Field Evaluation of a Pool Sustainability Predictor in Gravel Bed Rivers

S. Parkinson[1], D. Caamaño[2], P. Goodwin[3], and R. Benjankar[3]
[1]U.S. Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho
USA
[2]EULA-Chile Center for Environmental Research
University of Concepcion
Concepcion
CHILE
[3]Center for Ecohydraulics Research
University of Idaho, Boise
Boise, Idaho
USA

E-mail: sparkinson@usbr.gov

Abstract: *Velocity reversal in pool-riffle sequences has been postulated as the primary mechanism for sustaining pools in gravel-bed rivers. Recent criteria have been developed to predict the occurrence of velocity reversal for a wide range of data published in the literature, but it is unclear whether velocity reversal will sustain pools under all field conditions and what the exceptions might be. The results of a 12-year geomorphic monitoring program in the South Fork Clearwater River in Idaho, USA are presented. This monitoring program incorporates river restoration projects that span five different restoration design approaches. The restored, degraded and protected reaches have each responded differently during the past decade providing a rigorous test of the pool sustainability criterion. The monitoring program showed that if the criterion is applied using post-restoration channel conditions, then a good correlation was achieved between the occurrence of velocity reversal and pool persistence, formation or disappearance. Exceptions were noted for forced pools created by constructed features such as grade control structures, as a result of local conditions caused by woody debris or constrained channel geometry.*

Keywords: *river, restoration, pool, riffle, velocity reversal.*

1. INTRODUCTION

1.1. Overview

The cross section characteristics of a river at any location along the watercourse, are a function of the flow, the quantity and character of the sediment movement and the character or composition of the materials making up the bed and banks of the channel (Leopold et al. 1964; Knighton, 1998; Federal Interagency Stream Corridor Restoration Working Group, 1998). Pool-riffle sequences are one of the river reach morphologies created by these interactions. Many habitat restoration projects attempt to restore pool morphology in a dynamically sustainable, minimal maintenance manner.

A hypothesis to explain the persistence of pools has been that of 'velocity reversal' (Keller and Florsheim, 1993). A recent study developed simple criterion that unifies and explains previous disparate findings regarding the occurrence of velocity reversals (Caamaño, 2009). The criterion is based on a simple 1-d analysis and is intended to use measurements that can easily be collected in the field. Preliminary results show that reversal is critically dependent on the ratio of riffle-to-pool width, residual pool depth (difference between pool and the downstream riffle thalweg elevations) and the depth of flow over the riffle (Caamaño et al., 2009).

In this study, the simple criterion was compared to results from the 10th Anniversary monitoring of the Red River Restoration Program conducted by the authors in collaboration with the Idaho Department of Fish and Game, US Forest Service (Nez Perce Forest), Nez Perce Tribe, US Bureau of Reclamation, US Fish and Wildlife Service, and NOAA National Marine Fisheries Service in October 2010. The restoration site had a broad range of field conditions and the criterion was tested against these different conditions to determine the accuracy of this equation for assessing pool habitat vulnerability within a stream. If successful, the criterion can be used as a valuable design parameter for professionals and resource managers involved in restoration projects. The intent is to produce guiding principles for design that are concise and easily understandable by engineers, scientists and interested stake-holders in the development of sustainable pools in gravel-bed rivers. The approach can also be used to determine whether the current condition of a pool is likely to persist.

1.2. Theoretical Background

This analysis builds on the foundation of pool-riffle sustainability mechanisms developed by Caamaño (2009). Caamaño presented criterion that could predict velocity reversal in the one-dimensional sense and compared the simple 1-d formulation with 3-d flow measurements and numerical simulations for two pool-riffle sequences at the Red River Wildlife Management Area. Further, he explored the hypothesis that velocity reversal is the primary process for ensuring the persistence of pool riffle morphology.

The simplest form of the Caamaño model may be expressed as:

$$\frac{B_R}{B_P} - 1 = \frac{Dz}{h_{Rt}} \qquad (1)$$

The full derivation is available in Caamaño et al. (2009). The following symbols (Figure 1) are used:

z_{Pt}, z_{Rt} = pool and riffle thalweg elevations.
h_{Pt}, h_{Rt} = pool and riffle thalweg water depths.
B_P, B_R = pool and riffle water surface widths.
D_z = residual pool depth defined as the difference between the pool and riffle thalweg elevations (z_{Rt} - z_{Pt}).

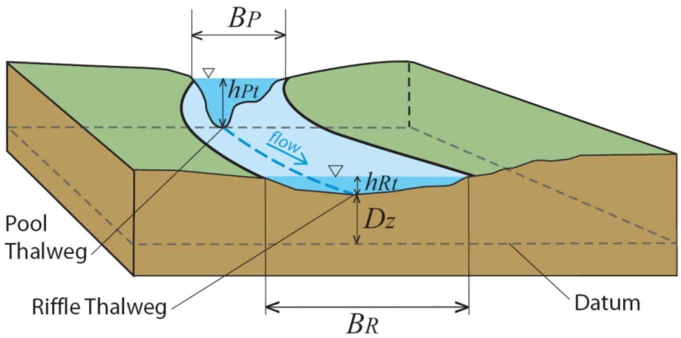

Figure 1. Definition of symbols used in the pool-riffle sequence

At low flows, the velocity across the riffle exceeds the velocity through the pool. Velocity reversal, of when the velocity on the pool exceeds the velocity across the riffle is predicted to occur when $B_R/B_P - 1 > D_z/h_{Rt}$. For a given width ratio (B_R/B_P) and residual pool depth (Dz), the water depth over the riffle thalweg (h_{Rt}) will indicate the critical condition when the average velocity across the riffle is equal to the average velocity through the pool, with deeper flows required for reversal. In addition, the riffle must be wider than the pool (B_R/B_P > 1) for velocity reversal to occur.

2. FIELD SURVEY

2.1. Study Reach Description

The Red River is located in north central Idaho and forms the easternmost tributary to the South Fork Clearwater River. The restoration project at the Red River Wildlife Management Area (RRWMA and managed by Idaho Department of Fish and Game), was part of the Northwest Power and Conservation Council's Columbia Basin Fish and Wildlife Program (FWP) (1994, 2000) and funded by the Bonneville Power Administration (BPA). As part of the FWP, the project was one of BPA's many efforts at off-site mitigation for damage to salmon and steelhead runs and wildlife habitat caused by the construction and operation of federal hydroelectric dams on the Columbia River and its tributaries.

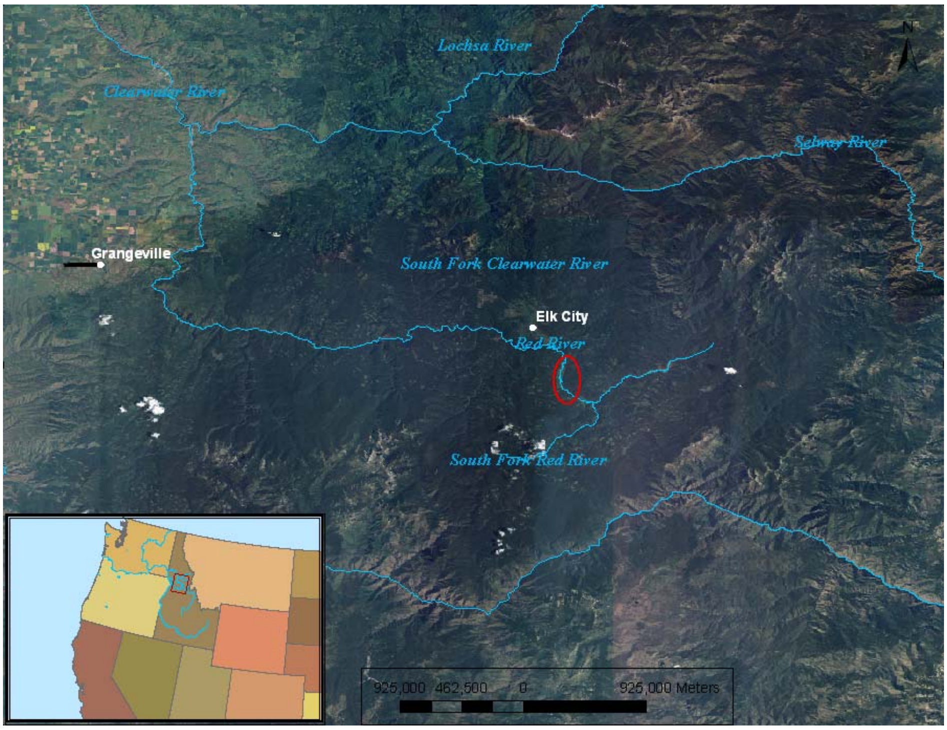

Figure 2. Location Map of the Red River Wildlife Management Area

The restoration of the RRWMA was a multi-phase endeavor that restored natural physical and biological processes in an effort to stop the trend of incision, reduce the rates of channel bank erosion to historic levels, restore the channel sinuosity and morphology to conditions of dynamic equilibrium, reestablish native riparian plant communities, and enhance the quantity and quality of fish and wildlife habitat. Several decades of human disturbances in the watershed and meadow (including artificial straightening by instream mining) had resulted in the degraded condition of the river and its associated fish and wildlife habitats (Klein et al., 2007).

2.2. Objectives

While Reclamation has designed various stream restoration projects, few field measurements under post-construction conditions have been performed. An opportunity existed to conduct an on-site survey and analyse the 10-year post-restoration monitoring data of the RRWMA. The RRWMA has also been one of the most comprehensively monitored sites in the Columbia Basin (Marmorek et al., 2002). Previous surveys of the lower meadow delineated locations of fish habitat features (pool, riffle, glide, and run). The goal of this study was to supplement the annual monitoring program by comparing the channel condition immediately post-restoration and October 2010. This comparison identified newly formed pools, pools that had disappeared over the last ten years, as well as pools that had shown little change. In addition, three new pool-riffle features were surveyed. The Caamaño criterion was applied to each of the pool locations. Thalweg elevations and bankfull depths were estimated from previous surveys in 2004. Pool and riffle widths were determined from aerial photographs of the site, supplemented by the cross-section monitoring program if the cross-sections still coincided with the pool and riffle location. Inherent in the implementation of these criteria was judgement in defining the pool or riffle width alignment. This process was considered to be typical of information that may be available for an initial assessment of a stream restoration project with limited information or data. The outcome of this exercise was to demonstrate the practical applicability of the criteria and ascertain whether additional refinement or qualifications are required.

3. RESULTS

The 2010 surveyed pool-riffle and habitat features in the lower meadow are shown in **Figure 3**. However, one pool riffle feature was surveyed in the upper meadow of the Red River and is not shown. There were three types of pools identified in the survey:

I. Pool has persisted since the full post-restoration survey of 2004.
II. Pool existed at the completion of the restoration project but has since disappeared.
III. Pool did not exist at the completion of the restoration project, but has self-formed in the past decade.

In addition, the pools were classified into U (unforced pool) and F (pool created by a constructed feature such as a grade-control structure or bank stabilization).

Figure 3. Lower Red River Meadow restoration project phases I – IV.

Pools located downstream of engineered structures tend to be very localized scour features at RRWMA and not all of these pools are included in Table 1 since the forcing is considered outside the basic assumptions in the pool sustainability analysis. The two features that were surveyed fully were selected because the first pool had been in existence for a minimum of 10 years. A clay lens appeared to be confining the channel and contributing to the pool-riffle sequence. The second pool-riffle sequence surveyed had been classified as a glide in 2000 and then identified as a pool in 2004.

Figure 4. Historic S-Curve pool riffle sequence locations.

Figure 4 illustrates the location of cross-sections used to apply the pool sustainability criterion through a series of historic bends (Historic S-Curve) that were reconnected in the stream restoration implementation. These curves followed the historic channel alignment but the cross-sectional area was intentionally less than the predicted dynamic equilibrium cross-section at the time of construction to see how the channel would evolve naturally. The pool sustainability criterion was applied to both the surveyed pools and all the pools that were visually observed to have changed since 2000. In these visually observed pools, the 2004 channel bathymetry was used in eqn. 1 to determine if velocity reversal would occur, as the 2004 condition would have initiated the change in the channel. The 2010 observations were used to confirm the predicted response of the channel assuming the occurrence of velocity reversal (eqn. 1) would result in the persistence or creation of pools.

A total of 17 pools were considered, 16 in the lower meadow and one forced pool in the upper meadow. Table 1 shows there are 6 unforced pools (Type I-U) that have persisted for the past 10 years and velocity reversal is predicted to occur in all these cases using 2004 bathymetry. Velocity reversal does not occur in the two forced pools (Type I-F) that have persisted during this same period. This finding indicates that pools forced by a constructed feature or a local natural constriction allows a pool to be sustained without velocity reversal having to occur. For the 3 pools that disappeared since the restoration project (Type II), none predicted velocity reversal using 2004 channel bathymetry. This finding would support the hypothesis of Keller and Florsheim (1993) that velocity reversal is a necessary condition for the sustainability of unforced pools. For the six pools that appeared in the meadow since 2004, two were forced pool created by erosion around a grade control structure or channel constriction created by bank stabilization measures (Type IIIF). Two of the four new pools (Type III-U) met the eqn.1 criterion using 2004 bathymetry indicating that eqn. 1 has some power to predict that pools will form if the cross-sectional characteristics of the channel indicate that velocity reversal will occur at or before bankfull discharge is reached. There are three cases of a new Type III-U pool being formed that did not meet the velocity reversal criteria. One was the ‘surveyed pool riffle sequence 2’ in Table 1. In this case, it is possible that this pool has migrated downstream from ‘pool-riffle sequence absent’ location shown in Table 1. This could be a channel response created by the large pool and 90-degree channel bend at the upstream boundary of the project site. A complex flow structure has been observed at high flows in this local area and may have forced the secondary pool to migrate downstream to the location identified in 2010. The other case of a new pool being formed without velocity reversal occurring is in the historic S curve, where an old back channel was reconnected to create the restored main channel and the channel cross-section does not yet convey the design bankfull discharge used elsewhere in the restoration project. The other example of a pool formed without velocity reversal occurring is at Heevey Bend 2. This area has experienced significant deposition on the point bar since 2004 but additional survey data will be collected in 2011 for all these new pools, particularly to assess the trend of the reversal criteria (toward or away from the line) and the potential influence of sediment flux on this dynamic.

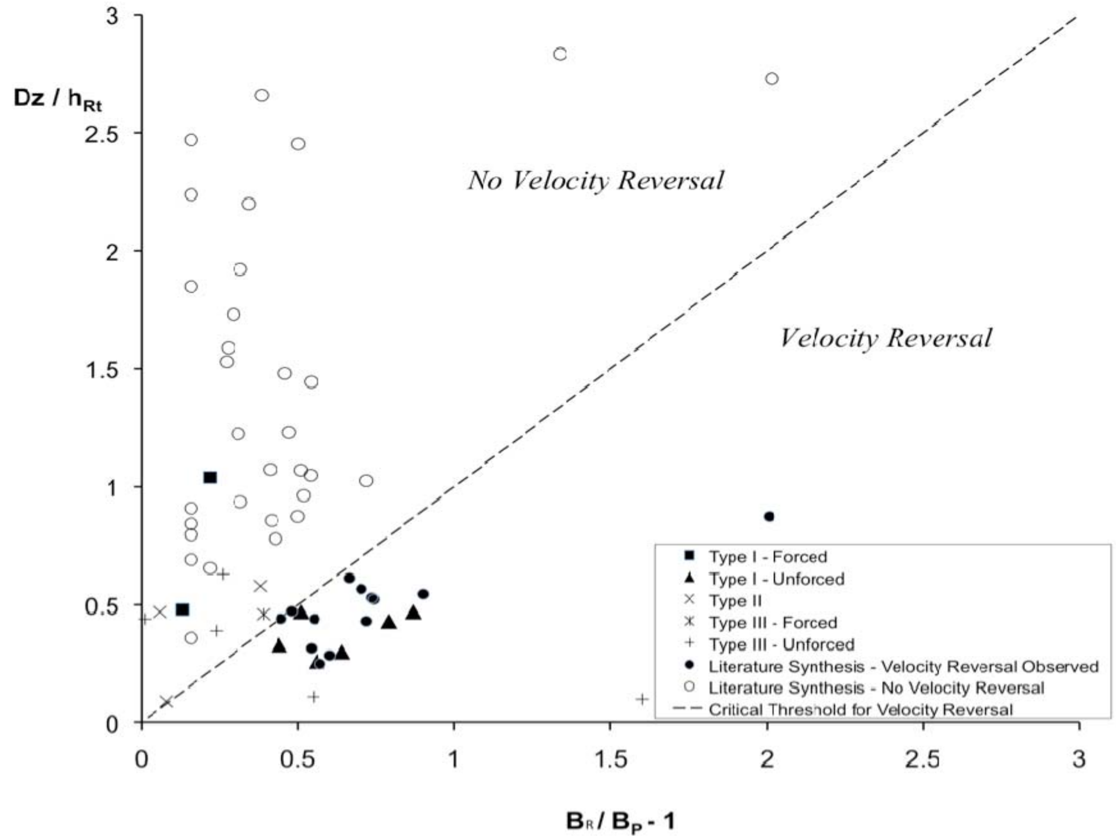

Figure 5. Graphical result of applied reversal criteria to 2010 surveys and observations (adapted from Caamaño et al., 2009)

4. CONCLUSIONS

The 10 years of annual monitoring at the RRWMA allows the trends of channel evolution to be tracked and the original performance criteria of the design to be assessed. One of the elements of this assessment program has been to track the channel evolution toward its projected dynamic equilibrium form and thereby restore the natural hydroperiod characteristics of the floodplain. This paper presents the monitoring results for just one of the multiple objectives – the sustainability of pools throughout the meadow.

The results for the Upper and Lower Red River Meadows, indicate that forced pools may be sustained without velocity reversal occurring. Since the Red River is a supply limited system the existence and persistence of forced pools becomes a function of the structure that created them and whether the local flow structure is such that sediment does not accumulate in the pool.

In unforced pools, the existence of pools is subtle since the channel form can adjust to the prevailing flow and sediment transport conditions. The persistence of pools depends on whether the flux of sediment through the pools exceeds the flux of sediment through riffles and runs under certain flow conditions, thus allowing the pools to scour out sediments deposited since the last high flows. The 17 pools analyzed here indicate that the occurrence of velocity reversal appears to be a good indicator of whether pools will persist or even form in unforced conditions. Additional data will be collected during the 2011 field season. Particularly of interest are the dimensions of the new and existing pools that indicate non-reversal characteristics. The value in obtaining more detailed survey information on these sites will be to further assess the behavior of the reversal trends and sediment flux characteristics. These results also demonstrate the value of a simple indicator (eqn. 1) for predicting whether pools will persist in a dynamic river system.

Table 1. Status of Pools at Red River, October 2010. Pools are listed from upstream to downstream.

Pool Location	$B_R/B_P – 1$	D_z	h_{Rt}	D_z/h_{Rt}	Reversal (yes/no)	Pool Status identified in 2010 Field Monitoring
Upper Meadow (2010 survey)	**0.13**	0.43	0.90	**0.48**	No	Type I-F
Phase I boundary Surveyed pool-riffle sequence 1 (2010 survey)	**0.22**	4.26	4.10	**1.04**	No	Type I: pool considered constrained by clay lens
Pool-riffle sequence absent	**0.06**	1.8	3.86	**0.47**	No	Type II: 2004 survey indicated pool formation
Surveyed pool riffle sequence 2 (2010 survey)	**0.26**	2.01	3.18	**0.63**	No	Type III: 2001 survey indicated a glide, 2004 survey and 2010 site visit indicates pool formation.
Goose Island	**0.64**	1.03	3.4	**0.30**	Yes	Type I: existing pool, stable since 2001
Phase II boundary	**0.39**	1.52	3.3	**0.46**	No	Type III-F: 2001 survey indicated a glide. The new pool is located at beginning of Phase II construction
Historic S-Curve 1	**0.56**	1.28	5	**0.26**	Yes	Type I: existing pool, appears stable
Historic S-Curve 2	**0.38**	2.43	4.17	**0.58**	No	Type II: 2001 survey indicated a glide, 2004 survey indicated a pool feature. 2010 site visit noted lack of pool feature
Historic S-Curve 3	**0.24**	1.63	4.13	**0.39**	No	Type III: 2010 site visit noted shallow pool feature
Mirror Bend	**0.44**	1.8	5.44	**0.33**	Yes	Type I: existing pool appears stable
High Back Bend	**0.87**	1.84	3.89	**0.47**	Yes	Type I: existing pool appears stable
Little Ponderosa	**1.60**	0.45	4.48	**0.10**	Yes	Type III-U: new pool feature in 2010 site visit
Heevey Bend 1	**0.55**	0.6	5.3	**0.11**	Yes	Type III-U: new pool feature, 2010 site visit
Heevey Bend 2	**0.01**	1.8	4.1	**0.44**	No	Type III: new pool feature, 2010 site visit
Chinook Bend	**0.79**	2.2	5.1	**0.43**	Yes	Type I: existing pool, appears stable since 2004
Camas Bend	**0.08**	0.6	7	**0.09**	No	Type II: new pool noted in 2004 survey, 2010 site visit noted lack of pool feature.
Pool Riffle 1 – Caamano, 2009	**0.51**	2.6	5.5	**0.47**	Yes	Type I: existing pool appears stable

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