Stream restoration solutions for challenging environments

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Abstract

Implementing effective flow conveyance on reclaimed land presents many challenges that vary with site constraints and landscape types. While drainage swales with manufactured linings are effective runoff conveyance measures for areas affected by mining, these channel linings are unnatural and require materials to be purchased and brought on-site. Comparatively, stream restoration measures and natural channel design techniques using native materials such logs, woody debris, and rock gradations ranging from small gravels to boulders have been successfully implemented across varying and challenging landscape types including reclaimed mine land. Use of native materials with the presented stream restoration techniques can provide environmental benefit in addition to effective conveyance of surface runoff.

Three case studies are presented as applicable to applying stream restoration to challenging environments commonly encountered in mine land reclamation. The case study environments include steep slopes, culvert crossings, and unvegetated areas with erosion prone soil. The respective restoration techniques consist of reference reach-based design for steep reaches, grade control and promotion of sediment transport through culverts, and terracing for floodplain connectivity. While the studied landscape types vary, the goal of each case study is to achieve habitat and water quality improvements through creation of stable, natural channels that function structurally and biologically like an undisturbed reference stream. The presented case studies will outline how stream restoration techniques have been shown to effectively manage surface runoff as applicable to mine land reclamation.

Keywords: Stream restoration, reference reach, culvert crossings, floodplain connectivity, reclamation

Introduction

Drainage concerns, loss of base flow, and reduced hydraulic capacity due to debris or sediment deposition in streams are some of the detrimental environmental impacts that can occur due to mining activities. Review of the Bureau of Land Management's (BLM) "Stream Reclamation Basics" Technical Brochure, Issue 1 (Varner et al. 2023) indicates that research occurring after year 2000 has concluded that stream channels left after mining, and in some cases after reclamation, can become unstable. These unstable channels on reclaimed land have then affected the water quality, loss of stream function, and degraded fish habitat. Furthermore, the publication "Application of Fluvial Geomorphic Techniques at Abandoned Mine Sites" (Greenfield et al. 2001) describes how a stable natural channel system to transport runoff while preventing erosion and flooding is critical for flow management at reclamation sites. Thus, successful reclamation of mined lands must account for conveyance of surface drainage and stormwater runoff.

Common techniques for stormwater management on reclamation projects include riprap drainage swales, concrete lined channels, and turf reinforced matting. While these measures can provide effective conveyance, they can also be costly and are unnatural. Conversely, published research has shown that fluvial geomorphologic techniques, including natural channel design, have been successfully implemented at sites in the Anthracite Region of Pennsylvania (Greenfield et al. 2001) as well as in mined streams across Alaska (Varner et al. 2023). Both of those challenging environments were met with practical design solutions, and this paper will outline how stream restoration techniques have been shown to effectively manage surface runoff at case study sites in West Virginia and Indiana. These case studies will present a variety of natural channel design-based stream restoration solutions each of which provides opportunity for increased aquatic habitat and the potential for improved water quality.

This paper will present three case studies across unique and challenging landscape types. Landscape types presented include steep terrain, a roadway crossing, and an open valley with erosion prone soil. Thus, as reclaimed lands can present a variety of challenges across landscape types and topography, innovative solutions for stream restoration can be employed in accordance with the presented case studies. Each case study will include discussion of design considerations, construction challenges, adaptive solutions, and lessons learned. While the details and effectiveness of each solution presented herein vary with landscape type, the goal of successful stream restoration is to create a stable channel that promotes natural transport of sediment and exhibits balance within its watershed. While the degree of balance and environmental benefit can be difficult to quantify, it should be noted that stream stability and habitat enhancement can be quantified using rapid assessment protocols as presented in the second case study.

Case Study 1: Effective Conveyance on Steep Terrain in West Virginia

Surface water management on reclaimed land often requires conveyance of flows down hillsides with slopes exceeding 20%. Trapezoidal channels at a constant slope with a manufactured lining have been used to manage conveyance on reclaimed lands. An example of riprap drainage for stormwater conveyance in West Virginia is shown in Fig. 1.

While manufactured linings are effective for conveyance, neither turf-reinforced matting (TRM) or riprap linings encourage natural sediment transport. Thus, this case study demonstrates how natural channel design in the form of cascade riffles and step pools was utilized to achieve effective conveyance and slope stability while also providing environmental benefit on reclaimed land in Doddridge County, West Virginia (WV), USA. The project reaches for this case study had watersheds ranging from 0.007 to 0.010 km2 (1.7 to 2.5 ac) and slopes ranging from 19% to 37%. Limited published guidance is available for remediating slopes

Figure 1 Riprap used for Conveyance on Reclaimed Land in West Virginia

on steep headwater streams, as commonly used stream design references for step pools only include data for slopes up to and 16% (Harman 2018), and the BLM's Technical Report #65 for Reclamation (Harman et al. 2023) is focused on stream types that exhibit slopes less than 10%. Thus, the riffles and step pools in this case study were designed using reference reaches. A reference reach is commonly defined as a stable segment of stream with consistent slope, geometry, planform, and sediment load that represents, to the best available knowledge, a comparable condition to the project reach.

The reference reaches utilized for this case study are located on comparable landscapes to the design reaches, have watershed sizes ranging from 0.008 to 0.009 km2 (2.1 to 2.3 ac), and exhibit slopes of 16% and 22%, respectively. Longitudinal profile data, or data plotted along the stream bed showing slopes and locations of riffles, steps, and pools for each reference reach, was collected using a transit (laser) level. The reference reach with the 16% slope was found to have pools spaced at 3 to 7.5 times the bankfull width (or channel forming flow width), and the reference reach with the 22% slope was found to have pools space at 1.2 to 4.2 times the bankfull width. Thus, for the project reach step pools were designed for placement at 2 to 7.5 times the bankfull width for consistency with the reference reach ratios. In a similar manner, the reference reach data was utilized to establish step heights, or the amount of drop down to each pool. For the reference reaches, step heights ranged from 0.10 to 0.60 m (0.33 ft to 2.0 ft), or 0.7 to 4.3 times the mean bankfull depth. Thus, step heights for the project stream were designed to have heights of 0.5 to 4.0 times the mean bankfull depth. A reference reach and the constructed step pools are shown in Fig. 2.

In addition to reference reach data, we also utilized hydraulic modelling to aid in design of step pools on subsequent projects. These projects had very limited access and the work area was limited to a subject right-of-way; these constraints required design of step heights outside the ranges provided by the previous reference reaches. For this situation, one dimensional hydraulic models were created using the United States Army Corps of Engineers (USACE) Hydraulic Engineering Center's, River Analysis System (HEC-RAS) program. The design stream geometry and slopes were input to the HEC-RAS program which gave resulting shear stress, water surface elevations, and velocity for the proposed steps and drops. These hydraulic outputs allowed for an assessment of stability, and additional boulders were added to the design in areas where shear stress and velocity exceeded the average for the reach or the allowable shear stress limit for a given rock size.

Both the case study project and the subsequent projects were constructed in accordance with design plans, and these sites are exhibiting stability post-construction. The materials used for construction include logs, boulders, mixed gradations of stone, and coir fiber erosion control matting. Some of the logs and boulders were found on-site, and the other materials are comparable in cost to riprap, TRM, and other manufactured linings.

***Figure 2** Reference Reach (Left) and Constructed Step Pools (Right) for Headwater Streams*

Thus, the use of step pools for conveyance on steep slopes can be constructed at a similar price point to manufactured linings, but installation of the step pools can also result in environmental improvements. These improvements include increased energy dissipation through reaches due to the drops and flatter, deeper, pool areas; less likelihood of accelerated bank erosion; more habitat diversity through creation of pools; use of native bed material or a bed material similar in gradation to a headwater stream to provide sediment transport downstream; improved water quality in both the subject reaches at the headwaters and those downstream. Thus, as demonstrated by this case study, the use of the step pool structures resulted in constructed, but natural, stream reaches that are both structurally and ecologically comparable to the reference reaches and provide effective conveyance on steep slopes.

Case Study 2: Promoting Natural Conditions Through a Culvert Crossing in WV

Reclamation sites often need to incorporate roads for access or recreation, making road crossings of streams an inevitable requirement. This case study demonstrates how stream restoration was combined with a culvert replacement to create a successful restoration reach with environmental benefits in a limiting setting. The Case Study Site is in Harrison County, WV, where the subject stream parallels a local road. Under the obstructed condition, an undersized culvert combined with accelerated sediment transport resulted in aggradation and bank erosion upstream of the culvert and an unnatural scour hole downstream of the culvert (Fig. 3). These conditions were a barrier to fish passage due to the drop in elevation at the culvert outlet and a hazard to the community as the roadway and driveway overtopped during storm events.

The implemented stream restoration included replacement of the existing circular culvert with an open bottom box culvert. A dissipater pool, which is a circular shaped energy dissipater filled with riprap and gradual transitional slopes at the downstream end, was installed at the culvert outlet. The dissipater pool was designed to have dimensions comparable to similar pool structures within the restoration reach. The dissipater pool was constructed by placing boulders in a circle around the perimeter of the pool, which results in a pool that creates a natural environment for energy dissipation at the outlet as opposed to a traditional riprap apron. The streambed elevation at the culvert outlet has remained constant through four years of monitoring, thus the dissipater pool has been an effective form of grade control. However, the open bottom culvert did not include fish baffles or grade control at the upstream entrance and degradation of the stream bed, in the form of sediment transport downstream, has occurred at the culvert inlet. This trend is evidenced by the stream bed elevation at the inlet decreasing by up to 0.30 m (1 ft) over four years of monitoring.

Figure 3 Obstructed Conditions at an Undersized Culvert Inlet (Left) and Outlet (Right)

Figure 4 *Restored Conditions at Stream Inlet (Left) and Outlet (Right) During Year 3 Monitoring*

While the stream is still stable, use of fish baffles within the culvert or placement of boulders across the streambed at the culvert inlet, similar to what was successful for grade control at the outlet, are recommended for projects where site conditions show substantial sediment movement.

Over four years of monitoring, this case study demonstrated similar environmental improvement and benefit to Case Study 1. For this study, environmental conditions were monitored using the Habitat Assessment Valuation (HAV) according to the United States Environmental Protection Agency's (USEPA's) Rapid Bioassessment Protocols (RBP). The HAV uses a score (1–20) to evaluate ten different physical parameters related to habitat for a total score of 200 (for intermittent and perennial streams). The HAV was initially conducted by GAI in November 2014 at a reference reach located upstream from the affected location, but on the same stream, to represent a pre-disturbance, baseline condition. The RBP for the representative reference stream was then adjusted to estimate parameter scores at five-year maturity post-restoration. Thus, the parameter scores projected for year five after the restoration are currently being used to evaluate success criteria during the five-year monitoring period.

Following restoration in 2019, habitat parameter scores for bank stability and bank vegetative protection showed the most lift when compared to the baseline and projected conditions. This trend is mostly attributed the installation of more stable dimensions and native riparian species through native seeding and live staking. The sedimentation parameter score has been lower than predicted due to the loss of streambed material at the culvert inlet and the resulting deposition in the dissipater pool downstream. However even with the described material movement, the overall HAV results in the fourth year of monitoring (score of 135) gave a score that was higher than the Year 5 goal (score of 126), and only slightly lower than the baseline reference score (138). Thus, the restoration is performing better than anticipated, and it is becoming very close to exhibiting the same habitat parameters as the reference condition.

In addition to improved HAV scores, this case study has also demonstrated geomorphic improvements. The scour hole at the culvert outlet was eliminated, and the replacement culvert promotes passage of stream bed material downstream. The stream restoration and culvert replacement have decreased the likelihood of flooding and erosion that could affect the surrounding roadway infrastructure. It should also be noted that the stream restoration in this case study remained stable through two measurable storm events (with rainfall values greater than a 10-year event), which occurred over the ongoing 4-year monitoring period. This site is currently meeting the geomorphic success criteria outlined in the annual monitoring reports, and the reach is well vegetated while demonstrating stability. Thus, considerable environmental benefit can be obtained through culvert crossings if stream restoration is applied successfully.

Case Study 3: Stream Relocation for Soil Prone to Erosion

This case study shows how stream restoration in the form of channel relocation was effective in an open area with limited vegetation, multiple utility conflicts, and erosion prone soils, all challenges that are also faced in reclamation. In the affected condition, the subject stream reach exhibited sharp bends, irregular meanders, and an oxbow that had become a secondary channel. The surrounding floodplain consisted of low-cut grass and limited bank vegetation, so the combination of exposed banks, sandy soils, and a watershed subject to short duration, high intensity storm flows led to an unstable channel putting both the subject property and surrounding utilities at risk of flooding and bank washout. Alternatives such as placement of riprap or other hard armament to stabilize banks near utilities in place were considered for repairs. However, as part of the conceptual design, stream relocation was shown to have greater potential for long term stability of both the channel and floodplain when compared to stabilization in place. Thus, the channel relocation was designed to include regrading the property so that the stream could have a terraced floodplain in addition to a stable dimension, pattern, and profile.

A key to the Project's success was conducting hydraulic modeling in conjunction with the stream relocation design and incorporating terraces to effectively convey a 1% Annual Exceedance Probability (AEP) or 100-year base flood without increasing water surface elevations. The stream was re-aligned to eliminate the sharp bends and steep curves to allow for stable meanders. Under the unstable condition, the stream bank height on the outside of several bends was 2 to 3 times the bankfull height. These tall, steep banks were especially prone to erosion (Fig. 5), and under the proposed relocation, the ratio of bank height to bankfull height was reduced to 1 to 1.4. This reduction of bank height ratio allowed for benching and construction of a floodplain closer in elevation to the active stream channel. A series of terraces were used to connect the floodplain to the surrounding topography at the original ground level. Fig. 5 shows a bank height comparison under both unstable and post-construction conditions.

A biodegradable, Coir Fiber, erosion control matting system was placed on the banks of the relocated channel in the active floodplain. The matting incorporated a netting pattern to allow for placement of live stakes and plantings within the netting matrix. Use of plastic netting was avoided, as plastic netting can create a tangling hazard for fish, snakes, frogs, and other aquatic creatures. Placement of the matting increased stability of the newly constructed banks by limiting the soil's exposure to channel flows, providing erosion control during construction, and promoting establishment of native vegetation on the established banks post-construction.

Benefits of restoration through stream relocation demonstrated by this case study

Figure 5 *Bank Height Comparison for Unstable (Left) and Restored Stream (Right)*

include protection of property and both above and underground utilities, improvements in fish habitat though increasing the number of pools and amount of woody material, a more gradual bend radius between the channel and downstream bridge, and design of a stream that is connected to its floodplain system improving hydraulic performance during flood events.

Conclusions

The case studies present adaptable natural channel design-based solutions for restoring streams during reclamation. Conclusions from each case study are summarized below.

Utilizing stream restoration in the form of log and rock step pools on steep terrain can achieve effective conveyance and management of runoff. These measures utilize natural materials in-lieu of manufactured linings and result in creation of streams that are both structurally and environmentally comparable to a stable natural stream or reference condition.

Culvert crossings can provide habitat improvement and stability if they are designed considering sediment transport. Use of boulders for grade control and energy dissipation performed well through four years of monitoring, and the design held up against multiple storm events that occurred during the monitoring period. Additionally, habitat scores during environmental monitoring have exceeded the projected values and are comparable to those of the uninfluenced reference reach.

Erosion prone soil can be addressed during stream restoration through creation of a multi-stage channel, reducing bank height ratios, and placement of environmentally conscious erosion control matting. The final case study reduced bank erosion and promoted recreational opportunities.

The above examples demonstrate a balance between engineered and natural solutions for both stream restoration and stormwater conveyance. Reclamation of abandoned mine lands presents many of the same challenges outlined above, and we hope these examples may encourage the use of stream restoration to address site constraints faced during reclamation.

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