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Evaluating sediment production from native and fluvial geomorphic-reclamation watersheds at La Plata Mine

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A R T I C L E I N F O

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A B S T R A C T

San Juan Coal Company reclaimed 743 ha at its La Plata Mine using the GeoFluv™ fluvial geomorphic reclamation design method from 1999 through 2008 to achieve long-term stability against erosion (no major slope blowouts and rill and gully formation), reduced maintenance, and increased biodiversity as compared to traditional reclamation methods (e.g. terrace, berm, and downdrain designs). Qualitative inspections of the completed reclamation confirmed the fluvial geomorphic reclamation method benefits. In the fall of 2011, the company began implementing a research study to quantify the sediment production rate from these geomorphic landforms and surrounding undisturbed native lands.

Data were acquired from subwatersheds differentiated as native (undisturbed by mining), fluvial geomorphic design with topdressing and poorly established vegetation, and fluvial geomorphic design with topdressing and significant vegetation establishment. The three subwatersheds were selected to ensure similar size, aspect, and slope and were located close together to minimize storm variation effects. Temporary check-dam-type sediment control structures designed to impound runoff from a 2-yr, 1-h storm were installed at each subwatershed outlet. Erosion pins in the impounded area facilitated sediment deposition measurement. Precipitation was recorded by the La Plata Mine Meteorological Station and supplemental site-specific precipitation gauges.

Precipitation sufficient to cause sediment transport provided data for the end of the 2012, all of the 2013, and the beginning of the 2014 water years. The site data provided direct relationships between sediment production and precipitation. The sediment yield from the undisturbed native site was 9.53 t ha^{-1} yr^{-1}, while the fluvial geomorphic design with topdressing and poorly established vegetation site averaged 13% lower than the native site, and the fluvial geomorphic design with topdressing and significant vegetation establishment averaging 41% lower sediment yield than the native site. Land-disturbing activities that can accelerate erosion and sediment yield will accompany global population growth. The results of this study indicate that use of this land reclamation method can mitigate erosion and sediment yield increases associated with that growth.

1. Introduction

The UN State of World Population 2014 report predicts global population will increase to 11 billion by 2100. Increases in land-disturbing activities that can accelerate erosion and sediment yield will accompany that population growth. Managing that growth and finding sustainable solutions for those problems have been described as “the great challenges of this century” (Tarolli and Sofia, 2016). The search for the best possible land reclamation solutions associated with land transformed and degraded by earth movements is one of those challenges. This study describes and evaluates one of those land reclamation methods and confirms that it can provide one of those solutions. We include an overview of previous efforts to monitor sediment discharges from other similar sites, as well as this reclaimed site. The benefits and limitations that are described for the different methods help to clarify why and how this study method was developed and used to eliminate uncertainty, and to provide reliable sediment yield quantification.

San Juan Coal Company (SJCC) began 743 ha of reclamation of its La Plata Mine utilizing the GeoFluv™ 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).

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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.

This study's reproducible measurement method to quantify sediment yield can be used alone to verify reclamation performance, and also to calibrate and verify equations and models used to predict performance. Sediment yield estimates made using predictive equations may not be accurate if the parameter collection period is not representative of the longer-term conditions or if the data set used to make the predictive equation is based on conditions that are very different from the site where the predictions will be used (Bugosh, 1988). Grab samples taken during low- or high-yield periods can misrepresent the greater period and many factors within the upper watershed and stream can affect sediment yield by storing or by releasing sediment (Megahan and Nowlin, 1976; Beschta, 1979; Keller and Tally, 1979; Marston, 1982; Lisle, 1986; Bugosh and Custer, 1989). We suggest that the sediment yield measurement method used in this study provides reliable results that can both minimize the effects of short-term temporal variations and better represent the sediment yield from project-scale catchments.

Jeldes et al. (2015) presented a computational method to compare sediment loss from longitudinally concave slopes to planar (constant-gradient) slopes. The results predicted less erosion from longitudinally-concave slopes, but the various estimates (using USLE, CREAMS, SIBERIA, RUSLE2, and experimental plots) varied from 0 to 85% less erosion leaving uncertainty about what would actually happen in the field.

Theoretical equations like the RUSLE, SWAT, and WEPP have been used to predict sediment yield from reclaimed sites (West and Wali, 1999; Evans, 2000; Norman et al., 2017). Soil loss estimates using the RUSLE erosion model in Spain's 2112 km^2 Martin River basin averaged 13.8 t ha^{-1} yr^{-1}, with slightly higher 16–23 t ha^{-1} yr^{-1}values from coal mines reclaimed using local contemporary practices (Trabucchi et al., 2012). The SIBERIA computer model is used to predict erosion rates and spatial distribution of topographic changes by using a three-dimensional surface file of the landform being evaluated (Hancock et al., 2000, 2002). Observed Siberia model output discrepancies: "… the field data has deeper and narrower rills than the simulated data. The simulations also produce fewer rills than are measured in the field" and "… the inability of the model and parameterization to correctly capture the erosion processes particularly at high slopes …" (Hancock et al., 2007, p. 1015) can be mitigated with a proper calibration (Hancock et al., 2016).

An Australian study used SIBERIA to predict erosion rates for three different reclamation designs: a traditional constant-gradient slope and terrace with down-drains, a modified traditional design with concave outslopes between terraces and with down-drains, and a fluvial geomorphic design. The predicted erosion was generally on the order of hundredths of a millimeter per year and all the predicted rates were less than 2 mm per year (Loch, 2010). They noted that a limitation of this model as they applied it to natural landforms was that they had difficulty modeling abrupt slope changes in short distances, such as can occur between nodes in a three-dimensional model of a complex slope.

Predictive modeling studies provide a 'best guess' estimate of sediment yield that have varying levels of uncertainty involved in model outputs based on the model inputs, how the underlying model algorithm reflects real world behavior of sediments, the user's skill in applying the model, etc. Models are useful and needed to predict behaviors prior to taking actions, or when monitoring the action may not be feasible, but models need calibration and verification to provide predictions that have a satisfactory degree of certainty. The sediment yield quantification method described in this paper could be useful for verification and calibration of these applications of predictive equations and models, and similar studies, and to reduce uncertainty and promote confidence in the results.

Many variables in other sediment yield quantification methods make it difficult to relate sediment yields to a specific factor. Sediment yield has been quantified by measuring sediment that accumulated in sinks (like reservoirs, or against raised railroad beds or road ways) on a large watershed scale, but the sediment yields for these large watersheds may not aid in the calibration and verification of predictive models used on project-scale catchments. Sediment yield values reported for northern Idaho forest roads (Ketcheson and Megahan, 1996) and for the Mojave Desert (Griffiths et al., 2006) are examples of the large watershed approach. Sediment storage within the watershed, uncertainty about the timing and extent of storms on the land surface, period of observation (Godfrey et al., 2008) and land condition variations within the watersheds: impervious areas of bedrock, forested areas, grasslands, shrub cover, road surfaces, etc., can make it difficult to determine the sediment yield from a particular portion of the watershed of a given land condition. Changes in sedimentation rates have been estimated in New Zealand by relating floodplain sediment thickness to historic stratigraphic marker beds, which are a stored fraction of the watershed's sediment yield (Clement et al., 2017); this provides an estimate of sedimentation rate variation but does not quantify sediment yield. A sediment yield study comparing sediment accumulated in ponds draining contiguous un-mined and mined land subwatershed areas in Wyoming estimated sediment yields of 0.26 t ha^{-1} yr^{-1} from un-mined land and 2.96 t ha^{-1} yr^{-1} from mined lands, but the conditions of the subwatersheds had many differences including area, average slope, proportion of sediment storage areas, surface grading and cover material, and percentage and type of vegetation, that make it impossible to assign a definitive sediment yield value to a particular land reclamation practice (Ringen et al., 1979).

All of these approaches have provided sediment yield quantification, but the numerous variables introduced in their large study areas make it difficult to use those sediment yield values to attribute the effectiveness of a particular reclamation practice from a project-scale catchment. This study's method is designed to greatly reduce those variables and increase confidence in sediment yield comparisons among different land reclamation practices.

The only other study that the authors are aware of that made a focused measurement of sediment yield from watershed-scale (larger than a small slope) test plots is the recent El Machorro Study. Land reclamation was conducted at the operating El Machorro surface mine near the Alto Tajo Natural Park in Spain (Zapico et al., 2018). The El Machorro reclamation sediment yield was monitored during the 2012 to 2017 period from two adjacent GeoFluv-reclaimed subwatersheds. It compared baseline three-dimensional digital elevation models (DEM) of the site ground surface to DEMs made at subsequent monitoring dates during the study.

The El Machorro study identified construction grading errors (high spots on a portion of a slope and in a channel reach) in one subwatershed that caused an initial sediment spike, but after erosion cut through the high spots and brought the surface to design grade, and vegetation cover reached about 30%, the measured 18.4 ± 3 t ha^{-1} yr^{-1} sediment yield decreased for the subsequent July 2016–August 2017 period and stabilized at 4.26 t ha^{-1} yr^{-1} during the July 2016–August 2017 period. These lower rates were comparable to stable natural land and caused no on-site or off-site environmental degradation (Zapico et al., 2018).

The goal of this paper's study was to quantify sediment yield from native, un-disturbed land and adjacent fluvial geomorphic-reclaimed land to verify the performance of the reclaimed land as compared to the natural land (i.e. whether the watersheds reclaimed by this method function as intended to produce equivalent or reduced sediment yield versus the native, undisturbed, watersheds). SJCC began monitoring in the fall of 2011 and data collection continued into 2013 in three subwatersheds that were matched in physical characteristics as closely as possible so that the variations in sediment yield among them could be explained by whether the land was un-disturbed or fluvial geomorphic reclamation, and also whether the fluvial geomorphic reclamation had well-established vegetation or not.

This study was designed to remove the uncertainty associated with using theoretical predictive equations or models to compare sediment yield from reclaimed and native lands by taking direct measurements of discharged sediment that accumulated behind temporary sediment traps in the study subwatersheds. This study further sought to eliminate the factors within the subwatersheds and channels that can store sediment, or release stored sediment, so that differences in the measured sediment yields among the study subwatersheds can be attributed to whether the subwatershed was native or reclaimed, and whether the reclaimed subwatershed had minimal vegetation or well-established vegetation.

The contributions of this research are to: 1) quantify the sediment yield from land drastically disturbed and reclaimed by the GeoFluv fluvial geomorphic land reclamation design method and adjacent undisturbed land and determine if the reclaimed land can produce sediment yield values equal to or better than undisturbed lands, 2) to demonstrate a simple, reproducible method for measuring sediment yield at the catchment scale that has application for evaluating reclamation performance and aiding in calibration and verification of predictive equations and models of erosion, and 3) to compare sediment yield to rain events to determine which were most strongly related in the study.

1.1. Study area

The test sites were located at the rehabilitated San Juan Coal Company - La Plata Mine in northwestern New Mexico in the U.S.A (Fig. 1). Elevation at the mine site ranges from 1795 to 1892 m msl. Mean annual precipitation of 285 mm (11.21 in.) was extrapolated by linear regression from three nearby meteorological stations, each covering at least 50 years of records. Pan evaporation rates at La Plata range from 1270 to 1520 mm per year, resulting in a hydric deficit many times that of mean annual precipitation (New Mexico Mining and Minerals Division, 2006).

The coal was mined from the Upper Cretaceous Fruitland Formation dated at 70 ma old (Fassett, 2000 in Mercier, 2010). Strata enclosing the coal seams include lenticular sandstones, siltstones, carbonaceous mudstones, and clay-rich mudstones. "Some significant faulting was encountered while surface mining at the La Plata operation … This structure appears to be related to flexuring in the Hogback to the north … Dip of strata at the La Plata operations ranged from 30 to 50 degrees off horizontal" (Mercier, 2010). The faulting and steep dips give rise to a general terrain characterized by rough broken topography consisting of cuestas, hills, and valleys. The landforms and associated soils can be divided into three groups: Lithic Torriorthents and rock outcrops dominate the uplands, Ustollic Haplargids occupy transitional areas between uplands and valley positions, and Ustic Torrifluvents dominate the bottomlands (Musslewhite et al., 2001). These descriptions are for the native, pre-disturbance soil types. The growth medium placed at the reclamation surface is referred to as topdressing because the severe land disturbance disrupts and homogenizes the soil horizons, both in structure and as discrete compositional units and it is no longer a true soil. Tables 2 and 3 show that this material had similar bulk density values varying by only 0.6%. Textural analysis of the topdressing material used to determine the bulk density found a 5.5% greater sand, silt, and clay fraction in the moderately vegetated (MV5) site than the well-vegetated (WV3) site. Underlying that is a mixture of broken rock (overburden).

These three positions on the landscape and their associated soils likewise support three vegetation types: Pinyon-juniper, Sage-grassland, and Greasewood-sagebrush. The Pinyon-juniper woodlands are in upland positions. This is the dominant vegetation type at La Plata Mine and is associated with shallow soils on hills and cuestas. Tree species (*Juniperus osteosperma* (Torr.), Utah Juniper and *Pinus edulis Engelm*, Colorado pinyon tree) provide nearly 80% of relative cover, shrub species (*Sarcobatus vermiculatus* (Hook.) Torr, Greasewood shrub) about 13%, and grass and forbs about 7% of relative cover. The Sage-grassland vegetation type is characterized by virtually pure stands of big sagebrush (*Artemisia tridentata wyomingensis*) and occurs in transitional areas between the upland and bottomland landscape positions. The soils in these areas are deep and medium to heavy textured. Total relative cover of shrub species was nearly 81%, grasses 7%, and forbs about 6.5%. The Greasewood-sagebrush vegetation type occurs adjacent to and inclusive of drainages. These communities are found on flat and gently sloping areas that consist of very deep, medium and heavy textured soils. This vegetation type is predominately greasewood and sagebrush with minor proportions of grass and forb species. These characteristics combine to present a high elevation, semi-arid, highly erosive terrain.

This fluvial geomorphic reclamation method is being used successfully at sites internationally that have different climates and earth materials, but the site selected for this study is in a very erosive regime. Greater precipitation does not directly lead to greater erosion in all environments as researchers have long known because greater precipitation generates thicker soils and more abundant vegetation that intercept precipitation, 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. Fig. 2 shows that the La Plata Mine site 285 mm (11.21 in.) average precipitation value is in the range that results in the maximum erosion and sediment yield. The data presented in Fig. 2 are from 94 small watersheds of the same size but in a variety of climates that are grouped into effective precipitation categories. These watersheds were in the conterminous United States but the findings should be applicable to similar watersheds and climate categories globally.

As evidence of the high sediment yield in the region, are samples collected from discharge in a large arroyo that drains 360 km^2 upstream of the mine site and flows through the site. Total suspended sediment samples taken from a discharge event in this arroyo on 8 September 2005 by mine staff averaged 42,700 mg/L; these values are in the long-term sample range and are typical of suspended sediment concentrations during runoff events in the region.

1.2. Previous site sediment monitoring

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

Subjective evaluations of erosion and sedimentation are possible after every storm. Since the onset of the fluvial geomorphic reclamation at the site, mine staff reported that two extreme storms recorded by the on-site meteorological station were estimated to match the 50-yr, 4-h and 193-yr, 3-h NOAA Atlas storm events for the area and only two minor erosion repairs were needed. These two repairs were attributable to construction grading errors, rather than design failures, and required moving only a few cubic meters of material to correct. Similarly, qualitative observations by a mine inspector following an extreme storm in 2002 at the San Juan sister mine using this fluvial geomorphic method concluded: *"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, p. 1.)

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 in comparison to the natural, undisturbed land.

A synoptic storm water runoff sampling event on 7 October 2007

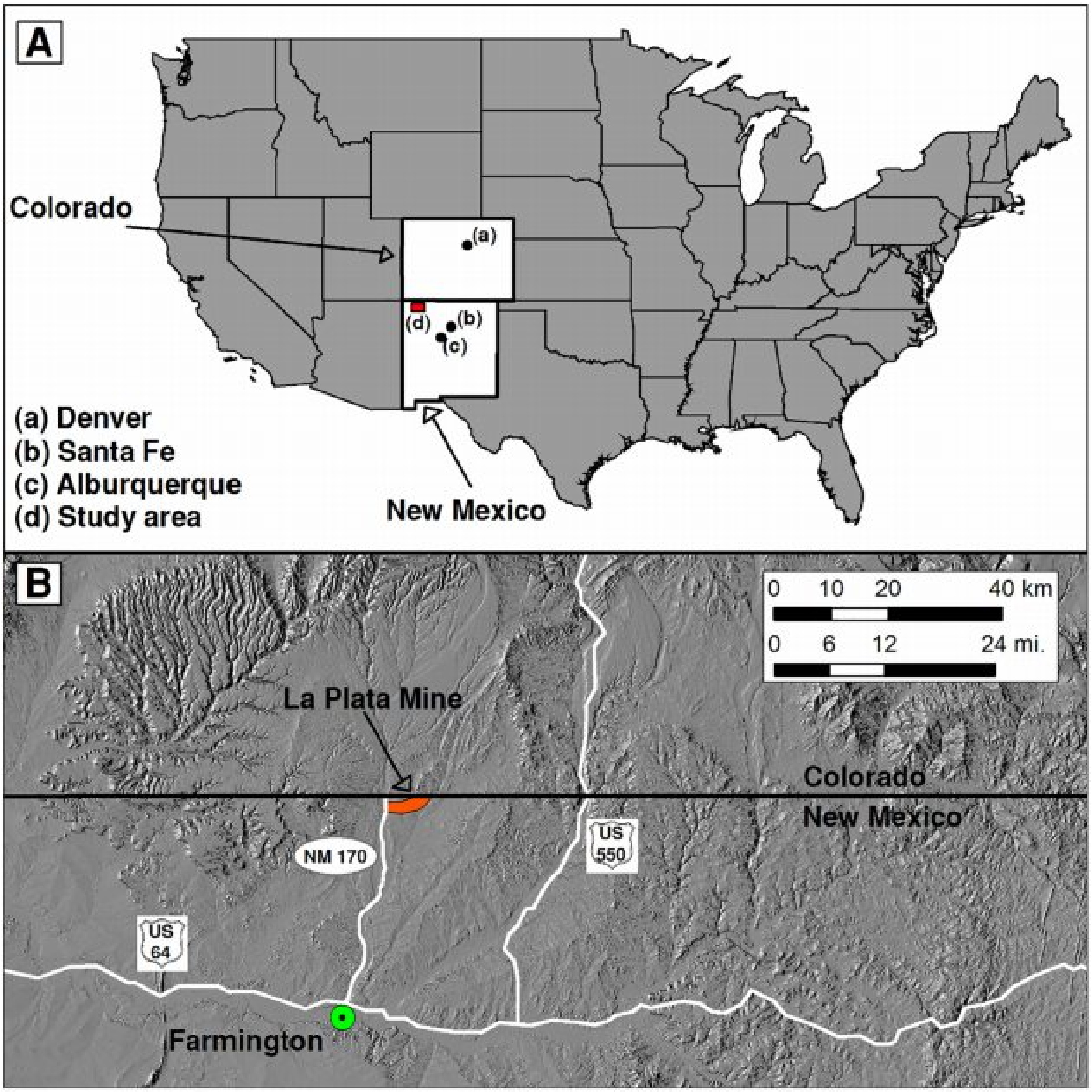

Fig. 1. Study site location map.

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. The samples were grab samples collected by driving from one site to the next during the storm event.

The synoptic total suspended solids results from the 2007 sample event, presented graphically in Fig. 3, show that the constructed fluvial geomorphic designs without vegetation generated suspended sediment concentrations similar to the undisturbed native land. The constructed fluvial geomorphic site with established vegetation generated suspended sediment at an order of magnitude lower concentration than the undisturbed native land. These results show that vegetation has a significant effect on reducing suspended sediment discharge, but also that the fluvial geomorphic design alone can achieve sediment discharge comparable to undisturbed native land. However, the synoptic sampling results do not quantify the total mass of sediment over time, i.e. the sediment yield. The synoptic total suspended sediment results show only a "snapshot" of the sediment discharge concentration at the moment of sampling.

2. Material and methods

2.1. GeoFluv fluvial geomorphic reclamation design method description

GeoFluv is a fluvial geomorphic method for land reclamation design that helps the user design the kind of landforms that naturally would form by erosional processes under the climatic and physiographic conditions at the site. A suitable and stable reference area has to be identified to provide critical input values for the reclamation design. Natural Regrade is the software that helps users to rapidly make and evaluate GeoFluv designs in a CAD format from the input values (Bugosh, 2000, 2009).

2.2. Geomorphic design and construction using GeoFluv

This fluvial geomorphic landscape design method first gained recognition when its use in surface mined land reclamation was described at a US Office of Surface Mining 'Alternatives to Gradient Terraces' workshop (Bugosh, 2000). Fluvial means 'produced by river action' or streams and geomorphic literally means 'earth form' or shape (American Geological Institute, 1976) (Strahler, 1971). The purpose of introducing topographic reconstruction has been described as making a steady-state landscape with approximate balances among erosive forces

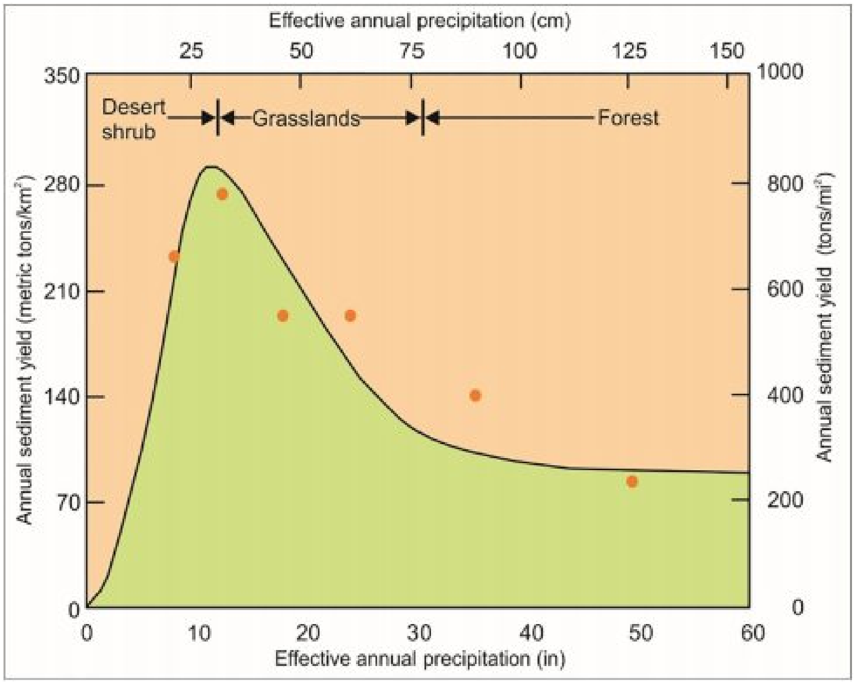

Fig. 2. Graphic representation of the relationship between sediment yield, precipitation, and vegetation type (Langbein and Schumm, 1958). The La Plata Mine study site's 285 mm (11.21 in.) average precipitation value is in the range associated with the maximum erosion and sediment yield.

and resistances (Toy and Chuse, 2004).

The landforms in many parts of the world in loose, unconsolidated earth material are largely the result of that material's response to rain and snowmelt runoff processes that have been at work since the Pleistocene Epoch about 2 million years before present (Bloom, 1978) and for large areas of middle-latitude Europe and North America for about 10,000 to 12,000 years since the last ice age retreat began (Strahler, 1981). If no attempt was made to reclaim disturbed land, but instead rain and snowmelt ran off it for thousands of years, it would be expected to eventually form a stable landform. The GeoFluv method designs that stable natural landform now; it essentially compresses time.

Measurements of specific reference landform physical characteristics that define how it has adjusted over time to convey the runoff from the land without high erosion rates are taken and used as inputs to design a reclamation landform that will perform similarly to the 'stable' reference area landform. These include: slope downstream of the local base level, local base level elevation, ridge-to-head of channel distance, drainage density, the straight-line stream reach lengths on channels greater than 4% slope, bankfull and flood prone channel width and depth, and sub-watershed ridge and swale convex and concave lengths. Precipitation values that will relate to bankfull and flood prone discharges are used, as are hydrologic values such as the maximum stream velocity associated with bankfull discharges in the local reference areas (Rosgen, 1994, 1996). The input values, and site topographic information, are used to design the site (Bugosh, 2000,

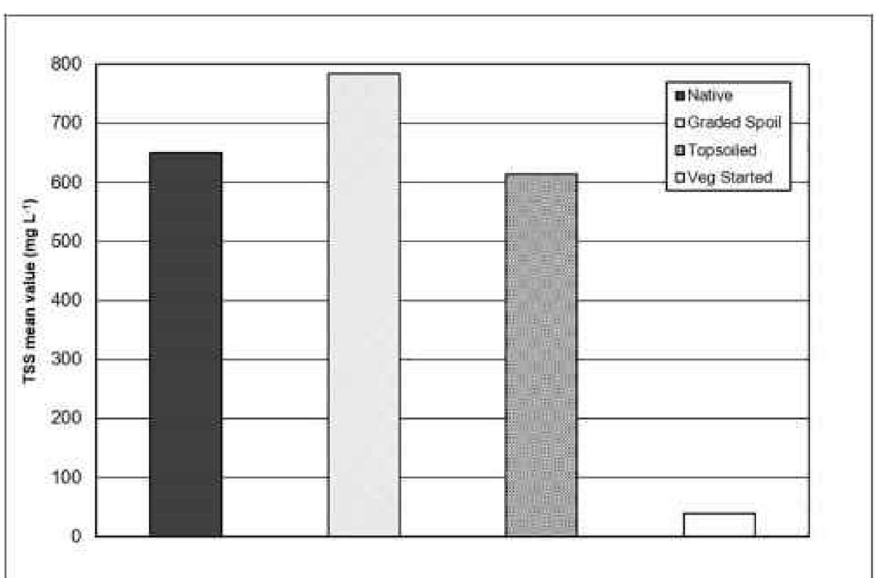

Fig. 3. Average suspended sediment concentration (TSS) in grab samples from native and constructed fluvial geomorphic reclamation on the mine site; October 7, 2007.

2009).

Importantly, these measurements define how the earth materials in the local reference area *have responded* under the great range of climatic and vegetation conditions that have occurred over time. The same landscape responses happen world-wide, forming similar landform physical characteristics, but the measured values vary in response to the local earth materials, climate, and vegetation.

The GeoFluv-Natural Regrade geomorphic reclamation process includes the following steps:

(i) identifying natural, stable, reference landforms in the project locality
(ii) getting necessary hydrologic input information for the project area
(iii) getting topographic information for the project area and its surroundings
(iv) making alternative and iterative fluvial geomorphic reclamation draft designs using GeoFluv – Natural Regrade
(v) inspecting the design to ensure that it provides correct performance
(vi) exporting the 3D design to guide construction
(vii) constructing the designed landforms to specified tolerances, and
(viii) monitoring to verify that the performance is consistent with the design.

As described above, the first step in the GeoFluv design process is taking input value measurements from a stable reference landform in the local project area. Fig. 4 shows a reference area as described in step (i) in the project locality with no signs of active erosion.

Fig. 5a–f show a 3D GeoFluv example design and how a specific design for a highwall reclamation was constructed at the La Plata Mine. Fig. 6a–f show the construction of a waste material dump at the mine. The highwall reclamation is an example of what might be done at any over-steepened cut, like a highway roadcut, and the waste material dump is an example of application of the method to any loose material, like excess construction earth fills, landfills, etc.

The 3D design lines defining the ridge, swale bottom, and stream channels can be seen in Fig. 5a as well as the triangles making up the triangular irregular network (.tin) format surface. The designers evaluated the efficiency of constructing fill areas of the fluvial geomorphic design for a highwall project in 'layer cake' fashion by spreading earth material of different thickness intervals from lower to higher elevations to make the design. The plan view in Fig. 5b shows a draft of this approach; the highest elevations are the across the bottom and upper third in this view. The bottom (south) is the highwall.

The perspective view in Fig. 5c is from the left (west) side of the design shown in Fig. 5b looking northwest to southeast. The highwall at the bottom (south) of Fig. 5b is at the upper right of the image. The efficient construction for the fluvial geomorphic reclamation landform by placing earth material in lifts of a specified thickness is underway.

The general shape of the ridges and valleys of the reclamation landform are becoming apparent in Fig. 5d. The fluvial geomorphic design for this 15.4 ha subwatershed made a stable, functional reclamation landform that required 182,000 m^3 less earth movement than a traditional reclamation alternative design would have required and this resulted in significant earth-moving cost savings. Lower earth-moving costs can provide opportunities to enhance reclamation with features like watering ponds; the reclaimed highwall and its contiguous pond are designated special wildlife enhancement features.

The view in Fig. 5e shows the completed highwall reclamation area after grading to the design, coverage with a topdressing to provide growth medium for the desired vegetation, and seed application, but before the reclamation vegetation has established. The waste pile awaiting reclamation in the top center of this image has been reclaimed in Fig. 5f.

Fig. 5f shows the constructed fluvial geomorphic highwall reclamation five years after completion of grading, topsoil placement, and seeding. The view distance to the background is approximately 3.2 km.

Fig. 6a–f show reclamation phases from a highly disturbed landscape to a completed and functional fluvial geomorphic design for a large out-of-pit waste dump that highlight steps (iv) and (vii).

The portion of the disturbed area shown in the Fig. 6b view is looking across the area where subsequently the fluvial geomorphic design reclamation sites in this study were located. The three sites used in this study are within the Fig. 6f view: the moderately vegetated fluvial geomorphic site is near the bare area center left just above the cloud shadow, the well vegetated fluvial geomorphic site is to the right of the road emerging from the line of trees at center-right, and the native, undisturbed site is in the tree covered area at the upper center.

A close-up view of the completed fluvial geomorphic reclamation at the La Plata Mine is shown in Fig. 7. It shows that the complex slopes have convex upper portions that transition to concave lower portions and that the slopes are not only concave in two dimensions (longitudinally down slope) but are concave across the slope as well (in three dimensions). That gives rise to the variation in sunlight and water harvesting that promotes diversity in vegetation species and composition. These factors combine to produce a reclamation landform function that is similar to the steady-state, 'mature' reference area as this study has demonstrated.

2.3. Methodology

2.3.1. Experimental layout

A method was developed to quantify the actual sediment discharges coming from the natural (undisturbed) and reclaimed lands. Temporary sandbag dams were constructed that would contain the discharge from

Fig. 4. Example reference area for the GeoFluv reclamation project. River terraces, into which a drainage network has developed, can be an analogue for how unconsolidated earth materials in disturbed land, like a surface mine, respond over time to the local conditions.

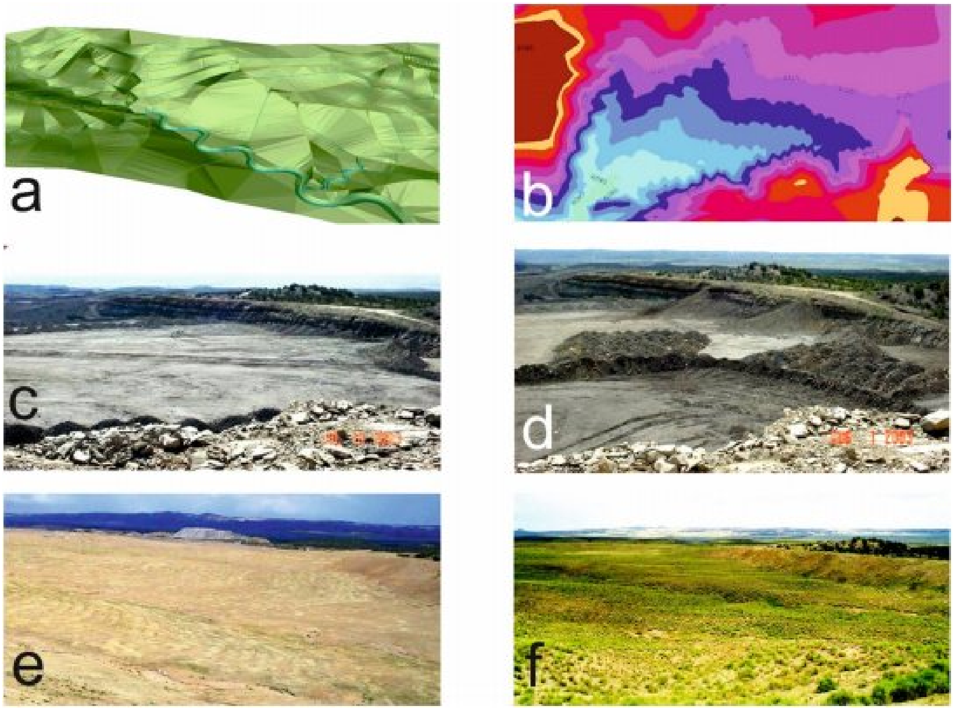

Fig. 5. a) shows a 3D perspective view of an example GeoFluv design, b) is a plan view draft of a highwall reclamation project colored by elevation intervals, c) the early stage of reclamation earthwork to reclaim a highwall, d) the waste earth material is beginning to be placed according to the fluvial geomorphic design to make the reclamation landform, e) earth material has been graded to the fluvial geomorphic design and a suitable topdressing for reseeding applied, and f) shows the completed fluvial geomorphic highwall reclamation on the upper right to center (much of the remaining 15.4 ha subwatershed area is shown on the left).

bankfull discharge-generating storm events in study watersheds. The watersheds were matched in physical characteristics of area, aspect, average subwatershed slope, channel slope range, and channel profile so that the differences among them would be limited, to the extent possible, to whether they were natural and undisturbed, or reclaimed. The reclaimed sites were further distinguished as to whether or not they had a robust establishment of vegetation. The sites' physical characteristics are shown in Table 1. Three study watershed types resulted: native (undisturbed by mining,), fluvial geomorphic design with topdressing where vegetation had failed to robustly establish following seeding, and fluvial geomorphic design with topdressing where vegetation had established robustly following seeding. The difference in vegetation establishment at the two fluvial geomorphic sites was not caused for the purposes of this study, but instead the sites were selected that had different revegetation success to measure the sediment yield produced from the fluvial geomorphic landform alone and how much additional improvement was related to the vegetation cover. After a storm, the sediment discharge from the watershed upstream of the dams settled behind the dams, it was measured, and sediment yield from the watersheds calculated.

The general project area within the 743-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: 1) conducive to the construction of the temporary sediment dams and installation of the precipitation monitoring equipment and 2) amenable to 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

Fig. 6. a) The view looking northwest over a portion of the project site shows a very large out-of-pit waste dump (upper right of the figure) before reclamation to the fluvial geomorphic design; b) The equipment on the haul road is near the toe of the large out-of-pit waste dump that will be reclaimed to the fluvial geomorphic design. The view is looking northwest. The lobate ridge at the upper left of the image is a portion of the mine highwall and will be the viewpoint for the Fig. 6e and f; c) a 3D computer aided design (CAD) view of the dump from perspective similar to Fig. 6b with a possible channel pattern superimposed on the dump; d) 3D CAD view of a GeoFluv design for the dump from perspective similar to Fig. 6a, b and c; e) The tour group is standing on what used to be the top of the mine highwall and the view is to the northeast. The large out-of-pit waste dump reclaimed to the fluvial geomorphic design is across the valley from left center to center of the image; f) looking northeast toward the large out-of-pit waste dump, which is the area without trees established, at the upper right of the image.

Fig. 7. Completed fluvial geomorphic reclamation in the study project area. Note the transition of the slopes from convex upper to concave lower portions, both longitudinally and across the slope.

Table 1
Study watershed characteristics. N7 is native (undisturbed by mining), MV5 is fluvial geomorphic design with topdressing and poor to moderate vegetation, and WV3 is fluvial geomorphic design with topdressing and significant vegetation establishment.

	N7	MV5	WV3
Area (acres ha^{-1})	1.6/0.65	1.5/0.61	1.2/0.49
Aspect	SE	SW	SSE
Average slope (%)	11.1	12.4	17.0
Slope range	3–22	8–11	1–19
Channel profile[a]	C KP	S	C

[a] C = concave, KP = with knickpoint, S = straight.

bisected by a permanent, un-paved, access road (the area is in central portion of Fig. 6f and the road is located at the right-center).

Twenty-seven subwatersheds (including the three study sites) were identified within the general area. The three types of subwatersheds were located within 4.2 km of one another to minimize effects of often localized storm events. The site identification convention uses a letter to identify the type of site and a number to distinguish the site from others of the same type: for example, N7 is the seventh native site among the selected sites. This work began with the project approval in August 2011 and the sites were ready for baseline measurements to be taken following a sediment discharge event in May 2012.

2.3.2. Installation

The preliminary designs to determine the temporary sediment pond dimensions and material needs were made in the fall of 2011. Images of the three sites are shown in Figs. 8, 9, and 10.

A valley pond (stock dam) was designed at each site having the width and height capable of impounding a bankfull discharge producing event: 2-yr, 1-h was used as the bankfull-generating storm (Rosgen, 1994, 1996). 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 the water after sediment had settled behind the dam.

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; typical detail can be seen in Fig. 11. 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 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.

Challenges to the study 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 dams' sand bags 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

Fig. 8. N7 native subwatershed site. Note the pinyon-juniper vegetation type, typically dominant in undisturbed areas of the mine.

Fig. 9. MV5 subwatershed site. Fluvial geomorphic design with topdressing and poor to moderate vegetation establishment.

Fig. 10. WV3 subwatershed site. Fluvial geomorphic design with topdressing and significant vegetation establishment.

Fig. 11. N7 sediment dam site with survey in progress, horizontal string for full-pool elevation, and sediment pins installed.

storms, the sediment surface at some sampling stakes was sometimes immersed by pooled water and could not be measured until the clear water had been fully drained. Later in the study some of the stakes were covered completely with sediment resulting in some loss of measurement resolution. Frost heave was observed to occur around the survey stakes following the winter season. 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 or making additional site measurement visits when the site was accessible.

2.3.3. 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 precipitation events and then decided if a site visit was warranted. When on site, each station was visited to determine if a sediment generating event had occurred, and if so, measurements were taken.

The sediment measurements were taken using the matrix of surveyed sediment pins at each site. A localized survey was used to define the northings and eastings (x and y) of each pin and its ground surface elevation (z). 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. The precision and accuracy of these measurements likely has the greatest potential for systemic error in this method. For example, the measuring tape used would allow plus or minus 0.5% accuracy in the measurements, but because this is relatively small, we do not think it introduces a significant concern for the validity of the results. Also, like the various challenges described in Section 2.3.2, the effect would be consistent across all watershed types and would not tend to introduce bias to any particular site.

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 difference triangular irregular network (TIN) models. The vertical difference between event surfaces is the thickness of sediment. The areal difference of the two surfaces is the volume of sediment. 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 from a site can be compared to study the changes in sediment over the periods corresponding to the TINs.

The storm monitoring began after the installation of the three sites was complete in September of 2011. Unfortunately, there was not

Fig. 12. View downstream to the N7 temporary sediment dam after the first sediment event.

sufficient precipitation to produce a sediment-generating event for many months and a baseline measurement was taken in May of 2012. A typical view of freshly deposited sediment in a monitoring area is shown in Fig. 12.

The last sediment pin measurements were made in October 2013. The sediment data period includes eight months in 2012 and 10 months in 2013. 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.

3. Results

3.1. Cumulative measurement period sediment yields

Table 2 shows the measured sediment (fill) impounded by the temporary sediment dam at each of the three sites and the calculated sediment yield as tons per hectare per year ($t\,ha^{-1}\,yr^{-1}$) for six *cumulative measurement periods*. The sediment yield values reported here vary slightly from the preliminary reports because they are calculated using measured bulk density values from the site that were not available when the preliminary reports were presented; the preliminary reports used a standard aggregate-industry density value for all site calculations (Bugosh and Epp, 2014). Field density tests were done according to ASTM 1556. Bulk density values were calculated for each watershed by Byrne et al. (2017) and provided to the authors via personal communication.

The cumulative periods are from the 18 May 2012 measurement to the day that the sediment accumulation was measured at the sites' surveyed pins. The shortest period was 122 days and the longest period was 525 days. The 525-day period spans the last part of the 2012 water year, the entire 2013 water year, and the beginning of the 2014 water year. The Fig. 13 graph compares the sediment yields at each site for the six cumulative monitoring periods.

The N7 native, undisturbed-by-mining, site had the highest sediment yield in each period and the fluvial geomorphic sites yielded less sediment.

Table 3 shows the measured sediment (fill) impounded by the temporary sediment dam at each of the three sites and the calculated sediment yield as tons per hectare per year ($t\,ha^{-1}\,yr^{-1}$) for each of six *interim measurement periods*. The periods are from 18 May 2012 to the next date that the sediment accumulation was measured at the surveyed pins, and then from that date through the following date that sediment accumulation was measured, and so on. The shortest period was 23 days and the longest period was 234 days. The sum of the days of these six periods is the entire 525-day period.

Fig. 14 shows the linear relationships (ordinary least squares) comparing cumulative precipitation during a period to sediment as tons per hectare. The R^2 values in the cumulative sediment ($t\,ha^{-1}$) versus cumulative precipitation (mm) graph range from 0.60 for the moderately-vegetated GeoFluv site data (MV5) to 0.74 for the well-vegetated GeoFluv site data (WV3), resulting in a good, but not strong correlation between sediment production and precipitation.

Fig. 15 shows cumulative period sediment compared to the cumulative period number of storms greater than $0.25\,mm\,h^{-1}$. The R2 values in the cumulative sediment ($t\,ha^{-1}$) versus cumulative number of storms greater than $0.25\,mm\,h^{-1}$ range from 0.71 for the native, undisturbed-by-mining site data (N7) to 0.95 for the well-vegetated GeoFluv site data (WV3) and suggested the strongest correlation between sediment production and precipitation.

Fig. 16 graphically displays the measured sediment yield for the 403-day period that represents the 2013 water year and the entire 525-day study monitoring period at each of the three sites. The moderately-

Table 2
Cumulative period sediment yield by site.

Site	Cumulative period interval	Cumulative period	Fill (m^3)	Density ($t\,m^{-3}$)	Area (ha)	$t\,ha^{-1}$	Period (yrs)	$t\,ha^{-1}\,yr^{-1}$
N7	1	120,518–120,917	2.02	1.51	0.65	4.70	0.33	14.1
	2	120,518–130,509	3.13			7.28	0.98	7.46
	3	120,518–130,715	2.45			5.69	1.16	4.91
	4	120,518–130,807	2.33			5.43	1.22	4.44
	5	120,518–130,917	4.93			11.5	1.33	8.65
	6	120,518–131,025	5.89			13.7	1.44	9.52
MV5	1	120,518–120,917	0.99	1.66	0.61	2.69	0.33	8.05
	2	120,518–130,419	1.10			3.00	0.92	3.26
	3	120,518–130,715	0.47			1.27	1.16	1.10
	4	120,518–130,807	0.86			2.36	1.23	1.92
	5	120,518–130,918	2.89			7.89	1.34	5.90
	6	120,518–131,025	4.35			11.9	1.44	8.25
WV3	1	120,518–120,917	0.25	1.65	0.49	0.86	0.33	2.56
	2	120,518–130,409	0.80			2.72	0.89	3.05
	3	120,518–130,715	0.42			1.43	1.16	1.23
	4	120,518–130,807	0.67			2.28	1.22	1.87
	5	120,518–130,918	1.57			5.34	1.34	3.99
	6	120,518–131,025	2.39			8.11	1.44	5.64

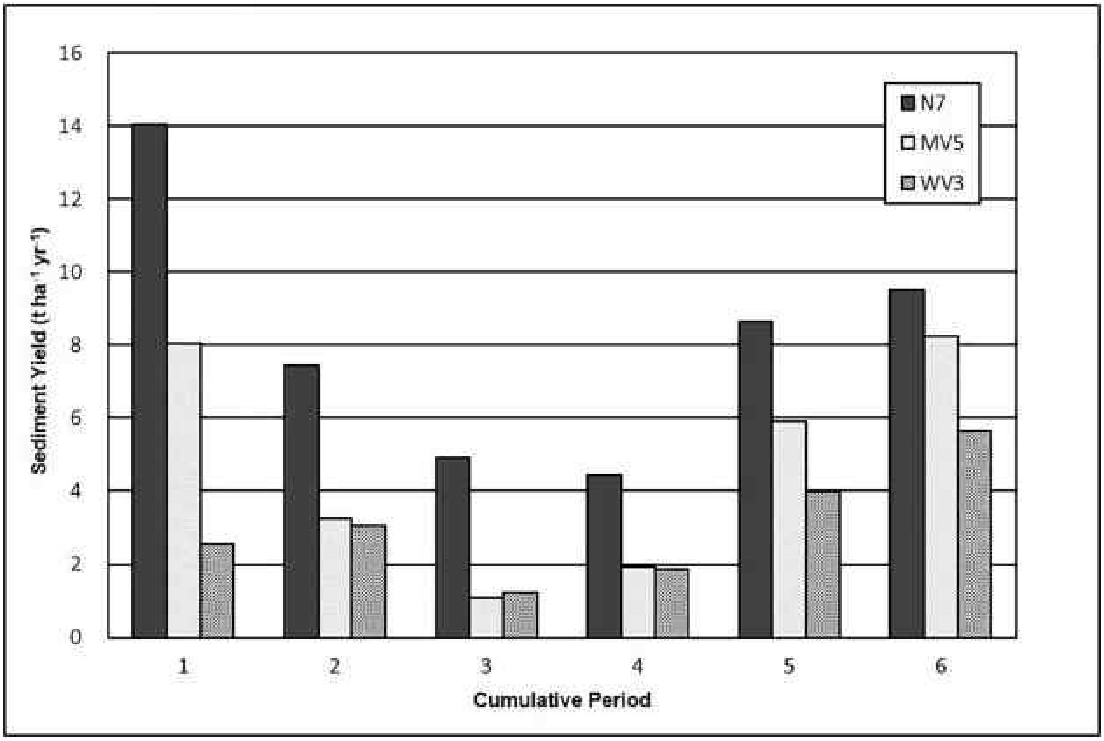

Fig. 13. Sediment yield comparison by site for six cumulative periods. Dark gray is N7 native (undisturbed by mining), light gray is MV5 fluvial geomorphic design with topdressing and poor to moderate vegetation, and medium gray is WV3 fluvial geomorphic design with topdressing and significant vegetation establishment.

Table 3
Interim period sediment yield by site.

Site	Interim period interval	Interim period	Fill (m^3)	Density ($t\,m^{-3}$)	Area (ha)	$t\,ha^{-1}$	Period (yrs)	$t\,ha^{-1}\,yr^{-1}$
N7	1	120,518–120,917	2.02	1.51	0.65	4.70	0.33	14.1
	2	120,917–130,509	1.32			3.06	0.64	4.77
	3	130,509–130,715	0.08			0.20	0.18	1.07
	4	130,715–130,807	0.28			0.66	0.06	10.5
	5	130,807–130,917	2.87			6.67	0.11	59.4
	6	130,917–131,025	1.00			2.33	0.10	22.4
MV5	1	120,518–120,917	0.99	1.66	0.61	2.69	0.33	8.05
	2	120,917–130,419	0.48			1.31	0.59	2.24
	3	130,419–130,715	0.04			0.10	0.27	0.39
	4	130,715–130,807	0.49			1.34	0.06	21.2
	5	130,807–130,918	2.06			5.63	0.12	49.0
	6	130,918–131,025	1.54			4.19	0.10	41.4
WV3	1	120,518–120,917	0.25	1.65	0.49	0.86	0.33	2.56
	2	120,917–130,409	0.67			2.28	0.59	3.89
	3	130,409–130,715	0.22			0.75	0.27	2.83
	4	130,715–130,807	0.29			0.99	0.06	15.6
	5	130,807–130,918	1.16			3.94	0.12	34.2
	6	130,918–131,025	0.96			3.27	0.10	32.2

vegetated ($8.25\,t\,ha^{-1}\,yr^{-1}$) and the well-vegetated GeoFluv ($8.64\,t\,ha^{-1}\,yr^{-1}$) reclamation sites both had lower sediment yield than the native, undisturbed by mining site ($9.52\,t\,ha^{-1}\,yr^{-1}$) for the 525-day period. The moderately-vegetated site had 13% lower sediment yield than the native site and the well-vegetated site had 41% less sediment yield than the native site over the entire 525-day period. The moderately-vegetated site matched the native site sediment yield ($11.0\,t\,ha^{-1}\,yr^{-1}$) and the well-vegetated site had 19% less sediment yield ($9.0\,t\,ha^{-1}\,yr^{-1}$) than the native site over the 403-day period that represents the 2013 water year.

4. Discussion

Here we will discuss how the study results document that the fluvial geomorphic land reclamation design method can produce sediment yield values equal to or better than undisturbed lands, and that this sediment yield quantification method is effective, and our findings about the rain events that were most strongly related to sediment yield in the study.

4.1. Sediment yield from the fluvial geomorphic land reclamation design method compared to adjacent undisturbed lands

The results show that the fluvial geomorphic reclamation consistently provided lower sediment yield than the native, undisturbed-by-mining control site for all events over the entire period. These are the only quantitative published data showing the low offsite effects of fluvial geomorphic reclamation compared to adjacent natural land. The site with fluvial geomorphic design, topdressing, and moderate vegetation (MV5) yielded 13% less sediment than the native, undisturbed-

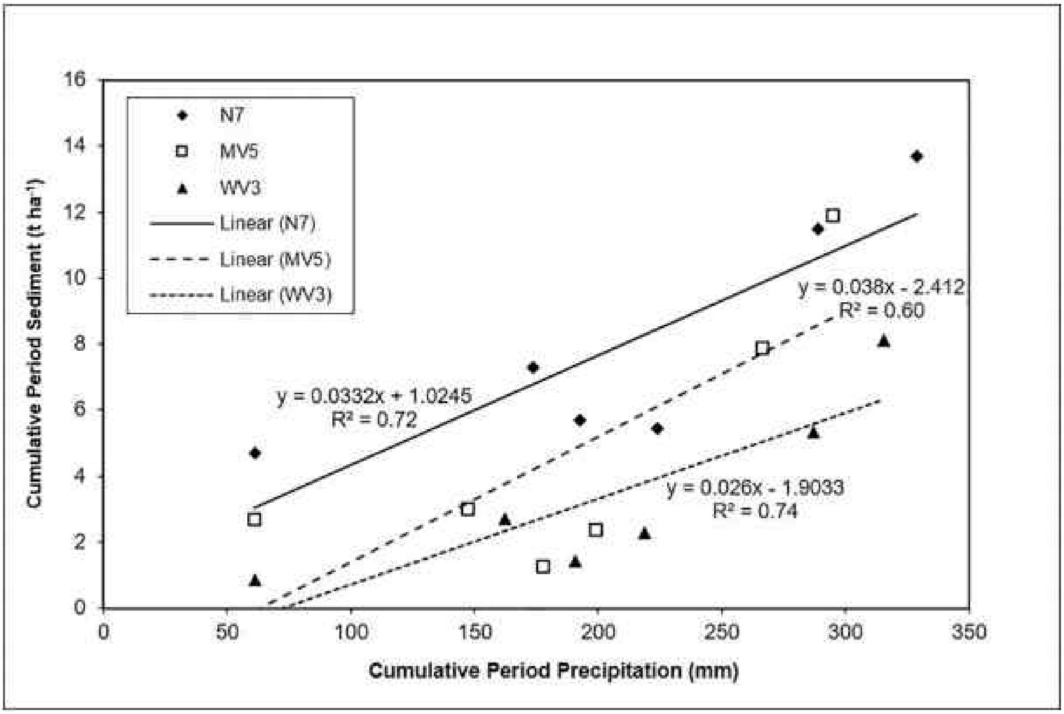

Fig. 14. This cumulative period sediment versus cumulative period precipitation plot shows the linear regression relationships that presented for the three sites.

by-mining site (N7) over this 525-day period as depicted graphically in Fig. 16. The moderately-vegetated fluvial geomorphic site (MV5) had the benefit of a more 'steady-state' or 'mature' landform than N7, allowing it to yield less sediment than the N7 site, but not as little sediment as the WV3 site that benefitted from *both* the more steady-state, 'mature' landform and well-established ground vegetation. The moderately-vegetated site had a 5.5% greater sand, silt, and clay fraction than the well-vegetated site and that finer material would be more easily transported than the topdressing material at the well-vegetated site and would have also been expected to account for some of the observed sediment yield difference between those sites (no coarser material was transported to the sampling areas).

If the goal is to make landforms with sediment yield less than or equal to native, undisturbed lands, then the study results indicate that the fluvial geomorphic landforms can achieve that goal as soon as they are graded and covered with topdressing because both of the reclaimed

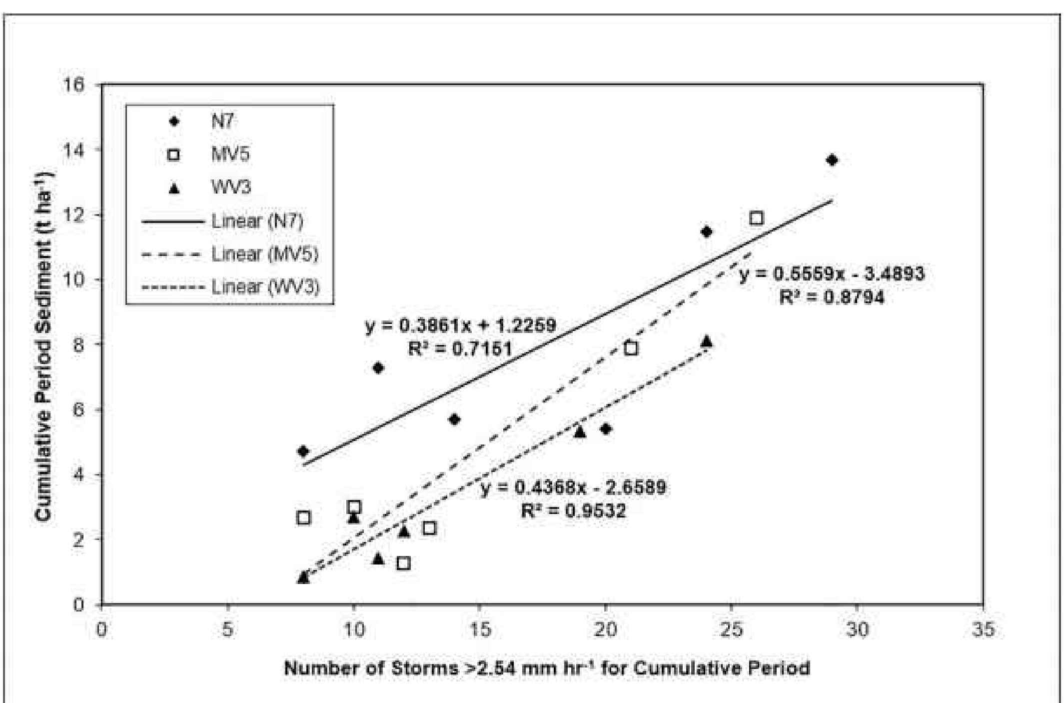

Fig. 15. Cumulative period sediment versus cumulative period number of storms greater than 2.54 mm h^{-1} produced the strongest linear relationships of sediment to rain event.

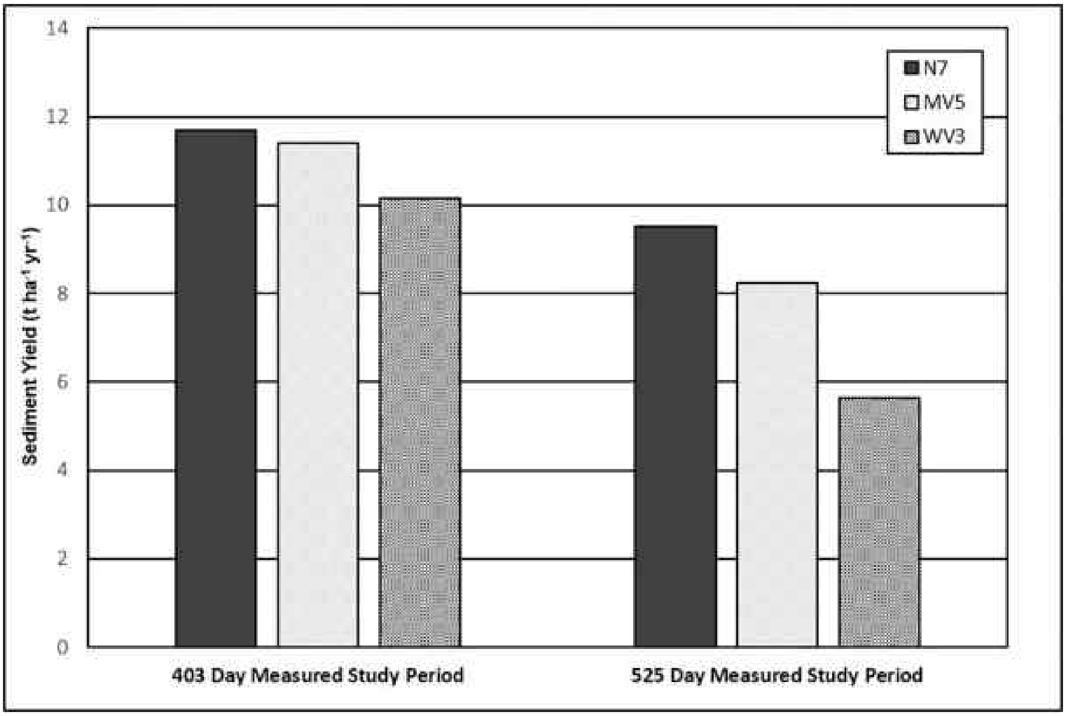

Fig. 16. Measured sediment yields for the 403-day monitoring period most representative of the 2013 water year and for the entire 525-day study monitoring period.

sites yielded less or equivalent sediment than the native, undisturbed-by-mining site. The results also indicate that as vegetation establishment continues, this trend becomes more pronounced, as evidenced by the site with well-established vegetation having 28% further reduction in sediment yield. The entire 28% reduction cannot be attributed to the vegetation alone because the textural analysis reported 5.5% greater transportable sediment sizes in the moderately-vegetated site. Separating the effects of the difference in particle size from the effects of the vegetation was outside the scope of this study, but the study results do show that the moderately-vegetated site with a slightly greater fraction of sand, silt, and clay matched the sediment yield of the native, undisturbed site.

The study results can be considered representative of fluvial geomorphic reclamation made by the GeoFluv™ method as described in Section 2.1, which is a very specific, patented, fluvial geomorphic landform design algorithm. The method is described as Best Technology Currently Available (BTCA) in the New Mexico, U.S.A. coal mining program and is presently being formally recognized as such by the European Union. The reader is cautioned that these results cannot be assumed to apply to other reclamation that is described generically as 'geomorphic reclamation' or 'fluvial geomorphic reclamation'. For instance, approaches that just try to 'copy' the topography of natural landforms, but without any rationale or understanding of the difference in hydrologic response of a consolidated rock landform (such as might be present before an earth-moving project) and a landform that is appropriate for un-consolidated earth material (such as might be present after an earth-moving project), would not be expected to provide a stable, functional hydrologic system.

4.2. *Effectiveness of the sediment yield quantification method at the catchment scale*

This simple method that provides *quantitative* sediment yield uses smaller catchments that eliminate many variables that can confound interpretation of sediment yield values taken from large watersheds (Dunne and Leopold, 1978).

The sediment yield values for the study's smaller catchments are realistic when compared across the range of published values determined by other methods for larger watersheds and are consistent with published values for this semi-arid region. Sediment yield values an order of magnitude lower, ranging from 0.09 to 0.47 t ha^{-1} yr^{-1}, have been estimated from the Mojave Desert (Griffiths et al., 2006). Sediment yield values reported for eight New Mexico streams were in the range 0.02–7.32 t ha^{-1} yr^{-1} (Gellis et al., 2005). Ketcheson and Megahan (1996) reported down slope sediment yield estimates for northern Idaho forest roads averaging 34.8 m^3 ha^{-1} yr^{-1}. The measured values for this study's semi-arid site fit between those reported for the arid Mojave Desert and the humid northern Idaho forest roads.

The greatest complication to using this study's sediment quantification method was the occurrence, or lack, of rain. 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 when the study ended as the mine began preparations for transfer of the operation. Further considerations that should be made when using this method are for all-weather site access and exposure of the temporary sediment dams to the elements. Wet-weather site access limited our ability to take some measurements when desired (We had to wait for roads to dry near the end of the water year). Local conditions that could wear out the site equipment should be considered, as when we found sunlight damage to the dam sandbags could be mitigated by covering them with replaceable plastic tarps. The height of the sediment pins should be considered if the study is to continue for an extended period because they can eventually become covered by sediment.

The sediment yield variation seen among the periods on the Fig. 13 graph can be attributed to monitoring site conditions and to variation in the rain. Tables 2 and 3 show that some periods have greater or lesser yields than the periods before or after at a given site. We interpret these variations as the result of small changes, like frost heaving, sediment settling, and measurement error described in Sections 2.3.2 and 2.3.3, in addition to the greater effect of some shorter periods containing more frequent or more intense precipitation events. Those using this method must pay close attention to the affect that monitoring period can have on the results, especially that very short duration monitoring can over- or under-estimate the sediment yield. The user should take care that the monitoring period is representative of typical conditions and not an unusual precipitation period. Those changes that effect the calculated yields are minimized over a longer period.

How the study period can affect interpretation of the results can be appreciated by trying to narrow the entire 525-day study results to a single water year. The 525-day period includes two rainy periods and one dry period that could exaggerate erosion at the more erodible N7 site. The site water year begins on 1 October and ends 365 days later on 30 September of the following calendar year. A rain event occurred twelve days before the end of the 2013 water year, but circumstances (a site access issue) did not allow a site visit until 25 days after the end of the 2013 water year. The best representation of the 2013 water year sediment yield is presented graphically in Fig. 16 for a 403-day period that uses directly measured values, rather than inferring what happened at the 365-day endpoints. There was no calculated percentage difference between the native and moderately-vegetated site, while the well-vegetated site had 19% lower sediment yield than the other sites over the 403 days. If we had used 365 days for the water year period, the sediment discharge estimate could vary by 3% on the high side to 7% on the low side (dividing a given tons per acre by fewer days yields a higher value and vice-versa), whereas the 403-day period is based on measured values. In any case, the same period was used at all sites and does not affect the relative relationships of the values among the sites; the moderately vegetated fluvial geomorphic reclamation performed similar to the native land and the well-vegetated fluvial geomorphic reclamation performed even better.

4.3. Sediment yield related to rain events during the study

We compared sediment yield to various characteristics of precipitation. Although snow occurs at this high elevation site, during the study period all the sediment-producing events were related to rain. The characteristics that we compared included: cumulative precipitation during the period (mm), maximum storm (mm) during the period, maximum precipitation intensity (mm/h) during the period, the number of storms greater than 3.8 mm/h during the period, and the number of storms greater than 2.54 mm/h during the period.

Fig. 14 shows that for a given amount of cumulative precipitation through the 285 mm average precipitation value the moderately-vegetated fluvial geomorphic site can be expected to produce less sediment than the native, undisturbed-by-mining site. The trend of the MV5 regression line predicts that at a precipitation value above the range measured in the study (and above the 285 mm inch average precipitation value) the moderately-vegetated site would produce sediment at a rate similar to the native site. The graph also shows that the well-vegetated fluvial geomorphic site produced less sediment than the native, undisturbed-by-mining site and the trend of its regression line predicts that the well-vegetated site will perform better as compared to the native site as precipitation increases. These results are consistent with the 2007 synoptic sampling results shown in Fig. 3 that suggested that the fluvial geomorphic design alone can achieve sediment yield comparable to undisturbed native land and that vegetation has a significant effect on further reducing suspended sediment discharge. The relationship between sediment yield and cumulative precipitation shows that the fluvial geomorphic sites can be expected to have lower sediment yields than the native site at cumulative precipitation values greater than the average year's 285 mm, but we found that the relationship of cumulative sediment to the number of storms greater than 2.5 mm h^{-1} was stronger.

The stronger linear relationships are shown in the Fig. 15 graph between cumulative sediment and precipitation for the number of storms greater than 2.5 mm h^{-1} that occurred during the monitoring periods, not cumulative precipitation. This is consistent with observations that the most highly erodible sites are not those in humid areas with high precipitation, but instead in semi-arid areas with intense, short storms. That the highest geomorphological effectiveness can be associated with more frequent, moderate magnitude events has been described by Guthrie (2015). The general trend of the regression lines is similar to those in Fig. 14 but with less variance, indicating that the relationships better agree with these data and better predict future behavior. The R^2 values in the cumulative sediment (t ha^{-1}) versus cumulative number of storms greater than 2.5 mm h^{-1} shown in Fig. 15 range from 0.70 for the native, undisturbed-by-mining site data (N7) to 0.95 for the well-vegetated fluvial geomorphic site data (WV3).

We interpret the consistently better relationships of sediment yield to precipitation characteristics at the well-vegetated fluvial geomorphic site (WV3) to indicate that it had fewer other variables, like more 'youthful' and erodible landforms (site N7) or moderately-well established vegetation (site MV5), that interfered with the direct relationship of sediment yield to precipitation than were present at those sites. The moderately-vegetated fluvial geomorphic site (MV5) had the benefit of a more 'steady-state' or 'mature' landform than N7, allowing it to yield less sediment than the N7 site, but not as little sediment as the WV3 site that benefitted from *both* the more steady-state, 'mature' landform and well-established ground vegetation.

Using this method to quantify sediment yields and develop these strong relationships can aid predictive model calibration. For example, we note that Hancock et al. (2007, p. 1017) wrote that "… the parameters in SIBERIA are derived from average annual data", yet the strongest relationship we found supports using the number of intense, short storms rather than average annual data". This suggests that at this site SIBERIA erosion modeling (and other predictive tools) could be improved by using the number of intense storms to develop rain-based input parameters.

4.4. Applying the study results and conclusions to other sites

The reader is cautioned to consider varying site conditions when interpreting the results from this study for application to other sites. This fluvial geomorphic method uses reference areas that have attained a geomorphic steady-state ('mature') that have similar local climate and vegetation as the project area to get fluvial geomorphic input values. This similarity of reference area characteristics is necessary for the reclamation design to make a reclamation landform that functions like the reference landform. If the undisturbed, natural land (here the native N7 site) near the reclamation is less geomorphically steady-state ('mature') than the reclamation project area designed using a more 'mature' reference area, the undisturbed land would be expected to generate sediment at a much greater rate than desired for the reclamation area.

If the undisturbed, natural land near the reclamation is mature, then its sediment yield would be expected to be closer to the reclamation area sediment yield designed using a more 'mature' reference area. In this case, the difference between the comparison area and the reclamation area would be less pronounced, but the fluvial geomorphic landform would still be expected to function like the steady-state, 'mature' reference landform from which its design inputs were measured.

4.5. Recommendations for future study

Increasing the number of sites would increase the confidence level of the results. Conducting the experiment at other types of sites, like road ways, aggregate mines, and so on, would provide additional assurance to operators of those sites that the method is applicable to them. Making the study in other regions would add confidence for operators that the results were transferable to their area. Additional work studying the relationships of storm intensity and duration could help identify the events that trigger erosion in various regions. Making regressions at the interim-period scale between rainfall volume and maximum rainfall intensity could help identify if sediment yield in the reclaimed lands is weathering limited or transport limited (weathering may generate soil particles during the inter-events period that are ready to be transported by runoff.) Further clarification of the relationships between storms and monitoring periods and sediment yield would help decide what events might be considered sufficient to prove the effectiveness of a landform design project; this could be useful for defining appropriate monitoring period and bond release criterion. It would also be useful to study the effects of subwatershed slope, area, and aspect on sediment yield and how the local fluvial geomorphic input parameters might vary in relation to those landform characteristics.

5. Conclusions

The study results quantitatively support qualitative observations that the new fluvial geomorphic-based alternative to traditional reclamation practices can provide sediment yield that meets reclamation erosion control and water quality goals. Reclamation subwatersheds designed using the GeoFluv method and constructed to the design had measured sediment yields over the entire 525-day monitoring period that were equal to or lower than the adjacent un-disturbed native subwatershed. The site with fluvial geomorphic design, topdressing, and *moderate vegetation* yielded the same sediment as the native, undisturbed-by-mining site over the 403-day period chosen as most representative of the 2013 water year. The site with fluvial geomorphic design, topdressing, and *well-established vegetation* yielded 19% less sediment than the native, undisturbed-by-mining site during the same period. These results indicate that use of this fluvial geomorphic land reclamation method can mitigate erosion and sediment yield increases associated with land-disturbing activities accompanying global population growth and associated infrastructure development.

This method for measuring sediment yield is a simple and reproducible means of quantifying sediment yield that can be used in most reclamation areas world-wide, as it has at La Plata Mine. The method can provide quantified sediment yield information that increases confidence for project decision makers. The quantified sediment yield information can also be used to help calibrate and quantify sediment-yield predictive equations and models.

The number of storms greater than 2.54 mm precipitation produced stronger relationships to sediment yield than did the cumulative total precipitation for the monitoring period. These data from the measured events produced linear relationships for some precipitation events that can provide meaningful predictions of threshold events for sediment yield target values. The results of the study 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. The sediment to rain event relationships also indicate that in the study area, if the long-term sediment yield target is to be less than or equal to adjacent undisturbed lands, then the use of this fluvial geomorphic design method can achieve that goal without requiring additional sediment controls or long-term monitoring and maintenance.

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