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U.S. Department of the Interior, OFFICE OF SURFACE MINING RECLAMATION AND ENFORCEMENT

Hydrology-Based Design of Geomorphic Evapotranspiration Covers for Reclamation of Mine Land

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Abstract

Surface mining imposes severe ecological effects on the land because it not only alters the vegetation, soils, bedrock, and landforms, but also changes the surface hydrology, groundwater, and flow paths. A consequence of these changes is degraded ecology and water quality. This study investigated a geomorphic evapotranspiration (GET) cover by integrating the evapotranspiration (ET) cover and geomorphic grading (GG) technologies. Watershed surface water and groundwater (SW/GW) flow was considered during GET cover design so that the post-reclamation SW/GW flow is managed to be most protective of the environment. A GET may consist of one or more layers, depending on the site-specific conditions such as precipitation, potential evapotranspiration (PET), contaminant level in the waste, etc. The GET cover concept was evaluated at the Tin Pan mine site near Raton, New Mexico, by conducting computer simulations. Based on the features of the stable topography in the nearby region of the site, three geomorphic grading alternatives were designed for the Tin Pan site using the GeoFluv^{TM} land reclamation design method. Three alternative GG designs were made and referred to as Alternatives #1, #2, and #3. Alternative #2 GG design held promise for fully satisfying all the site design criteria and was used for further evaluation of the performance in reducing percolation. At the Tin Pan site, the PET is about three times of precipitation and the gob pile material has sufficient capacity to store precipitation, hence vegetation can be directly planted on the regraded gob piles without other layers. The coupled SWAT-MODFLOW hydrologic simulator was used to simulate the SW/GW hydrology of the watershed where the Tin Pan mining site is located. The performance of the GET cover under different vegetation and precipitation conditions was evaluated with site-scale hydrological simulations using the eSTOMP simulator. The results indicate that vegetation coverage played a very important role in limiting percolation.

Graphical Materials List

Introduction

Currently there are about half a million[1] abandoned mine sites in the U.S. and an estimated 15,000[2] in New Mexico. Surface mining imposes severe ecological effects on the land because it not only alters the vegetation, soils, bedrock, and landforms, but also changes the surface hydrology, groundwater, and flow paths (Nicolau and Asensio, 2000; Osterkamp and Joseph, 2000). Conventional reclamation of mining cuts and spoil banks nearly always have constant-gradient slopes with benches. They are usually combined with elements to redirect and slow runoff (Bugosh, 2006; Nicolau, 2002; Nicolau, 2003). The main shortcoming of conventional designs is that they give little consideration for proper hydrologic function for balanced conveyance of water and sediment from the land surface (Bugosh, 2004). This practice may lead to accelerated erosion and the reclamation landforms may require long-term maintenance and repair.

Most natural hillslopes consist of a variety of shapes (concave and convex) interspersed with ridges and swales (Ayres et al., 2006). Drainage follows natural drop lines with catchment sizes defined by undulating relief on the hillslope. Vegetation on natural slopes grows in discrete units depending on factors such as hillside hydrogeology and microclimate effects. For example, in many areas trees and shrubs often grow in lower concave areas, where soil moisture is higher, while grasses generally appear at the upper drier convex portions of a slope.

Many scientists and engineers favor geomorphic grading (GG) because nature can provide analogues for post-mining landscapes in terms of landscape stability (Hancock et al., 2003). Slope and landform designing based on natural analogues is more functional, long-lasting, more visually attractive, and more cost-effective (Schor and Gray, 2007) than conventional reclamation.

Although GG can make the surface condition of a mine land visually similar to a natural landscape, the hydrological condition of the disturbed subsurface materials in the reclaimed area can be tremendously different from the undisturbed natural materials under natural conditions. Compared to the pre-mine consolidated rock, the loose backfill has much (by several orders of magnitude) larger hydraulic conductivity (Brady et al., 1998). The soil layer of a natural system usually takes thousands of years or longer to develop and has the properties to retain precipitation and provide conditions for vegetation growth. Newly graded land surfaces generally lack the soil layers of the natural system. Often the measures taken to reduce erosion are to make very low-gradient slopes that enhance infiltration. Hence, the applicability of GG that uses this approach is in question for acid spoils and sites with acid

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[1] https://www.abandonedmines.gov/ep.html

[2] http://www.emnrd.state.nm.us/MMD/AML/amlmain.html

mine drainage. Therefore, for better performance, geomorphic reclamation of mine land having groundwater contamination potential needs to consider and manage both the surface and subsurface hydrology.

Surface evapotranspiration (ET) soil covers use two natural processes to control infiltration into the underlying waste zone - the soil provides a natural water reservoir for precipitation (P), and natural evaporation and plant transpiration empties the soil water reservoir. An ET cover is a self-renewing biological system and expected to last much longer than the conventional compacted clay barrier. ET covers have been used above *landfills* (e.g., Albright et al., 2004; Apiwantragoon et al., 2015; Barnswell and Dwyer, 2011; Benson et al., 2001; Benson et al., 2007; Santini and Fey, 2014; Scanlon et al., 2005), *waste sites* (e.g., Bowerman and Redente, 1998; Gee et al., 1997; Link et al., 1995; Pettit et al., 1994; Rutqvist et al., 2011; Scanlon et al., 1997; Waugh et al., 2010; Waugh et al., 2007; Wing and Gee, 1994; Zhang, 2015), and *mine lands* (e.g., Barber et al., 2015; Meiers et al., 2015; O'Kane and Wels, 2003; Zhan et al., 2006). The function of an ET cover is to protect the underlying materials, provide a medium for vegetation growth, store P within the cover, and release the stored P later into the atmosphere so that the infiltration of P to the waste zone is minimized. The storage capacity of an ET cover can be further enhanced by including a capillary break beneath the storage layer. If properly designed, application of an ET cover can considerably reduce or eliminate the percolation of P through the underlying mine material and hence reduce or eliminate acid mine percolation. However, the ET cover will not affect groundwater-caused acid generation if groundwater flows through the mine material. This is beyond the scope of this study.

Specific objectives are as follows:

- Develop geomorphic evapotranspiration (GET) cover designs by incorporating ET cover designs into GG to promote plant growth and minimize percolation.
- Investigate SW/GW flow processes for the best management of water balance under different GET cover designs via numerical simulation to demonstrate the potential impacts of integrating the ET cover and GG technologies.

This report documents the investigation of the hydrology-based GET cover (Zhang et al., 2018). A conceptual design study of the GET cover focusing on geomorphic grading was demonstrated at the Tin Pan mine site near Raton, New Mexico. The GET cover was expected to minimize hazardous mine drainage/percolation and hence prevent degradation of water quality in the discharge area.

Executive Summary

Surface mining imposes severe ecological effects on the land because it not only alters the vegetation, soils, bedrock, and landforms, but also changes the surface hydrology, groundwater, and flow paths. A consequence of these changes is degraded ecology and water quality. Nature can provide analogues for post-mining landscapes in terms of landscape stability and designing slopes and landforms based on natural landscapes being more functional, cost-effective, long-lasting, and more visually attractive. Although geomorphic grading can make the surface condition of mine lands function like a natural landscape, the hydrological condition of the subsurface materials in the reclaimed area can be tremendously different from the natural condition. Hence, for better hydrological performance when these subsurface modifications are great, geomorphic grading for surface mining reclamation should consider subsurface hydrology, in addition to surface hydrology, in the reclamation. To manage the subsurface hydrology, surface evapotranspiration (ET) covers have been used above landfills, waste sites, and mine lands.

This study introduced a geomorphic ET (GET) cover by integrating the ET cover and geomorphic grading technologies. The overall shape of a GET cover is designed to mimic the natural stable topography of the surrounding area, while the thickness and layering of the cover can be optimized for best vegetation growth and infiltration control. Watershed surface water /groundwater (SW/GW) flow needs to be considered during GET cover design so that the post-reclamation SW/GW flow is managed to be most protective of the environment. A GET cover may consist of one or more layers, depending on the site-specific conditions such as precipitation, potential evapotranspiration (PET), contaminant level in the waste, etc. The application of GET cover technology on mine land having ground water contamination potential is expected to substantially improve the reclamation effects by coupling the benefits of the geomorphic cover (drainage reduction, runoff management) with the benefits of ET

covers (vegetation growth and sustainability, protection of surface and groundwater). The GET cover concept was evaluated at the Tin Pan mine site near Raton, New Mexico, by conducting computer simulations of hydrology at both the watershed scale and site scale.

GET Cover Design

The goals of the design were to reclaim the gob piles with a drainage network with natural form and function, convey the on- and off-site runoff water through the project without accelerated erosion, reduce steep slope areas for minimal slope erosion, and improve re-vegetation success. The slopes of the gob piles at the Tin Pan site have an average of 58.1 percent steepness. Only 43.2% of the slopes were in the design range of ≤33 percent steepness, which was selected as the target range for this project. Previous field work in appropriate nearby stable areas provided input information for drainage density (83 m/ha; 110 ft/acre), ridge to head of channel distance (27 m; 90 feet), and 'A-channel' reach length (15 m/ha; 20 feet/acre). The zigzag pattern of the steeper channels results in a series of alternating ridges and opposing valleys that break the slope into smaller sub-watersheds. One zig or zag distance is called the "A-channel" reach length (Bugosh, 2008). These data were used to make alternative GET cover designs using the GeoFluv™ land reclamation design method. Three alternative designs were made and referred to as Alternatives #1, #2, and #3. Alternative #2 held promise for fully satisfying all the site design criteria. It resulted in decreased channel tractive force values that dropped from 32 to 11 kg m^{-2} at bankfull discharge, and from 78 to 17 kg m^{-2} at flood prone discharge at a point 71 m downstream of the road crossing knickpoint, and maintained values in this low range as flow continued across the waste to the channel's mouth.

At the Tin Pan site, the PET was estimated to be about three times of precipitation and hence all the precipitation stored in the soil can be potentially released back to the atmosphere via ET. The gob pile material had sufficient capacity to store precipitation and could be used as the material for the storage layer and for vegetation growth. Hence, the drainage layer, barrier layer, and foundation layer were all optional. In other words, vegetation could be directly planted on the regraded gob piles. The geomorphic design had to preserve the road grading that has changed the valley profile and that inserted a culvert that causes a hydraulic jump contributing to higher tractive forces; the culvert splash or low-water crossing outlet area and channel substrate would require care in material placement to keep fine-grained material subject to transport at these tractive force values from the channel bottoms. The remaining steeper upland slope areas are small and the observed storage capacity and effects of vegetation should be adequate to stabilize them against erosion.

Modeling Hydrology at the Tin Pan Watershed

The Tin Pan watershed was discretized into 23 subbasins with average area of 1.8 km^2. The total area of the watershed was 41.6 km^2, with elevation ranging from 2092 to 2457 m above mean sea level. The coupled SWAT-MODFLOW hydrologic model was used to simulate the surface and subsurface hydrology of the watershed.

The simulation indicated that the stream discharge at the outlet of Tin Pan watershed was mainly driven by intense precipitation events. Generally, the stream discharge was larger in the summer period when precipitation was high. The groundwater generally flowed from hills (with higher hydraulic head) to the stream (with lower hydraulic head). The highest horizontal and vertical groundwater flow were near and below stream networks, suggesting contaminants from the gob piles could enter the stream and the groundwater and be carried downstream.

Modeling Hydrology at the Tin Pan Mine Site

The simulation domain of the Tin Pan mine site was 150 m in the easting direction and 170 m in the northing direction. The vertical range was from 2170 to 2220 m elevation. The simulation domain consisted of the following geological or material units: river, regraded gob piles, soil, and rock. The simulation of flow through the gob piles at the Tin Pan site was conducted using the eSTOMP simulator on the conceptual grading Alternative #2. Four simulations (Cases 1 to 4) considered 2 levels of precipitation (P) and 2 levels of root depth:

- 2 levels of precipitation: near average (P_{avg} = 440 mm yr^{-1}) and 50% above average
- 2 levels of root depth: 0.5 m for shallow-root vegetation and 4.0 m for deep-root vegetation

In these four simulations, it was assumed that the vegetation was fully-grown with a leaf area index (LAI) of 2.9, meaning near maximum transpiration capability. Case 5 was conducted to examine the scenario of sparse vegetation with a LAI of 0.6.

The results show that, at the small depth of 0.4 m below ground surface, water content in the gob piles was higher when P was higher or when the LAI was lower than their counterparts; the root depth had almost no impact on the temporal variation of water content at the shallow depth. At the large depth of 1.2 m below ground surface, all the factors (i.e., P, root depth, and LAI) had some impact on water content variation with time. A larger P or a shallower roots or smaller LAI led to higher water content and, consequently, higher water storage in the gob piles. The percolation rate was affected by the P, root depth, and LAI. A larger P or a shallower roots or smaller LAI led to larger percolation.

For the two cases at P_{avg} (Cases 1 and 2), the annual ET was similar to but slightly (0.6% and 1.9%) higher than the P, while the annual percolation was only 0.5% and 1.4% of P. For the cases with $1.5P_{avg}$ (Cases 3 and 4) or with a low LAI (Case 5), the annual ET was 1.5% to 8.8% smaller than P, while the annual percolation ranged between 2.4% and 10.2% of P. The annual total percolation ranged from 2.1 to 44.8 mm, which were 0.5% and 10.2% of the corresponding P. The results indicate that vegetation coverage played a very important role in limiting percolation.

It was concluded that GET covers can be designed for abandoned mine land based on the stable topography and vegetation in the surrounding area. In the arid and semi-arid regions, simple designs without a drainage layer may be sufficient to reduce percolation. However, in more humid region, ET generally is insufficient to release all the precipitation to the atmosphere. For such cases, a drainage layer is needed to guide the clean water from precipitation out of the footprint of the waste area so the water will not be a driving force to mobilize contaminants. To protect the environment from potential pollution of a waste site, hydrological interaction between a site and the nearby surface water/groundwater need to be assessed using watershed-scaled and site-scale simulations.

Experimental

The Concept of the Geomorphic Evapotranspiration Cover

A typical ET cover (Figure 1a) consists of five components, which are, from top to bottom, an erosion-control layer, a water storage layer, a drainage layer, a barrier layer, and a foundation layer. The major functions for these layers are:

- The erosion-control layer resists wind- and water-caused soil erosion.
- The water storage layer is the medium for vegetation growth and stores infiltration water for vegetation growth and for reduction of percolation.
- The drainage layer is sometimes placed below the storage layer and above the barrier layer to remove excessive water from the storage layer and improve slope stability. The layer may deter intrusion of roots, animal burrowing, and/or human digging.
- The barrier layer minimizes percolation of water through the underlying waste by impeding water flow through it and promoting flow in the drainage layer. The barrier layer also restricts upward movement of any gases or volatile constituents that might be emitted by the waste.
- The foundation layer supports upper layers and heavy construction equipment.

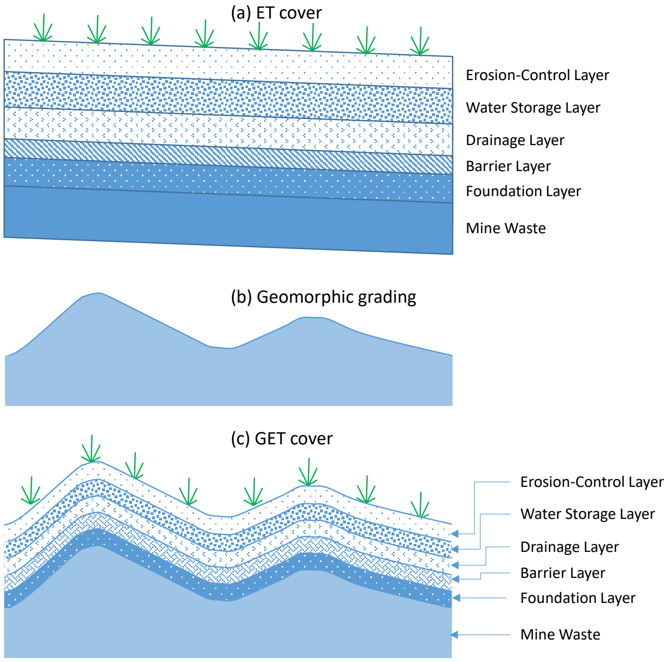


Figure 1. Schematic of an ET cover, geomorphic grading, and a GET cover (After Zhang et al., 2018).

Table 1 summarizes the possible components, their functions, and typical construction materials of a GET cover. Some layers may contain several sub-layers or materials. For example, a barrier layer may be composed of a geomembrane and a clay liner that together form a composite liner. Some layers may be combined. For example, the erosion-control layer and the water storage layer may be combined by mixing a proper fraction of gravels or cobbles with the soil. Not all components are needed for all GET covers. The simplest GET cover may only contain the storage layer. Additionally, the layers do not have to be laterally continuous and the thickness of the layers can vary.

Table 1. The possible components, their function, and typical construction material of a GET cover (Modified after Rumer and Ryan, 1995).

Layer	Primary Function	Typical Materials
Erosion-control layer	Resist wind and water erosion	Gravels; cobbles; paving materials; geosynthetic erosion control materials
Storage layer	Medium for vegetation growth and stores infiltration water	Soil; recycled or reused waste materials; organic materials
Drainage layer	Remove excessive water from the storage layer and improve slope stability; deter intrusion of roots, animal burrowing, and/or human digging	Sand, gravel, or cobbles; geonet or geocomposite
Barrier layer	Minimizes percolation of water through the underlying waste; restricts upward movement of any gases or volatile constituents	Compacted clay; geomembrane; geosynthetic clay liner; waste material; asphalt
Foundation layer	Supports upper layers and heavy construction equipment	Sand or gravel; soil; geonet or geotextile; waste material

The GG in mining reclamation makes the final landform geomorphologically and visually compatible with the surrounding area and remains stable for a long term (Figure 1b) while the properly designed ET cover can isolate problem waste material and control its release of pollutants and further helps to manage the fate of precipitation and vegetation growth.

The fluvial geomorphic grading that is stable against erosion and promotes sustainable land development is based on the essential landform characteristics of stable lands in the surrounding area. The landform characteristics include those that are in an equilibrium condition of hydrology and ecology (Bugosh, 2009):

- Local base level elevation
- Slope at the local base level elevation
- Slope steepness and aspect
- Drainage density
- Channel longitudinal profile
- Ridge to head of channel distance
- Stream plan view geometry (e.g., radius of curvature, meander length, sinuosity, meander belt width, and “A-channel” reach length)
- Stream width to depth ratio

A GET cover (Figure 1c) is a combination of a surface cover (Figure 1a) and geomorphic grading (Figure 1b). The key in the GET cover design is water balance, which is affected by many factors such as climate, soil type, and hydrogeologic setting (e.g., depth of groundwater table and flow direction). The mining activities create landforms and waste piles that are not in equilibrium with the surrounding environment. The GET cover can be designed in the way that re-establishes the equilibrium conditions of landform and hydrology. This can be achieved by proper GET cover design so the system is in harmony with the watershed hydrology and does not export any harmful constituents to the surrounding environment. The GET cover concept was demonstrated at the Tin Pan mine site near Raton, New Mexico, by conducting computer simulations of hydrology at both the watershed scale and site scale.

The Tin Pan Mine Site

Description

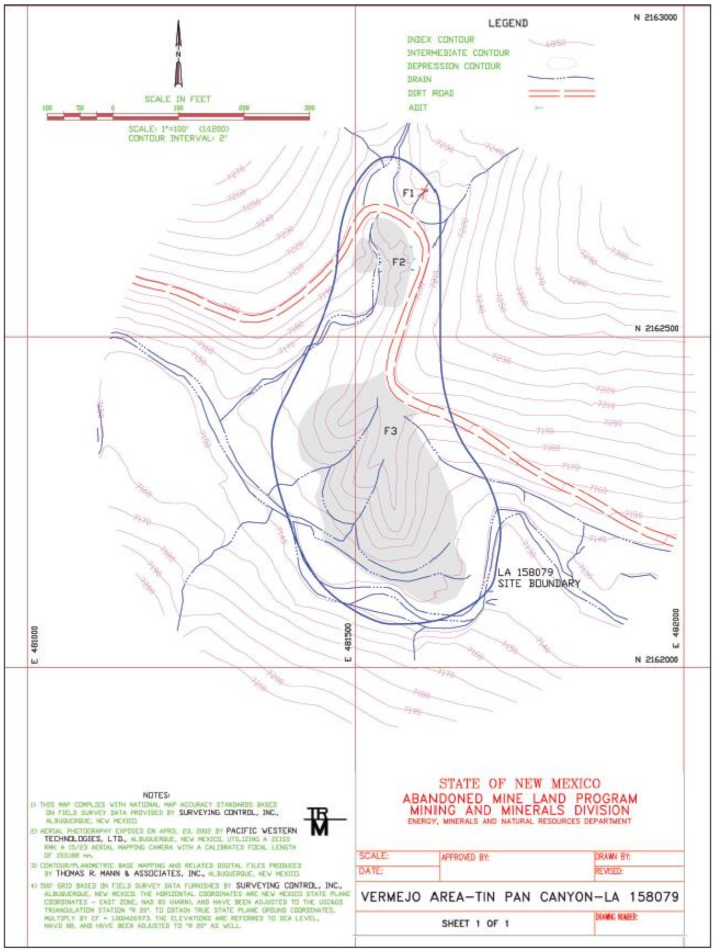
The Tin Pan gob is located at 36°56’30.47”N, 104°32’16.51” W (Figures 2 and 3), about 6 miles northwest of the Raton, NM. The Tin Pan waste site is shown in a 3-D contour view in Figure 5, which lies within the smaller circle in Figure 3 and covers about 1 hectare. The larger circle encompasses the 12.6-hectare upslope area that generates storm water runoff that drains through the waste site. The waste piles are in the foreground at the mouth of the tributary stream’s valley at its confluence with Tin Pan Canyon stream (Figure 3). The road angles upward across the contours from the lower right (eastern) to behind the disturbed area and then exits mid-slope at the left (western) side (Figure 3).

The waste site consists of two gob piles of mine waste, a small pile F2 and a large pile F3 (Figure 2). The Tin Pan Canyon stream flows by the large pile (Figure 4). The maximal relief of the waste material on the large pile is about 14 m. The stream meandering is controlled by a thick, competent sandstone ledge that crops out immediately downstream of the gob pile. The rock cropping out on the skyline in the upper left of Figure 4a in the tributary valley’s watershed and is a characteristic of the thin soils over bedrock in the area. Thin soils over this bedrock combined with short-duration, high-intensity storms in this semi-arid region can produce great peak storm discharges.

Figure 5 shows the three-dimensional contour view of the existing Tin Pan coal mine site and a two-dimensional contour view of the existing Tin Pan coal mine site. The actual bottom of the gob was unknown and was assumed to be the ground surface, which was estimated by extending the slope as shown in Figure 6a. The height of the gob piles above ground surface is shown in Figure 6b. The piles had the estimated area of 3,229 m^2, volume of 13,584 m^3, and average height of 4.2 m.

Hydrologic considerations for making a stable reclamation landform at the site include the storm water discharges across the road at its low-water crossing and the slope steepness that could contribute to rill and gully erosion. The tributary channel (Figure 3) discharges have eroded a gully along the west valley wall. The Natural Regrade (Carlson Software Inc., Maysville, KY) inspector tool was used to make an estimate of the erosive energy of the channel. Peak tractive force values of 32 kg m^{-2} at bankfull discharge and 78 kg m^{-2} at flood prone discharges indicated the runoff could erode and transport unconsolidated material. Those estimates were supported by the observations of deep gullies eroded into the piles and waste material on the Tin Pan Canyon Stream floodplain and in its channel.

The road that crosses the tributary valley at the upper end of the site (Figure 3) comprises a significant knickpoint in the tributary channel's longitudinal profile. The stream's erosive energy will drop as it flows across the flattened gradient of the road's low-water crossing and then abruptly increase as it drops off the road's downstream edge and on down the reclamation channel profile. Mitigations for the erosive energy associated with this knickpoint must be made in the fluvial geomorphic channel design to protect the road crossing and the downstream channel.



NOTES:

1) THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS BASED ON FIELD SURVEY DATA PROVIDED BY SURVEYING CONTROL, INC., ALBUQUERQUE, NEW MEXICO.
2) AERIAL PHOTOGRAPHY EXPOSED ON APRIL 23, 2002 BY PACIFIC WESTERN TECHNOLOGIES, LTD., ALBUQUERQUE, NEW MEXICO, UTILIZING A ZEISS RMK A 15/23 AERIAL MAPPING CAMERA WITH A CALIBRATED FOCAL LENGTH OF 153.388 mm.
3) CONTOUR/PLANIMETRIC BASE MAPPING AND RELATED DIGITAL FILES PRODUCED BY THOMAS R. MANN & ASSOCIATES, INC., ALBUQUERQUE, NEW MEXICO.
4) 500' GRID BASED ON FIELD SURVEY DATA FURNISHED BY SURVEYING CONTROL, INC., ALBUQUERQUE, NEW MEXICO. THE HORIZONTAL COORDINATES ARE NEW MEXICO STATE PLANE COORDINATES – EAST ZONE, NAD 83 (HARN), AND HAVE BEEN ADJUSTED TO THE USC&GS TRIANGULATION STATION "R 20". TO OBTAIN TRUE STATE PLANE GROUND COORDINATES, MULTIPLY BY CF = 1.000426973. THE ELEVATIONS ARE REFERRED TO SEA LEVEL, NAVD 88, AND HAVE BEEN ADJUSTED TO "R 20" AS WELL.

Figure 2. Location of Coal Gob Piles (F2 and F3) at Tin Pan Canyon.

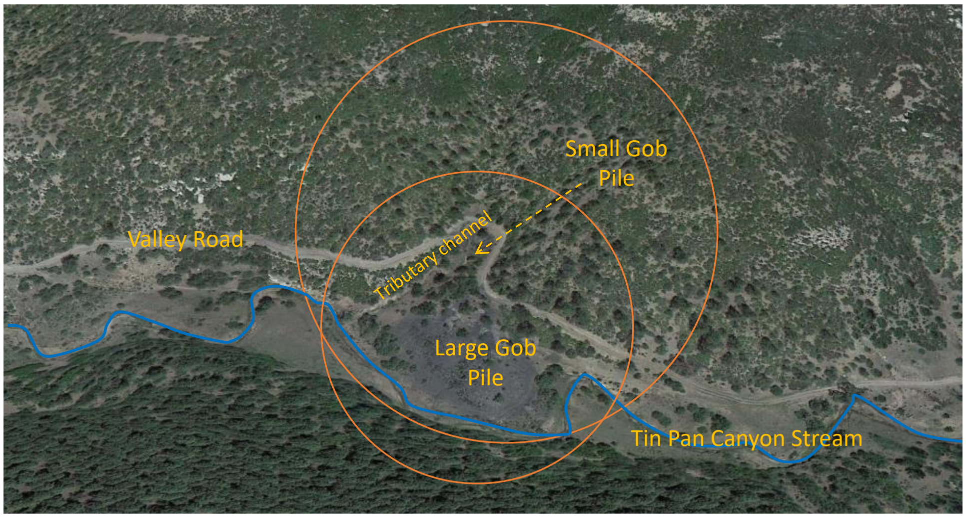


Figure 3. The Tin Pan Mine Site. The large circle indicates the upslope watershed and waste site to be considered in the design of geomorphic grading. The small circle corresponds the approximate area of geomorphic grading.

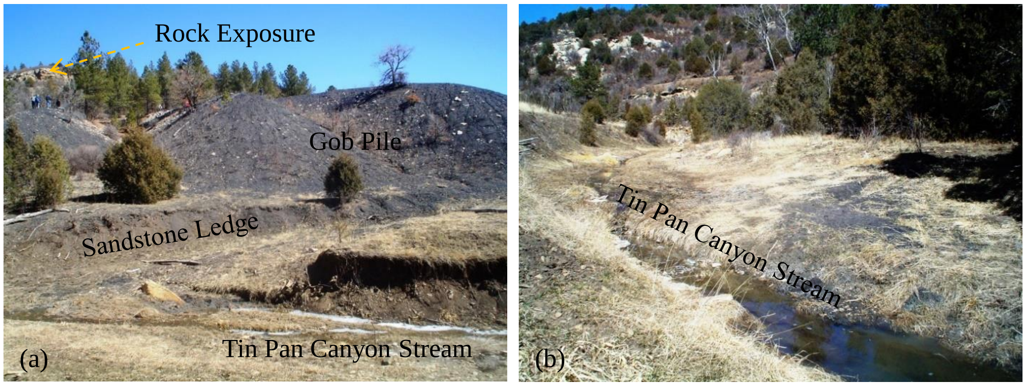


Figure 4. (a) The Large Tin Pan Mine Gob pile and (b) the Tin Pan Canyon stream by the Gob pile. The maximal relief of the waste material on the gob pile is about 14 m.

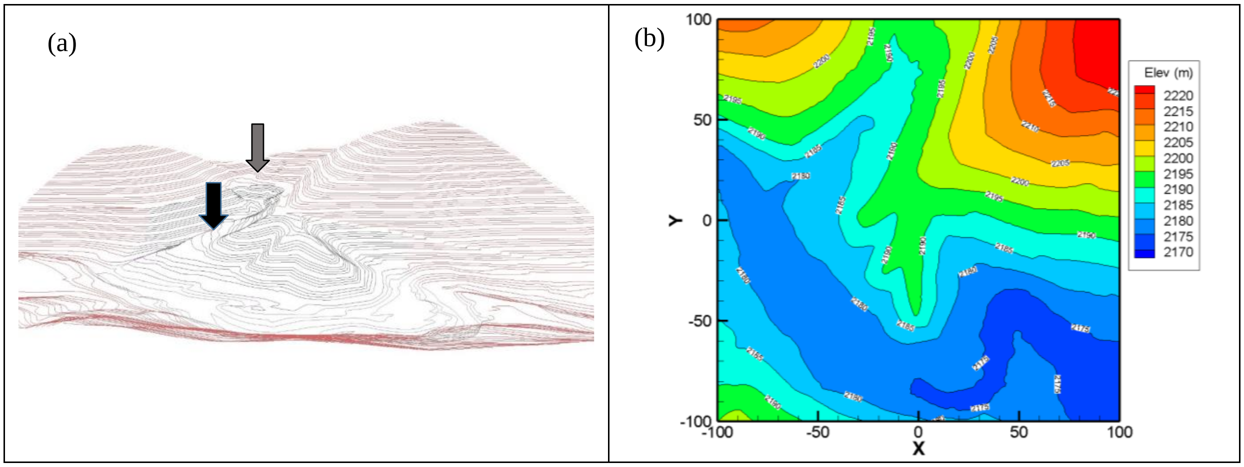


Figure 5. a) A three-dimensional contour view of the existing Tin Pan coal mine site. The view is south to north. The units in the x and y axes are in m. The arrows show the location of the upper end of the site at the valley road crossing (gray, upper arrow) and the channel eroded into the waste along the west valley wall (black, lower arrow). b) Two-dimensional contour view of the existing Tin Pan coal mine site.

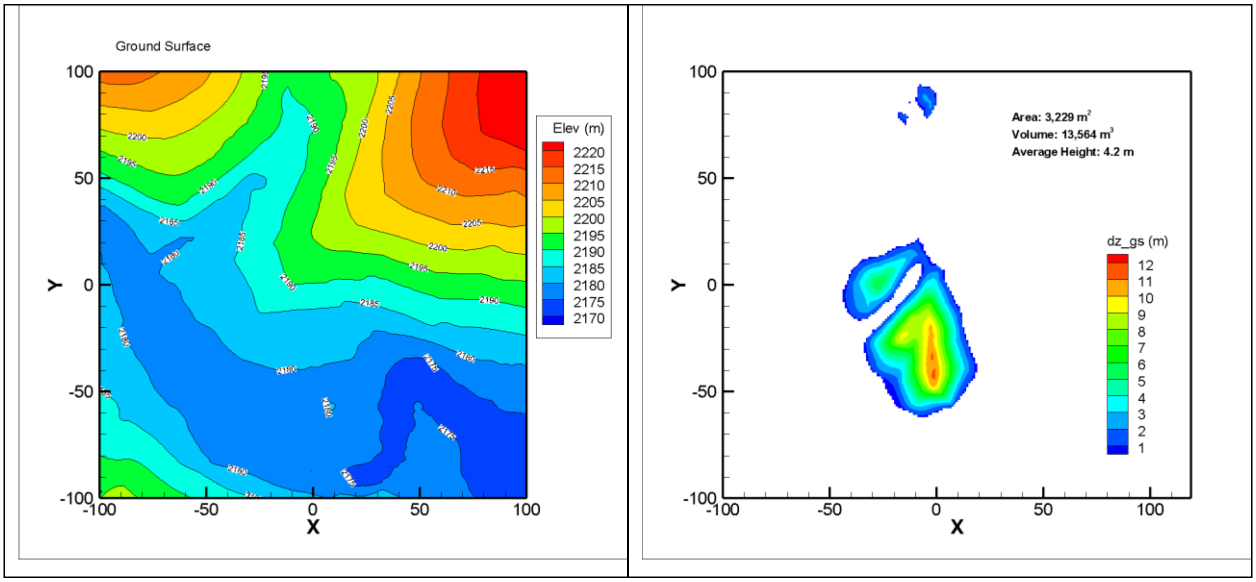
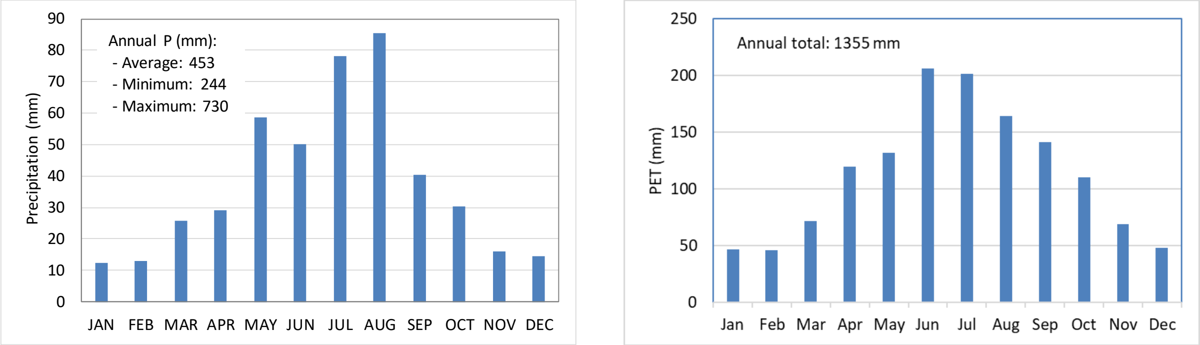


Figure 6. (a) Contour of the estimated ground surface and (b) the height of the gob piles above ground surface along with the estimated area, volume, and average height. The units in the x and y axes are in m.

Site Climate

There is no weather station located at the Tin Pan mine site. One of the closest weather stations to the Tin Pan mine site is at the Raton Filter Plant site[1] in Raton, NM. According to the weather data, Raton has a cold/dry winter and a hot/wet summer. The monthly average air temperature ranges from -0.3°C (in Jan.) and 20.6°C (in July) with an annual average of 9.7°C. The monthly average P and annual statistics at Raton, NM, is shown in Figure 7a. The P values ranges between 244 mm and 730 mm with an average of 453 mm.



(a) (b)

Figure 7. (a) The monthly average precipitation and annual statistics at Raton, NM. (b) The estimated average monthly potential evapotranspiration for the Tin Pan watershed.

The average monthly PET was estimated by the Soil and Water Assessment Tools (SWAT) model, which will be described in a following section, for the Tin Pan watershed as shown in Figure 7b. The annual average PET was 1355 mm, which is 3.0 times the annual average P. The large PET/P ratio indicates that a GET cover is suitable for the area and can be used to minimize runoff and percolation. As a result, the migration of any contaminants in the

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[1] Data were available at https://wrcc.dri.edu/summary/Climsmnm.html.

mine piles would also be minimized and the risk of the contaminants migrating to the groundwater and surface water would be reduced.

The Watershed

The boundary of the watershed area encompassing the Tin Pan Mine site was delineated based on a 10 m Digital Elevation Model (DEM) extracted from the US Geological Survey data[1]. The total area of the watershed was 41.6 km^2, with elevation ranging from 2091.5 to 2457.2 m above mean sea level. For the purpose of hydrological modeling, the watershed was discretized into 23 subbasins following their slope, soil and land cover characteristics with average area of 1.8 km^2. Figure 8 shows the watershed location, the subbasins, the topographic pattern, the stream network derived from DEM analysis and location of the Tin Pan mine site.

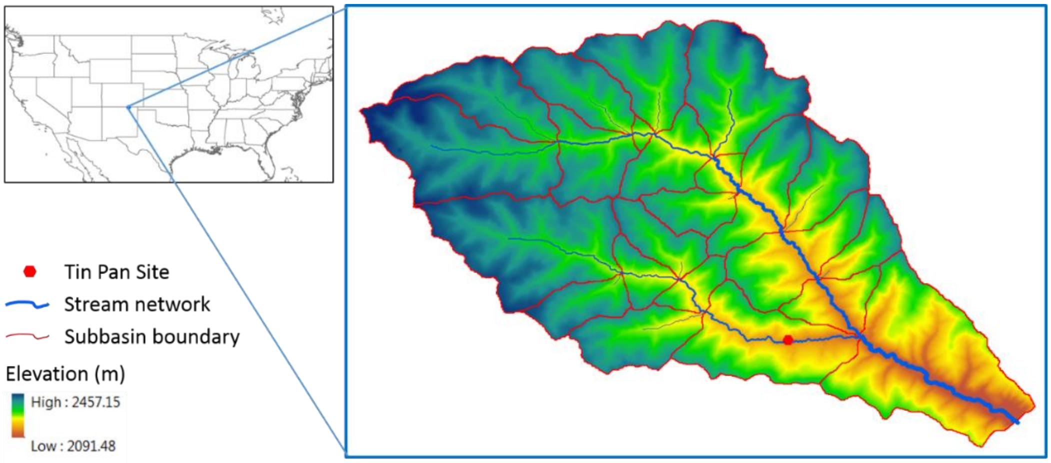

Figure 8. The watershed boundary delineated for hydrologic simulation, its elevation, the subbasins within it, the stream network derived and the location of the Tin Pan mine site.

Grading and GET Cover Design

The fluvial geomorphic approach to designing landforms was used for stability against erosion and to promote sustainable land development. It incorporated essential characteristics of stable landform into the design for proper hydrologic function.

The GeoFluv™ land reclamation design method (Bugosh, 2004; Bugosh, 2009) is a patented approach based on fluvial geomorphology. The method uses inputs taken from natural stable reference sites in the surrounding area that have similar earth materials, climate, and vegetation to the disturbed project site, and that have attained a high degree of stability against erosion over thousands of years of time. The method is the heart of the Carlson Software Natural Regrade[2] (Carlson Software Inc., Maysville, KY, USA) module, an Office of Surface Mining Technical Innovation and Professional Services Core Software, which was used to make and evaluate the reclamation designs. The designs have stream channels and upland areas that are fully integrated in three dimensions and that honor the fluvial geomorphic input parameters. One of the benefits of the computerized design is that designs can be relatively easily edited to conform to new site information such as a difference from the design assumptions for the bottom of the gob and the actual elevations discovered during excavation.

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[1] https://lta.cr.usgs.gov/NED.
[2] http://www.carlsonsw.com/solutions/mining-solutions/natural-regrade/

Modeling Hydrology at the Tin Pan Watershed

The Soil and Water Assessment Tools Numerical Simulator

The SWAT (Arnold et al., 1998) model is a physically-based effective tool designed to predict the impact of management on water and sediment chemical yields in a watershed. Developed for over three decades, it has gained international acceptance as a robust watershed modeling tool. In the United States, SWAT has been used in various applications, for example, evaluation of effectiveness of conservation practices within the USDA Conservation Effects Assessment Program (CEAP, 2007) initiative and supporting Total Maximum Daily Load analyses (Borah et al., 2006). Numerous studies (over 2200 journal articles[1]) have reported successful applications of SWAT for reproducing observed hydrologic and/or pollutant loads across a wide range of watershed scales and environmental conditions, as well as its applications in assessing impacts of conservation practices, land use, climate change, water management, and other scenarios (Gassman et al., 2007).

In SWAT, a watershed is discretized into a network of Hydrologic Response Unit (HRU), within which the hydrologic characteristics are assumed consistent. A total of 417 HRUs were defined for the Tin Pan watershed. Because there is no precipitation and temperature measurements within the Tin Pan watershed, measurements from a nearby site (Geldon and Abbott, 1985) were used.

The DEM was obtained from the national elevation dataset (Gesch et al., 2002) at 10 m resolution. The elevation of Tin Pan watershed ranges between 2091.5 m and 2457.2 m with the high elevation in the northwest and low elevation in the southeast. The land use and land cover change were from the national elevation dataset (Gesch et al., 2002) at 30 m resolution. The soil data were from the Soil Survey Geographic Database SSURGO[2]. Soil thickness ranged from 0.3 to 2.0 m and the saturated hydraulic conductivity was between 0.9 and 5.6 m d^{-1}. The stream network data were from the National Hydrography Dataset[3].

The MODFLOW Groundwater Flow Numerical Simulator

MODFLOW is a standard 3-D finite-difference groundwater model. For decades, it has been used extensively for studying groundwater dynamics and SW-GW interactions. In this study, the MODFLOW-NWT[4] was used to set up the model. The LMT package (Zhang et al., 2001) was used to provide linkage between MODFLOW and SWAT.

To couple MODFLOW with SWAT, we set up the MODFLOW with the same spatial resolution (10 m) as the SWAT. Based on the geological settings, we defined three vertical layers for the MODFLOW. The top layer was the soil layer. Its layer thickness (about 2 m) and aquifer properties were defined using the Soil Survey Geographic Database SSURGO dataset. The second layer had a thickness of about 150 m and contained a portion of the Poison Canyon formation and Raton basin formation, and some young terrace near the stream alluvial fan. The bottom layer had a thickness of 300 m and was mainly Raton basin formation. The geological data was obtained from the US Geological Survey's National Geologic Map Database[5].

Horizontally, the groundwater divide was used to define the groundwater model domain boundary. The spatial extent of this boundary was obtained through the SWAT model. Because groundwater recharge data were unavailable in this area, pseudo-recharge were used to setup the model simulation. A steady state simulation was used to generate the initial hydraulic head of all layers. After that, the simulation in transient mode was run with a daily time step.

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[1] https://www.card.iastate.edu/swat_articles
[2] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr12/tr/?cid=nrcs142p2_010596.
[3] http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd.
[4] https://www.usgs.gov/software/modflow-nwt-a-newton-formulation-modflow-2005
[5] https://ngmdb.usgs.gov/Info/reports/

The SWAT-MODFLOW (Bailey et al., 2016) coupled hydrologic model was used to simulate the SW-GW hydrology of the watershed where the Tin Pan site is located. The focus was on the subbasin where the Tin Pan mine is located.

The MODFLOW simulation domain had the horizontal grid spacing of 10 m and contained about 2.3 million grid cells. Based on the availability of data, the SWAT-MODFLOW simulation was conducted only for a period of 7 years (1975-1982).

Modeling Hydrology at the Tin Pan Site

Numerical Simulator

All simulations were carried out using eSTOMP (Fang et al., 2015), the scalable version of the Subsurface Transport Over Multiple Phases (STOMP) subsurface flow and reactive transport simulator (White et al., 2015). All simulations were executed on Constance, a Linux-based cluster that is part of Research Computing of the Pacific Northwest National Laboratory.

Simulation of Evapotranspiration

The ET at the soil surface was determined as the PET scaled by the soil water stress factor (β_t) and scaled leaf area index (α). Both β_t and α range between 0 and 1 and their definitions are given below.

Soil Water Stress Factor

Soil water stress was simulated based on Oleson et al. (2013, Section 8.4) by defining a water stress factor β_t:

$$\beta_t = \sum_i w_i r_i \qquad [1]$$

where w_i is plant wilting factor for layer i and r_i is the fraction of roots in layer i. β_t ranges from 0 when the soil is dry to 1 when the soil is wet. The plant wilting factor w_i is defined (assuming no ice):

$$w_i = \begin{cases} 1 & if \quad \psi_i \geq \psi_0 \\ \dfrac{\psi_c - \psi_i}{\psi_c - \psi_0} & if \quad \psi_i < \psi_c \\ 0 & if \quad \psi_i \geq \psi_c \end{cases} \qquad [2]$$

ψ_i is soil water matric head; ψ_c is the ψ_i value when plant leaf stomata are fully closed and ψ_o is the ψ_i value when stomata are fully open. Typical values of ψ_c and ψ_o are given in Table 8.1 of Oleson et al. (2013).

The cumulative root fraction (Y) from ground surface is described by the two-parameter model (Zeng, 2001):

$$Y = 1 - 0.5\left[\exp(-az) + \exp(-bz)\right] \qquad [3]$$

where z is depth (m); a (m^{-1}) and b (m^{-1}) are plant-dependent root distribution parameters. Typical values of a and b are given Table 8.3 of Oleson et al. (2013). In numerical implementation, the root fraction in each soil layer is defined as

$$r_i = \begin{cases} 0.5\left[\exp(-az_{h,i-1}) + \exp(-bz_{h,i-1})\right] & \text{for the last layer} \\ 0.5\begin{bmatrix} \exp(-az_{h,i-1}) + \exp(-bz_{h,i-1}) - \\ \exp(-az_{h,i}) - \exp(-bz_{h,i}) \end{bmatrix} & \text{for other layers} \end{cases} \qquad [4]$$

where $z_{h,i}$ (m) is the depth from the soil surface to the interface between layers i and i+1 ($z_{h,0}$ = 0, the soil surface).

Scaled Leaf Area Index

Leaf area index (LAI) is a dimensionless quantity that characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area. When the LAI is zero, the transpiration is deemed to be zero. When the LAI is high enough, the plant transpiration can reach the PET. A scaled leaf area index is defined as (Fayer, 2000):

$$\alpha = \min\left(1, 0.52\sqrt{LAI}\right) \qquad [5]$$

Site-Scale Model of the Tin Pan Site

The simulation domain (Figure 9) of the Tin Pan mine site was similar to but slightly less than size shown in Figure 5b. The horizontal dimension was 150 m (from -100 to 50 m, Figure 5a) in the x (easting) direction and 170 m (from -100 to 70 m) in the y (northing) direction. The vertical range was from 2170 to 2220 m elevation. The domain was discretized into 413,440 (= 64×85×76) cells with the horizontal spacing ranging between 2.0 to 5.0 m and vertical spacing between 0.2 to 2.0 m. The simulation domain consists of the following geological or material units: river, regraded gob piles, soil, and rock. The hydraulic properties of these components are listed in Table 2.

Table 2. Hydraulic properties

Components	K_s (m s^{-1})	θ_s (m^3 m^{-3})	θ_r (m^3 m^{-3})	α (cm^{-1})	n (-)
Gob Piles	2.37×10^{-6}	0.35	0.034	0.005	2.25
Soil	8.39×10^{-5}	0.35	0.047	0.017	1.73
Rock	1.0×10^{-4}	0.15	0	0.017	1.73
River	1.2×10^{-4}	0.99	0	0.1	1.374
K_s: saturated hydraulic conductivity; θ_s: saturated water content; θ_r: residual water content; α: inverse of capillary length; n: pore-size distribution parameter.					

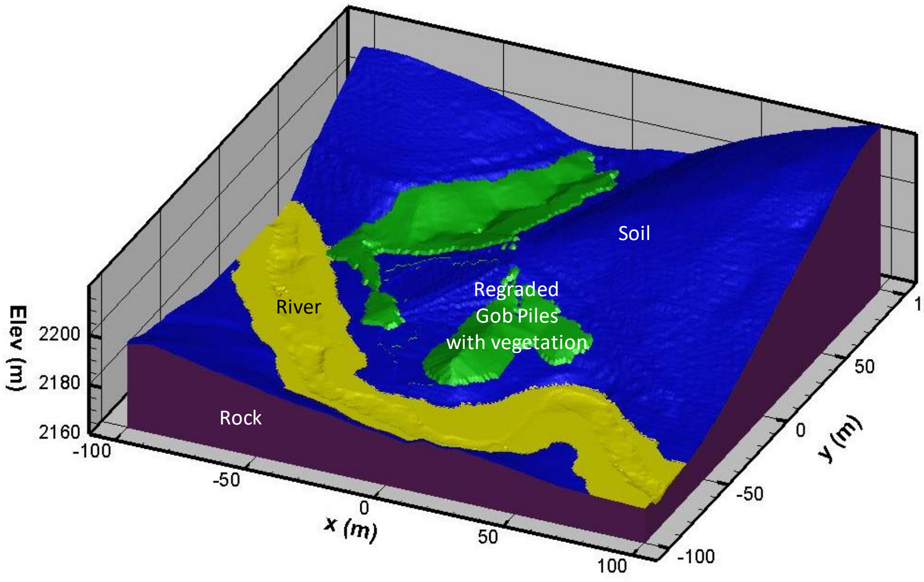
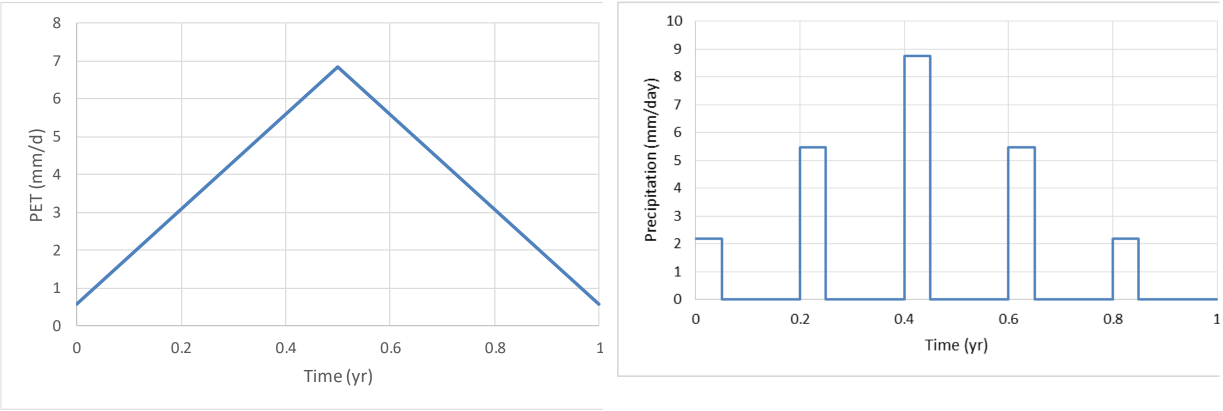


Figure 9. The domain and components for site-scale simulation.

Boundary and Initial Conditions

The top boundary included two conditions – PET and P (Figure 10). The PET was based on the SWAT simulated values (with an average of 1355 mm yr^{-1}) for the Tin Pan watershed. In the simulation, the scaled LAI was assumed to be 0.88 (LAI = 2.9). The annual precipitation was determined based on the observation at Raton Filter Plant[1] near Raton, NM. However, in order to understand the temporal variation of P on the performance of the GET barrier, the annual P was allocated in five pulses, as shown in Figure 10b, with the total of 440 mm yr^{-1}. The groundwater flowed from west to east. The average groundwater level was determined by the MODFLOW simulation over the Tin Pan watershed as described in the previous section. The initial condition was determined by repeating the simulation for two year. The results for the third year were analyzed and reported.



(a) (b)

Figure 10. (a) Daily potential evapotranspiration (PET) and (b) daily precipitation.

Simulation Scenarios

The simulation of flow through the gob piles at the Tin Pan site was conducted on the conceptual grading Alternative #2. Four simulations (Cases 1 to 4 in Table 3) considered 2 levels of P and 2 levels of root depth:

- 2 levels of P: near average (P_{avg} = 440 mm yr^{-1}) and 50% above average
- 2 levels of root depth: 0.5 m for shallow-rooted vegetation and 4.0 m for deep-rooted vegetation

Table 3. Simulation scenarios.

Case No.	Case Name	LAI	Scaled LAI	Root Distribution	Precipitation Level
1	DR Avg P	2.9	0.88	a = 4.372; b = 0.978 m^{-1} Depth = 4.0 m†	Average (P_{avg})
2	SR Avg P	2.9	0.88	a = 8.992; b = 8.992 m^{-1} Depth = 0.5 m†	Average (P_{avg})
3	DR High P	2.9	0.88	Depth = 4.0 m	High (1.5 P_{avg})
4	SR High P	2.9	0.88	Depth = 0.5 m	High (1.5 P_{avg})
5	SR Avg P, Low LAI	0.6	0.4	Depth = 0.5 m	P_{avg}
DR: deep-rooted; SR: shallow-rooted; LAI: Leaf area index; P: precipitation; P_{avg}: mean precipitation. †Zeng et al. (2001, Table 1).					

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[1] Available at https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm7279.

In these four simulations, it was assumed that the vegetation was fully-grown with an LAI of 2.9 and a scaled LAI of 0.88, meaning near maximum transpiration capability. Case 5 was conducted to examine the scenario of sparse vegetation with an LAI of 0.6 and scaled LAI of 0.4 (Table 3).

Results and Discussion

In this section, we sequentially present the conceptual geomorphic grading alternatives and GET cover at the Tin Pan site, the hydrology of the Tin Pan watershed, and the hydrology at the Tin Pan site. It is noted that the models were not calibrated for the Tin Pan watershed or the Tin Pan site. Some results are just snap shots to demonstrate the simulation capability for hydrology-based GET cover design. As a result, the results may not accurately represent the actual processes and should not be used in a quantitative way for decision making.

Geomorphic Grading and GET Cover at the Tin Pan Site

Grading Options

The goals of the design were to reclaim the gob piles with a drainage network with natural form and function, convey the on- and off-site runoff water through the project without accelerated erosion, reduce steep slope areas for minimal slope erosion, and improve re-vegetation success.

The Tin Pan site had special characteristics that need to be considered in the design, which may also be encountered at other reclamation sites.

- The waste material was dumped into a narrow valley making near angle of repose slopes where it is against the tributary channel valley walls and on its outer slopes approaching Tin Pan Canyon stream (Figure 3 and Figure 5).
- A pioneered two-track valley road along the Tin Pan valley is still in use and follows the north valley wall defining the upper end of the site. It is desired to retain it with a low-maintenance, low-water crossing (Figure 3 and Figure 5).
- The watershed area of the tributary valley above this road, because of the shallow soils over bedrock and minimal vegetation cover, has a high runoff coefficient that can result in erosive storm water discharges crossing the waste piles.
- There are limited areas for alternate waste disposal, making on-site final placement desirable. This means that a balanced cut and fill design that does not require material export is preferable.
- The GET cover had to be integrated into the design to sequester the designated waste volume.

The slope zone analysis of the existing waste piles on the site (Figure 11) represents areas of different slope ranges as determined from a triangulated surface made from the site topographic map. The New Mexico Abandoned Mine Land (NM AML) Program reported good vegetation recovery on nearby sites on slopes less than 80 percent[1]. They also noted that slopes having a southwest aspect were much slower to recover.

A target slope steepness of ≤33 percent was selected based on that experience. The dark blue color in Figure 11 indicates that the site waste material slopes are predominately in the steepest slope category (averaging 58.1 percent steepness) and only 43.2% of the slopes are in the target range of ≤33 percent steepness.

Previous field work in appropriate nearby stable areas provided the reference site input information for drainage density (83 m/ha; 110 ft/acre), ridge to head of channel distance (27 m; 90 feet), and 'A-channel' reach length (15 m/ha; 20 feet/acre). The site topographic information came from an AutoCAD .dwg format file provided by the NM AML Program from its site survey, and from Google Earth for the upstream tributary watershed area.

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[1] Personal communication between J. Kretzman and N. Bugosh in December 2017.

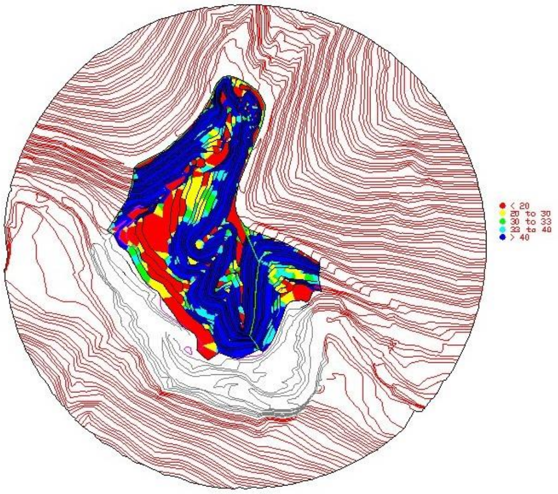


Figure 11. Slope zone analysis of the existing waste piles on the site. The legend shows the slope steepness (in percent) represented by the different colors. The actual design area for the reclamation design was 0.96 ha. The area approximately corresponds to the small circle in Figure 3.

These data were used to make alternative GG designs. A change in almost any landform element affects the rest of the integrated 3-D design, but because the entire design can be revised relatively easily using a computer, many alternative designs, and variations of each design, can be investigated to find an optimal solution. We will simplify the discussion here to three main GG alternatives and refer to them as Alternatives #1, #2, and #3.

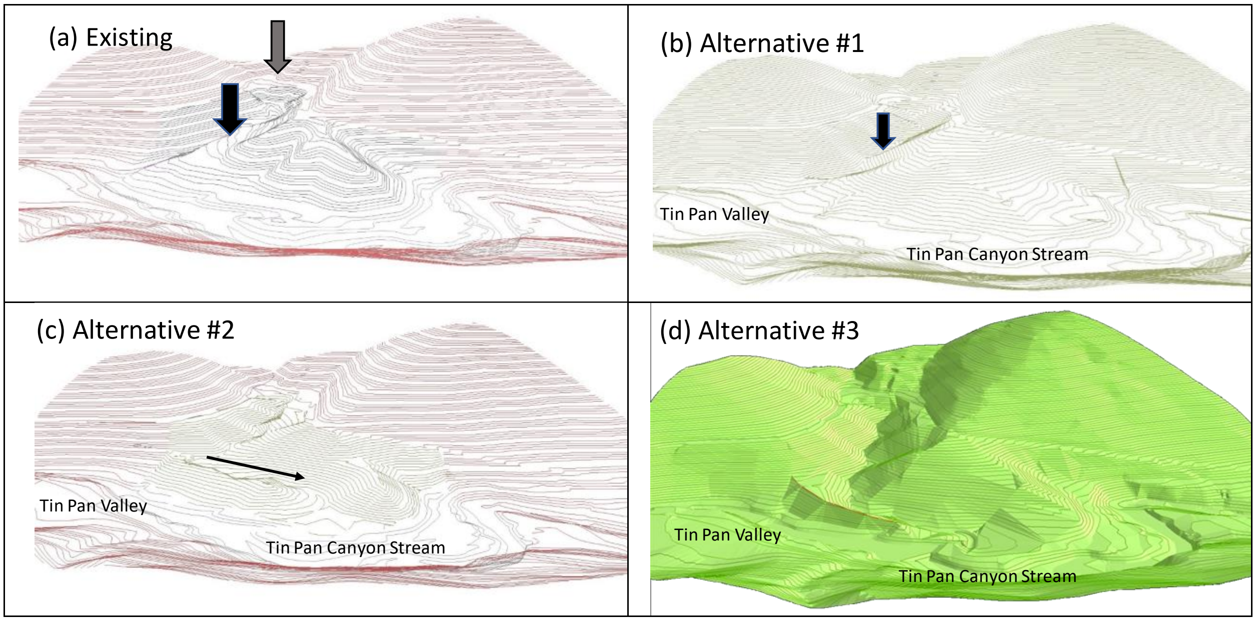


Figure 12. 3-D contour view of the current condition and three alternative GG designs. The view is south to north with Tin Pan Canyon stream in the foreground. The arrows in (a) show the location of the upper end of the site at the valley road crossing (gray, upper arrow) and the channel eroded into the waste along the west valley wall (black, lower arrow). The arrow in (b) indicates the tributary channel along the west valley wall. The arrow in (c) shows the change in valley direction from the design Alternative #1. The actual design area for the reclamation design was 0.96 ha.

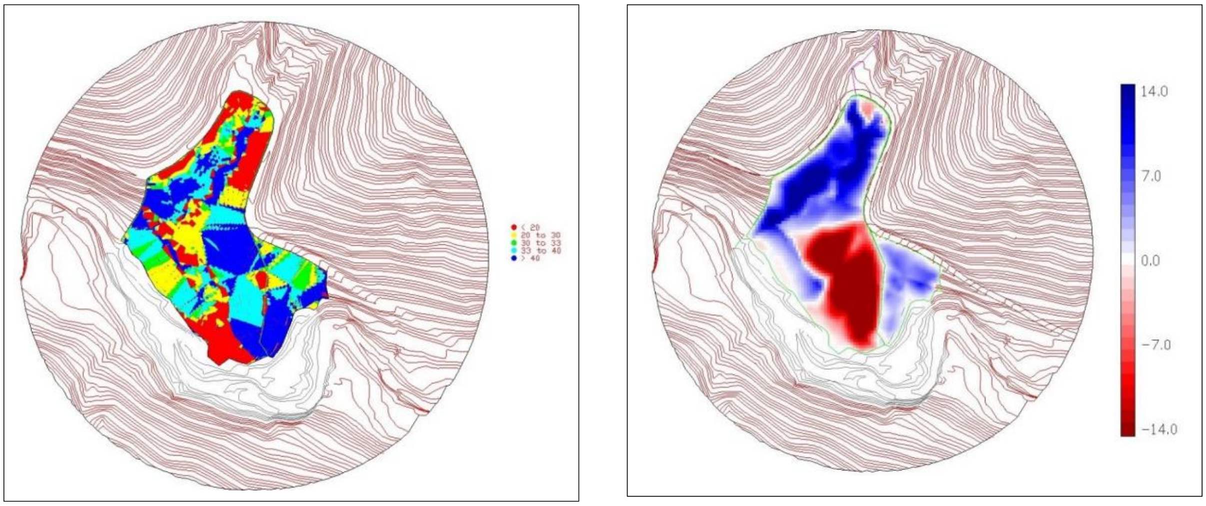
The Alternative #1 design (Figure 12b) had a channel trending north to south over the waste to its confluence with Tin Pan Canyon stream. This design confirmed that a reclamation landform based on the reference area input values could achieve a balanced cut to fill ratio that would eliminate the need for material import or export. Alternative #1 also showed that steep slope areas could be reduced toward the target values.

Stable natural stream channels in unconsolidated material develop a smooth concave longitudinal profile that helps dissipate the energy of increased discharge in the downstream direction by commensurately decreasing the slope. The tributary channel's tractive force values changed little with the better concave profile in Alternative #1 because, despite the improved profile, the very steep average slope from the road crossing knickpoint to the channel's confluence with Tin Pan Canyon stream remained. This informed the decision to make alternative designs that would add channel length to decrease the channel's slope and tractive forces that led to Alternative #2.

Alternative #2 design (Figure 12c) is the best fit for channel alignment to accomplish this reduction in slope and also meet the other project criteria of slope reduction, material balance, and accommodating the GET waste cover. As the channel enters the Tin Pan valley, it bends eastward and then turns southward to its confluence with Tin Pan Canyon stream. This appears to coincide with the original channel mouth location.

The added valley length in Alternative #2 resulted in decreased channel tractive force values that dropped from 32 to 11 kg m^{-2} at bankfull discharge, and from 78 to 17 kg m^{-2} at flood-prone discharge at a point 71 m downstream of the road crossing knickpoint, and maintained values in this low range as flow continued across the waste to the channel's mouth.

Figure 12d shows how the reclamation surface ties into the surrounding undisturbed land with a different GG design - Alternative 3. The most obvious element that differentiates Alternative 3 from Alternative 2 is that the western channel's mouth has been moved to the east to coincide with the cut in the stream embankment that was likely the pre-disturbance channel mouth. The valley wall slopes convey the runoff in swales to the channel that is designed for the discharge at the receiving point. The tributary channel turns to the east in the direction of Tin Pan Creek and flows into Tin Pan Creek at the notch in the bank believed to be the pre-disturbance tributary channel mouth. Restoring this additional channel length (which the spoil piles blocked) reduces the channel slope and related erosional energy (tractive force) considerably.



(a) (b)

Figure 13. (a) Slope zone of analysis of the Alternative #2 fluvial geomorphic design with 71% of the slopes in the lower slope target steepness of ≤33 percent. (b) Cut fill color map of revised fluvial geomorphic design Alternative #2. Positive values are for material fill and negative values for material cut. The actual design area for the reclamation design is 0.96 ha. The area approximately corresponds to the small circle in Figure 3.

Figure 13a shows the slope zone analysis of the design Alternative #2. The target range in this analysis was set at ≤33 percent steepness. Alternative #2 increases the fraction of slopes that are in the target range from only 0.43 in the existing topography to 0.71. The fluvial geomorphic design also produces a much more varied topography than the existing site depicted in Figure 12a, resulting in a mosaic of slopes that promotes variation in vegetation species diversity and composition through variation in sunlight and soil moisture (Clark, 2008).

The site material balance shown in the cut fill color map view in Figure 13b helps to visualize how the material movement can occur to facilitate the GET cover waste construction. The darkest red areas east and northeast of the reclamation channel alignment are where the maximum material cut is generated. The first cuts of that material can be placed against the west valley wall where the darkest blue indicates the maximum fill requirement. Placement of this material there reduces those slopes toward the target values. Alternative #2 holds promise for fully satisfying all the site design criteria in a final design for the reasons explained above. The Alternative 3 design alternative incorporates this approach but with subtle refinements to better meet the site design criteria.

GET Cover

At the Tin Pan site, the PET is about three times of precipitation and hence all the precipitation can be potentially released back to the atmosphere via ET. Because the gob pile material has a fine texture of clay loam with sufficient capacity to store precipitation and can be used as the material for the storage layer and for vegetation growth. Hence, the drainage layer, barrier layer, and foundation layer are all optional. In other words, vegetation can be directly planted on the regraded gob piles. Despite the fine texture, it is still recommended that the relatively finer materials be used for this layer during the regrading operation because some coal material can be very blocky. Because the geomorphic design had to preserve the road grading that has changed the valley profile and that inserted a culvert that causes a hydraulic jump contributing to higher tractive forces, the culvert splash or low-water crossing outlet area and channel substrate would require care in material placement to keep fine-grained material subject to transport at these tractive force values from the channel bottoms. The remaining steeper upland slope areas are small and the observed storage capacity and effects of vegetation should be adequate to stabilize them against erosion (consistent with observations at reclamation completed nearby[1]).

This simple design can be used for gob piles of a fine texture in arid and semi-arid areas. In cases where the gob pile has a very coarse texture such that does not have good water storage capacity or cannot support the growth of vegetation, soils are needed from elsewhere to construct the storage layer. In case of relatively wetter areas with a semi-humid or humid climate, the PET is generally insufficient to transfer all the precipitation to the atmosphere. In this case, a more complex cover similar to that shown in Figure 1 is needed.

Watershed Modeling

Results from the watershed numerical simulations included both surface and subsurface hydrologic processes. In the following, results of surface hydrologic processes (stream discharge) and subsurface hydrologic processes (hydraulic head, horizontal and vertical flow rates) are discussed.

Stream Discharge

Figure 14 shows that the simulated stream discharge at the outlet of Tin Pan watershed was mainly driven by intense precipitation events. Generally, stream discharge was greater in the summer period when precipitation was higher.

Hydraulic Head of Groundwater Flow

Figure 15 demonstrates the simulated spatial distribution of the hydraulic head as the elevation of groundwater in the top layer for the Tin Pan Watershed and the Tin Pan site on the first day of 1980. The groundwater generally flowed from the hills (with higher hydraulic head) to the stream (with lower hydraulic head). At the Tin Pan site, the water table was approximately 2 to 30 m below land surface. The depth of the groundwater table it was less in areas closer to the stream channel.

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[1] Personal communication between J. Kretzman and N. Bugosh in December 2017.

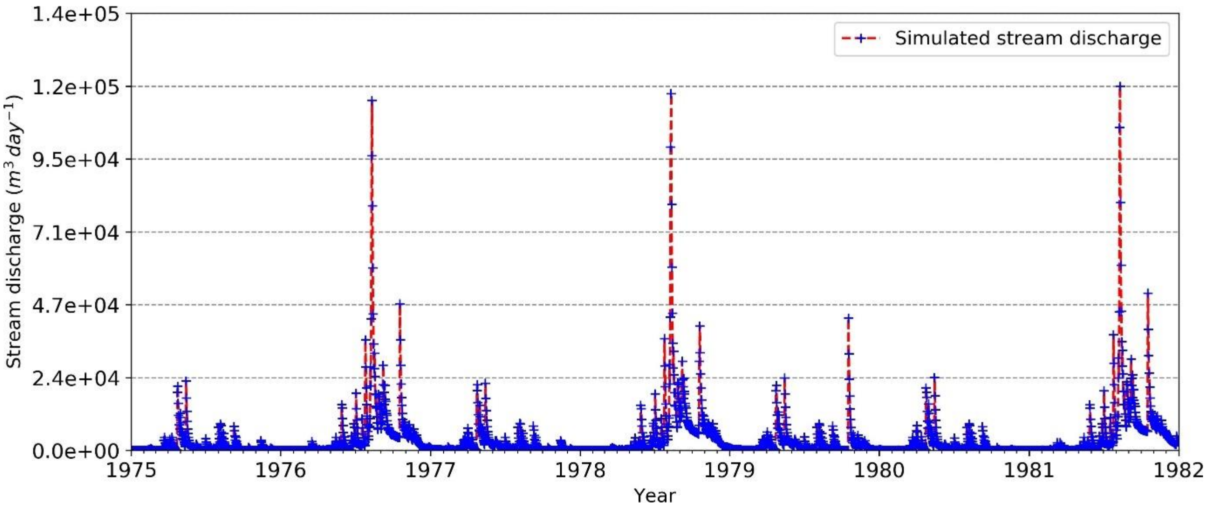


Figure 14. Daily stream discharge at the watershed outlet

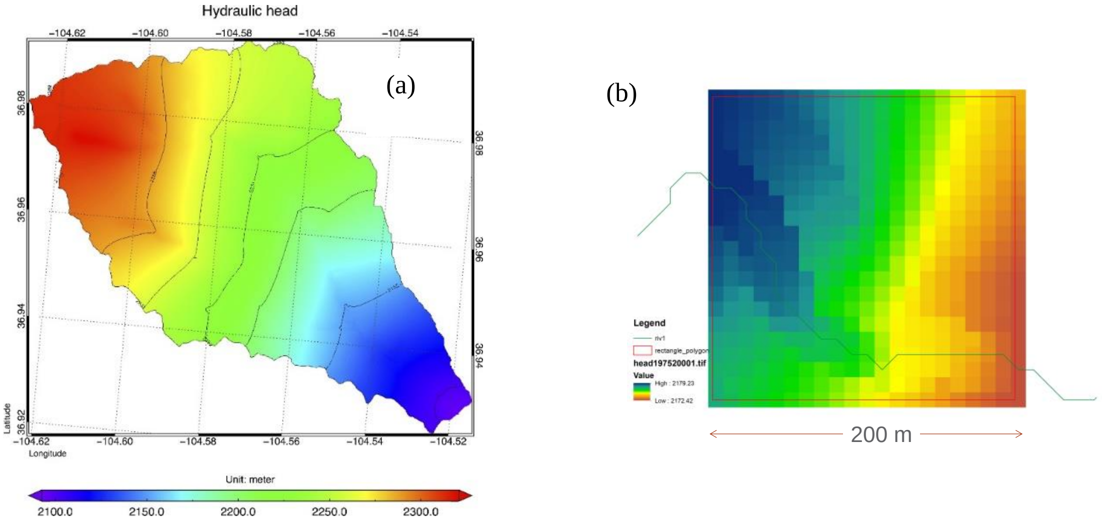
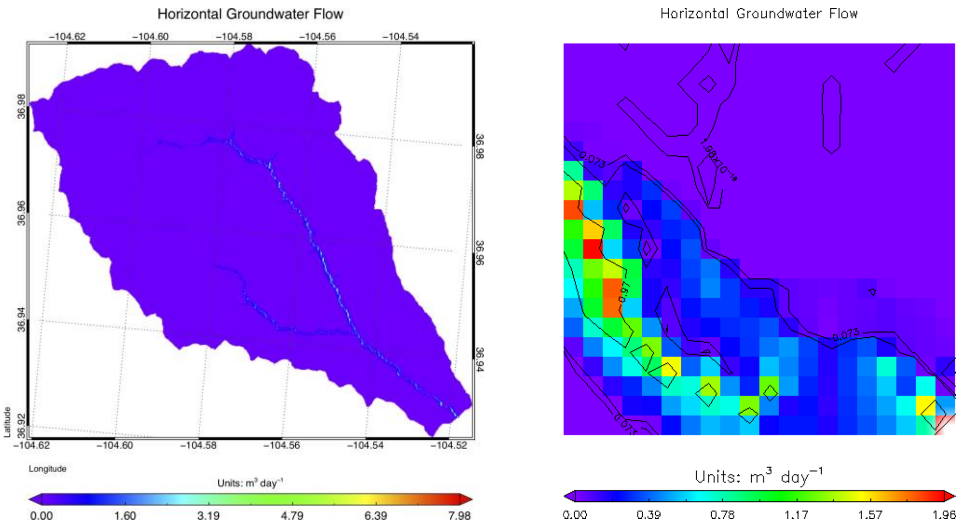


Figure 15. The spatial distribution of the hydraulic head as the elevation of groundwater in the top layer for (a) the Tin Pan Watershed and (b) the Tin Pan site on the first day of 1980.

Horizontal Groundwater Flow

Figure 16 shows the simulated horizontal groundwater flow in the top layer of the Tin Pan watershed and the Tin Pan site on day 200 of 1978. The highest horizontal groundwater flow was near and below stream networks. The maximal horizontal groundwater flow rate in the top layer near the Tin Pan site was approximately 2.0 $m^3\,day^{-1}$ per 10 m width.

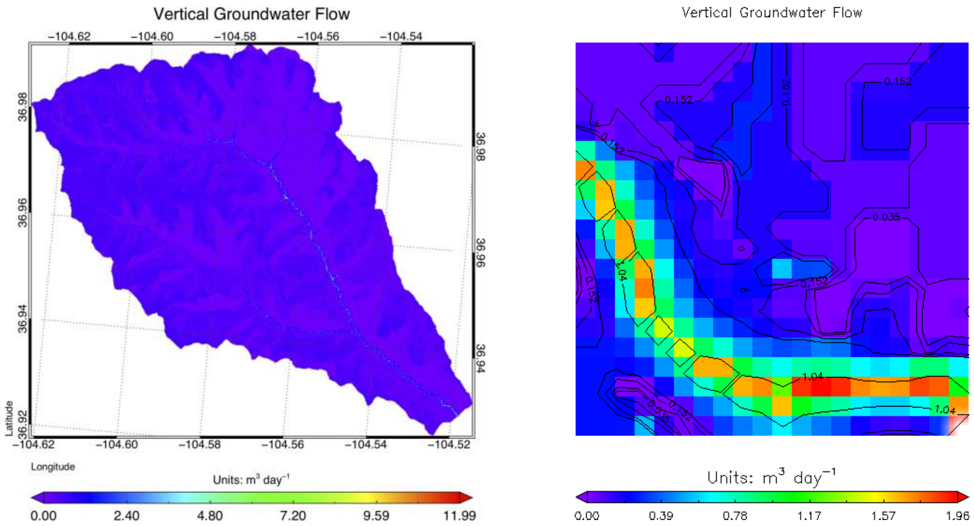


(a) (b)

Figure 16. The spatial distribution of the horizontal groundwater flow rate per 10 m width in the top layer of a) the Tin Pan watershed and b) the Tin Pan site on day 200 of 1978.

Vertical Groundwater Flow

Figure 17 plots the spatial distribution of simulated vertical groundwater flow rates (absolute values) between the top and middle layers on day 200 of year 1978. In general, the high vertical groundwater flow rates were near and beneath the stream networks with the maximum of about 12.0 m^3 day^{-1} per cell (120 mm day^{-1}). The maximal vertical flow rate near the Tin Pan site was approximately 2.0 $m^3 day^{-1}$ per cell (or 20 mm day^{-1}, Figure 17b).



(a) (b)

Figure 17. The spatial distribution of the vertical groundwater flow rate (absolute value) per 100 m^2 between the top and middle layers at a) the Tin Pan watershed and b) the Tin Pan site on day 200 of 1978.

Potential Evapotranspiration

Figure 18 shows the SWAT-estimated mean PET with one standard deviation at the Tin Pan Watershed. The daily PET ranged between 1.5 mm d^{-1} (in January) and 6.8 mm d^{-1} (in June). The annual PET ranged between 1214 to 1452 mm with the mean and standard deviation of 1355±45 mm, which is roughly 3 times the average annual precipitation of 453 mm. These values were used to determine the PET at any given time in the site-scale simulations as described in Section 0.

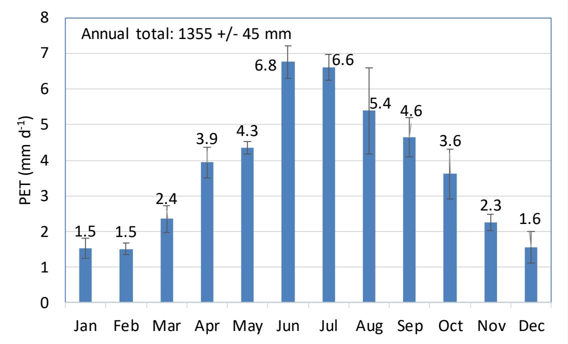


Figure 18. SWAT-estimated potential evapotranspiration with one standard deviation at the Tin Pan Watershed.

Site-Scale Modeling

The site-scale simulations were to evaluate the hydrological performance of conceptual GET covers that were based on the GG design Alternative #2.

Water Content Dynamics and Storage in the Gob Piles

Figure 19 depicts seasonal variation of water content at three depths (i.e., 0.4, 0.8, and 1.2 m) in the gob piles and Figure 20a plots the water storage in the gob piles with different vegetation coverage or P. As expected, at all the depths, water content and storage increased during the periods with rainfall and decreased during the periods without rainfall. The range of water content variation with time was larger in smaller depths (e.g., at 0.4 m, Figure 19a) than in larger depths (e.g., 1.2 m, Figure 19c).

At the small depth (e.g., 0.4 m, Figure 19a), the water content in the gob piles was higher when P was higher or when the LAI was smaller than their counterparts; the root depth had almost no impact on water dynamics at this depth. At the large depth (e.g., 1.2 m, Figure 19c), all the factors (i.e., P, root depth, and LAI) had some impact on water content. A larger P or a shallower roots or smaller LAI led to higher water content (Figure 19c), and consequently, higher water storage in the gob pile (Figure 20a).

Water Balance

At the Tin Pan site, the precipitation that entered into the gob piles would be released to the atmosphere via ET or to the underlying groundwater as percolation, or remain in the pile. Figure 20b shows the temporal variation of ET from the gob piles with different vegetation coverage or precipitation. Consistent with the soil water content and water storage in the gob piles (Figure 19), the ET rate was higher in the periods with rainfall than those without rainfall (Figure 20b).

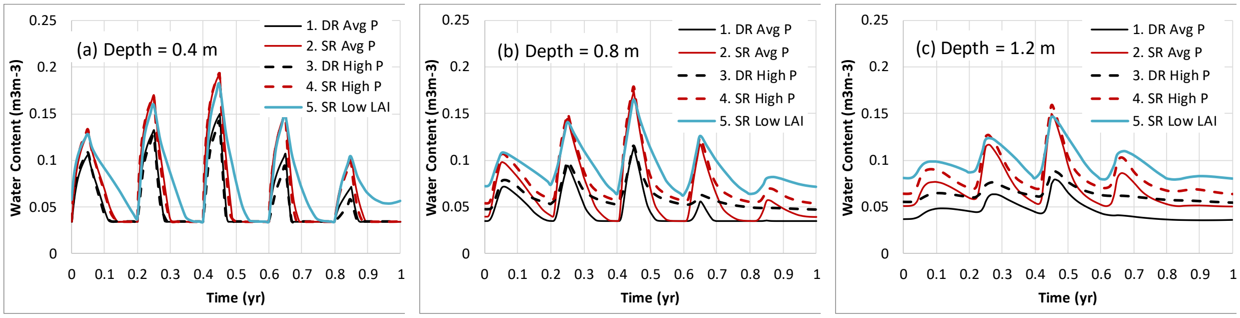
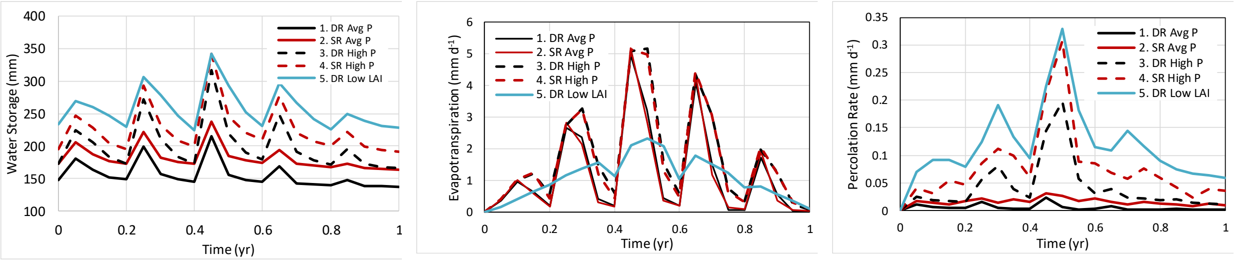


Figure 19. Water content dynamics at different depths in the gob piles with different vegetation coverage or precipitation. DR: deep-rooted; SR: shallow-rooted; P: precipitation; LAI: leaf area index. The numbers in the legend correspond to the case number in Table 3.



(a) (b) (c)

Figure 20. (a) Water storage in the gob piles, (b) evapotranspiration from the gob piles, and (c) percolation through the gob piles with different vegetation coverage or precipitation. DR: deep-rooted; SR: shallow-rooted; P: precipitation; LAI: leaf area index. The numbers in the legend correspond to the case number in Table 3.

Figure 20c depicts the percolation through the gob piles with different vegetation coverage or P. The percolation rate varied temporally, with higher values in the periods with rainfall than those without rainfall (Figure 20c). However, the percolation rate was affected by P, root depth, and LAI. A larger P or a shallower roots or smaller LAI led to larger percolation (Figure 20c).

Table 4 tabulates the annual water balance at the gob piles. During the year, there was a small net loss of the stored water, ranging between 3.9 and 10.3 mm. For the two cases at P_{avg} (Cases 1 and 2), the annual ET was similar to but slightly (0.6% and 1.9%) higher than P, while the annual percolation was only 0.5% and 1.4% of P. For the case with $1.5P_{avg}$ (Cases 3 and 4) or with a low LAI (Case 5), the annual ET was 1.5% to 8.8% smaller than P, while the annual percolation ranged between 2.4% and 10.2% of P. The differences in ET and percolation between the shallow- and deep-rooted vegetation (Cases 1 vs. 2; 3 vs 4) were very small probably because the vegetation LAI of 2.9 was sufficiently high and ET was primarily controlled by the availability of soil water. For Case 5 with a LAI of 0.6, the ET rate was probably controlled by the limited transpiration and hence was much smaller than that of its counterpart with a higher LAI of 2.9 (Case 2).

The annual total percolation ranged from 2.1 to 44.8 mm (Table 4), which were 0.5% and 10.2%, respectively, of the corresponding P. The results indicate that vegetation coverage played a very important role in limiting percolation.

GET covers may be applied to regions with a semi-arid or drier climate and PET/P > 2, like ET covers (INAP, 2009). However, the material type for constructing the GET covers must have sufficient water storage capacity in order to have the store-and-release mechanism to function efficiently.

Table 4. Annual water balance (mm) at the gob piles

Case No./Name	1. DR Avg P	2. SR Avg P	3. DR High P	4. SR High P	5. DR Low LAI
P	440.0	440.0	660.0	660.0	440.0
ΔW	-10.3	-8.7	-5.9	-3.9	-5.9
ET	448.2	442.8	650.1	634.2	401.1
ET/P	1.019	1.006	0.985	0.961	0.912
D	2.1	6.0	15.9	29.8	44.8
D/P	0.005	0.014	0.024	0.045	0.102

DR: deep-rooted; SR: shallow-rooted; LAI: leaf area index; P: precipitation; ΔW: water storage change; ET: evapotranspiration; D: percolation.

Conclusion

This investigation introduced a GET cover by integrating the ET cover and geomorphic grading technologies and modeling alternative approaches under conditions found at the Tin Pan mine site near Raton, NM. Based on the study, we have the following findings.

- GET covers can be designed for abandoned mine land based on the stable topography and vegetation in the surrounding area. Often multiple alternative GET covers can be designed for a given site to achieve the objectives. For sites that contain contaminants, the GET cover should be designed to minimize infiltration of precipitation through the waste piles.
- In the arid and semi-arid regions, simple designs without a drainage layer may be sufficient to reduce percolation. However, in more humid regions, ET generally is insufficient to release all the precipitation to the atmosphere. For such cases, a drainage layer is needed to guide the clean water from precipitation out of the footprint of the waste area so the water will not be a driving force to mobilize contaminants.
- To protect the environment from potential pollution of a waste site, hydrological interaction between a site and the nearby surface water/groundwater need to be assessed using watershed-scaled and site-scale simulations.
- Despite the high water storage capacity of the material in the gob piles at the Tin Pan site, because the material can be blocky, it is recommended that the finer fraction be used as the top layer for better vegetation growth and water storage.
- Sufficient vegetation coverage is needed in order for the GET cover to function efficiently and to considerably reduce percolation.

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