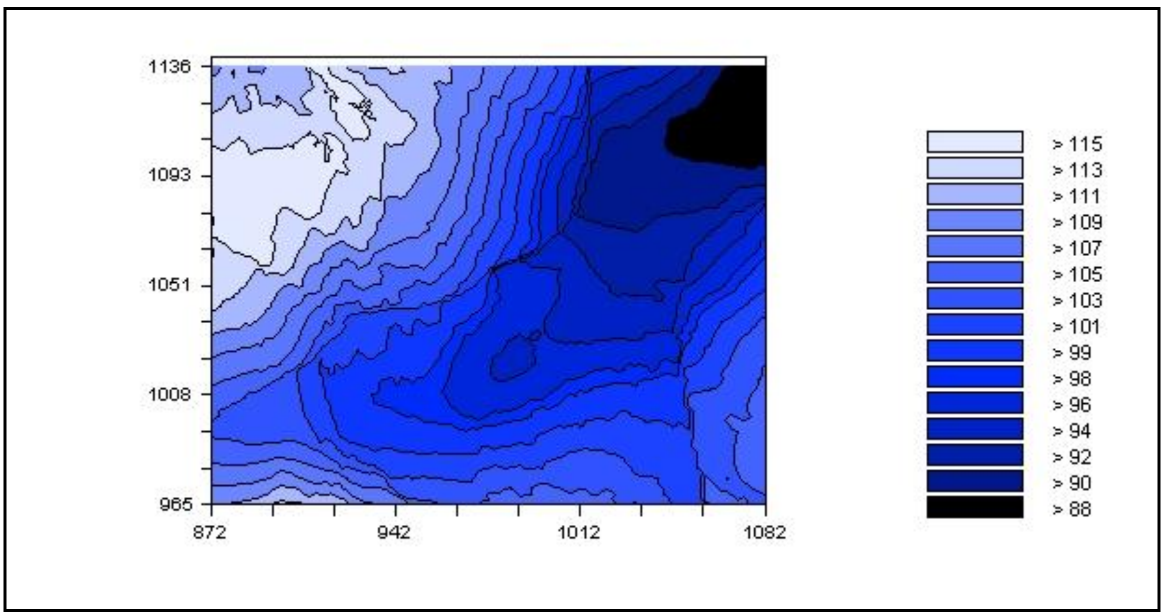
Interpolated surface from Reach 8 survey



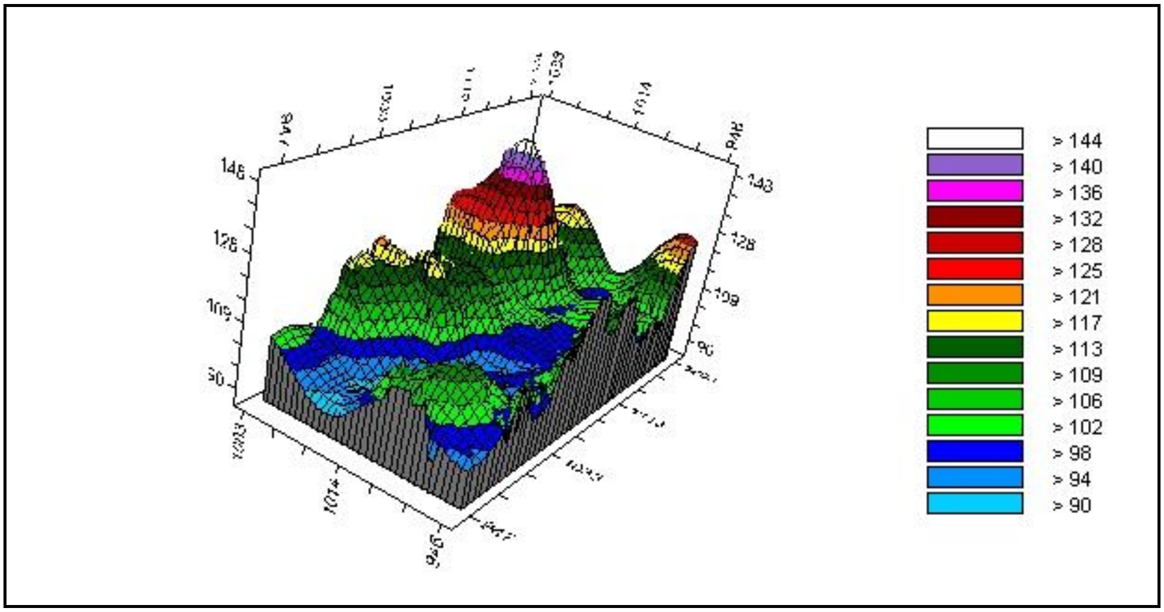
Digital contour model from Reach 8 survey



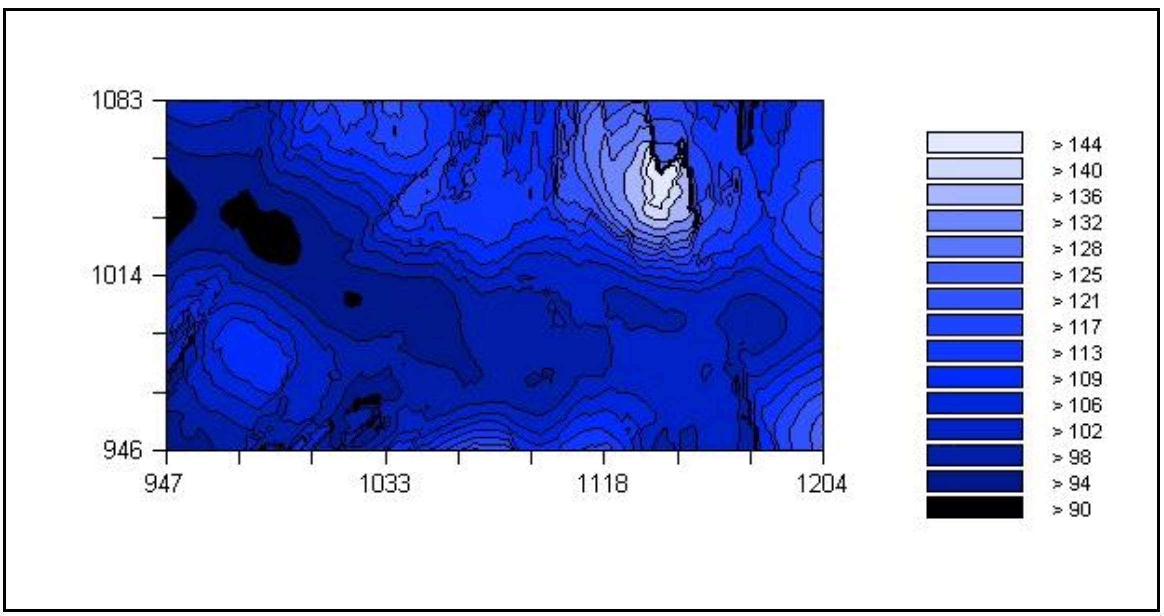
Interpolated surface from Reach 9 survey



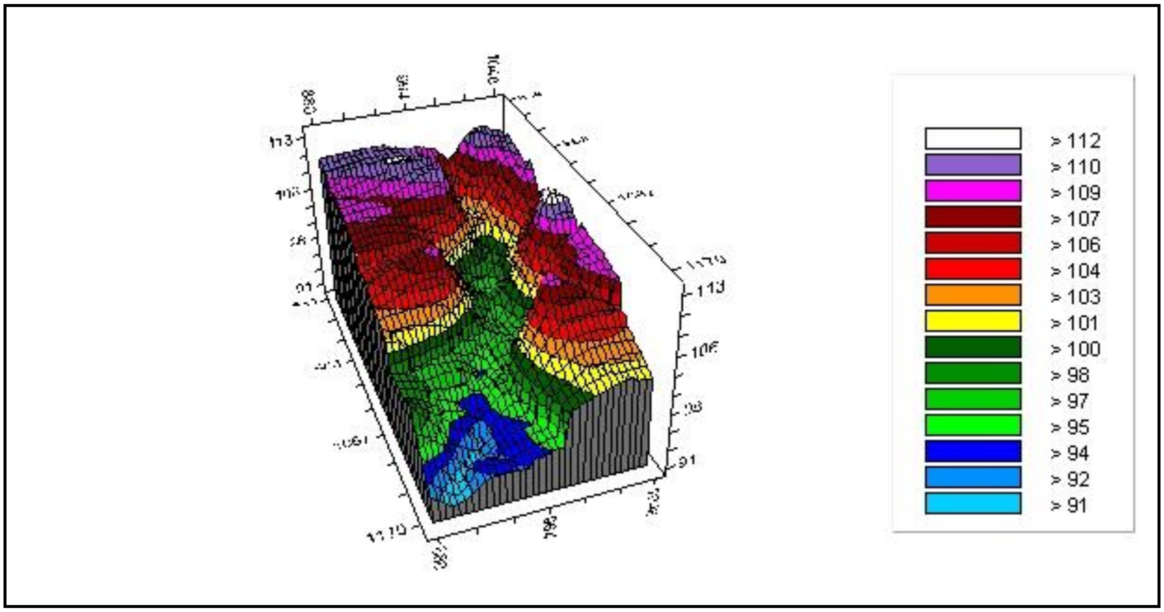
Digital contour model from Reach 9 survey



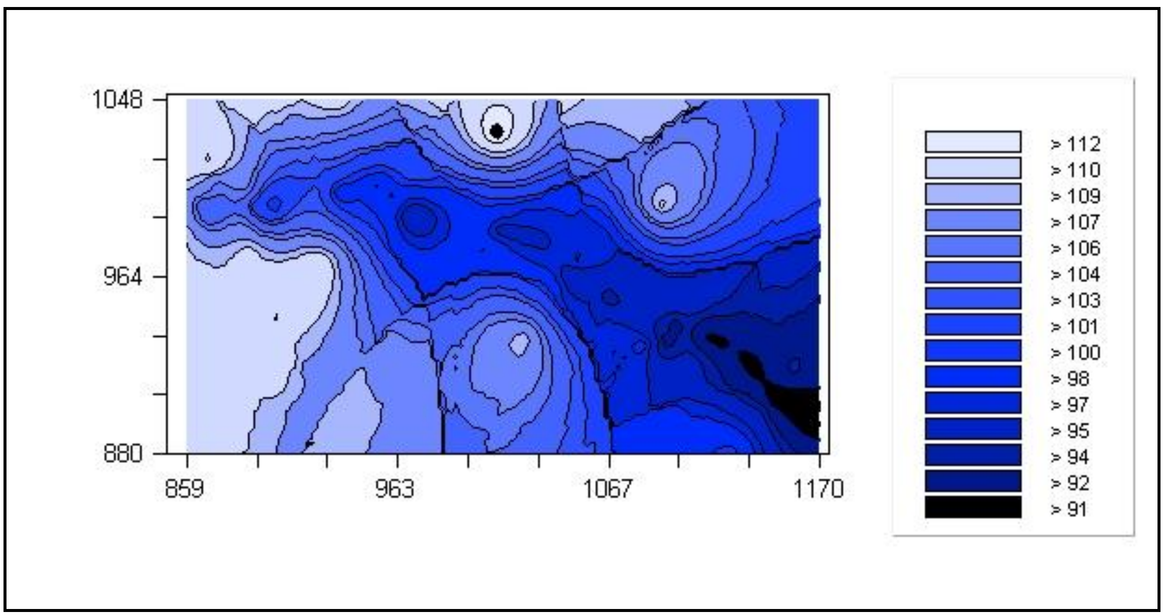
Interpolated surface from Reach 10 survey



Digital contour model from Reach 10 survey



Interpolated surface from Reach 11 survey



Digital contour model from Reach 11 survey