Evaluating Sediment Production from Watersheds at La Plata Mine[1]

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Abstract

San Juan Coal Company (SJCC) began 1,835 acres of reclamation of its La Plata Mine utilizing the GeoFluv^{TM} fluvial geomorphic reclamation design method in 1999 (Bugosh, 2000). The final fluvial geomorphic reclamation grading, topdressing, and seeding was completed in 2008. The aim of the fluvial geomorphic reclamation was to achieve long-term stability against erosion (notably no major slope blowouts and formation of rills and gullies), reduced maintenance, and increased biodiversity as compared to mines reclaimed using traditional reclamation methods (e.g. terrace, berm, and downdrain designs) (Bugosh, 2003). Inspections of the completed reclamation at La Plata Mine qualitatively confirmed the benefits of the fluvial geomorphic reclamation method. However, there was a desire to quantify the sediment production rates from these landforms and compare them to the rates measured in surrounding undisturbed native lands. In the fall of 2011, SJCC began implementation of a research study at La Plata Mine to test the effectiveness of its geomorphic reclamation to reduce sediment loading from reclamation areas.

Data were acquired from three types of sub-watersheds differentiated as native (undisturbed by mining), geomorphic design with topdressing and poorly established vegetation, and geomorphic design with topdressing and significant vegetation establishment. The three sub-watersheds were selected to ensure similar size, aspect, and slope and were located as close as possible together to minimize storm intensity variation effects. The three sites were each instrumented with a temporary check-dam-type sediment control structure at the outlet of each subwatershed. These were designed to impound runoff from a 2-year, 1-hour storm. Erosion pins facilitated measurement of sediment deposition in the impounded area. Lastly, site-specific precipitation gauges were placed at each site to understand storm effects. The La Plata Meteorological Station helped study storm event precipitation in relation to longer-term precipitation records.

Monitoring of the study sites included a pre-project survey of the study subwatershed uplands, receiving channels, and sediment control structures to provide an accurate base-level measurement of the landform surface. Data collection included note taking and photo-documenting the condition of each subwatershed, and measuring sediment accumulation at sediment pins, following potential runoff-producing storm events.

In coordination with GeoFluv, SJCC will provide sediment production analysis. The results will provide quantification of sediment production as tons/acre related to individual storm events that produced runoff during the first year of the study. SJCC will also summarize data, from several runoff-generating storms, to facilitate a sediment production estimate as tons/acre/year. The analysis will also provide quantification of the difference in sediment production among the three subwatershed types.

Introduction

San Juan Coal Company (SJCC) began 1,835 acres of reclamation of its La Plata Mine utilizing the GeoFluv^{TM} fluvial geomorphic reclamation design method in 1999 (Bugosh, 2000). The final fluvial geomorphic reclamation grading, topdressing, and seeding was completed in 2008. The aim of the fluvial geomorphic reclamation was to achieve long-term stability against erosion (notably no major slope blowouts and formation of rills and gullies), reduced maintenance, and increased biodiversity as compared to mines reclaimed using traditional reclamation methods (e.g. terrace, berm, and downdrain designs). Inspections of the completed reclamation at La Plata Mine qualitatively confirmed the benefits of the fluvial geomorphic reclamation method. However, there was a desire to quantify the sediment production rates from these landforms and compare them to the rates measured in surrounding undisturbed native lands. In the fall of 2011, SJCC began implementation of a research study at La Plata Mine to test the effectiveness of its geomorphic reclamation to reduce sediment loading from reclamation areas.

Test Sites

The test sites were located in the rehabilitated BHP Billiton La Plata Mine in northwestern New Mexico in the U.S.A. The elevations at the mine site range from 5,980 to 6,210 feet (1,795 to 1,892 metres). The annual precipitation at the site ranges from 12 to 14 inches (30.5 to 35.6 cm). The area soils are thin and sandy and bedrock crops out regularly. Local vegetation is sparse and consists of bunch grasses, forbes, and stands of pinon pine and juniper. These characteristics combine to present a high elevation, semi-arid, highly erosive terrain.

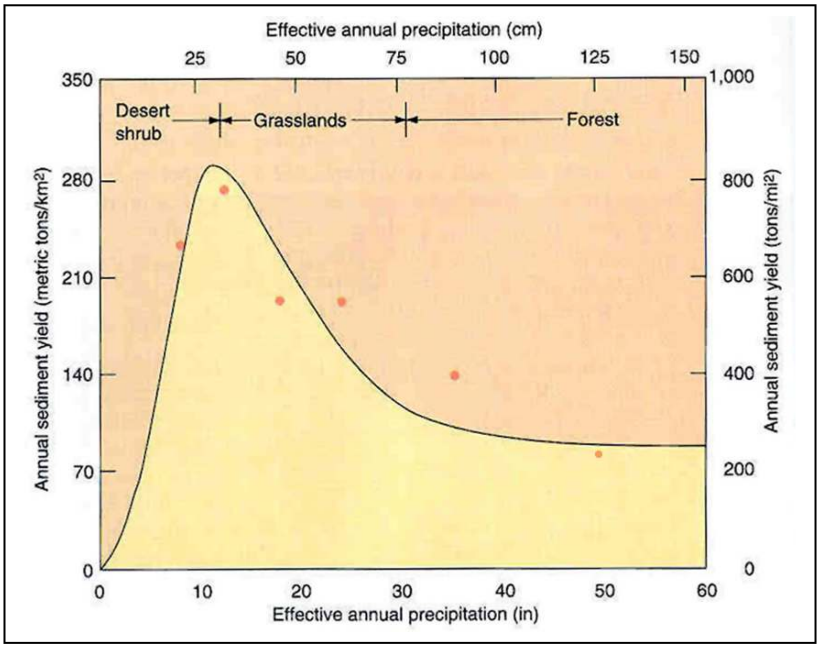


Figure 1. Graphic representation of the relationship between precipitation, vegetation, and sediment yield. (Langbein and Schumm, 1958)

The study site is in an extremely erosive environment that provides a rigorous test of the landform rehabilitation design. Greater precipitation does not directly lead to greater erosion as researchers have long known because greater precipitation generates thicker soils and more abundant vegetation that intercept vegetation, promote infiltration rather than runoff, and make a through flow hydrologic condition. Conversely, lesser precipitation forms thin soils over bedrock with little intervening vegetation and makes for flashy runoff and overland flow conditions. The figure above shows that the La Plata Mine site conditions are those that lead to the maximum erosion and sediment yield.

Previous Site Sediment Monitoring

Background sediment concentrations had been measured for many years during the life of mine. Sediment discharge sampling is difficult because there are only about six precipitation events per year that generate sediment discharges and these typically occurring during the night or early morning.

A large arroyo (ephemeral channel) drains 139 square miles upstream of the mine site (360 square kilometers) and flows through the site. Total suspended sediment samples taken from a discharge event in this arroyo on 8 September 2005 averaged 42,650 mg/L, values that are in the long-term sample range. A sample taken from a first-order ephemeral channel was 660 mg/L.

Subjective evaluations of erosion and sedimentation are possible after every storm. Since the onset of the fluvial geomorphic reclamation by the GeoFluv method at the site, extreme storms have been measured at the site and only two minor erosion repairs were needed. These were attributable to construction grading errors, rather then design failures, and required only a few cubic yards of material to correct. Similarly, qualitative observations by a mine inspector following an extreme storm in 2002 at a sister mine using this fluvial geomorphic method concluded with

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. (New Mexico Mining and Minerals Division, 2002.)

While these subjective evaluations did support the success of this fluvial geomorphic reclamation method at minimizing erosion and sedimentation, they did not quantify the erosion and sedimentation rates as compared to the natural, undisturbed land rates.

A synoptic storm water runoff sampling on 7 October 2007 provided some quantification of sedimentation. Samples collected during this event came from sites identified as: 1) native, undisturbed land, 2) spoil graded to the fluvial geomorphic design without topsoil or vegetation, 3) spoil graded to the fluvial geomorphic design with topsoil, and 4) spoil graded to the fluvial geomorphic design with topsoil and vegetation.

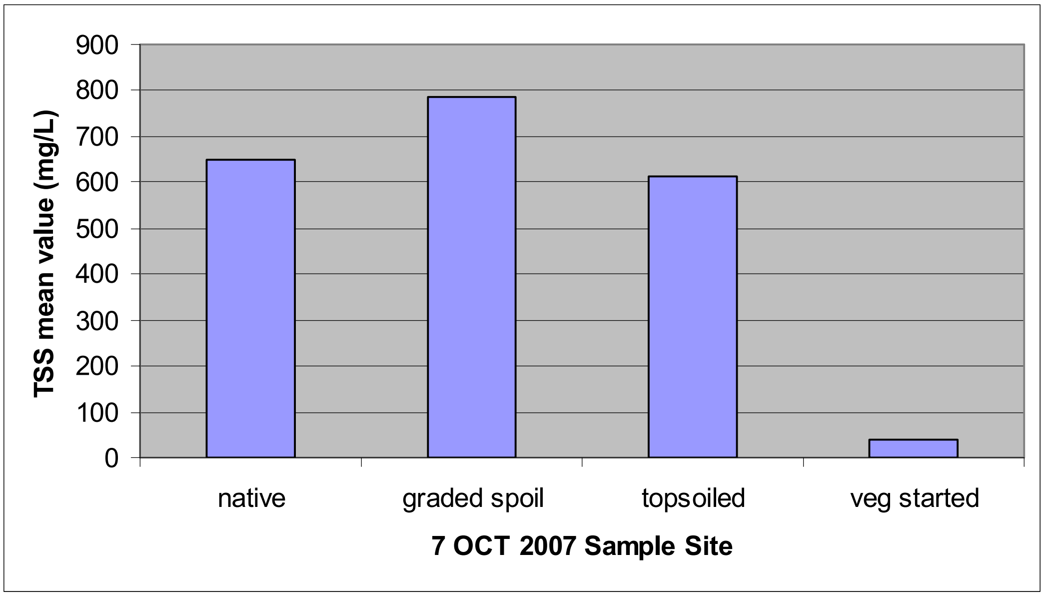


Figure 2. Graph of 7 October 2007 synoptic storm water runoff sampling from native and constructed GeoFluv reclamation.

The synoptic total suspended solids results presented graphically above show that the constructed fluvial geomorphic designs without vegetation generated suspended sediment loads similar to the undisturbed native land. The constructed fluvial geomorphic site with vegetation established generated suspended sediment at an order of magnitude lower concentration than the undisturbed native land. This lower concentration can be explained by the fluvial geomorphic reclamation having taken critical design input values from geomorphically "mature" reference areas that are relatively stable against erosion. The undisturbed native land is more geomorphically "youthful" and tends to erode at a greater rate. The synoptic sampling results indicate that the fluvial geomorphic designs generate sediment discharge equal to, or less than, natural undisturbed land, but they do not quantify the total volume of sediment. The total suspended sediment results show only a "snapshot", i.e., the sediment discharge concentration at the moment of sampling. They did not tell the soil volume or tonnage involved.

Methodology

A simple method was developed to quantify the actual sediment discharges coming from the natural, undisturbed and reclaimed lands. Dams were constructed that would contain the discharge from bankfull discharge-generating storm events in study watersheds. The watersheds were matched in physical characteristics so that the differences among them would be limited to whether they were native, undisturbed or reclaimed. The reclaimed sites were further distinguished as to whether or not they had a robust establishment of vegetation. Three study watershed types resulted: native (undisturbed by mining), GeoFluv design with topdressing and poor to moderate vegetation, and GeoFluv design with topdressing and significant vegetation establishment. After a storm, the sediment discharge from the watershed upstream of the dams would settle behind the dams and could be measured.

The general project area within the 1,835 acre (742 ha) reclamation area was first identified. The criteria used included not only having the three subwatershed types in close proximity, but also access that was conducive to the construction of the temporary sediment dams and installation of the precipitation monitoring equipment and repeated site visits during wet ground conditions with minimal disturbance to the completed reclamation. A general project area that met these criteria was found in the eastern end of the mining area that was bisected by a permanent unpaved access road.

Twenty-seven sub-watersheds that included the three study sites were identified within the general area. The three types of sub-watersheds were located within 2.6 miles (4.2 kilometres) of one another to minimize effects of the often localized storm events. The three study sub-watersheds were selected to closely match the characteristics of area, aspect, average subwatershed slope, channel slope range, and channel profile. This work began with the project approval in August 2011 and the sites were able to take baseline measurements for their first sediment discharge events in May 2012.

Installation

The preliminary designs to determine the temporary sediment pond dimensions and material needs were made in the fall of 2011. The three sites were: a natural, undisturbed site (N7), a site constructed to a GeoFluv design that had been covered with topdressing, but which had little to no vegetation established (MV5), and a site constructed to a GeoFluv design with good vegetation establishment (WV3). GeoFluv designed a valley pond (stock dam) at each site to determine the width and height of a dam capable of impounding a bankfull discharge producing event (2-yr, 1-hr was used as the bankfull-generating storm). Those dimensions and a drawing of the temporary dam sandbag construction details was provided to site staff so that they could procure the required sandbags, sand, PVC pipe and other materials locally. The sandbag dam design has been refined at other extreme weather sites (Spotts, 2011). The dams had a spillway to pass events greater than the bankfull discharge event. The dams also were fitted with a drain pipe to allow decanting of the water after sediment had settled behind the dam.

	N7	MV5	WV3
Area (acres)	1.6	1.5	1.2
Aspect	SE	SW	SSE
Average slope (%)	11.1	12.4	17.0
Slope range	3-22	8-11	1-19
Channel profile*	C KP	S	C

Table 1. Study watershed characteristics. * C = concave, KP = with knickpoint, S = straight

The dam sites were located in the field and site personnel constructed the dams according to the design. The surveyor used a hand level to locate the full-pool elevation based on the dam spillway elevation. The sediment pins (lengths of steel reinforcement bar stock) were located below the full pool elevation along the valley walls and channel and pond bottom upstream of the dam. After the construction was completed, the surveyor returned to the sites and accurately surveyed each project site. The mine hydrologist installed a recording rain gauge at each site to augment the long-term mine meteorological station that was located approximately 3.5 miles (5.6 km) from the sediment project study sites. It was important to capture site specific precipitation information because the precipitation events in the region are extremely localized.

Figure 3. N7 sediment dam site with survey in progress and sediment pins installed.

Figure 4. WV3 study site after construction of temporary sediment dam.

Images of three sediment study sub-watersheds

Figure 5. N7 native subwatershed site.

Figure 6. MV5 GeoFluv design with topdressing and poor to moderate vegetation establishment.

Figure 7. WV3 GeoFluv design with topdressing and significant vegetation establishment.

Challenges to the study sites arose as the project continued. The grade of the access road directed road runoff into the top of the well vegetated site and had to be intercepted by installation of coir logs. Seepage was observed between the sand bags from which the dam was constructed and the sand bags were subject to rapid deterioration from the intense sun; both of these problems were resolved by covering the temporary dams with plastic sheeting. The sheeting both helped seal the seepage and protected the sandbags from sunlight. Additionally, the sheeting was easier to replace than the sandbags. When arriving on site to measure the sediment elevation after some storms, the sediment surface at some sampling stakes or the top of the stakes was sometimes immersed by pooled water and could not be measured until the water had been fully drained. Frost heave was observed to occur around the survey stakes in the extremely cold periods and this elevated sediment surface affected the measurements until the sediment subsided again during moderate weather. Each of these challenges was overcome by adjusting the site construction, making additional site measurement visits, or recognizing the effect in the data.

Monitoring

The extremely localized nature of precipitation events at the project site made it difficult to monitor sediment-generating events. The site hydrologist monitored regional weather reports to anticipate local precipitation events and then decided if a site visit was indicated. When on-site, each station was visited to determine if a sediment generating event had occurred, and if so, sediment measurements were taken.

The sediment measurements were taken using the matrix of surveyed sediment pins at each site. A localized survey was used with the northings and eastings of each pin located along with its ground surface elevation. The distance from the top of the pin to the ground surface measurement after a storm could be compared with the previous measurements to determine the change in ground surface elevation at the pin.

These coordinate values, x, y, and z for each pin in the matrix were then used to generate a three-dimensional surface model using the Carlson Natural Regrade and Civil Computer Aided Design (CAD) software. The surface models are finite different triangular irregular network (tin) models. The vertical difference between event surfaces is the thickness of sediment between the surfaces. The areal difference of the two surfaces is the volume of sediment between them. When the area of the two surfaces compared is constant (the full-pool elevation line upstream of the dam was used at each site) the difference of sediment volume within the area can be compared among events. Any two tins can be compared to study the changes in sediment over the periods corresponding to the tin.

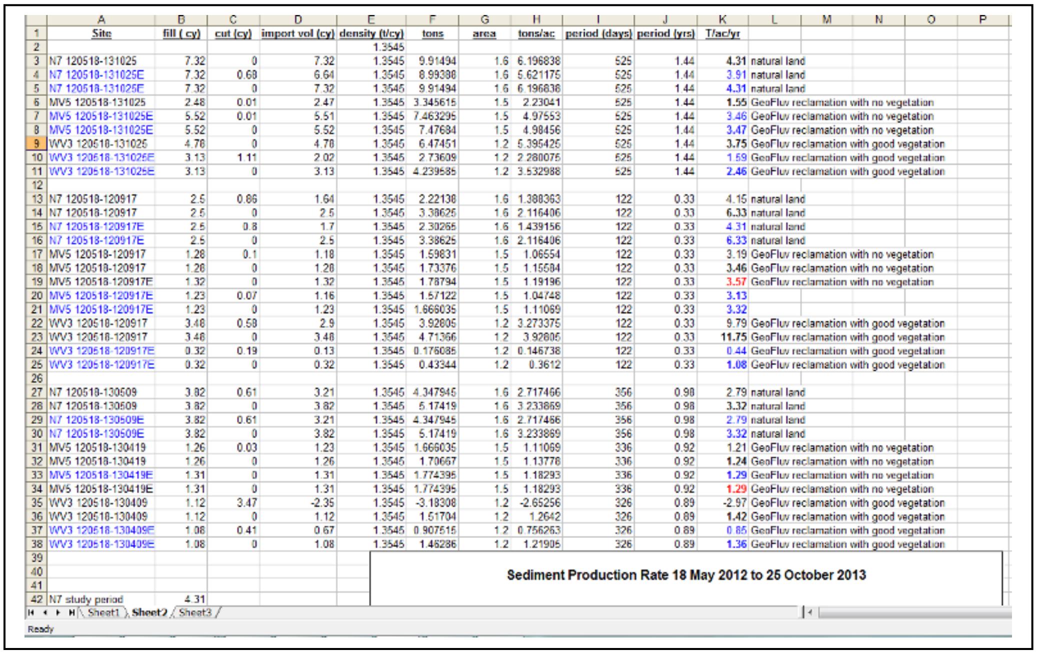
The storm monitoring began after the installation of the three sites was complete in September of 2011. Unfortunately, there was not sufficient precipitation to produce a sediment-generating event and a baseline measurement was taken in May of 2012.

Figure 8. View downstream to the N7 temporary sediment dam after the first sediment event.

The last sediment pin measurements were taken in January 2014. The data period includes seven months in 2012, 12 months in 2013, and one month in 2014. These data represent the latter part of the 2012 water year, span the entire 2013 water year, and conclude with the beginning of the 2014 water year.

Results and Conclusions

The table below shows a spreadsheet used to make the calculations. After each sediment discharge event, the surface elevations at the sediment pins were measured. A three-dimensional surface model was then made from the survey pin data. Any two three-dimensional surface models can be compared and the vertical difference between them is the change in thickness during that period. The difference within an area, as if a cookie-cutter were pressed into the surface, is the volume of sediment that accumulated during that period.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Site	fill (cy)	cut (cy)	import vol (cy)	density (t/cy)	tons	area	tons/ac	period (days)	period (yrs)	T/ac/yr					
2					1.3545											
3	N7 120518-131025	7.32	0	7.32	1.3545	9.91494	1.6	6.196838	525	1.44	4.31	natural land				
4	N7 120518-131025E	7.32	0.68	6.64	1.3545	8.99388	1.6	5.621175	525	1.44	3.91	natural land				
5	N7 120518-131025E	7.32	0	7.32	1.3545	9.91494	1.6	6.196838	525	1.44	4.31	natural land				
6	MV5 120518-131025	2.48	0.01	2.47	1.3545	3.345615	1.5	2.23041	525	1.44	1.55	GeoFluv reclamation with no vegetation				
7	MV5 120518-131025E	5.52	0.01	5.51	1.3545	7.463295	1.5	4.97553	525	1.44	3.46	GeoFluv reclamation with no vegetation				
8	MV5 120518-131025E	5.52	0	5.52	1.3545	7.47684	1.5	4.98456	525	1.44	3.47	GeoFluv reclamation with no vegetation				
9	WV3 120518-131025	4.78	0	4.78	1.3545	6.47451	1.2	5.395425	525	1.44	3.75	GeoFluv reclamation with good vegetation				
10	WV3 120518-131025E	3.13	1.11	2.02	1.3545	2.73609	1.2	2.280075	525	1.44	1.59	GeoFluv reclamation with good vegetation				
11	WV3 120518-131025E	3.13	0	3.13	1.3545	4.239585	1.2	3.532988	525	1.44	2.46	GeoFluv reclamation with good vegetation				
12																
13	N7 120518-120917	2.5	0.86	1.64	1.3545	2.22138	1.6	1.388363	122	0.33	4.15	natural land				
14	N7 120518-120917	2.5	0	2.5	1.3545	3.38625	1.6	2.116406	122	0.33	6.33	natural land				
15	N7 120518-120917E	2.5	0.8	1.7	1.3545	2.30265	1.6	1.439156	122	0.33	4.31	natural land				
16	N7 120518-120917E	2.5	0	2.5	1.3545	3.38625	1.6	2.116406	122	0.33	6.33	natural land				
17	MV5 120518-120917	1.28	0.1	1.18	1.3545	1.59831	1.5	1.06554	122	0.33	3.19	GeoFluv reclamation with no vegetation				
18	MV5 120518-120917	1.28	0	1.28	1.3545	1.73376	1.5	1.15584	122	0.33	3.46	GeoFluv reclamation with no vegetation				
19	MV5 120518-120917E	1.32	0	1.32	1.3545	1.78794	1.5	1.19196	122	0.33	3.57	GeoFluv reclamation with no vegetation				
20	MV5 120518-120917E	1.23	0.07	1.16	1.3545	1.57122	1.5	1.04748	122	0.33	3.13					
21	MV5 120518-120917E	1.23	0	1.23	1.3545	1.666035	1.5	1.11069	122	0.33	3.32					
22	WV3 120518-120917	3.48	0.58	2.9	1.3545	3.92805	1.2	3.273375	122	0.33	9.79	GeoFluv reclamation with good vegetation				
23	WV3 120518-120917	3.48	0	3.48	1.3545	4.71366	1.2	3.92805	122	0.33	11.75	GeoFluv reclamation with good vegetation				
24	WV3 120518-120917E	0.32	0.19	0.13	1.3545	0.176085	1.2	0.146738	122	0.33	0.44	GeoFluv reclamation with good vegetation				
25	WV3 120518-120917E	0.32	0	0.32	1.3545	0.43344	1.2	0.3612	122	0.33	1.08	GeoFluv reclamation with good vegetation				
26																
27	N7 120518-130509	3.82	0.61	3.21	1.3545	4.347945	1.6	2.717466	356	0.98	2.79	natural land				
28	N7 120518-130509	3.82	0	3.82	1.3545	5.17419	1.6	3.233869	356	0.98	3.32	natural land				
29	N7 120518-130509E	3.82	0.61	3.21	1.3545	4.347945	1.6	2.717466	356	0.98	2.79	natural land				
30	N7 120518-130509E	3.82	0	3.82	1.3545	5.17419	1.6	3.233869	356	0.98	3.32	natural land				
31	MV5 120518-130419	1.26	0.03	1.23	1.3545	1.666035	1.5	1.11069	336	0.92	1.21	GeoFluv reclamation with no vegetation				
32	MV5 120518-130419	1.26	0	1.26	1.3545	1.70667	1.5	1.13778	336	0.92	1.24	GeoFluv reclamation with no vegetation				
33	MV5 120518-130419E	1.31	0	1.31	1.3545	1.774395	1.5	1.18293	336	0.92	1.29	GeoFluv reclamation with no vegetation				
34	MV5 120518-130419E	1.31	0	1.31	1.3545	1.774395	1.5	1.18293	336	0.92	1.29	GeoFluv reclamation with no vegetation				
35	WV3 120518-130409	1.12	3.47	-2.35	1.3545	-3.18308	1.2	-2.65256	326	0.89	-2.97	GeoFluv reclamation with good vegetation				
36	WV3 120518-130409	1.12	0	1.12	1.3545	1.51704	1.2	1.2642	326	0.89	1.42	GeoFluv reclamation with good vegetation				
37	WV3 120518-130409E	1.08	0.41	0.67	1.3545	0.907515	1.2	0.756263	326	0.89	0.85	GeoFluv reclamation with good vegetation				
38	WV3 120518-130409E	1.08	0	1.08	1.3545	1.46286	1.2	1.21905	326	0.89	1.36	GeoFluv reclamation with good vegetation				
39																
40																
41																
42	N7 study period	4.31														

Sediment Production Rate 18 May 2012 to 25 October 2013

Table 2. Example Calculations

The volume multiplied by a density value yields tons of sediment. The tons of sediment divided by the acreage upstream of the dam yields tons per acre. The tons per acre divided by the period in years during which the sediment accumulated yields the tons per acre per year value.

A bar graph can be used to compare the resulting values among the three sites and helps visualize the trends in sedimentation. The graph below shows six different periods for each of the three sites. The bar on the left side of each site's grouping shows the tons per acre per year value for the entire study period, from the baseline site sediment measurement on 18 May 2012 through the last sediment event measurement on 25 October 2013. The N7 native site had the greatest sedimentation rate at 4.3 tons per acre per year, followed by the MV5 fluvial geomorphic design with topdressing and little to moderate vegetation site at 3.47 tons per acre per year, and the WV3 fluvial geomorphic design with topdressing and well-established vegetation site had the lowest sedimentation rate at 2.46 tons per acre per year.

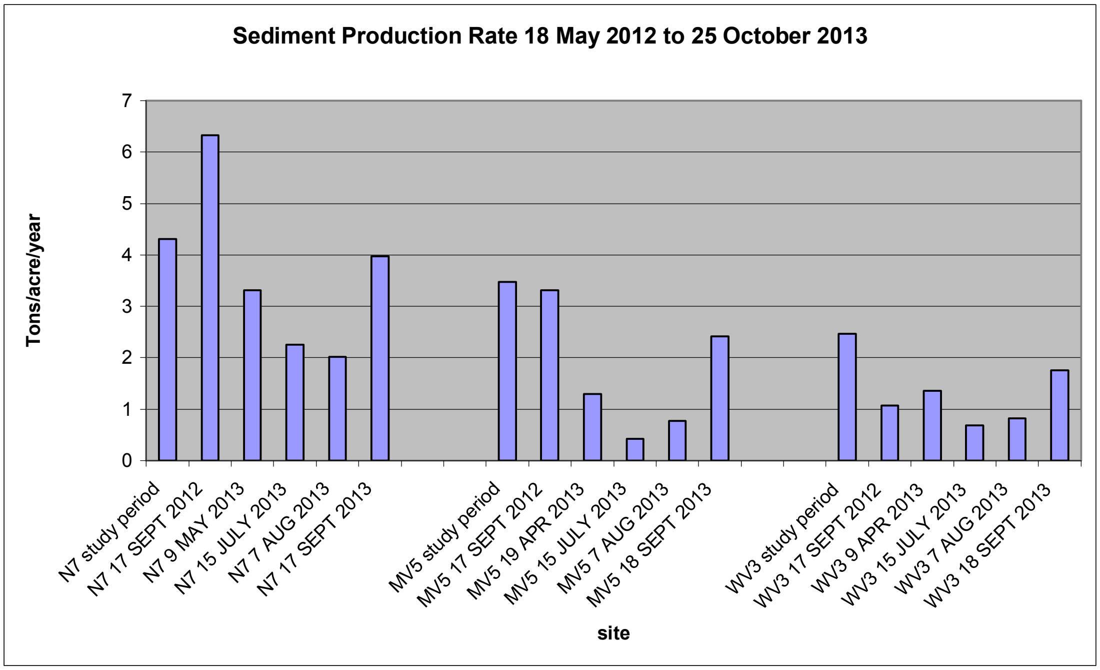


Figure 9. Bar graph of tons per acre sediment rate for six different periods for each of the three sites.

The remaining five bars in each site grouping show the average sedimentation rates at various times throughout the study period. They are the result of comparing the starting surface with the sediment surface at the date on the graph's horizontal axis label. The rates among the sites are not seen to change at fixed rates. This would be expected because some periods experienced greater or lesser storms and resulting runoff, vegetation changed during the year, degree of soil moisture content varied at the onset of storms, etc. The overall trend for all the periods is similar with both of the fluvial geomorphic sites having sedimentation rates better than or equal to the native, undisturbed site.

The three sediment monitoring sites were installed and ready to collect sediment data in September 2011, but a sediment-producing discharge event did not occur for twelve months, until September 2012. The six sediment discharge events occurred during 14 months from September 2012 to October 2013. The sporadic nature of the sediment-generating events complicates reporting and interpretation of the data.

The water year is described in the United States as the period from 1 October of a given calendar year through 30 September of the following calendar year. This is set to correspond to the hydrograph, with the lowest flows in perennial streams occurring around 1 October followed by rising discharges until a peak is reached and then declining discharges on the falling limb that end at the low discharge that begins the next water year. In a system like a perennial stream, a measurement can be made of a parameter of interest on any day because there is a discharge to sample every day. The sporadic nature of the sediment-generating events in this study complicated that by occurring before and after the 1 October/30 September change in water year.

In point of fact, an event occurred twelve days before the end of the 2013 water year and circumstances did not allow a site visit until 25 days after the end of the 2013 water year at which time measurements showed additional sediment had accumulated, but the precipitation records did not allow a determination as to whether the sediment arrived before or after the end of the water year. This means that by using 365 days for the water year period, the sediment discharge estimate could vary by 3 percent on the high side to 7 percent on the low side (dividing a given tons per acre by fewer days yields a higher value and vice-versa). In any case, the effect applied equally to all sites and does not affect the relative relationships of the values among the sites.

Given the information above, the chart below displays what the authors believe are the values most representative of the conditions on site because they use values directly measured rather than inferring what happened at the end of the year between measurements. They compare the sediment surface that existed on 17 September 2012 with the 25 October 2013 surface that existed 403 days later. The entire 2013 water year is contained within these measurements. The tons per acre values are divided by the 403 day (1.1 years) period to calculate the tons per acre per year values shown.

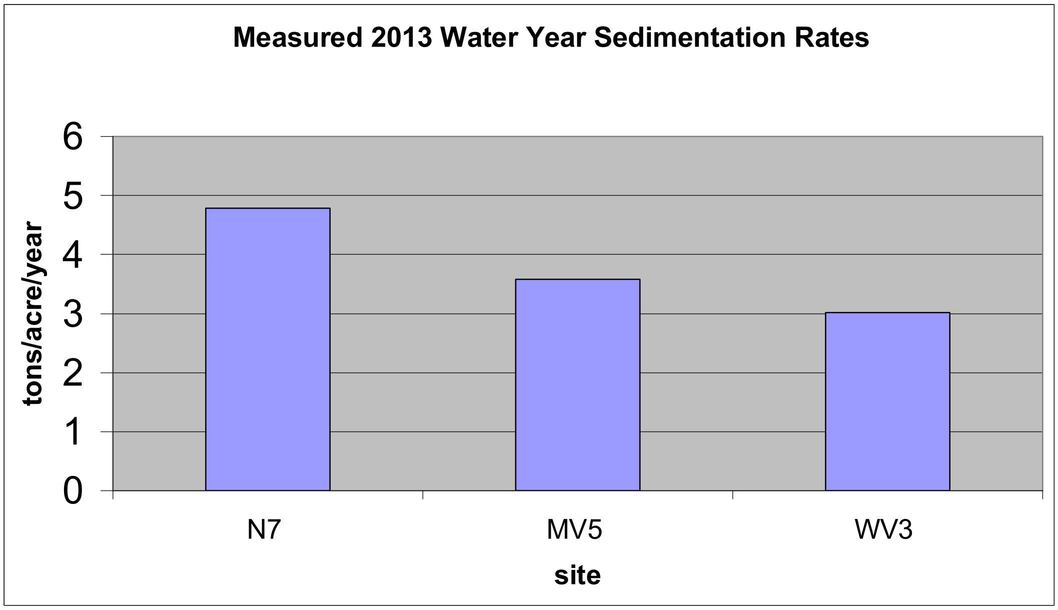


Figure 10. Bar graph of sedimentation rates calculated from 17 September 2012 and 25 October 2013 3D surfaces. The data include the entire 2013 water year.

The tons per acre per year values shown are: N7 4.79, MV5 3.58, and WV3 3.02. The relative differences can be more readily seen in this simpler chart. The GeoFluv design with topdressing and poor to moderate vegetation site, MV5, produced 25 percent less sediment than the native, undisturbed land site, N7. The GeoFluv design with topdressing and well-established vegetation site, WV3, produced 37 percent less sediment than the native site. These results suggest that the fluvial geomorphic landform accounted for a greater portion of the sediment reduction (the initial 25 percent) than the vegetation effect (the additional 12 percent).

These results can help decision making regarding erosion and sedimentation effects. The necessary duration of storm water runoff discharge monitoring and when bond release criteria are satisfied are just two examples. Because the rehabilitated land sediment discharge is less than the undisturbed natural land, the runoff monitoring is not needed once the land is regraded and topdressing has been applied. Similarly, when the land has been regraded and topdressing has been applied, bond release criteria related to erosion and sedimentation control are satisfied.

Recommendations for Future Study

Recommendations for future study are to:

- Increase number of sites
- Study other site types
- Conduct studies in other regions
- Study the effects of storm intensity and duration
- Develop slope, area, aspect relationships
- Develop monitoring period relationships

Acknowledgements

The authors thank BHP Billiton – San Juan Coal Company, Carlson Software, and GeoFluv for their support of this research project.

Additional Key Words: erosion rates, geomorphic reclamation, sediment production, tons per acre per year.

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1 Oral paper was presented at the 2014 OSM National Technical Forum: Advances in Geomorphic Reclamation on Mined Land, Albuquerque, New Mexico, May 20-22, 2014.
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