



Unintended consequences of restoration: Loss of riffles and gravel substrates following weir installation

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ABSTRACT

We used pre- and post-restoration channel surveys of the Donner und Blitzen River, Oregon, to evaluate the effects of grade-control structures on channel morphology and baseflow habitat conditions for native redband trout and other aquatic biota. Six years after installation, we found that the channel had a smaller proportion of riffles and pools and less gravel substrate, combined with an increase in the proportion of flat waters and consolidated clay on the bed surface. Both local scour downstream from weirs and backwater effects upstream from weirs appear to have caused the general flattening and fining of the channel. A direct-step backwater calculation indicates that backwaters extended to the upstream weir at both low and high flows, creating long sections of flat water separated by short, steep drops. Despite backwater effects, a comparison of longitudinal profiles before and six years after weir installation showed bed erosion downstream of nearly all weirs, likely a consequence of the cohesive clay material that dominates the channel bed and banks. A deep inner channel reflects the cohesive nature of the clay and the mechanisms of abrasion, and indicates that sediment load is low relative to the transport capacity of the flow. Unfortunately, weirs were problematic in this system because of the cohesive clay substrate, limited sediment supply, and low channel gradient. Although deeper flows due to backwaters might be more favorable for resident trout, less gravel and fewer riffles are likely to negatively impact trout spawning habitat, macroinvertebrate communities, and biofilm productivity. Our results demonstrate the potential limitations of a single-feature approach to restoration that may be ineffective for a given geomorphic context and may overlook other aspects of the ecosystem. We highlight the need to incorporate geomorphic characteristics of a system into project design and predictions of system response.

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1. Introduction

Grade-control structures, such as rock weirs, are commonly installed to control channel incision and increase pool frequency, potentially improving instream fish habitat. Several studies have shown that weir overflow can cause local erosion downstream from weirs (e.g., Bormann and Julien, 1991; D'Agostino and Ferro, 2004; Doddiah et al., 1953; Rouse, 1940). In some incised streams, local erosion downstream from weirs can enhance physical heterogeneity and increase fish diversity and abundance (Winger et al., 1976; Knight and Cooper, 1991; Shields and Hoover, 1991). However, Shields et al. (1998) showed that an increase in pool area and volume may not increase habitat diversity if the substrate is

homogenous or if too many pools are formed, resulting in the loss of other habitat types. Weirs may be problematic in channels with cohesive substrates or low gradients. Channels cut into bedrock or consolidated clay are prone to incision and the formation of deep inner channels (Wohl and Ikeda, 1997; Johnson and Whipple, 2007), and a shallow channel gradient results in extensive backwaters upstream from weirs. An increase in deep, flat areas may be ecologically detrimental if there is a compensating loss of riffle or pool tail habitats, which are important for instream primary production (Cardinale et al., 2002), macroinvertebrate diversity (e.g., Duan et al., 2008), and spawning fish that prefer shallow, high-velocity areas of loose gravel substrate (e.g., Muhlfield, 2002). Ecological benefits of this restoration strategy therefore depend on geomorphic characteristics of the system, including channel substrate and gradient.

We studied the impacts of weirs on instream habitat in a section of the Donner und Blitzen River (hereafter referred to as the Blitzen River), Oregon, a low-gradient channel dominated by a consolidated

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clay substrate overlain by a thin cover of gravel and sand. Rock weirs were installed on the Blitzen River in 2002–2003 with the goal of improving instream habitat for redband trout (*Onchorynchus mykiss gairdneri*) by increasing topographic variability and wood recruitment (USFWS, 2001). We use pre- and post-restoration surveys to assess the impact of weirs on baseflow habitat conditions and evaluate how a low channel gradient, cohesive substrate, and thin gravel cover affect channel change.

2. Study site

The Blitzen River is located in Harney Basin, southeastern Oregon (Fig. 1); the river drains from Steens Mountain (elevation 2967 m) approximately 97 km northward to Malheur Lake (elevation 1265 m). The Blitzen River provides habitat for one of the few intact migratory populations of native redband trout in Oregon's Great Basin and may be the only drainage in the region that supports an adfluvial life history of redband trout (Bowers et al., 1999; CRFPO, 2005). The Blitzen River is also the main source of water to the Malheur National Wildlife Refuge, one of the oldest wildlife refuges in the western United States and a crucial resting ground for migratory waterfowl.

Harney Basin is a hydrologically closed watershed at the northern edge of the Basin and Range (Baldwin, 1981). The geology of Harney Basin is characterized by a thick sedimentary cover over Miocene–Pliocene volcanics. Extensive Miocene basalt flows formed a broad, virtually uniform land surface. Harney Basin developed as a topographic feature in the late Miocene to Pliocene, probably as a result of faulting and structural downwarping (McDowell, 1992). Subsequent ash-flow tuff eruptions buried most of the basin with extensive but thin deposits. In some places, these silica rich rocks have been eroded and their detritus now forms fine-grained fluvial and lacustrine sediments (Piper et al., 1939). Overall, the Pliocene was characterized by infilling of pre-existing

relief with fluvial and lacustrine deposition that later became tuffaceous sandstones, siltstones, and pebble conglomerates (Greene et al., 1972). Some of the tuffaceous sedimentary rocks were diagenetically altered to bentonitic clay minerals, zeolites, and potassium feldspar (Walker and Swanson, 1968), particularly where sediments were deposited in ancient lakes. In the mid- to late-Pleistocene, the alluvial basins filled with alluvial fans and fine-grained lacustrine deposits. Melting glaciers on Steens Mountains during the late Pleistocene formed extensive stream networks that carried coarse-grained glacial deposits into the Blitzen Valley (Smith, 1927). Today, these fluvial sand and gravel deposits dominate the basin margins, while lacustrine deposits dominate the central part of the basin (Leonard, 1970). Lacustrine deposits are composed of semi- to well-consolidated clay, silt, and minor amounts of peat and volcanic ash layers (Leonard, 1970). In the study section of the Blitzen River, the channel is composed of consolidated clay with a thin alluvial cover and sediment supply of loose silt, sand, and gravel.

Climate of the Blitzen valley is arid to semi-arid; mean annual precipitation ranges from approximately 25 cm in the valley to 130 cm on Steens Mountain (NRCS, 2006). Thunderstorms generally occur between July and August. The highest elevation parts of Steens Mountain are typically covered with snow from late October to June or July. Timing of floods depends on climatic conditions, occurring in mid-winter or early spring from rain-on-snow events or late spring/early summer during the main period of mountain snowmelt. Before settlers began controlling flows in the early 20th century, inundation of the valley during spring floods created large natural seasonal wetlands (USFWS, 1996). Today, streamflow is controlled by an extensive distribution system of dams, reservoirs, canals, and water control structures that facilitates irrigation and maintenance of wetlands.

Water management and irrigation in the Blitzen Valley is designed to provide riparian and floodplain habitat for refuge

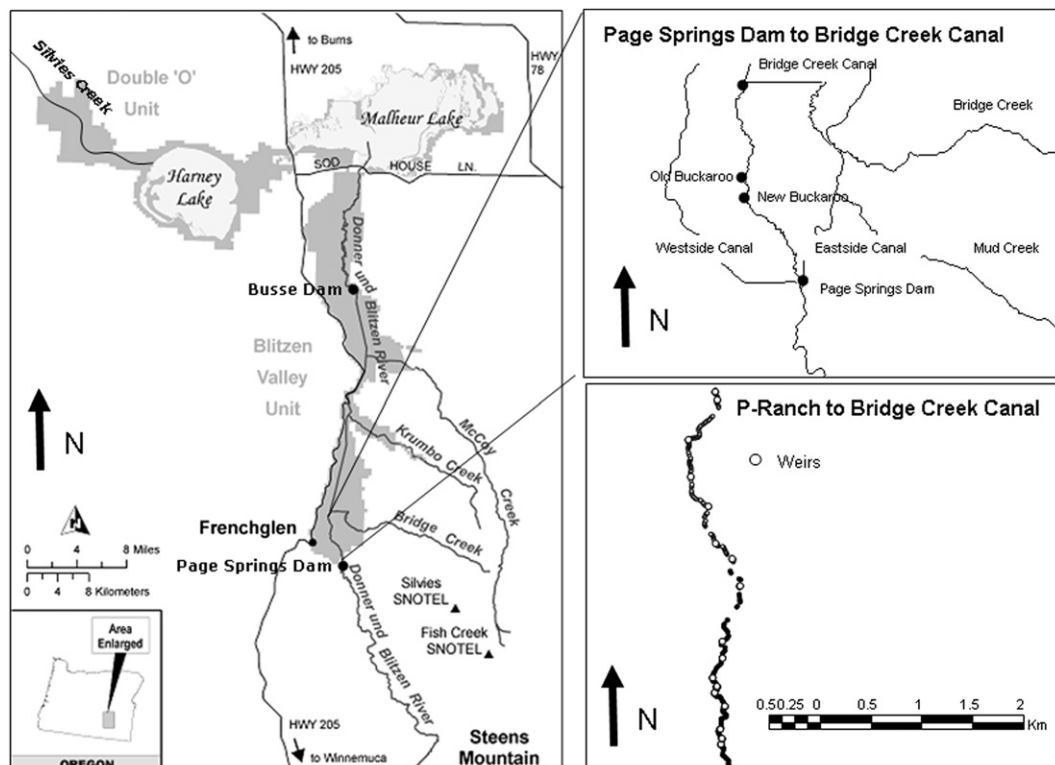


Fig. 1. Map of study site and locations of weirs along section from New Buckaroo Dam to Bridge Creek Canal, Donner und Blitzen River, Oregon.

wildlife (USFWS, 1996, 1998). At the upstream boundary of the refuge, Page Springs Dam (drainage area $\sim 540 \text{ km}^2$) diverts water from the Blitzen River into the Eastside and Westside canals (Fig. 1). Water in the main channel flows from Page Springs Dam northwest to New Buckaroo Dam, where it can be diverted or continue to Old Buckaroo Dam, where diversions occur only at high flows. Approximately 3 km downstream from Old Buckaroo Dam, the river is channelized for $\sim 29 \text{ km}$ between Bridge Creek Canal and Busse Dam. During low flows, diversions to Eastside or Westside canals at the Page Springs Dam can remove up to 50% of the flow entering the valley. In low flow years, diversions occur at Page Springs Dam throughout the year to maintain wetlands and wet meadows. In high runoff years, diversions at both Page Springs and Old Buckaroo increase during peak flows to stabilize mainstem flows and prevent flooding. Otherwise, diversions only occur during spring, reflecting management efforts to maintain canal water levels during periods of moderate flow. The refuge regulates diversions in order to maintain discharges in the mainstem and East Canal for fish habitat (Tim Mayer, USFWS, personal communication).

From 2002 to 2003, 18 rock weirs were installed along a 9-km section of river between New Buckaroo Dam and the confluence with Bridge Creek Canal (Fig. 1). The primary goal of this project was to improve instream habitat for native redband trout (USFWS, 2001). Restoration activities were intended to enhance habitat heterogeneity by increasing bed scour and wood recruitment; wood recruitment was expected as a result of raised water surface elevations and improved riparian growth. Weirs were built where pools were expected to occur naturally. Rootwad revetments were installed at the head of pools to enhance scour and revetments and pole plantings were placed in areas where additional bank roughness was desired. All weirs had a common design (NRCS, 2000), with a maximum height of 1.2 m, a maximum cross-sectional width of 3.7 m, a downstream angle of 20° , and a minimum drop height at baseflow of 0.30 m.

3. Methods

We used three sources of pre- and post-restoration data to assess changes to instream habitat following weir construction: 1) visual habitat surveys, 2) bed and water surface profiles, and 3) bed substrate assessments. All data were collected along the section where weirs were installed, New Buckaroo Diversion to Bridge Creek Canal.

3.1. Pre-project data

We obtained an October 2000 habitat map from a field survey that was part of early restoration planning efforts (field visit by Bianca Streif, October 4, 2000, unpublished data). Visual assessments of pre-project instream and riparian habitat conditions were made, identifying the relative locations of bars and habitat units (“pools”, “riffles”, and “flatwaters”), the type and condition of riparian vegetation, and other distinctive habitat characteristics (e.g., large woody debris, sloughs, instream clay shelves). Specific characteristics of the different habitat unit types were not specified, so we only make qualitative use of this survey information. In our study, we define “pools” as concave depressions that span the thalweg and have a maximum depth of at least 1.5 times the tailout depth (Heitke et al., 2008); “riffles” as short, relatively shallow and coarse-grained sections of stream over which flows are fast and highly turbulent (Hawkins et al., 1993, Fig. 2A); and “flatwaters” as the low-turbulence sections intermediate in depth between riffles and pools, with either fast or slow flow, thus including what have previously been referred to as “sheets”, “runs”, and “glides” (Hawkins et al., 1993). In February 2001, the same reach was surveyed by an engineering team for construction planning.



Fig. 2. Photographs from A) July 2001 and B) November 2009 of the Donner und Blitzen River at a location approximately $\sim 2.5 \text{ km}$ upstream of Bridge Creek during baseflow conditions (photographs were not taken at exact same position in the two years).

A robotic total station and standard survey methods were used to record relative elevations of the bed, water surface, and bank top (Doug Ferguson P.E. L.S., Ferguson Surveying and Engineering, personal communication).

In July 2001, the Columbia River Fisheries Program Office (CRFPO) conducted the pre-project component of a multi-year study to evaluate biological and physical responses to weir installation. In addition to macroinvertebrate and fish population sampling, physical habitat parameters (depth, velocity, and substrate) were measured along 22 channel cross-sections immediately up- and downstream from proposed weir locations. The dominant substrate was identified visually and by touch at 50 evenly spaced points along each cross-section as “clay”, “silt” (0.004–0.06 mm), “sand” (0.06 mm–2 mm), “gravel” (2–64 mm), or “cobble” ($>64 \text{ mm}$), from which the percent of each substrate type was computed for each cross-section. The distinction between “clay” and “silt” was based on the strength and stiffness of the fine material. “Clay” was used for material that was stiff and resistant to touch, and commonly formed hard ledges within the channel. “Silt” was specified for loose, easily mobilized material (Sam Lohr, CRFPO, personal communication). Based on our field observations, the “clay” substrate is in situ consolidated Pleistocene lacustrine sediment, whereas “silt” is modern fine-grained sediment derived from upstream sources.

3.2. Post-project data

In November 2009, we identified all riffle units along the restored reach, as defined in Section 3.1; we did not include artificial weirs in the riffle count because their tall drop height, large substrate, and steep downstream face make them similar to boulder steps, which do not occur naturally in this section of river. We also visually characterized the dominant bed substrate at several locations along the reach. We surveyed bed and water surface elevations of the reach with a high-precision Topcon Hiper Pro GPS RTK surveying system, collecting survey points along the channel centerline at each change in topography. Because of high water depths, we were unable to survey the minimum bed elevation immediately downstream of weirs 7–12.

CRFPO repeated physical habitat measurements on the same cross-sections in 2005. Because of higher discharges during the 2005 survey (average discharge of cross-sections = 1.0 m³/s), we do not compare 2005 depth and velocity measurements with those from the 2001 survey (average discharge of cross-sections = 0.80 m³/s). We do, however, use substrate data from the 2005 survey to assess changes in bed conditions following weir construction.

4. Results and analysis

In the 2000 habitat survey, a total of 42 riffles, 41 pools, 39 flat waters, and 13 sand or gravel bars were identified along the ~4 km reach; eight of the bars were located in the ~1 km upstream of the Old Buckaroo Diversion. In most locations, riparian conditions were described as “fair” or “poor” with “no recruitment of willows.” The river had limited amounts of woody debris, willow growth, and high quality habitat. At four locations downstream of Old Buckaroo,

the channel had a “clay shelf” on both sides and a central “trench” that was classified as either a pool or flat water. In the 2009 survey, we found only four natural riffles. Long stretches of low-turbulence water dominated most of the reach, up- and downstream of each weir (Fig. 2B).

Comparing the 2001 and 2009 longitudinal profiles, we found additional evidence for a loss of riffles and an increase in flat water areas following weir installation. We determined the percentage of pools, riffles, and flat waters in each profile from water surface and bed surface slopes using habitat criteria. Between consecutive survey points, we computed the water surface and bed slope. We classified each section as a “pool”, “riffle”, or “flatwater” based on the following criteria: pools and flat waters both had water surface slopes less than bed surface slopes (Fig. 3A), but pools had the additional criteria of maximum depths >1.5 times the downstream tailout depth (Heitke et al., 2008). Therefore, what we called flat waters were often essentially shallower pools (Fig. 3B), though several were steeper gradient transitional sections between riffles and pools (Fig. 3A). We defined riffle sections as sections with water surface slopes equal to bed surface slopes (Lisle, 1982; Prestegard, 1982). We identified pool heads and tails visually from the profile, which occasionally corresponded with either a run or a riffle section. We combined adjacent sections classified as one habitat type into one habitat unit, unless separated by a weir. We excluded weir locations from the analysis. We summed the length of all sections classified as a given habitat type and computed the percentage (by length) of each habitat in 2001 and 2009. We found that riffles occupied 13% of the total length in 2001 and 10% in 2009, a decline of 20%. Interestingly, the proportion of pools also declined, from 71 to 63% – a 10% decrease. A decrease in the proportion of riffles and pools was balanced by a 65% increase in flat water areas, from 15 to 25% of the total length.

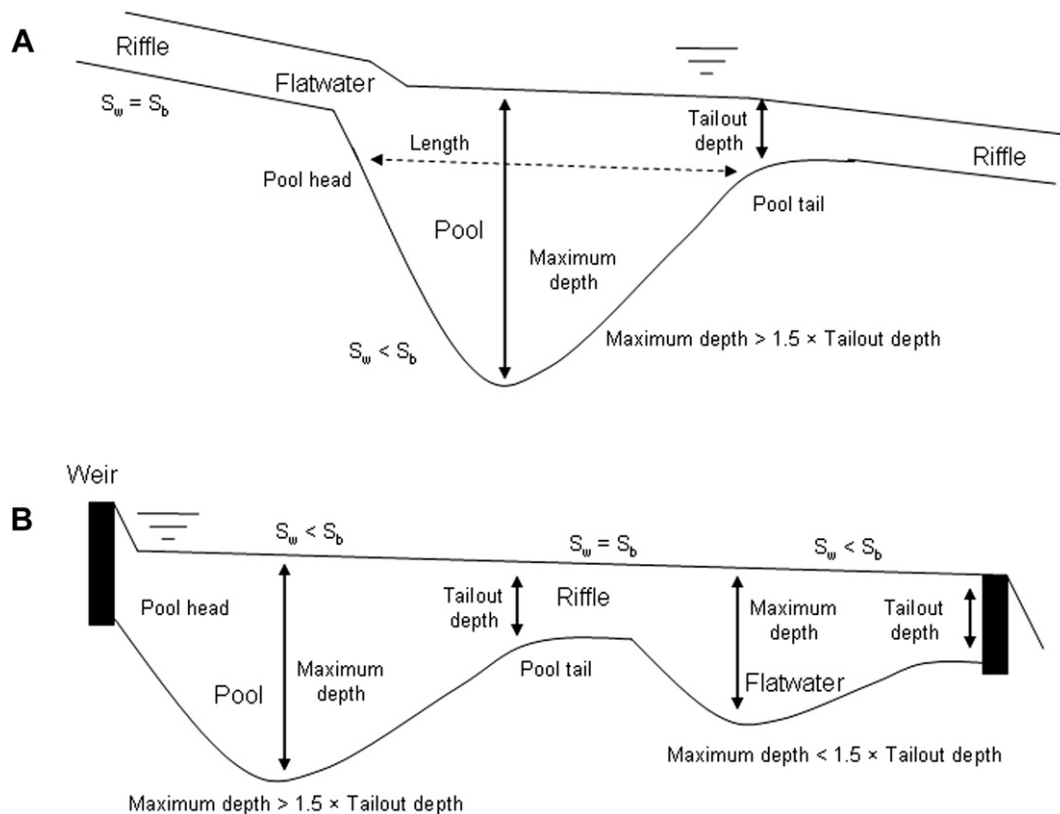


Fig. 3. Schematics illustrating how habitat units and pool geometry were determined from the longitudinal profile, including A) a typical riffle-run-pool sequence and B) the sequence commonly found on the Donner und Blitzen River, which had few short riffle sections and several long, deeper flat water sections (pools and runs). S_w = water surface slope; S_b = bed surface slope.

With the addition of weirs and increase in flat waters, the shape of the water surface profile has changed. We compared topographic variability of the two profiles by constructing hypsometric curves of the percent elevation lost versus percent downstream distance (Fig. 4). In 2001, 75% of the elevation loss occurred over 12% of the distance; in 2009, the same elevation loss occurred over only 4% of the distance, reflecting an increased number of sharp elevation drops (weirs) and long sections with little change in slope (flat water areas).

Changes to substrate conditions following weir installation reflected the loss of coarse-grained riffles. On the CRFPO cross-sections, the percentage of gravel and sand declined from 2001 to 2005, corresponding with an increase in both silt and clay (Fig. 5). On average, silt increased from 24% to 41% and clay increased from 46% to 55% due to exposure of the underlying lacustrine sediments. The percentage of clay downstream from weirs ranged from 20% to 100% in 2001 and increased at all but three of the locations in 2005, ranging from 50% to 78%. On average, gravel decreased from 29% to 13% and sand decreased from 8 to 0%. Clay substrates were also dominant at most locations along the channel in 2009 (Fig. 6).

Although weirs caused a shift in the proportion of habitat types, pool geometry did not change significantly. We tested for a significant difference between pool maximum depth and pool length (head to tail) in 2001 and 2009 with a Student's *T*-test; we considered a *p*-value < 0.01 to be significant. Average length (\pm SE) of pools was not significantly greater in 2009 (2001: 38.8 ± 3.4 m; 2009: 41.7 ± 4.7 m; $t = -0.49$, $DF = 108.4$, $p = 0.62$). Similarly, maximum pool depth was not significantly higher in 2009 (2001: 1.34 ± 0.68 m; 2009: 1.54 ± 0.05 ; $t = -1.92$, $DF = 81.94$, $p = 0.06$). We also tested for differences between the mean baseflow depth in 2001 and 2009 (Fig. 7); mean daily discharges were similar in February 2001 and November 2009 (~ 1.1 m³/s) so that flow depths could be compared. Despite fewer shallow riffles in 2009, mean flow depth was not significantly different between years (2001: 0.87 m; 2009: 0.93 m; $t = -1.47$, $DF = 340.7$, $p = 0.14$), likely due to the concurrent reduction in deep pools.

Two mechanisms may have led to the changes in pool-riffle structure and substrate composition following weir construction: local erosion downstream from weirs and backwater effects upstream from weirs. To estimate the extent of erosion, we calculated the change in the depth of pools downstream from weirs in 2001 and 2009. Although the exact position of the 2001 profile was unknown, we were able to match all riffle-pool sequences in the 2001 and 2009 profiles (Fig. 6) using the location and elevation of the Old Buckaroo rock drop (identified in both profiles). We calculated the mean depth of erosion for the pool downstream from

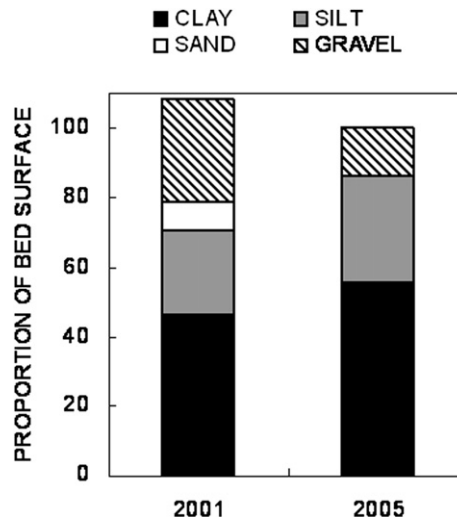


Fig. 5. Proportion of different particle size classes on the streambed before (2001) and after (2005) weir installation (2002–2003) on the Donner und Blitzen River. Error bars on columns are the standard error around the mean of 22 cross-sections.

each weir by dividing the area between the bed profiles by length of the eroded bed. Because we were unable to survey the bed elevation directly downstream from weirs 7–12 in the 2009 profiles, our estimates of erosion depth for these weirs was only a minimum. We determined the mean (\pm SE) erosion depth downstream from weirs to be 0.75 ± 0.19 m, but the change in depth ranged from -0.07 (indicating deposition) to 1.58 m (Table 1). Depth of erosion downstream from weirs depends on weir dimensions, channel width, flow conditions, and substrate type (Bormann and Julien, 1991; D'Agostino and Ferro, 2004; Doddiah et al., 1953; Rouse, 1940).

In addition, the backwater from the next downstream weir can reduce the maximum potential depth and length of erosion (Lenzi and Comiti, 2003; Marion et al., 2004). So-called “geometrical interference” has been evaluated in high-gradient channels, where structures are often built only a few tens of meters apart (Lenzi and Comiti, 2003). In contrast, weirs on the Blitzen River were ~ 60 –550 m apart (Table 1; mean \pm SE = 284.5 ± 34.6 m). A direct-step backwater calculation was made for each weir based on channel geometry, channel gradient, channel roughness, and weir dimensions (Chanson, 2004). Weir heights determined from our 2009 survey ranged from 0.56 to 1.42 m (Table 1). At baseflow (~ 1 m³/s), modeled backwaters for all 18 weirs extended to the

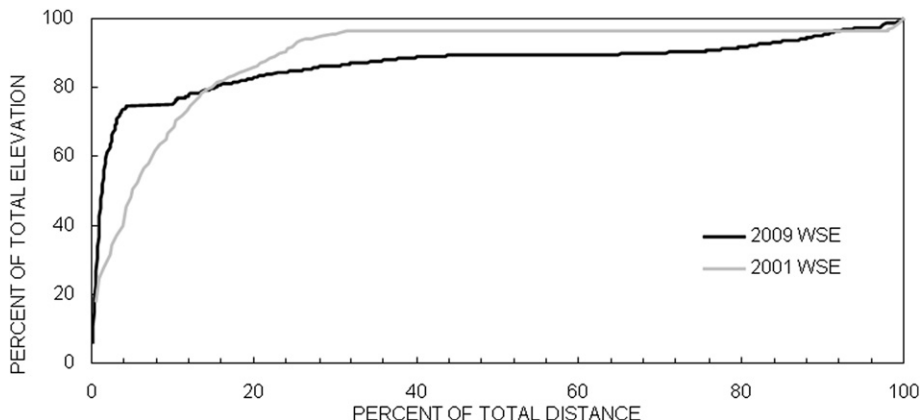


Fig. 4. Hypsometric curve of water surface elevation (WSE) loss along the channel from New Buckaroo Diversion to Bridge Creek Canal, Donner und Blitzen River, in 2001 and 2009.

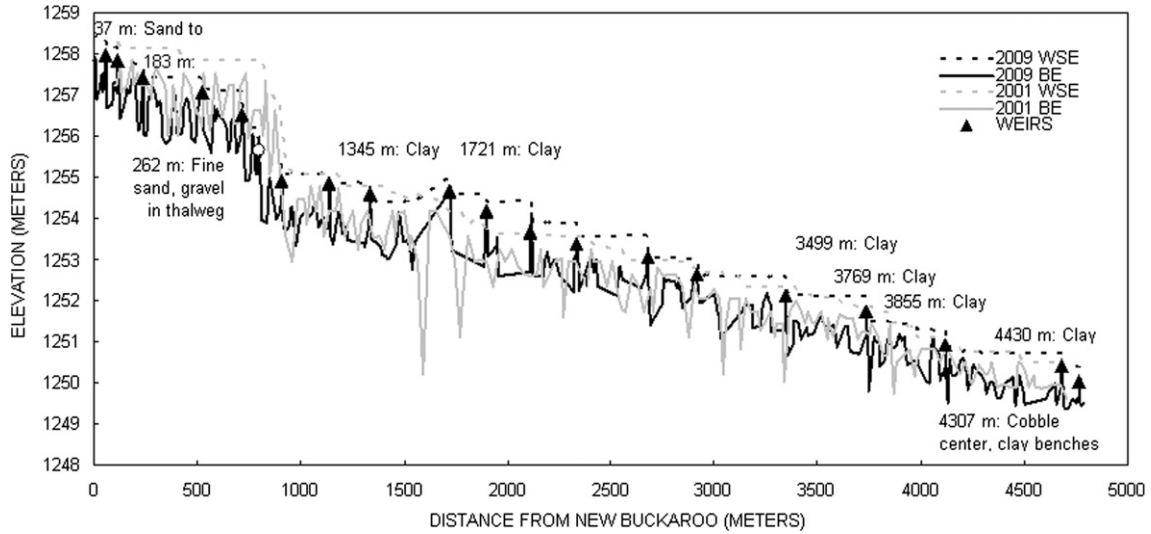


Fig. 6. Bed and water surface elevation profiles, locations of weirs surveyed in February 2001 and October 2009, Donner und Blitzen River, New Buckaroo Diversion to Bridge Creek Canal. Also indicated are the substrate conditions visually identified in 2009 at select locations along the channel. Open circle indicates the midpoint of the Old Buckaroo rock drop, where the two profiles were tied together. BE = bed elevation; WSE = water surface elevation.

upstream weir, with depths 10–400% greater than the normal depth (Table 1; 0.2–0.8 m). At the 2-year flood discharge of 41 m³/s (Salant et al., 2010), backwater depths at the upstream weirs were 3–60% greater than the normal depth (Table 1; 1.5–2.3 m). Because of the low channel gradient and relatively tall weir heights, a backwater extended to the upstream weir in all cases, for both baseflow and flood flow. These backwaters created long stretches of flat water evident in the 2009 longitudinal profile (Fig. 6) and habitat survey. Backwater effects at high flows may have reduced the extent of scour below tall weirs and/or between closely spaced weirs. We found that the depth of erosion decreased with downstream weir height, although this relationship varied due to different distances between weirs (Fig. 8).

The occurrence of floods prior to field observations could have caused short-term scour or fill that might mask or augment apparent

long-term changes in channel topography. To investigate this possibility, we analyzed flow records from a gaging station at the Old Buckaroo rock drop and found no record of any riffle-scouring flows prior to either the February 2001 or the November 2009 surveys. We estimated the discharge required to mobilize a D₅₀ of 23 mm (estimated from pebble counts on emergent bars, sampled in November 2009) with the Shields equation, channel slope from the surveys, and the relation between flow depth and discharge from measurements at the Old Buckaroo gage. Assuming a critical shear stress of 0.047 (Meyer-Peter and Müller, 1948), we computed a critical flow depth of 0.68 m and corresponding discharge of 3.0 m³/s. In the month prior to the 2001 survey, all flows were <3.0 m³/s; in the month before the 2009 survey, all flows were <1.5 m³/s (Shelley Fluter, USFWS, personal communication). We therefore expect that any short-term scour-fill effects were minimal.

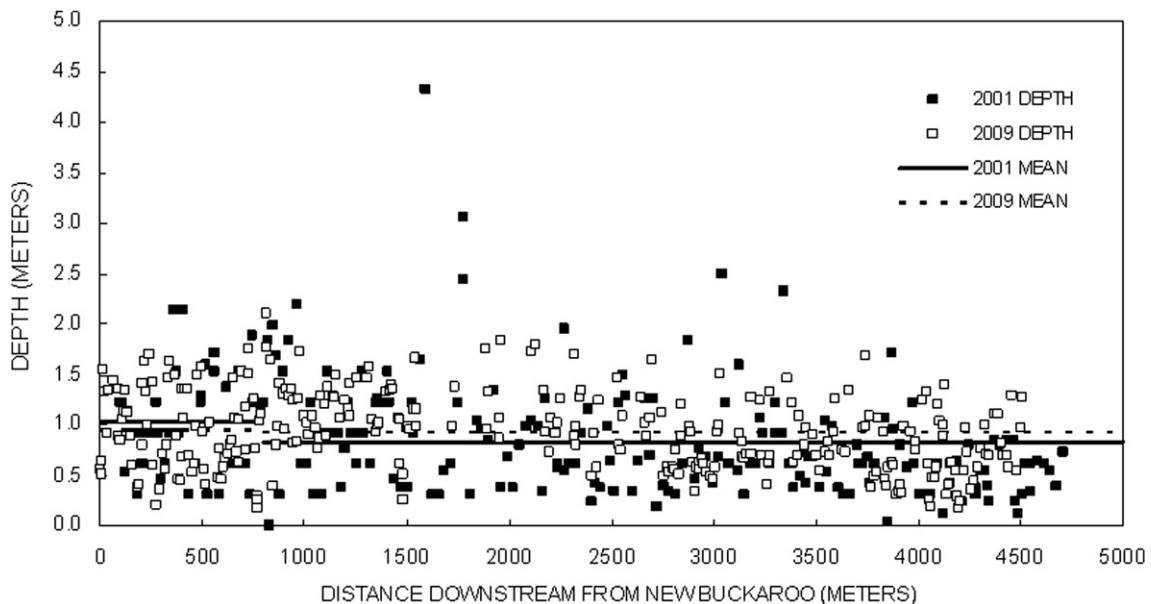


Fig. 7. Flow depth at each survey point along the channel from New Buckaroo Diversion to Bridge Creek Canal, Donner und Blitzen River, February 2001 and November 2009 (discharge ~1.1 m³/s). Horizontal lines are the reach-averaged flow depth for each year.

Table 1
 Characteristics of weirs in 2009 on the Donner und Blitzen River, Oregon. Weirs are numbered from upstream to downstream. NA = data not available because location was not surveyed in 2001 or 2005. Backwater depths calculated from a simple direct-step backwater model. Baseflow = 1 m³/s; bankfull = 40 m³/s.

Weir	Height (m)	Mean erosion depth (m)	Downstream interdistance (m)	Percent clay downstream from weir		Backwater depth at upstream weir and percent greater than normal depth			
				2001	2005	At baseflow (m)		At bankfull (m)	
1	0.77	0.43	168.4	24.0	59.1	–	–	–	–
2	0.79	1.40	59.5	13.2	58.3	0.65	336.2	1.71	19.3
3	0.58	0.49	116.7	57.1	63.6	0.60	302.7	1.61	12.3
4	0.83	2.51	283.8	25.5	77.8	0.76	410.1	1.79	25.3
5	0.64	0.64	376.2	100.0	71.4	0.37	148.3	1.55	8.1
6	0.72	1.02	227.4	60.0	50.0	0.33	121.5	1.55	8.5
7	0.93	1.01	172.1	85.0	56.5	0.72	383.2	1.79	25.3
8	0.89	–0.65	145.2	50.0	63.6	0.76	410.1	1.79	25.3
9	1.42	0.00	541.5	57.4	67.9	1.32	785.9	2.31	61.7
10	1.14	1.40	213.8	20.0	77.8	0.51	242.3	1.70	19.0
11	0.90	0.69	216.6	42.4	61.9	0.70	369.8	1.77	23.9
12	0.86	–0.07	339.8	NA	NA	0.67	349.7	1.73	21.1
13	0.97	0.46	239.3	NA	NA	0.62	316.1	1.72	20.4
14	0.84	0.07	420.6	NA	NA	0.62	316.1	1.70	19.0
15	0.84	1.58	383.8	NA	NA	0.39	161.7	1.59	11.3
16	0.92	1.56	378.2	NA	NA	0.51	242.3	1.66	16.2
17	0.56	0.33	554.1	NA	NA	0.19	27.5	1.47	2.9
18	0.73	NA	553.9	NA	NA	0.17	10.7	1.50	4.6

5. Discussion

Along the rehabilitated section of the Blitzen River, we found that the proportion of riffles and pools was lower in 2009, six years after weir construction, than in 2001. This decline was due to a 65% increase in the proportion of flat waters, with depths intermediate between riffles and pools. Weirs did not raise baseflow water surface elevations, but did change the shape of the water surface profile. Most of the elevation loss now occurs in the weirs, separated by long sections of relatively flat water. In conjunction with the change in topography and pool-riffle morphology, the proportion of coarse-grained sand and gravel substrates declined in favor of an increase in silt and consolidated clay.

Two mechanisms appear to have caused these changes in morphology: erosion of coarse-grained material and drowning of topographic variability by backwaters, effects enhanced by the low channel gradient, consolidated clay substrate, and low sediment supply of the river. Erosion by weir overflow is not only common (Rouse, 1940; Doddiah et al., 1953), but generally desired as a means of creating pools and reducing bank erosion (by redirecting flow to the channel center). On the Blitzen River, properties of the channel substrate likely influenced the depth of erosion and the resulting bed composition. In many rivers, erosion selectively removes finer-grained material from the bed, resulting in the formation of a pavement or armor layer on the channel bottom that limits the extent of erosion (Lane and Borland, 1954; Lisle, 1979; Conesa-Garcia and Garcia-Lorenzo, 2008). Erosion on the Blitzen River, however, appears to have removed the loose coarser-grained gravel and sand at the bed surface and cut into the hard clay material present along most of the channel.

Incision into cohesive clay material has been observed in other regions dominated by lacustrine surface deposits, such as the Lower Mississippi River (Kim et al., 2008; Parker, 2009), and has been simulated in experimental studies of erosion into a cohesive substrate (Shepherd and Schumm, 1974; Wohl and Ikeda, 1997; Johnson and Whipple, 2007). Erosional mechanisms and morphological characteristics of these systems are similar to bedrock channels. Erosion occurs via hydraulic action and abrasion by sand and gravel “tools” (Chatanantavet and Parker, 2009). Sediment supply influences bedrock incision in opposing ways: by providing tools for abrasion or by reducing bedrock exposure (the “cover

effect”) (Sklar and Dietrich, 2001, 2004). When sediment supply is limited, erosion may remove alluvial cover, causing bed lowering, clay exposure, and the formation of distinctive features, including potholes, longitudinal grooves, and narrow, smooth-sided and often undulating inner channels (Wohl and Ikeda, 1997). Field notes from 2001 surveys of the Blitzen River report at several locations the presence of a “clay bench with silt cover,” “clay ledges with deep hole,” and “clay ledges, deep hole, gravel in hole.” We also observed clay ledges and inner slot channels throughout the 2009 survey.

Deep inner channels reflect the cohesive nature of the clay material (e.g., Wohl and Ikeda, 1997) and suggest that sediment load is low relative to the transport capacity of the flow (Johnson and Whipple, 2007). In 2005, the proportion of loose sand and gravel was smaller than that of hard clay at the bed surface, further indicating that rates of sediment transport exceeded the supply of alluvial material (Johnson et al., 2005). During our 2009 field survey, we found abundant coarse-grained material in the reach upstream of the study section (e.g., gravel bars, frequent pool-riffle sequences), indicating that a gravel supply was available, even

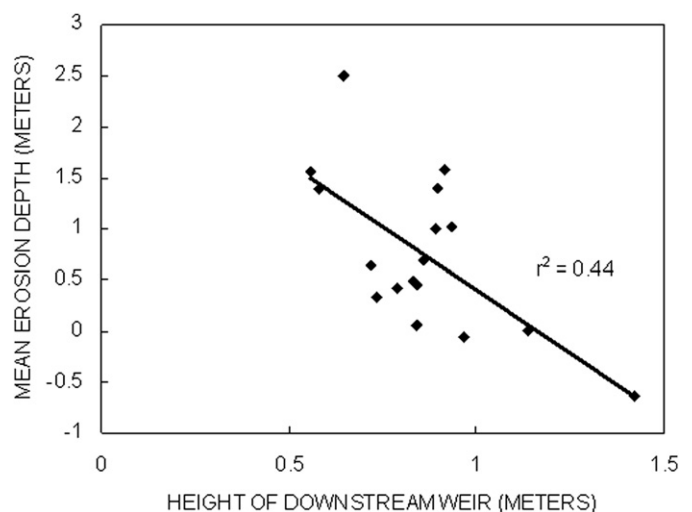


Fig. 8. Relationship between observed erosion depth and the height of the downstream weir.

though little was found in the study reach. Between the 2001 and 2009 surveys, the largest flood (~5-year) occurred in May 2005, two months prior to the channel substrate surveys, which likely mobilized and evacuated much of the sand and gravel present at the bed surface. Furthermore, in bedrock channels a positive feedback exists at topographic lows where sediment collects and abrasion is enhanced, causing continued erosion of deep parts of the channel (Johnson and Whipple, 2007). Deep pools and inner channels observed on the Blitzen River are therefore likely a consequence of the cohesive clay material that dominates the channel bed and banks.

Given that changes to channel morphology were not restricted to areas downstream from weirs, however, backwater effects and sediment deposition likely also contributed to the loss of riffles and gravel substrates. In this system, weirs act like small dams, raising the local water surface level to the height of the structure; backwaters behind weirs slow flow velocities and promote fine sediment deposition in zones that can extend for several tens to hundreds of meters upstream (Goitom and Zeller, 1989). Due to the low gradient and relatively tall weir drop heights on the Blitzen River, modeled backwaters for all weirs extended to the next upstream weir, creating long stretches of flat water and low-velocity deposition zones. Channel slope is a crucial factor to consider when selecting the spacing and dimensions of grade-control structures (Biedenharn and Hubbard, 2001). Engineering guidelines typically suggest that structures should be spaced such that the upstream structure does not interfere with the deposition zone of the next downstream structure (Heed and Mulich, 1973). Approximate spacing can be determined by extending a line from the top of the first downstream structure at the equilibrium slope upstream until it intersects the original streambed (Johnson and Minaker, 1944), thus defining the length of the deposition zone upstream from the structure (Mussetter, 1982).

Defining the equilibrium slope is therefore a critical part of the design process; equilibrium slope is a function of sediment load and channel characteristics. Equilibrium slope can be determined using a number of methods (Mussetter, 1982; Federal Interagency Stream Restoration Working Group, 1988; Watson et al., 1999), including detailed sediment transport modeling (Thomas et al., 1994; HQUSACE, 1993) and simple empirical relationships (Lacey, 1931; Simons and Albertson, 1963). The number of structures required for a given length of channel (N) can then be determined from the desired equilibrium slope (S_r), the original bed slope (S_0), the reach length (X), and the height of the structures (h) ($N = (S_0 - S_r)X/h$; Goitom and Zeller, 1989). On the Blitzen River, 14 weirs were constructed over the ~4 km section below Old Buckaroo. For an average weir height of 0.85 m, this would mean an anticipated loss of ~12 m of elevation from the reach, corresponding to a loss in slope of 0.003. Given that the original bed slope in 2001 was only 0.0014, a decrease of 0.003 would imply an equilibrium slope less than zero (-0.0016; i.e., an upward sloping channel), suggesting that the structures were inadvertently built too close together and/or too tall, possibly because there was inadequate information available to describe the equilibrium slope.

Given a water surface slope of ~0.0013 and a bankfull discharge of ~40 m³/s, the Blitzen River meets the criteria for a meandering river (Leopold and Wolman, 1957) with pool-riffle morphology (Montgomery and Buffington, 1997). Typical pool spacing in these systems is 5–7 channel widths. In contrast, step-pool morphology occurs in streams with slopes of 0.03–0.10, characterized by channel-spanning accumulations of large clasts ('steps') separated by pools spaced at a frequency of 1–4 channel widths. Steps are functionally important in steep streams because they provide hydraulic resistance, dissipating energy through tumbling flow and limiting the amount of erosion and sediment transport. Close

spacing of steps in these systems creates hydraulic variability. On the Blitzen River, the clast size and height of weirs are suggestive of steps, but neither the channel gradient nor spacing of bedforms in this system reflects natural step-pool conditions. Weirs on the Blitzen River were spaced on average 9.4 channel widths apart. Because of the low channel gradient and tall weir heights, the sections of flat backwater were much greater than in natural step-pool systems and hydraulic variability was low. Pondered water and deposited sediment likely flooded and buried natural shallow-water riffle areas, increasing the spacing between pools. A more effective technique in this type of system might have been to construct less-frequent, lower-profile riffles with smaller clast sizes (i.e., pebbles, cobbles).

Weir installation was intended to increase wood recruitment and enhance topographic variability by promoting pool erosion. Unfortunately, we found that weirs actually caused a loss of riffle and pools in favor of shallow flat water areas – in turn decreasing habitat heterogeneity. Habitat heterogeneity has long been shown to increase the richness and abundance of aquatic organisms (e.g., Dean and Connell, 1978; Beisel et al., 2000; Brown, 2003; Taniguchi and Tokeshi, 2004). Habitat diversity provides niches for different species and physical variability for organisms with varying life-history requirements (e.g., suitable breeding, foraging, and resting places for fish). For example, redband trout predominantly use coarse-grained pool tailout or riffle habitats for spawning (Muhlfeld, 2002) and deep, stable pools for resting and rearing (Muhlfeld et al., 2001a, 2001b). A shift in the number of pools and riffles may also affect other biota whose distribution is strongly affected by physical habitat (Brown and Brown, 1984). For instance, macroinvertebrates are generally more abundant in riffles than pools (Brown and Brussock, 1991). Whereas drift-feeding fish such as trout reside mainly in pools and feed on macroinvertebrates produced in riffles, grazing fish use shallow flats and riffles to scrape biofilm and avoid predators (Power, 1985). Pool-riffle sequences can also drive hyporheic exchange through intra-gravel flow, facilitating the transport, transformation, and uptake of solutes (Bencala, 2005). Therefore, changes in pool-riffle morphometry likely altered both ecological structure and function. Furthermore, the loss of gravels may have reduced the quality of habitat for spawning redband trout, who have been shown to select redd sites based on the presence of abundant gravels (Muhlfeld, 2002). Less gravel could impact not only the quality and quantity of trout spawning habitat, but also biofilm growth and the diversity and abundance of macroinvertebrate communities (Parker, 1989; Merz and Ochikubo Chan, 2005). An earlier study by the Columbia River Fisheries Program Office (CRFPO, 2005) found that macroinvertebrate assemblages had a high proportion of gathering and filtering collectors relative to scraper and shredder species, indicating a dominantly heterotrophic system and a dependence on fine rather than coarse particulate organic matter (S. Lohr, USFWS-CRFPO, personal communication). Low levels of autotrophy may reflect the lack of suitable substrates for instream plant growth, while low proportions of shredders are likely due to the limited riparian growth and woody debris in the system. However, CRFPO (2005) also found that macroinvertebrate assemblages were generally similar pre- and post-installation and between sub-reaches with and without structures, suggesting that the weirs had little impact on invertebrate communities.

Although weirs and other grade-control structures can provide channel stability, increase pool availability (e.g., Cooper and Knight, 1987; Shields et al., 1990), and even trap gravel material (Jackson, 1974), these responses are not assured in all cases and structures may also have negative environmental effects. Potential impacts can be assessed prior to restoration from an understanding of system history, baseline conditions, and potential trajectories of

response. In addition, an understanding of limiting conditions can aid restoration objectives. For instance, the extent of erosion downstream from weirs on the Blitzen River was strongly influenced by the cohesive clay substrate of the channel and the limited supply of gravel material; the length and depth of backwaters were enhanced by the low channel gradient. Prior to restoration, riffle habitats occupied only 13% of the study section, suggesting that riffle frequency and the heterogeneity of habitat units were more limiting than pool availability. However, measurements of additional habitat variables are needed to adequately assess habitat quality for redband trout. Redband trout habitat suitability depends on conditions of stream shading, bank cover, bank stability, fine sediment in the stream substrate, cover for adults, and distance from stream headwaters (Zoellick and Cade, 2006). Furthermore, it is possible that the weirs could alter trout migratory life history by impeding or slowing the movement of adult or immature trout, although this has not been studied. Research on the migration patterns of redband trout has shown that diversion dams on the mainstem of the Blitzen River can present problems for migrating trout, causing delays or preventing passage despite access to fish ladders (Anderson et al., 2009). Migrating trout ranged in age from 1 to 5 years, suggesting that the spring upstream migration included both spawning adult trout and immature trout seeking seasonal thermal refuge. Given that young trout exhibit migrations on the mainstem, it is possible that the weirs could pose problems for these smaller fish. Further research is needed to evaluate this potential effect; however, fish migration patterns are beyond the scope of our study. More information about the effects of physical barriers on the migratory patterns of redband trout in the Blitzen River can be found in Anderson (2007) and Anderson et al. (2009).

6. Conclusions

We used pre- and post-restoration data to assess changes in channel morphology following weir installation on the Blitzen River. Six years after installation, the channel had a smaller proportion of riffles and pools and less gravel substrate. Physical changes alone, however, are insufficient to assess whether this restoration project was successful, an important consideration for those who must decide what further action (if any) is needed and if similar strategies should be used elsewhere. Whether a restoration project can be considered successful depends on the overriding project objectives and the strategies intended to accomplish those goals. On the Blitzen River, the primary objective was to improve instream habitat and ultimately increase populations of native redband trout. Weirs were intended to promote bed scour and wood recruitment – as a result of raised water surface elevations and improved riparian growth – thereby increasing habitat complexity.

Our analysis suggests that the project did not accomplish its primary goal; instream habitat was unfortunately degraded, not improved, and habitat heterogeneity was reduced following weir construction. Although deeper flows due to backwaters provide thermal refugia and cover from predators for adult redband trout, the loss of riffles and gravel substrate likely degraded habitat for spawning trout and other aquatic biota. In order to be effective, features intended to enhance one type of habitat should be designed with other types of habitat in mind. In this case, the number, height, and spacing of the constructed weirs served to reduce riffle habitat. For example, in this system, fewer, lower weirs may have left sufficient reach length to allow local deposition and topographic heterogeneity to develop between a weir and the backwater from the next downstream weir, thereby preserving or enhancing riffle habitat. The effect of these changes on aquatic organisms requires further analysis of all relevant habitat features

and monitoring of fish and macroinvertebrate populations. In order to fully appraise restoration success we must evaluate unintended effects (positive and negative). Weirs had effects on instream habitat that were probably unanticipated and certainly unintended. We fully recognize that restoration projects can be costly and difficult to implement; the effectiveness of these projects is often limited by time and resources. To facilitate restoration success, we recommend that baseline attributes and historic conditions be assessed and integrated into project design and implementation, because strategies with benefits for one system may be less effective or detrimental to another.

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