Hydraulic and geomorphic assessment of St. Regis River boulder clusters
by Shawn Francis Boelman

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
The St. Regis River in western Montana has been relocated and or channelized along most of its 59 kilometer length by railroad and highway construction activities. In partial mitigation for habitat loss due to I-90 construction, the Montana Department of Transportation placed boulder clusters and other fishery improvement structures in several kilometers of river reach between 1972 and 1982. Three specific reaches (two with boulder clusters and one without) were selected to assess the long-term stability and impacts of boulder clusters on channel morphology, hydraulic capacity, and sediment transport. Detailed topographic and velocity surveys were conducted during five site visits between October 1995 and August 1997 including data collected during one estimated 37-year event. These data are combined with stereoscopic aerial photographs and continuous stage data to assess the influence of the boulder clusters.

Results indicate that clusters are successful in increasing bed elevation diversity as compared to reaches without clusters. The typical scour pattern is a scour hole surrounding the cluster with a gravel bar immediately downstream, but different clusters exhibited different morphologic responses. Only one cluster in 12 surveyed had significant movement of boulders in response to three flood events in excess of 25-year return intervals. Modeling with HEC-RAS software indicates that clusters increase channel roughness by nearly a factor of two during low (boulder exposed) flow, but have insignificant effect on roughness for high (boulder submerged) flow. The conclusion is that boulder clusters increase morphological diversity generally associated with improved habitat while having minimum influence on flood risk in cobble bed rivers.

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APPROVAL

of a thesis submitted by

Shawn Francis Boelman

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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VITA

The author, Shawn Francis Boelman, was born January 3, 1970 in Jerome, Idaho to Daryle and Jean Boelman. He graduated from Corvallis High School, Corvallis, Montana in 1988. In September 1988 he entered the University of Washington in the biology department. In January 1989 he entered Montana State University at Bozeman, Montana and in May 1993 he graduated with a Bachelor of Science degree in Industrial and Management Engineering. In the fall of 1993 he began work for the U.S. Army Engineers Waterways Experiment Station in the Environmental Engineering Lab. In January 1994 he began taking graduate studies at the University of Mississippi and in the fall 1994 he was accepted into the College of Graduate Studies at Montana State University, though he continued to work and take graduate courses in Mississippi. In January 1996 he attended Montana State University full-time. He finished his course work at Montana State University in May 1997 and was married on the 24^{th} of that month to Amy Lynne Bowman. In August 1997 he began work full time with the U.S. Bureau of Reclamation, Albuquerque Area Office, as a hydraulic engineer.

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ABSTRACT

The St. Regis River in western Montana has been relocated and or channelized along most of its 59 kilometer length by railroad and highway construction activities. In partial mitigation for habitat loss due to I-90 construction, the Montana Department of Transportation placed boulder clusters and other fishery improvement structures in several kilometers of river reach between 1972 and 1982. Three specific reaches (two with boulder clusters and one without) were selected to assess the long-term stability and impacts of boulder clusters on channel morphology, hydraulic capacity, and sediment transport. Detailed topographic and velocity surveys were conducted during five site visits between October 1995 and August 1997 including data collected during one estimated 37-year event. These data are combined with stereoscopic aerial photographs and continuous stage data to assess the influence of the boulder clusters.

Results indicate that clusters are successful in increasing bed elevation diversity as compared to reaches without clusters. The typical scour pattern is a scour hole surrounding the cluster with a gravel bar immediately downstream, but different clusters exhibited different morphologic responses. Only one cluster in 12 surveyed had significant movement of boulders in response to three flood events in excess of 25-year return intervals. Modeling with HEC-RAS software indicates that clusters increase channel roughness by nearly a factor of two during low (boulder exposed) flow, but have insignificant effect on roughness for high (boulder submerged) flow. The conclusion is that boulder clusters increase morphological diversity generally associated with improved habitat while having minimum influence on flood risk in cobble bed rivers.

Chapter 1

INTRODUCTION

A renewed appreciation for the benefits of preserving our diminishing natural resources and subsequent tightened regulatory requirements have led to a recent profusion of channel restoration projects and the incorporation of environmental features into channel modification projects. At present, there is a great interest in utilizing hydraulic structures to accomplish environmental objectives. Structural features such as flow deflectors, boulders, rock drop structures, and bank protection are incorporated to provide environmental benefits. These features improve the quantity and quality of available habitat during low-flow periods, which are critical for many aquatic species in streams.

The placement of individual boulders or boulder clusters is one of the simplest and most commonly applied instream treatments that can improve habitat on streams of any size (Wesche, 1985). Boulders are ideal construction materials for habitat improvements. If properly selected, they are durable and have a pleasing natural appearance which harmonizes with the river landscape.

Instream boulder structures are believed to enhance aquatic habitat by creating velocity vortices and non-uniform velocity fields. The non-uniform velocity fields in turn create scour holes and other micro-scale geomorphic features desirable to aquatic species.

Strategic placement of instream boulder structures within modified channels may provide sufficient quantities of diverse aquatic micro-habitats, mitigating impacts to desirable aquatic organisms. It may also be feasible to rehabilitate unproductive streams into healthy ecosystems with proper placement of boulder structures.

Although several projects have successfully employed boulder cluster enhancement techniques, the attainment of environmental objectives has been as much by chance as by design. The selection, layout and design of boulder cluster features have historically been accomplished by subjective analyses, frequently without the benefit of engineering opinion. This is due, in part, to the fact that comprehensive design guidance based upon physical processes has not been developed for boulder cluster enhancement features. Scientifically-verified information on the ability of boulder structures to increase populations of desirable species is limited (Nunnally and Shields, 1985). Even less information on changes in channel stability, discharge carrying capacity, and sediment transport (collectively referred to as "hydraulic performance") of streams with boulder structures is available.

The primary objective of this study is to assess the effect of boulder clusters on overall hydraulic performance and channel morphology of a river system. The findings will assist in the development of comprehensive design guidance for the placement of boulder clusters within a stream, optimizing the habitat rehabilitation and hydraulic performance considerations. The specific objectives of this thesis are twofold:

1) To characterize physical changes in channel morphology due to boulder cluster placement.

2) To quantify the impact of instream boulder clusters on discharge carrying capacity (hydraulic grade line, energy grade line and Manning's roughness coefficient, *n*).

Meeting these objectives required the selection of a suitable field site. A reach of the St. Regis River, MT, was selected due to it's history of rehabilitation utilizing instream boulder clusters and previous fish monitoring studies. Pressure transducers were installed in November, 1995, to continuously record water surface data in a reach void of boulder clusters (control reach) and a reach rehabilitated with boulder clusters. Topographic field surveys were conducted in October, 1995, May, June, and August, 1996, and May and July, 1997 at these two sites and a third reach rehabilitated with boulder clusters. Velocity surveys were conducted in October 1995, July and August, 1996, and May 1997. Bed material samples were collected in October, 1995. These data were combined to measure: 1) scour/deposition patterns as influenced by the boulder clusters morphology, 2) changes in these patterns with time, 3) movement (failure) of boulders caused by high flows, and 4) influence of the boulder clusters on channel carrying capacity.

This thesis is divided into five chapters. Chapter 2 reviews the state of the art in utilizing boulder clusters in stream rehabilitation projects and the current ability to predict the effects on bed morphology and flow conveyance. Chapter 3 describes the methodology used in this study. A description of the study area, data collection, and methodology used in the analysis is presented. Chapter 4 presents the data compilation and study results. The effects of boulder clusters on channel morphology and hydraulic performance are reported. Finally, Chapter 5 summarizes the entire work and presents the conclusions of this thesis.

Chapter 2

LITERATURE REVIEW

This chapter is divided into three main sections. First is an overview of the utilization of boulder clusters in stream rehabilitation. This section covers previous studies investigating the ability of boulder clusters to meet restoration objectives, design parameters, and impacts to channel morphology and hydraulic performance. The second section reviews previous fish monitoring studies on the St. Regis River. The third and final section summarizes and integrates the literature. The literature review summary identifies areas in the layout and utilization of boulder cluster features that are lacking in research and design guidance.

Overview of Boulder Cluster Application

Boulder clusters are a type of instream cover device that provide needed velocity breaks, refugia, and add substrate for invertebrates. Primary objectives of boulder placement include the provision of additional rearing habitat and cover for both adult and juvenile fish, improving and restoring pool-riffle and meandering patterns, and increasing flow diversity (Nunnally and Shields, 1985; Swales, 1989).

Boulder clusters change the local channel morphology and velocity regime through interaction with the stream flow. Boulder clusters alter the local water velocity, which modifies the drag and lift forces acting on the substrate particles. An immovable obstruction, such as a large boulder, alters the area of flow in a stream channel. Water backs up along the upstream edge of the obstruction, causing an increase in velocity around the sides, accompanied by the development of vortexes which scour the bed. Scour holes may develop, and the scoured-out material may be deposited downstream as a gravel bar. If the obstruction is overtopped during high water an additional erosive force is introduced as water plunges over the downstream face, impinging on the bed like a jet. This force can greatly enlarge the scour hole below the obstacle. These changed hydraulic forces cause the stream bed to deform into a more complex and diverse environment.

While the literature detailing the results of boulder placement is not abundant, most applications have been deemed successful. Ward and Slaney (1979) found boulders to be very effective in improving habitat conditions for juvenile steelhead trout (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch)* in the Keogh River on Vancouver Island, British Columbia. Significant increases in the abundance of both species occurred in improved sections of stream. Random rock clusters in channelized areas of the St. Regis River in Montana created mid-channel pools which provided good trout habitat (Schaplow, 1976 and Lere, 1982).

Channel Characteristics

Boulder placement is most effective in higher velocity areas that lack instream cover, i.e., within riffles and very shallow runs (Ward and Slaney, 1979; Payne and Copes, 1988). These should be placed in the thalweg, where the current is swiftest. Usually in the center half of the channel in straight reaches, and the outside half of the channel in bends. This will produce the best scour holes, and also insure that the rocks will not be left on dry land during periods of low flow (Barton and Cron, 1979). Generally, large rocks are effective only where velocities at medium flow exceed 0.6 to 0.9 m/sec (Barton and Cron, 1979; Nunnally and Shields, 1985).

In addition, channels should be characterized as having large gravel or cobble bed material. The substrate on which rocks are placed must be stable enough to prevent large rocks from being buried by undercutting. Braided, unstable sections should be avoided because durability of structures could be less than five years (Ward and Slaney, 1979). Randomly placed boulders are usually unsuccessful on streams with beds of sand and fine gravel (Nunnally and Shields, 1985). The placement of boulders in narrow channels with unstable banks or where diverted flow could cause erosion problems should also be avoided.

One reference does stand out in its attempt to provide guidance in evaluating the potential effectiveness of fish habitat improvement structures based on stream morphology and characterization. Rosgen (1996) developed a stream classification system based on stream morphologic and hydraulic characteristics. The applied stream classification system incorporates four levels into the geomorphic characterization, ranging from broad-based valley descriptions to detailed, quantified channel parameters.

Though a majority of Rosgen's (1996) analyses focus on the characterization of stream types, he does provide generalized rating guidelines to assist in evaluating suitability of various proposed fish habitat structures for a wide range of stream types. The main objective of the suitability guidelines is to bridge the gap between the"trial and error" methods and detailed hydraulic calculations for various installations.

Based on the author's applied stream classification system, boulder placement is rated excellent for two stream types. The two stream types, B3 and B4, are systems with channel gradients of 2-4 percent, width/depth ratios greater than 12, and sinuosities greater than 1.2. The sinuosity of a channel is defined as the stream length divided by the valley length. Both stream types are moderately entrenched, having an entrenchment ratio of 1.4 to 2.2. The entrenchment ratio describes the degree of vertical containment of the river channel and is computed by dividing the floodprone channel width at twice the maximum bankfull depth by the bankfull width. Type B3 streams have channel materials that are predominantly cobble with lesser amounts of boulders, gravel, and sand, whereas, type B4 streams have channel materials that are gravel dominated with lesser amounts of boulders, cobble and sand.

Type C3 streams are rated good. The C3 stream type is a slightly entrenched (entrenchment ratio greater than 2.2), meandering system with a channel slope of 2 percent or less, width/depth ratios greater than 12, and sinuosities greater than 1.2. Type C3 streams have channel materials that are predominantly cobble with lesser amounts of gravel and sand.

The lower gradient of these stream types provides more opportunity for bar development up and downstream of the boulder, unless placed in meander bends.

The afore mentioned channel types are most suitable for stream improvement utilizing random boulders. Their description and morphologic characteristics provide a frame work in which boulder placement is effective in producing instream fish habitat. Other stream types are rated from fair, to poor, to not applicable. In general, those channel types being rated fair require additional bank stability improvements or flow deflection to provide the flow conditions favorable for boulder placement, and the stream types being rated poor or not applicable are not suited for boulder placement.

Boulder Material, Size and Shape

Dense igneous and metamorphic rocks are preferable to sedimentary rocks such as sandstones and shales (Nunnally and Shields, 1985). Glacial and river boulders, talus fragments, quarry stone or large pieces of rock from the roadway excavation may be used for stream improvement. Angular rocks are more effective than rounded ones (Payne and Copes, 1988). Oblong boulders placed with the longest dimension perpendicular to the flow are most effective (Barton and Cron, 1979, Shields, 1983; Payne and Copes, 1988). Since exposure conditions are severe, only rocks of known durability should be used.

Boulder size will depend on stream size, flow characteristics, and bed stability. Random boulders should be sized to resist movement during high flow events (i.e., maximum velocities) but should be no larger in their greatest dimension than one-fifth of the channel width at normal summer flows (Barton and Cron, 1979; Shields, 1983). However, for channels that are steeper than 3 percent, some rocks may be as large as one third of the width to help dissipate some of the stream's energy (Barton and Cron, 1979). Barton and Cron (1979) also present suggested sizes for random boulder structures, which provide shelter and refugia for aquatic species. If the bottom is stable, a rock of 0.6 m diameter weighing about 450 kg will resist movement in current velocities up to 3 m/sec. A 1.2 m rock will be stable in velocities up to about 4 m/sec. Payne and Copes (1988) suggest using irregularly shaped large boulders having a volume of 0.67 m^3 or larger while Ward and Slaney (1979) recommend using somewhat smaller boulders (greater than 0.6 m diameter = 0.11 m^3 volume).

Boulder Cluster Placement and Pattern

Boulders can be placed either randomly or selectively, in clusters or individually (Barton and Cron, 1979; Wesche, 1985; Barton, 1980; Payne and Copes, 1988; Swales, 1989). Groupings often consist of upstream or downstream chevrons (V's). When placed in groups, Payne and Copes (1988) recommends leaving 2 to 3 m between individual boulders so that debris and sediments do not get trapped. Three to five boulders in a triangular configuration in staggered groups or clusters along the riffle or very shallow run appear to be most effective because each group guides turbulent "overhead cover" into a downstream group (Ward and Slaney, 1979). In steep channels, boulders may be placed in intermittent clusters to create "stair-step" pools (Nunnally and Shields, 1985).

Rocks are better habitat when they project above the surface during low and medium flows (Barton and Cron, 1979). Structures should be low enough so that their effects on the water surface profile will be insignificant at near-capacity discharges. Structures should be placed to avoid creating large areas of uniform conditions characteristics (Shields, 1983). As a rule of thumb, the maximum number of boulders placed should not exceed one per 27 m^2 of channel (Barton and Cron, 1979; Nunnally and Shields, 1985; Payne and Copes, 1988). A minimum spacing of three pool lengths between structures and a maximum pool length of five channel widths is recommended (Shields, 1983). The pool spacing lengths are based on pool and riffle spacings of unaltered rivers. Normally, boulder placement is not necessary when pool-riffle ratio exceeds 20 percent pools (Payne and Copes, 1988). The minimum and maximum pool spacing and pool-riffle ratio referenced by Shields (1983) and Payne and Copes (1988) are based on characteristics of undisturbed rivers and streams.

Bed Morphology

The two most common bed forms found near boulder clusters are gravel bars and scour pools (Cullen, 1991). Eddies existing in holes created downstream of boulder structures provide rest and feeding positions for aquatic organisms. Gravel deposits located downstream of the scour hole and, in some cases directly upstream of the structure, may provide suitable spawning gravels and food producing areas. Cullen (1991) analyzed the vortex mechanisms of local scour at modeled boulders. The author initiated this research because instream boulders, and the stream bedforms they create, are among the types of habitat used by both juvenile and adult salmonids. Preferred summer microhabitat for juvenile salmonids consists of deep water in conjunction with submerged cover. Boulder clusters can provide both deep water and cover when a scour pool is formed that undercuts the rock.

In a laboratory flume, Cullen (1991) used boulders of varying geometry to induce scour. He found that instream boulders create scoured areas in streams by increasing local water velocities near the substrate, which increases the local drag and lift forces that act on substrate grains. This high velocity, spiraling mass of water (a vortex) acts as the mechanism of local scour. Cullen (1991) concludes that the complexity of the local scour phenomenon arises from the hydraulic interaction among water flow, large roughness elements, vortices, and deformable substrate.

Fisher and Klingeman (1984) used laboratory flume studies, field experiments and field observations to search for evidence of quantifiable relationships between the variables involved in the scour process around boulder clusters. Flume studies were conducted in a 4.9 m long by 1.1 m wide by 0.5 m deep rectangular flat-bed flume with once-through flow. Median grain size comprising the bed was 1.5 mm. Runs consisted of establishing a uniform flow over the coarse sand bed and then placing a boulder on the bed surface. Two boulder sizes were utilized. The first boulder had a volume of 0.0018 m^3, height of 0.13 m, width of 0.19 m and length of 0.14 m. The second boulder had a volume of 0.0050 m^3, height of 0.17 m, width of 0.26 m and length of 0.23 m. Boulders were initially placed with their longest axis normal to the flow direction. Run durations were approximately 22 hrs. Flow depth varied from a depth which exposed the boulder tops to depths which submerged the boulders.

The scour patterns that developed in the flume experiments were horseshoe-and-wake types similar to those typically occurring at piers. The patterns showed scour around the leading edge of the rock, where the deepest scour occurred, and a series of successive scour and deposition zones (like ripples) forming a downstream "V" pattern with the rock at the apex. Deposition occurred downstream of the rock within the "V".

The authors found a similar pattern developed with the artificial rocks that were placed in Oak Creek, a small forest stream in western Oregon. The extent of the scour and deposition varied considerably, but the same general pattern as described in the flume study was evident in all cases. Natural rock placed in Tobe Creek, a small creek on the Oregon coast range, also induced a similar pattern of scour and deposition. In this case, the scour was not as evident but the deposition area was clearly defined.

Fisher and Klingeman (1984) used data from the flume studies to develop the following relationships:

$$D/D_{sm} = 0.026\,\mathbf{F}^{-2.61} \quad \text{with } R^2=0.80 \qquad (1)$$
$$D_{sm}/h_e = 0.306\,(V_s/V_r)^{0.459} \quad \text{with } R^2=0.83 \qquad (2)$$
$$V_s = 4.169\,D_{sm}^{1.911} \quad \text{with } R^2=0.91 \qquad (3)$$

where D = water depth (ft), D_{sm} = maximum depth of scour (ft), **F** = the Froude number, h_e = vertical height of rock (ft), V_s = volume of net scour (ft^3), and V_r = the volume of the boulder (ft^3). For the given coarse sand bed, with uniform flow and clearwater scour conditions, the authors make the following conclusions regarding boulders initially placed on a flat bed:

1) For a given water depth, the maximum scour depth varies with average channel velocity to the 2.61 power. Thus, if velocity doubles (as indexed by the **F**), the maximum scour will increase sixfold.

2) For a given velocity, scour depth is maximized at a single water depth. An increase or decrease in depth will cause a decrease in the maximum scour depth.
3) In general, the volume of scour varies with the maximum depth of scour to the 1.91 power. This relation may be dependent upon individual rock shape.
4) For a given velocity and boulder size, the volume of scour appears to be maximized when the ratio of water depth to rock height is between 0.4 and 0.6.
5) Individual fish rocks develop a horseshoe-wake scour pattern, with the maximum scour depth occurring at the upstream face of the rock. Deposition occurs immediately downstream of the rock.

Klingeman (1984) expanded on the research of Fisher and Klingeman (1984). The flume data and experimentation detailed in the previous paper were utilized in this paper. The author states that the maximum depth of scour compared to the volume of scour hole is dependent upon the size of the bed material. A nomograph showing the relationships of D_{sm} vs. V_s based on laboratory flume studies with bed sediment sizes of 1.5 and 6.8 mm was provided. It illustrates that for a given scour volume, the depth of scour was greater for the coarser bed sediment. It was also suggested that there is an upper limit to the volume of scour. A graph relating V_s/V_r vs. **F** indicated that for 0.34 m^3 boulders and 1.5 mm bed sediment, the a maximum V_s/V_r ratio was approximately 4.7 at a **F** of 0.25. The maximum V_s/V_r for 0.40 m^3 boulders and 1.5 mm bed sediment was approximately 2.0 at a **F** of 0.21. Froude numbers less than or greater than these values resulted in lower V_s/V_r ratios.

Further, Klingeman (1984) states that more of the scour volume occurs at the upstream side of the boulder than downstream. It was also observed that when severe scour first occurred, is caused the boulder to rotate upstream and to partially sink into the scour hole. Most likely due to the small bed sediment size as compared to the size of the modeled boulders.

St. Regis River Studies

Schaplow (1976) assessed the effects of stream channelization and habitat improvement structures on the St. Regis River, Montana. The study reach extended from the convergence of Borax Creek (approximately 5 km downstream from the St. Regis Lakes) to Saltese, Montana. Electrofishing techniques were used in sampling trout populations in unaltered, partially altered, altered with mitigating structures (step dams, random rocks, and jetties), and "old" altered sections. The step dams, random rocks and rock jetties were installed in 1972 and 1973. Mitigative devices (i.e., boulders and rock jetties) designed to alleviate the adverse effects of channelization were effective. Following two spring runoff events, Schaplow found that average trout populations in the mitigated sections were significantly greater in number and equal in weight when compared to unmitigated altered areas.

The author stated that morphological parameters, with the exception of thalweg deviation (the standard deviation of thalweg depths), suggest more trout habitat available in the random rock area than in the control and other mitigated areas. Scouring in the random rock section resulted in the greatest depth diversity in the study area. Pools in the control sections were spaced at 7.1 and 8.6 channel widths. Pools in the random rock section were spaced at 3.6 channel widths. Schaplow (1976) concluded that pools created around each boulder and rock jetty are probably the most important factor in maintaining trout populations in altered stream sections.

Lere (1982) evaluated randomly placed boulders, rock jetties, and log step dams that have been in Montana streams for at least five years. The author's objectives were to evaluate the changes in physical habitat associated with these improvement structures, to evaluate the persistence and integrity of these structures, and analyze the response of trout population to the habitats created by these structures. The author found that random boulders and rock jetties placed in channelized sections of the St. Regis River appeared to have restored habitat for cutthroat trout (*Salmo clarki*) and brook trout (*Salvelinus fontinalis*) populations. A 3 km reach of the St. Regis River located upstream of Saltese, Montana was studied. Total numbers of trout were least in a control section, greatest in a section mitigated with random boulders, and intermediate in a section mitigated with rock jetties. Sections with mitigative structures had greater pool frequencies than the control.

Boulders clusters created a pool frequency that was comparable to frequencies found in unaltered sections. Boulders were grouped in clusters that created a series of cascades and "stair-step pools" throughout a 455 m length of the study section located 2.5 km upstream of Saltese, Montana. Lere (1982) found that the number of boulders in the channel had not significantly changed since installation. However, the positions of these boulders had apparently been altered to some extent. The author did not provide a description of the altered boulder positions.

The expense of installing instream structures for enhancement and mitigation makes it imperative that placement produce effective and long-lasting results. Lere (1982) found the boulders installed in the St. Regis River were functionally stable 8 years following their installation. Twelve of the 18 rock jetties were functionally intact 7 years following installation. Lere (1982) stated that boulder stability is primarily a function of the boulder volume and size of the bed material upon which it is placed. However no guidance of proper boulder volume or bed material size was provided. Boulders utilized in this reach of the St. Regis River exceeded 0.6 m^3 and were placed on rubble bed material (89.8 percent of the bed material were greater than 6.4 cm).

Literature Summary

Attaining the requisite depth and velocity distributions to ensure a healthy aquatic ecosystem in modified channels often requires the use of instream boulder clusters; which, by virtue of their effect upon flow configuration, create depth and velocity diversity in an otherwise monotypic channel. A requirement of these features is that they facilitate "natural" channel conditions during low flow, but permit the channel to convey flood flows without an appreciable increase in depth.

A literature review was conducted to identify design guidance and instream restoration techniques utilizing boulder clusters. The literature review provides indicators of potentially successful methods and practices. The available design guidance utilizing boulder clusters to enhance aquatic habitat are briefly summarized in Table 1. It should be noted that the information in the table was derived from gravel bed stream projects.

Care must be taken when applying the guidelines presented in Table 1. The existing design guidance for instream features is largely biological in nature and of limited practical

Table 1. Summary of Boulder Placement Criteria (based on cited literature)

Design Parameter		Literature-Based Criteria	References (see footnotes)
Objective	-	increase instream cover, improve and restore pool-riffle and meandering patterns, and increase flow diversity	c, f
Stream Type	-	areas that lack instream cover, i.e., within riffles and very shallow runs	d, g
	-	wide, shallow, and high-velocity stream channels	
	-	avoid braided, unstable sections	g
Bed Composition	-	large gravel or cobble bottom types.	g
Stream Velocity	-	exceeds 0.6 or 0.9 m/sec	b, c
Boulder Type	-	angular igneous and metamorphic rocks	c, d
	-	rocks of known durability	
Stream Position	-	where the current is swiftest, usually in the center half of the channel in straight reaches, and the outside half in bends	b
	-	avoid diverting the current into soft or unstable banks	c
	-	project above the surface during low and medium flows	b
Pattern	-	placed either randomly or selectively, in clusters or individually	a, b, d, f, h
	-	a minimum spacing of three pool lengths between structures and a maximum pool length of five channel widths	e
	-	place oblong boulders with the longest dimension perpendicular to the flow	b, d, e
Size	-	not greater than one fifth the width of the channel at normal summer flows	b, e
	-	greater than or equal to 0.6 m in diameter	g
Frequency	-	one boulder per 27 m^2 of channel	b, c, d

a. Barton, 1980
b. Barton and Cron, 1979
c. Nunnally and Shields, 1985
d. Payne and Copes, 1988
e. Shields, 1983
f. Swales, 1989
g. Ward and Slaney, 1979
h. Wesche, 1985

use to the design engineer. Criteria that provide engineering guidance compatible with both flood conveyance and low-flow habitat enhancement objectives are lacking. A study by Fisher and Klingeman (1984) which was expanded on by Klingeman (1984) provided predictive correlations relating scour volume and maximum scour depth to boulder volume, boulder height and depth of flow. However, these correlations were developed in a sand bed flume and have not been verified by field analysis.

The lack of field-verified impacts of boulder size and placement on channel morphology and channel roughness results in a project designer relying on his/her experience or the successes and failures of other projects for guidance. Field-verified relationships are needed to expand the work of Fisher and Klingeman (1984) and quantify the impacts on channel roughness.

This research addresses two particular areas in the design and implementation of boulder clusters for stream rehabilitation that are lacking in current literature and design guidance. These two areas are: 1) the lack of field-verified predictive equations relating boulder cluster size/configuration and the resultant effects on bed morphology, and 2) the effects boulder clusters have on channel carrying capacity. The identification of an appropriate field site was required for these analyses. Additionally, detailed channel and boulder cluster surveys were required to quantify morphologic characteristics and resultant scour/deposition related to the cluster placement. This topographic data, in conjunction with detailed velocity measurements over a range of discharges, were required to quantify the channel hydraulic performance.

Chapter 3

DATA COLLECTION

Description of Study Area

The St. Regis River in west-central Montana, USA was selected as the field site to study hydraulic and geomorphic factors affecting boulder structure performance on a steep-gradient cobble-bed river system (Figure 1). The St. Regis River has its headwaters at the upper St. Regis Lake on the east slope of the Bitterroot Mountains in the northwestern corner of Mineral County, Montana, USA. The headwater is at an elevation of 1,707 m above mean sea level and the river flows southeasterly for 59 km to its confluence with the Clark Fork River at an elevation of 805 m above mean sea level near St. Regis, Montana. Mean annual, minimum, and maximum discharges measured near the town of St. Regis over a 17 year period ending in 1975 were 16.4, 1.2, and 273 m^3/second, respectively (U. S. Geological Survey, 1976). A channel forming discharge was calculated at approximately 118.3 m^3/second using a two year return interval discharge (Q_{2yr}).

The narrow valley of the St. Regis River (Figure 2) has been used as a transportation corridor since the late 1800's. Much of the river has been channelized or encroached upon as a result of railroad and highway construction. The Montana Department of Transportation was required to place structures in various locations along an approximate 24 km reach of

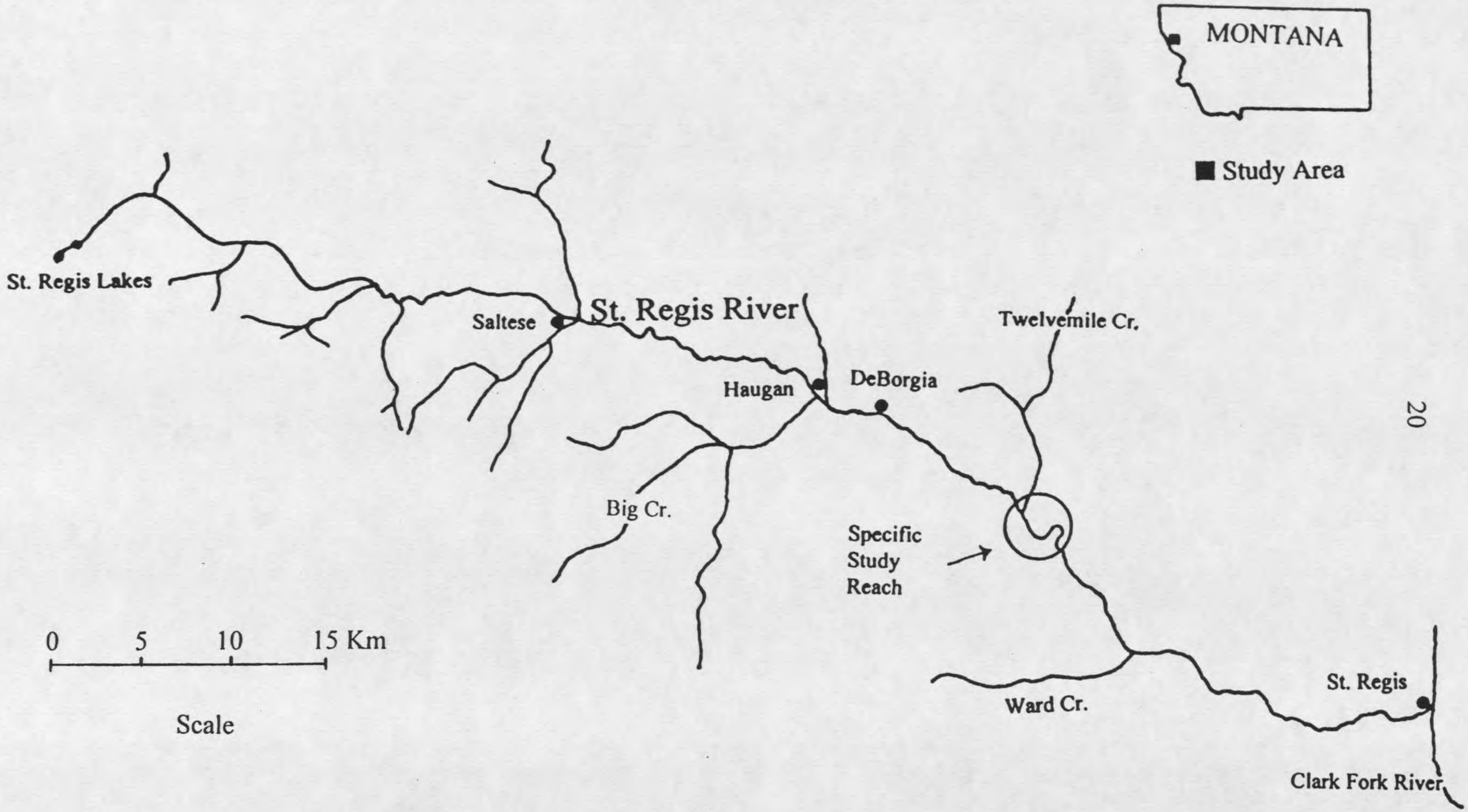

Figure 1. Map of St. Regis River, MT.