A SUMMARY OF SOME LAND SURFACE AND WATER QUALITY MONITORING RESULTS FOR CONSTRUCTED GEOFLUV LANDFORMS[1]

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Abstract: Modern mining methods can drastically change landforms in the project area. Traditional reclamation grading methods often do not address all the criteria that must be met for the desired post-mining land use including water quality standards, in-stream uses, vegetation diversity and other reclamation criteria. Inability to meet or mitigate for these changes caused by the proposed reclamation landform can even stop mining activity from proceeding. A new, natural approach to landform grading called GeoFluv™ (Bugosh, 2003) offers a cost-effective alternative for sustainable mineral development than can satisfy the reclamation criteria and is the heart of the ***Natural Regrade*** computer software module (Bugosh, 2006). Monitoring results of land surfaces and storm water discharge quality, including runoff that meets NPDES discharge limits before reaching sediment treatment ponds, at constructed projects strongly support the effectiveness of the GeoFluv design method at meeting the reclamation criteria (NMED, 2007). The objective of this paper is to summarize subjective observations of reclamation landforms constructed according to the GeoFluv design and the related objective data from large projects over approximately a seven year period to provide a status report of the effectiveness of the method for minimizing erosion and meeting water quality goals.

Additional Keywords*:* fluvial geomorphic, GeoFluv, sustainable, landform, erosion, water quality, vegetation diversity, invasive species

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[1] Paper was presented at the 2009 National Meeting of the American Society of Mining and Reclamation, Billings, MT, ***Revitalizing the Environment: Proven Solutions and Innovative Approaches*** May 30 – June 5, 2009. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

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Proceedings America Society of Mining and Reclamation, 2009 pp 153-175
DOI: 10.21000/JASMR09010153
http://dx.doi.org/10.21000/JASMR09010153

Introduction

Fluvial geomorphic principles were introduced to reclamation landform designs in the form of the GeoFluv design method at San Juan Coal Company's La Plata Mine in 2001 and San Juan Mine in 2002. These mines are in the Four Corners Region of northwestern New Mexico a little over 32 km (20 mi) apart, but vary in precipitation, vegetation, and topographic characteristics with the San Juan Mine in a more arid zone adjacent to the San Juan River and the higher elevation La Plata Mine contiguous with the Colorado border in the foothills of the La Plata mountains. The purpose of introducing the new reclamation landform design method was to enhance reclamation results directly related to the landform, including erosional stability, storm water discharge quality, and vegetation diversity.

The reclamation staff recognized that the traditional reclamation approach that uses long, constant-gradient slopes, straight rip-rapped channels and diversions, and terraces and down drains, makes a landform that is not in adjustment with the local climate, earth, and vegetative conditions. That lack of adjustment leads to erosion as the landform attempts to adjust to the site conditions. The GeoFluv approach provides a natural 'erosion control' because it designs a landform that is adjusted to the earth materials, climate, and vegetation in the reclamation area. The GeoFluv approach identifies geomorphic characteristics that define a landform and uses these as design inputs to make a reclamation landform. The input values are gotten from a stable, or geomorphically mature, landform that has earth materials, climate, and vegetation similar to the project area. When these inputs are measured from stable landforms and then used to design the reclamation landform, there is a high degree of confidence that the reclamation landform will perform similarly to the stable, mature landform from which the inputs values were measured.

The uniformity of traditional reclamation landforms results in fewer ecological niches and, as a result, tends to favor a vegetation monoculture, or worse, to be unsuitable for the desired reclamation species while inviting invasive species. Because the GeoFluv landform has diversity similar to the native, undisturbed land in the mine-site area, it provides the optimal niches for native species productivity which simultaneously provides natural invasive species control.

When this new fluvial geomorphic approach to landform design was introduced to mine land reclamation at the turn of the century, some questioned the feasibility of achieving the functionality of natural landforms in reclamation designs and how the performance of the fluvial geomorphic landform would compare to traditional methods and natural landforms. Since then, users at sites representing different mines and different climates have achieved similar successes with lower costs and improved performance. This paper will provide an overview of that performance, including subjective observations and quantified measurements, from the sites with the longest use of the GeoFluv method La Plata Mine and San Juan Mine. The methodology includes review of site inspection reports, weather monitoring data, NPDES discharge permit report monitoring results, and papers presented by others familiar with the sites.

Documenting the performance of the new approach is very important for gaining acceptance of the new approach among mine operators. Some operators (and some regulators) state that they are aware that the reclamation practices they are using are not meeting all their performance goals, but they are reluctant to try an alternative method without definitive evidence of the alternative's superior performance; this paper will provide supporting information of the results that can be expected from using the GeoFluv method for reclamation landform design. The event chronology dictates that the San Juan inspection report is inserted between La Plata reports.

La Plata Mine Background and Site Characteristics

The La Plata Mine was opened to provide a supplemental source of coal for the San Juan Mine to supply its mouth-of-mine San Juan electric generating station during its transition from surface dragline mining to underground longwall mining operation. The La Plata Mine used truck and shovel methods to mine more steeply-dipping beds of the same Fruitland Formation that the San Juan Mine targeted about 35 km (22 mi) to the southwest. The La Plata mine extracted 42 million tons of coal between 1986 and 2003. La Plata Mine used an unconventional open-cut mining method without contemporaneous backfill and reclamation because of concerns that the fill behind the down-dip advancing mine face might fail and present safety hazards to the mine workers. Consequently, the reclamation of the entire mine, about 836 hectares (2,066 acres) commenced near the end of mineral extraction.

The La Plata Mine was located in northwestern New Mexico contiguous to the Colorado border. Elevations at the mine range from approximately 1,795 to 1,892 m (5,890 to 6,210 ft). The annual precipitation is between 30.5 and 35.6 cm (12 and 14 in). The soils are thin and sandy with bedrock cropping out regularly. The vegetation is sparse, with bunch grasses, some forbes, and stands of pinyon pine and juniper. Together these elements comprise a high, semi-arid terrain that is highly erosive.

<u>San Juan Mine Background and Site Characteristics</u>

The San Juan Mine began in 1973 to supply the mouth-of-mine San Juan Generating Station. It was originally a dragline strip mine, but when the cost of removing overburden became uneconomical for surface mining methods, it converted to an underground longwall operation. Operated as a conventional strip mine, it had maintained contemporaneous reclamation using traditional grading methods until the introduction of the new grading approach at La Plata. The first application of the GeoFluv reclamation method at San Juan Mine was the Cottonwood Pit reclamation, a 46.5 ha (115-acre) area at the southernmost end of the mine near the San Juan River.

The San Juan Mine is 25.7 km (16 mi) west of the town of Farmington, New Mexico less than 0.8 km (0.5 mi) north of the San Juan River. Elevations at the mine range from about 1,590 to 1,645 m (5,220 to 5,400 ft). The precipitation is only about 23 cm (9 in) annually. The soils are thin and sandy with bedrock cropping out regularly. The vegetation is sparse, with bunchgrass and sagebrush covering most areas and cottonwoods and willows in riparian areas. This semi-arid terrane is approaching a high desert and is highly erosive.

Monitoring results

In this semi-arid environment, precipitation events great enough to generate discharge in the ephemeral channels occur about six times per year and often during the night and early morning hours when the environmental staff are not on site. The runoff from these storms drains to ponds with capacity to contain ordinary storm discharges as a sediment control measure during construction and in the early stages of completion of the reclamation projects. The combination of these factors means that collection of representative water quality discharge samples during storm events is difficult, although evaluations of observable erosion are possible after every storm. Given these constraints, the following examples of erosion monitoring and water quality sampling provide a clear picture of the landform’s performance over a seven-year period at these two sites, and are also typical of experiences at other sites.

First results at La Plata -2000 - 2001

The La Plata Mine reclamation plan was originally designed using traditional grading methods, i.e., terraced slopes with rock-lined down-drains, and erosion rates calculated for those designs predicted that post-reclamation erosion rates and sediment yields would not exceed pre-mine values. When the GeoFluv approach was applied to that proposed landform, the resulting greater number of subwatersheds shortened slope lengths and further reduced the erosion predictions. The 32 ha (80-ac) McDermott out-of-pit waste dump was the first application of the new grading method at La Plata Mine.

Reclaimed Channel Design Performance Verification

On 13 August 2001, 8.4 mm (0.33 in) of precipitation were recorded by the McDermott rain gauge from a storm during the night. This event caused runoff and channel flow, and although the flow had waned when staff arrived, allowed verification of the design estimates. Fourteen width and depth measurements of the main valley channel on the south side of the McDermott reclamation were taken using the wetted banks, and flow evidence on bank sands and straw mulch, as indicators of the maximum discharge width and depth. The cross sectional area and width-to-depth ratios were calculated for the event using the same method as was used for the design and the results compared. Table 1 below shows the results.

Table 1. Comparison of measured and designed channel cross sectional areas, and measured and designed bankfull width-to-depth ratios from 13 August 2001 McDermott main south channel flow event.

Reach	Measured Area (sq. ft.)	Designed Area (sq.ft.)	Calculated Velocity (ft./sec.)	W:D measured from Aug 2001 event	W:D designed for bankfull event
5	2.3	0.8	1.7	9:1	18:1
6	2.8	1.7	3.4	30:1	18:1
7	2.4	2.2	4.5	36:1	22:1
8	3	2.5	4.1	26:1	22:1

The stream reaches are listed in downstream order in Table 1**.** The valley-bottom channel reaches were defined as the channel between its confluences with subsequent tributaries. The measurements generally showed closer agreement between measured and designed values in the more downstream reaches. The calculated flow velocity at estimated peak discharge during the 13 August 2001 event, shown for each reach, tend to increase in the downstream direction.

The GeoFluv design approach uses input values taken from stable landforms in the project area that have similar earth materials, vegetation, and climatic conditions to the project area. The concept of geomorphic stability can include the idea of hydrologic balance; that water and sediment discharge are in balance. Because the GeoFluv design approach uses input values from these mature, stable landforms, the designer can have a high degree of confidence that the completed project will function similar to the stable landform from which the input values were taken.

A complete description of the GeoFluv design approach is beyond the scope of this paper, but some important channel characteristics relevant to Table 1 are described here. The channel design used geometry from the Williams (1986) relationships for plan view geometry and had a cross sectional area that included a bankfull cross section based on an annual storm event and a flood prone cross sectional area sufficient to contain the entire peak discharge for a 50-yr, 6-hr storm event at the design velocity. This channel was at the edge of the permit area and was constructed in native material which was predominantly medium-size sand; no additional channel lining was used. Four rocks were set into the bank at each meander bend placed at about the 9, 11, 1 and 3 o' clock positions (if the bend apex is considered 12 o' clock) such that the top of the rock was at bankfull elevation. The purpose of these rocks was to keep the stream's erosive energy away from the banks of the channel.

The channels do not have a constant width or depth, but are sized to convey the discharge at point in the channel based on its upstream watershed area; that is why the design cross-sectional areas increase in a downstream direction in Table 1. The target width-to-depth ratios were appropriate for stable sand bed channels in the 2 to 4 percent slope range. The channel's bankfull cross sectional areas were sized to convey the estimated peak discharge at 1.5 mps (5 fps) velocity based on San Juan Coal Company's Earthen Channel Study: Optimum Design Velocity (1998). The average calculated velocity for reaches 6, 7, and 8 is 1.2 mps (4 fps), good agreement with the design for this smaller than design event. Reaches 6, 7, and 8 are in a GeoFluv-designed channel on the south side of the McDermott that did not exist in the pre-mine landscape, whereas reach 5 is a GeoFluv design for the mouth of a tributary to the new channel in which reaches 5, 6, and 7 are found. The reasons for the different performance from reach 5, calculated much lower at 0.5 meters per second (1.7 fps), may be related to three causes: reach 5 is a short reach at the mouth of a relatively large (4.8 ha, 12 ac) undisturbed watershed that has a lower runoff coefficient, its narrower cross-sectional area may back up water, and the storm intensity may not have been as great over the reach 5 subwatershed.

Table 1 also compares the width-to-depth ratios observed for this less-than bankfull discharge event to the design width-to-depth ratios at bankfull discharge. The observed values are greater than the bankfull design values because at the lower discharge of the observed event the smaller volume of water did not fill the channel very deeply. The as-built channel cross section was slightly wider in reaches 6, 7, and 8 than designed for optimal low-discharge sediment transport. This construction deviation is attributed to the difficulty of building 6 to 10 foot wide channels using a D-10 bulldozer with a 17.5 ft-wide blade. Conversely, reach 5 was constructed using a backhoe and its as-built cross section dimensions are slightly narrower than designed. Consequently, the construction methods were adjusted to improve the as-built dimensions in GeoFluv-designed reclamation channels. Importantly, inspection of this McDermott reclamation channel showed that the stream flow had smoothed relict grading irregularities from construction with the D-10, but subjective observation of the designer was that no undesirable sediment deposition on the channel bed or bank erosion had occurred during the event, nor was an accumulation of sediment apparent in the downstream pond.

Early observations of the graded and topsoiled project, prior to establishment of vegetation, indicated that the new landforms were in fact less erosive than standard reclamation. Indications of the confidence that those with an interest in the performance of the new approach had at this time included these examples: the McDermott reclamation was recognized by the Mining and Minerals Division with a State of New Mexico excellence in reclamation award in 2001, and the company management decided to use the method on future reclamation projects with bond liabilities totaling more than $100,000,000 and 10 years.

Cottonwood Pit Reclamation at San Juan Mine - 2002

Following the initial demonstration of the GeoFluv design performance at the McDermott dump at La Plata Mine, the company applied the approach to the 46.5 ha (115-ac) Cottonwood Pit reclamation. The construction work began in October 2001 and was completed in February 2002. The design dissected the area into 32 subwatersheds that drained to four lower-gradient valley-bottom channels. The highwalls were situated in the face of ridges that rose 56 m (185 ft) above the valley floor. This required that the GeoFluv design begin with slopes as steep as 40 percent (2.5:1) and transition to slightly less than 3 percent on the valley floor. The design conveyed the discharges into two storm surge and infiltration basins of about 11,101 m^3 (9 ac-ft) capacity, with outlets engineered to convey overflow from very extreme events. The design included fluvial geomorphically functional landforms made from highwalls and a ridgeline that eliminated the need to move approximately 38,992 m^3 (51,000 yd$^{3)}$ of spoil material; the reader can use local material movement costs to convert that work savings into dollars.

Just seven months after grading and topsoil lay down ended a series of storms hit the San Juan Mine. An 8 September event yielded 14 mm (0.55 in) in 4 hours and started soil saturation. Then the automated monitoring site adjacent to the reclamation site recorded 28.7 mm (1.13 in) during a 4-hr event on 10 September, which was followed two hours later by six hours of rain that added 11.4 mm (0.45 in) for a total rainfall of 39 mm (1.54 in) during this 14-hour period. This was a regional storm affecting several states. The total 39 mm received over a little more than a half-day may not seem like a lot of precipitation to readers familiar with humid areas, but in this semi-arid landscape with very thin soil, a storm pattern like this can cause rapid runoff, flooding, and erosion. The following inspection report gives a very clear picture of the Cottonwood reclamation performance from the landform design alone, i.e., without vegetation or artificial erosion controls.

Inspector	Inspection Date	Inspection Type
Russell, Robert	19 September 2002	Complete

The mine had received several heavy rainfalls. Using the automated weather station on Gravel Hill, SJCC was able to document that they had received a 25hr/6yr (sic) event on the South Lease reclaim. They received several other rains totally approximately 78 millimeters (3 in) within one week. This created enough rain to cause the underground mine to shut down due to flooding. SJCC had to send in scuba divers to repair a pump.

The heavy rains occurred within the time frame of reclamation (within first years planting) most likely to cause erosion damage. However, there was only one noticeable erosion feature (some minor erosion features already existed due to irrigation pipe leaks) which occurred on the steepest slope and was predicted in the design. There is no need to complete any stabilization of this one minor feature. All of the drainage channels within the reclaim were stable with minor scouring and deposition occurring as predicted and designed for. The most remarkable result was that the impounded water resulting from the rain event was clear. This is the first time I have witnessed clear water coming off reclaim in 18 years of inspecting. Excellent job SJCC!

Grading of North Pinon is progressing nicely. Tying into existing reclamation with the new approach is causing some stress and field fitting but the end result should pay off. There were no signs of standing oil at the soil farm. No problems noted.

The fact that scuba divers had to be called in to the mine provides an image of the severity of the runoff. The effects of the storm caused many problems around the mine such as landslides 1.2 to 1.5 m (4 to 5 ft) deep covering a 0.4 km (0.25 mi) length of highway, cattle swept away in stream bottoms and never recovered and the city of Farmington had to close the water treatment plant intake. The combination of high-intensity storms, thin soils, and sparse vegetation makes for rapid and great storm water discharges in this area. Despite all of these effects surrounding the mine, Inspector Russell noted that there were "No problems noted". The view in Fig. 1, taken six days after the series of intense storms, is from the western end of the west storm surge/infiltration basin looking across the Cottonwood reclamation to two of the steep reclamation slopes in the central part of the reclamation area. The minor erosion that he mentioned as "predicted in the design" was related to the plus-and-minus in the grading tolerances; this first storm discharge moved channel bed material from high spots to low spots and smoothed the channel bottom to design grade as verified by subsequent surveys. The landform's performance at resisting erosion was part of the reason that the Cottonwood reclamation received two awards from the U.S. Department of the Interior/Office of Surface Mining in 2004; "National" and "Best of the Best" reclamation.

<u>La Plata Mine McDermott reclamation – 2003</u>

On 9 September 2003, three precipitation events occurred nearly back-to-back. About 9:30 in the morning an intense 4-hr storm hit the fluvial geomorphic reclamation; 44.7 mm (1.76 in) was recorded at the automated monitoring site over two miles away and a wedge rain gauge on the reclamation recorded about 46.7 mm (1.84 in), the rain let up for an hour, then a 6-hr storm dropped 20.3 mm (0.8 in) on the saturated earth and subsided, and after another hour-long break, a 6-hr storm brought another 7.4 mm (0.29 in). The total precipitation during this 18-hr interval was 72.4 mm (2.85 in) at the automated monitoring site and more in the wedge-type gauge. As a

point of reference, a 50-yr, 3-hr storm at the site is about 49.5 mm (1.95 in). All the designed ephemeral channels flowed that day.

Figure 1. 17 Sept 2002, Cottonwood reclamation west storm surge basin as Inspector Robert Russell saw it. The un-vegetated portions of the two steep hills in the background are GeoFluv reclamation also and needed no erosion repair after the series of intense storms during the second week of September.

Figure 2 shows a reach of the valley bottom channel on the south side of the reclaimed McDermott dump during waning discharge. The top of the rock at the center of the image is at bankfull depth and the stream is flowing in the channel. The stream is following the designed channel meander, but a portion of the flow has cut across the point bar as a result of the construction making the channel with-to-depth ratio greater than designed (as shown in Table 1 above for reaches 6, 7, and 8).

As described above in the La Plata 2000-2001 section, construction methods were subsequently changed to help build channel dimensions as designed. The main changes included slightly steeping the design channel banks and keeping construction, topsoil application, and seeding equipment out of the channel after the initial channel cut had been made.

Figure 2. 9 September 2003, South McDermott channel, reach between tributaries 5 and 4, during waning discharge.

In one upland slope area between channels 3 and 4, some minor surface rilling was observed. This upland area was designed as a ridge separating these two channels near their headwaters. After grading and topsoil application, the ridge did not have the relief necessary to convey all water off either side to the south and north into channels 3 and 4 respectively; it had become flattened and allowed some runoff in the extreme storms to flow west down the flattened ridgeline. The extreme 2003 event took place after the reclaimed area had sat dormant for over two years, as most revegetation seeds failed to germinate in the droughty conditions. All the constructed channels remained stable. The company and regulatory staff agreed that the reduction in reclamation runoff coefficient that would occur when the vegetation sprouted would be sufficient to prevent future rilling from this small headwaters area, and no repair work was necessary. This was another instance where the construction crews learned the importance of maintaining the design integrity through grading and topsoil application.

La Plata Mine reclamation – 2005

By 2005 the reclamation at La Plata Mine had progressed beyond the 32 ha (80-ac) McDermott demonstration project. The construction crews had gained experience at operating their equipment and in using GPS-guidance in their bulldozers to construct the more complex fluvial geomorphic landforms. They used precision end-dumping to the GeoFluv design of lifts of backfill spoil using trucks coordinated with dozer grading to the final design surface. Using an approach for fluvial geomorphic highwall and ridge reclamation similar to that successfully used at the San Juan Mine Cottonwood project, approximately 282,885 m^3 (370,000 yd^3) of material movement was saved in an area comprising about 55 ha (136 ac). The reader can use local material movement costs to convert that work savings into dollars. This savings represents a fraction of the total 836 ha (2,066 ac) reclamation efficiency realized. Significant material movement savings that resulted in cost reductions of 10 to 37 percent have been possible and reported at other reclamation sites, including an abandoned Indiana coal mine (Hause, 2006) and a limestone quarry (Spotts, 2007)

Figure 3 shows one of fourteen subwatersheds in the Northgate North project with spoil graded to design before topsoil application. The image above shows how Northgate North Subwatershed 1 was graded to a GeoFluv design before November of 2003. Close inspection will reveal construction equipment markings on the slopes, but there is no rilling or erosion. In the image, the landform has no topsoil, no vegetation, and no artificial erosion controls. The top of the ridge is 1,832 m (6,010 ft) elevation. The image was taken in January 2005, after the site endured the 2003/2004 snowmelts, 2004 monsoon rains, and the 2004/2005 snowmelts.

La Plata Mine reclamation – 2006

The La Plata mine had added hundreds of hectares to the total constructed GeoFluv reclamation by 2006. When coal extraction ended about 2002, the labor force was reduced and all effort was put into reclaiming the 836 disturbed hectares (2,066 ac). The reclamation designers were sometimes pressed to stay ahead of the construction when material handling constraints offered opportunities to make slight revisions to the reclamation design that could aid productivity and simultaneously save money.

Figure 3. La Plata Mine Northgate North Subwatershed 1 in January 2005

For example, a shovel has a specific optimal face cut efficiency and this in turn relates to bench height; by designing the fluvial geomorphic slope and channel elevations to honor these equipment constraints, considerable constructions efficiency could be gained without comprising the environmental goals. The GeoFluv design method had been incorporated into the Natural Regrade computer software and La Plata Mine used the beta software to design the project before the software was officially released in 2005. The ability to use high-speed computers to make the complex calculations greatly aided the design staff in its efforts to optimize the design for material handling and environmental considerations, while staying ahead of the construction operations.

The La Plata Mine received 53.8 mm (2.12 in) during an extreme 3-hour storm event on 8 July 2006. As mentioned earlier, a 50-yr 3-hr storm at the site is about 49.5 mm (1.95 in), and a 100-yr, 3-hr event is about 50.8 mm (2.0 in). This storm washed out a bridge on the highway that accesses the mine. Erosion monitoring following this event found two erosion areas on newly reclaimed slopes. An upland swale on one slope had rill features up to about 15 cm (6 in) deep, down to the spoil surface. At the second site, a point bar in a small channel overtopped, eroding the downstream side of the bar. This overtopping was caused by the sub-ridge that made the point bar being constructed lower than the design. These two instances constituted the only erosion repair work that the Mining and Minerals Division had prescribed on La Plata Mine reclamation since 1999.

The image in Fig. 4 was taken in mid-September of 2006 following the extreme July storm event. Figure 4 shows the same sub-watershed as Fig. 3 after the application of topsoil and seeding, and is typical of the reclamation landform response to the >100-yr recurrence interval storm. The vegetation in the image is just starting and mostly annual plants are visible, representing just the first season's volunteer growth shading the reclamation seeding sprouts. The erosion monitoring after this extreme storm event documented that the fluvial geomorphic landform performed its functions as designed and found only two areas needing repair, at least one of which was attributable to improper construction.

Figure 4. La Plata Mine Northgate North Subwatershed 1 in September 2006

La Plata Mine reclamation – 2007

During 2007, the La Plata Mine staff sampled runoff from different areas of the hundreds of hectares of GeoFluv-designed reclamation. These samples included areas of graded spoil, final graded surfaces with topsoil applied, and older fluvial geomorphic reclamation with vegetation establishing. These water quality analyses results provide some quantification of the GeoFluv reclamation discharge water quality as compared to the native stream water quality.

The mine has sampled runoff in the natural McDermott Arroyo channel that runs through the mine site as part of its regular water quality monitoring program. McDermott Arroyo is an ephemeral channel, but its 360 km^2 (139 mi^2) watershed area can generate significant discharge. The total suspended solids values for McDermott Arroyo samples taken on 8 September 2005 were 38,500 mg/L upstream of the mine and 46,800 mg/L downstream; the 42,650 mg/L average of these values is within the normal range for the McDermott Arroyo monitoring at these sites (NMED, 2005).

Table 2 below lists total suspended solids (TSS) values for storm water samples collected within the reclamation area and for undisturbed areas outside of the reclamation. In the relatively narrow and shallow ephemeral channels of smaller upland watersheds, the usual sampling method is a grab samples taken with a wide-mouth bottle with the inlet restricted by the sampler's fingers. If the stream is wadeable, the sample may be both depth- and width-integrated, but if the stream is not wadeable they will be sampled from one bank. The total suspended solids values taken on various sites within the GeoFluv reclamation during the October, 5 2007 event can give a 'snapshot' of erosion control by comparing concentration results among the various samples: from native (660 mg/L), graded spoil (2,140 mg/L), topsoiled (47 mg/L), and re-vegetated (39 mg/L) sites (NMED, 2007). These results are averaged for the different types of sites and presented graphically in Fig. 5 below. Figure 6 below shows a fluvial geomorphic reclamation area that has been topsoiled; all the landform without tree cover is graded and topsoiled reclamation. The image in Fig. 7 shows a fluvial geomorphic reclamation area that has vegetation starting.

Table 2. Total suspended solids (TSS) values from storm water samples inside the La Plata reclamation area taken during a 5 October 2007 storm and from the McDermott Arroyo that flows through the La Plata Mine taken during an 8 September 2005 storm.

5 OCT 2007	TSS mg/L
NM James – Native	650
Pond 27 – suitable spoil	2,140
Pond 40 – topsoil	47
Pond 3 – revegetated	39
S. Little Cinder – Regrade spoil	33
Little Cinder – topsoil	1,880
Lynch's Pond – spoil	182

8 SEPT 2005	TSS mg/L
Upstream McDermott – native	38,500
Downstream McDermott-native	46,800

(Note: McDermott Arroyo has about 360 km^2 (139 mi^2) watershed upstream of the site and gets contributions from lands adjacent to the site; the difference in upstream and downstream site values should not be interpreted as the result of mine discharge, but rather the range of values should be interpreted as typical higher-order native ephemeral channel values in this area.)

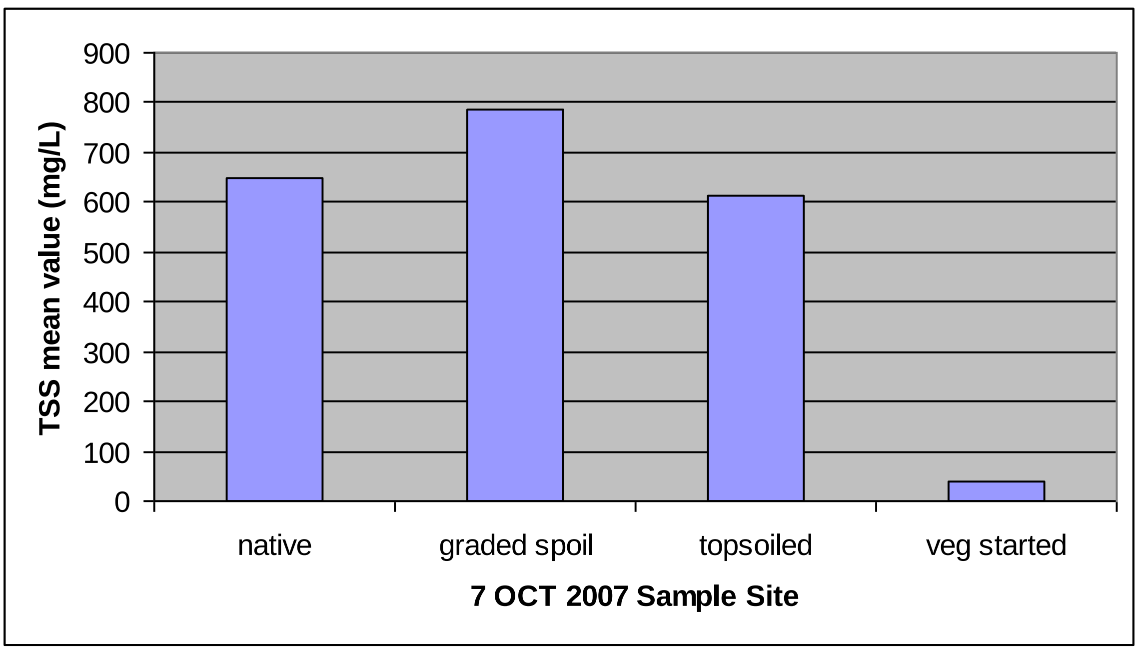

Figure 5. Graphic presentation of results of 7 October 2007 storm water sampling at La Plata Mine

Figure 6. A fluvial geomorphic reclamation area at La Plata Mine that has been topsoiled; all the landform in the fore-ground and mid-ground without tree cover is graded and topsoiled reclamation. Image captured during 28 October 2008 National Association of Abandoned Mine Land Programs national conference tour.

Figure 7. A view of a fluvial geomorphic reclamation area at La Plata Mine that has vegetation starting. The image of a subwatershed headwaters area was captured during the 12 September 2006 National Interactive Forum on Geomorphic Reclamation. The vegetation in the image is just starting and mostly annual plants are visible, representing just the first season's volunteer growth shading the reclamation seeding sprouts.

These results strongly suggest that the geomorphic-designed landform with merely a topsoil cover can satisfy erosion control needs sufficient to meet water quality goals, but they do not tell the *soil volume or mass* that was involved. Although the water quality samples from La Plata Mine give some indication of the erosion control benefit of this geomorphic approach, they do not directly quantify actual sediment load (volume). The concentration values, without discharge and duration data, and supplemental concentration values taken throughout the event, cannot quantify the actual amount of erosion associated with the storm event. Nonetheless, the 'topsoiled' and 're-vegetated' samples total suspended solids concentrations were an order of magnitude lower than the 'native' sample and three orders of magnitude lower than the native McDermott Arroyo. A research grant has been proposed to OSM to quantify the actual erosion rate associated with the GeoFluv landform and can provide valuable data to future reclamation designers and regulatory oversight staff.

Vegetation response

La Plata Mine attempted to establish multiple vegetation communities by using different topsoil depths and seed mixtures on the fluvial geomorphic landform. A topdressing thickness of 35 cm (14 in) was applied to relatively level areas along with a seed mixture designed to favor grassland establishment. A topdressing thickness of 15 cm (6 in) was applied on slopes greater than 6 percent along with either a north or south aspect upland shrub seed mixture. A stream seed mixture was developed for use adjacent to reclaimed stream channels. The mine staff estimated that approximately 41 percent of disturbed areas at La Plata Mine will be reclaimed to grassland type community, as shown in Fig. 8, 38 percent to an upland shrub community with southern exposures, 17 percent to an upland shrub community with northern exposures, and 3 percent to a grassland drainage type community.

The vegetation monitoring to date suggests that varying the seeding rates of the same species from one mixture to another is too subtle a difference to create discrete communities. Figure 9 shows a portion of the south face of the McDermott reclamation with the lower reaches of its valley bottom stream channel the day following a 50-yr, 4-hr discharge event. The forbes are Four-wing Saltbush that were seeded as part of the plant mixes described above. The Saltbush grew vigorously, whereas the grasses were slower to sprout, but eventually did in the cooler, shadier areas around the base of the Saltbush. Also, note that the channel bottom is relatively free of vegetation and the bent-over vegetation on the channel's point bar shows the flood prone area designed into the channel cross section.

Figure 8. 5 May 2005, 170 Arroyo endwall reclamation with grassland mixture sprouting

Figure 9. 10 September 2003, South McDermott valley bottom channel, reach 7 to 8

Conversely, the variation in moisture harvest resulting from the dissected topography will likely play a larger role in creating community diversity. The image in Fig. 10 below was taken in December 2005 and shows the variation in moisture harvesting that results from the complex fluvial geomorphic slope design. The north-facing slope at the left of the image is maximizing moisture harvesting because it is not exposed to the sun's energy all day. The south-facing slope across the valley has less snow cover overall, but the GeoFluv design has broken the slope into smaller subwatersheds that contain east and west aspects. The reclamation landform provides variation in water content and sunlight to naturally create niches for different plant species that will promote vegetation diversity.

Figure 10. December 2005, Northgate Arroyo headwaters showing variation in moisture harvesting from slope aspect diversity in fluvial geomorphic-designed landform.

Conclusion

The monitoring results presented above give an overview of the success of the GeoFluv fluvial geomorphic landform design method used since 2000 at the La Plata and San Juan Mines. They include the response of over 890 ha (2,200 ac) of reclaimed land to extreme storms, including a 50-yr, and >100-yr event.

The erosion monitoring showed that the landforms needed repair in only two small areas, a single rill that eroding up to 15 cm (6 in) and a channel flow that cut across a sub-ridge point bar, both in response to the >100-year storm. The point bar ablation was definitely caused by the grading not meeting the design specification, and although the inspection did not determine the reason for the single rill, it was likely the result of a grading error also as it was the only rill that formed in nearly 809 ha (2,000 ac) of fluvial geomorphic reclamation.

The 2007 snapshot water quality monitoring suggests that the fluvial geomorphic reclamation runoff water quality may be significantly better than adjacent native lands, by orders of magnitude, but further studies to quantify erosion and sedimentation needs to be conducted before this can be conclusively stated. The methodologies to do this could include sampling suspended and bedload sediment in combination with discharge throughout storm events or accurately surveying channel and ponds before and after events to allow quantification of sediment volumes that could be converted to units such as tons per acre per year.

This result is what would be expected because the undisturbed land is not geomorphically mature, but rather is relatively youthful and actively eroding in this highly-erosive semi-arid region, while the reclamation landforms *are* geomorphically mature. The undisturbed land is made of consolidated sandstone, shale, and coal with thin veneers of weathered regolith and soil. The reclamation land is made of a spoil mixture of unconsolidated fragments of sandstone and shale with a top-dressing of various growth-mediums. The fluvial geomorphic design that was used is appropriate for unconsolidated earth materials in this climate. Some have questioned whether the change in water quality from up- and down-stream areas will cause problems, but this kind of change can occur in the natural landscape whenever streams flow from one lithology (rock type) to another.

The vegetation monitoring suggested that varying seed mixtures to obtain species diversity and composition goals may not be as important as the variation in moisture harvesting and sunlight exposures offered by the complex fluvial geomorphic landform. More definitive conclusions are premature because droughty conditions immediately following seeding and a high point in the Western Cottontail and Jackrabbit populations conspired to frustrate plant growth.

Future studies are proposed to quantify the sediment load generated by GeoFluv-designed landforms. Additional compilation of water quality runoff results from different sites would be beneficial. A determination of sediment production expressed as tons per acre per year from constructed sites would be important, and a grant to make this determination is currently proposed (SES, 2009); this proposal includes incorporation of the Forestry Reclamation Approach grading methods when constructing the design to demonstrate the practicality of combining the approaches. A study will be undertaken in 2009 in Australia to compare predictions of landform erosion of over time in a mine project area to a GeoFluv design for the same area (HCEG, 2008). Follow-up studies that compare vegetation cover, species composition, and diversity at constructed sites to traditional landform sites can not only document any differences in vegetation, but can help document the effect of vegetation on sediment discharge and water quality from these landforms.

These studies will provide assurance to facilities posting reclamation bonds and agencies evaluating the effects of mining proposals that the method can make truly sustainable reclamation lands. Until those studies are completed, this record of reclamation performance in what is arguably one of the most erosive environments in the continental United States demonstrates that the by using GeoFluv design method reclamation landforms can have erosion resistance and discharge water quality equal to or better than surrounding undisturbed land.

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