Geomorphic reclamation applications in Central Appalachia

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Introduction: Mining reclamation in West Virginia

Traditionally, mountain top surface mines are reclaimed to the Approximate Original Contour (AOC) according to SMCRA, 1977.

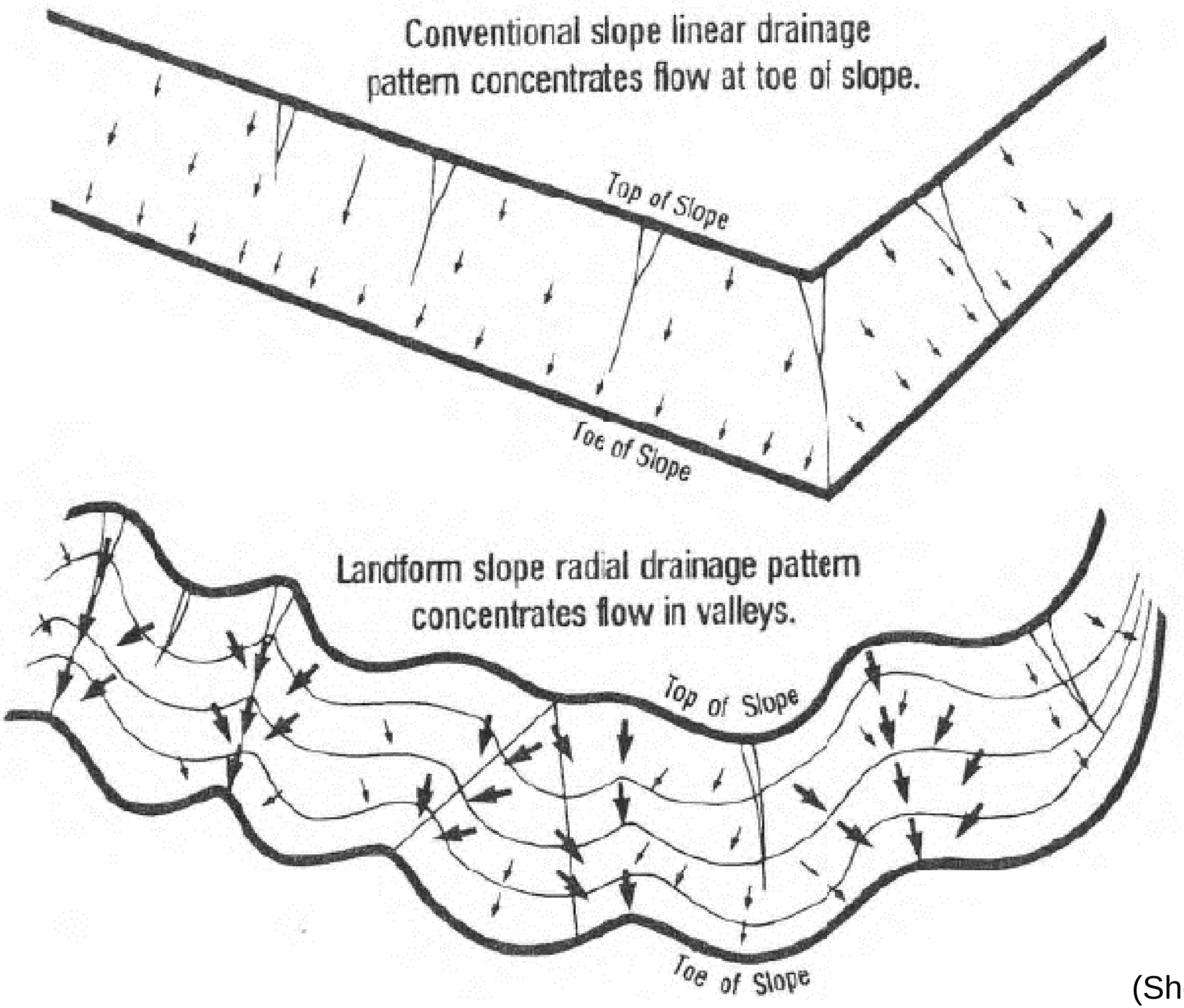
Other mine land reclamation may include coal refuse piles and impoundments

Valley Fill w/Traditional Reclamation

Coarse Coal Refuse Pile

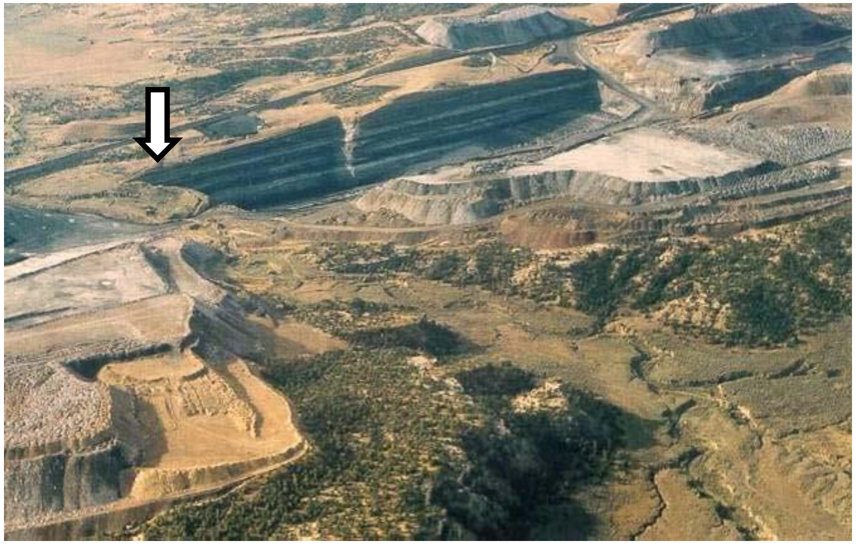
Valley Fill Concerns:

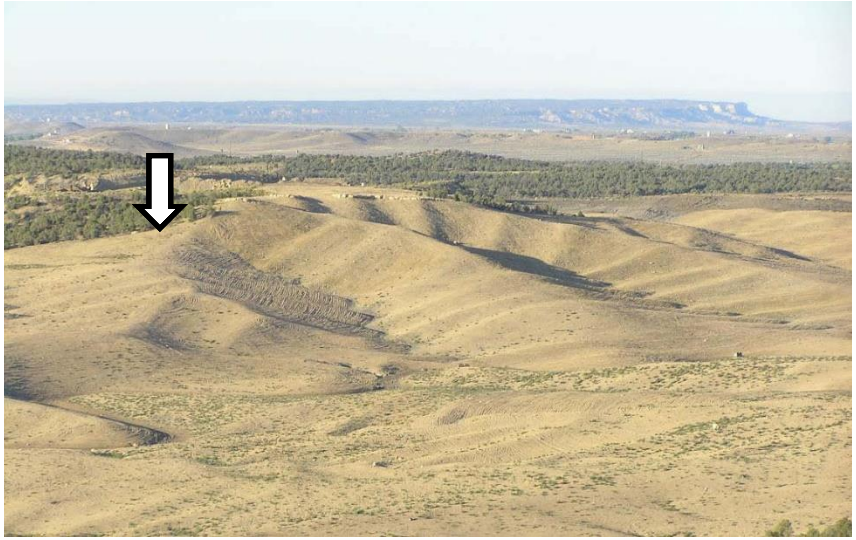
- Headwater stream loss
- Changes in downstream ecological habitat, and sedimentation
- Not aesthetically pleasing



(Shor and Gray, 2007)

Geomorphic landform design (GLD) attempts to mitigate some environment concerns





(OSM, 2006)

- Replicates undisturbed channel and basin geomorphology
- Designs landforms in long-term dynamic equilibrium
- Reduces erosion and improves water management
- Improves stability and aesthetics of landforms

The geomorphic landform design procedure builds a drainage network using a reference landform approach

(GeoFluv, 2009)

- From youthful, actively eroding landforms to mature, stable landforms
- Input collected measurements from surrounding area
  - Ridge to head of channel distance, drainage density, sinuosity…

Challenges

- Geomorphic properties need to be defined locally
- Steep slope topography does not ensure landform or channel stability
- Increased disturbance area
- Compliance with regulations
- Differences in mining / reclamation strategies

Benefits

- Landform aesthetics and slope / aspect variability
- Stream preservation / mitigation, habitat diversity
- Improved groundwater management
- Decreased contaminant release (particularly selenium)

Research Questions

1. How do we quantify characteristics of mature landforms in West Virginia?

2. Can stream mitigation be implemented on surface mine valley-fill sites in Central Appalachia?

3. Are geomorphic landform designs geotechnically stable?

4. Can a stable geomorphic landform be designed as an alternative to a conventional valley fill?

5. Is soil loss altered at the watershed scale by different valley-fill reclamation methods?

6. What is the potential hydrologic response?

How do we quantify characteristics of mature landforms in West Virginia?

This project defined the reference landform characteristics necessary for design.

- Drainage density
- Ridge to head of channel distance

- Main channel slope
- Channel characteristics
  - Bankfull width
  - W:D
  - Sinuosity
- Bed particle size distribution
- Vegetation zones
- Subridge angle
- Baseflow (where applicable)

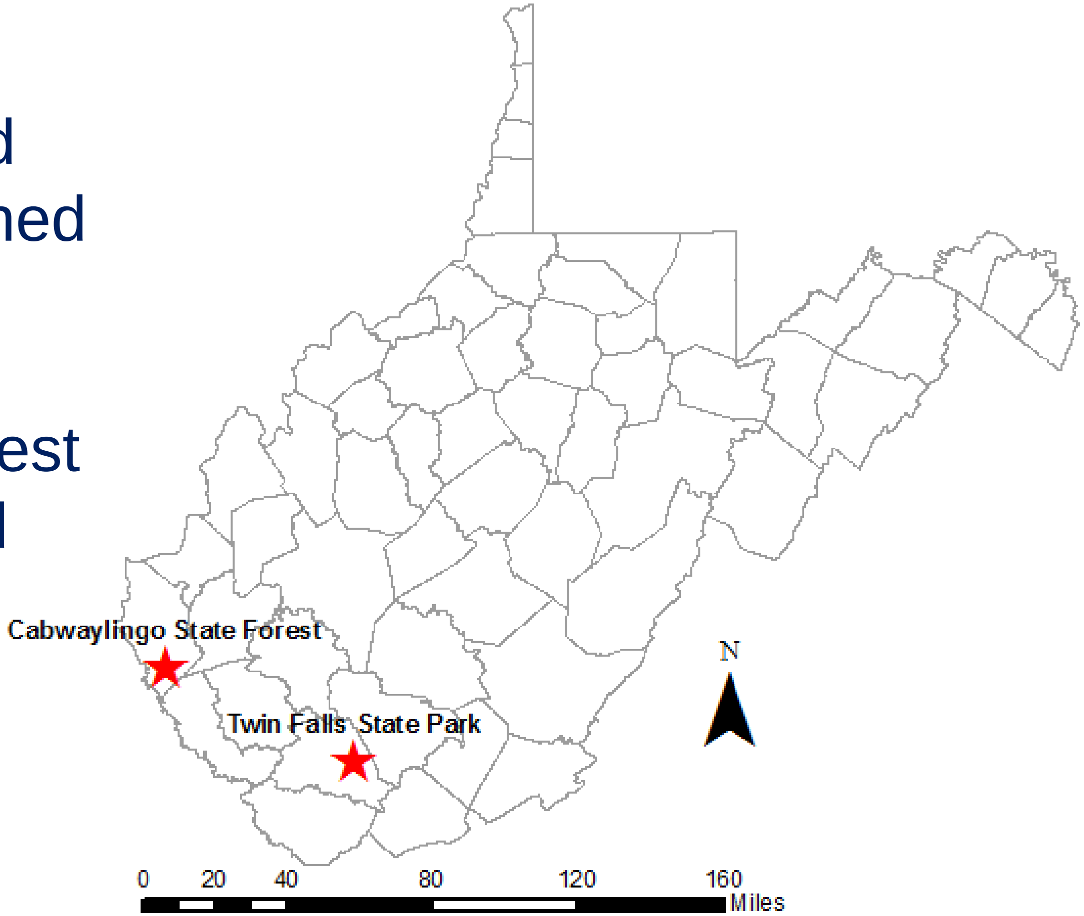
Two Field Site Locations

Twin Falls State Park

- Dixon watershed
- Jackson watershed

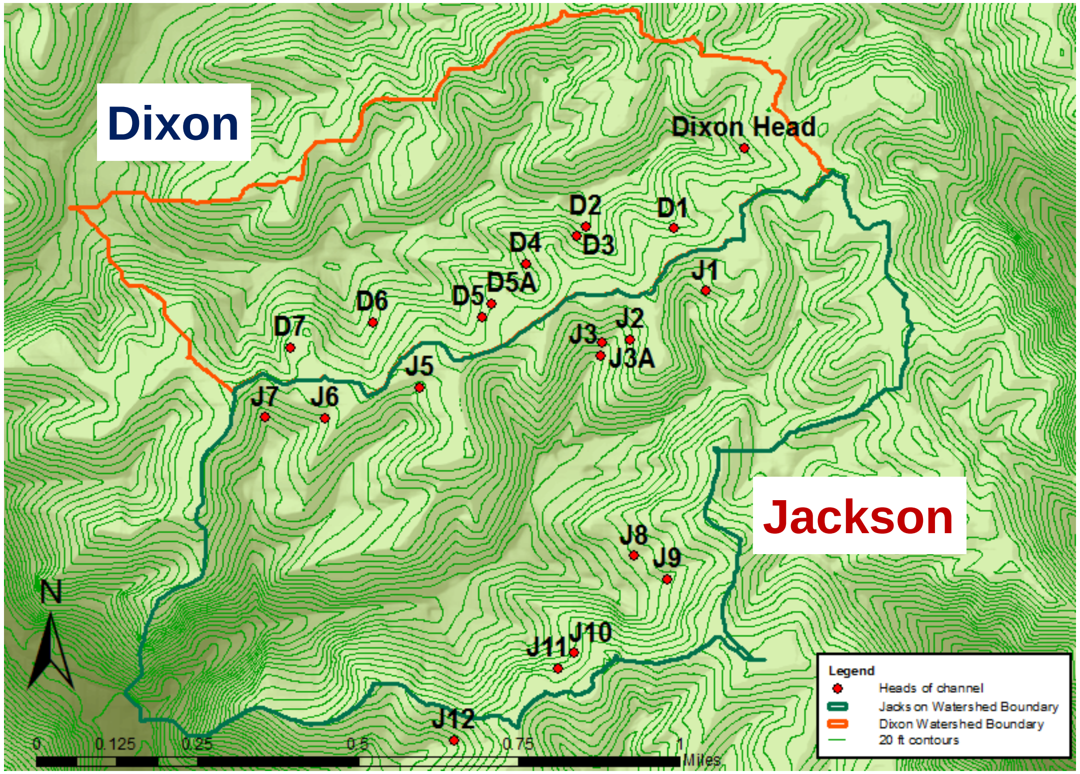
Cabwaylingo State Forest

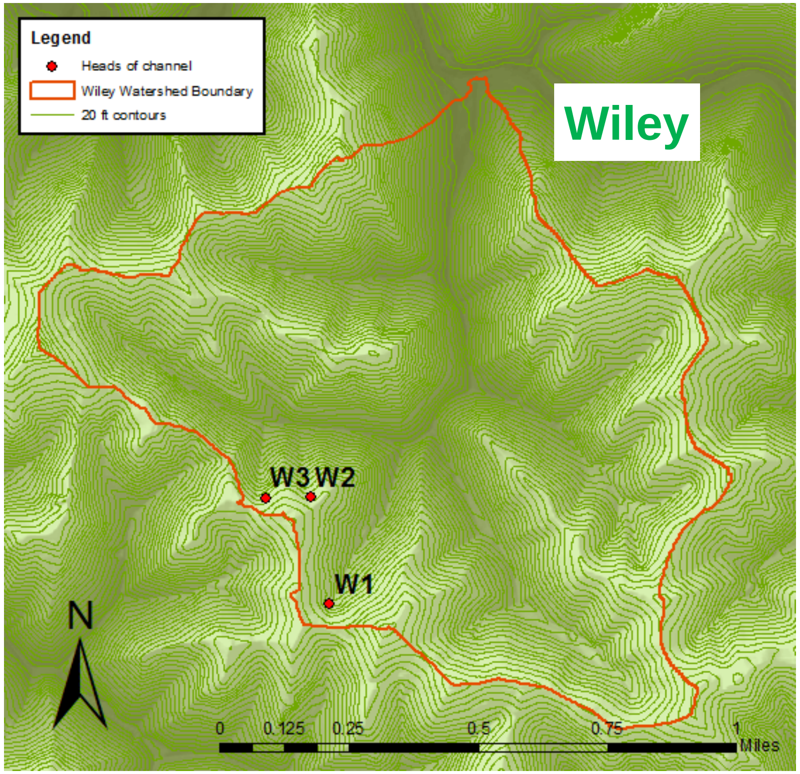
- Wiley watershed



Ridge to head of channel distance: Head of channel locations and ridge points were surveyed with a Topcon GPS.

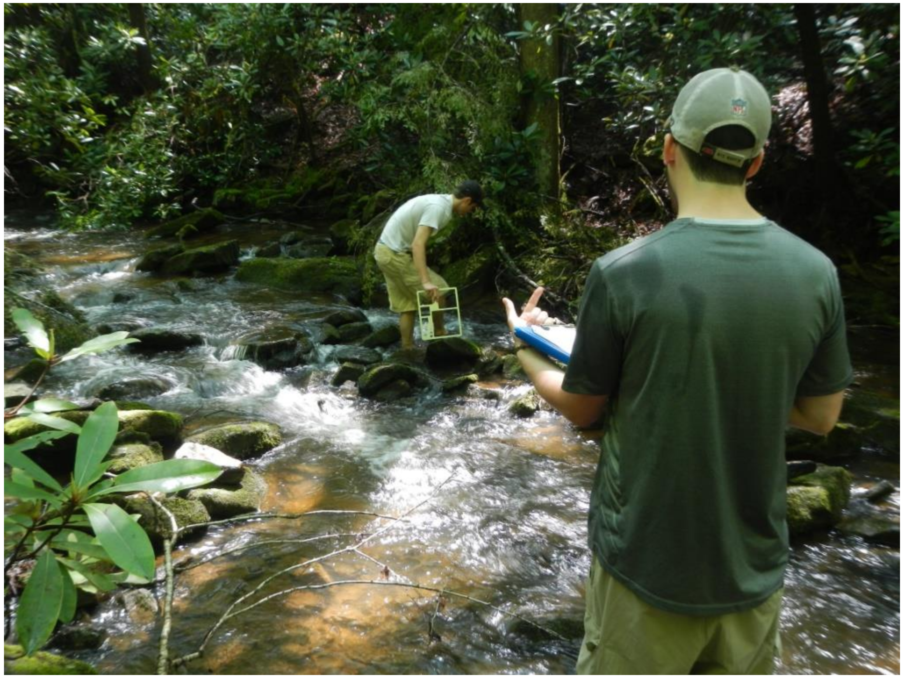
Field data were collected at 8 heads of channel in Dixon, 11 in Jackson, and 3 in Wiley.



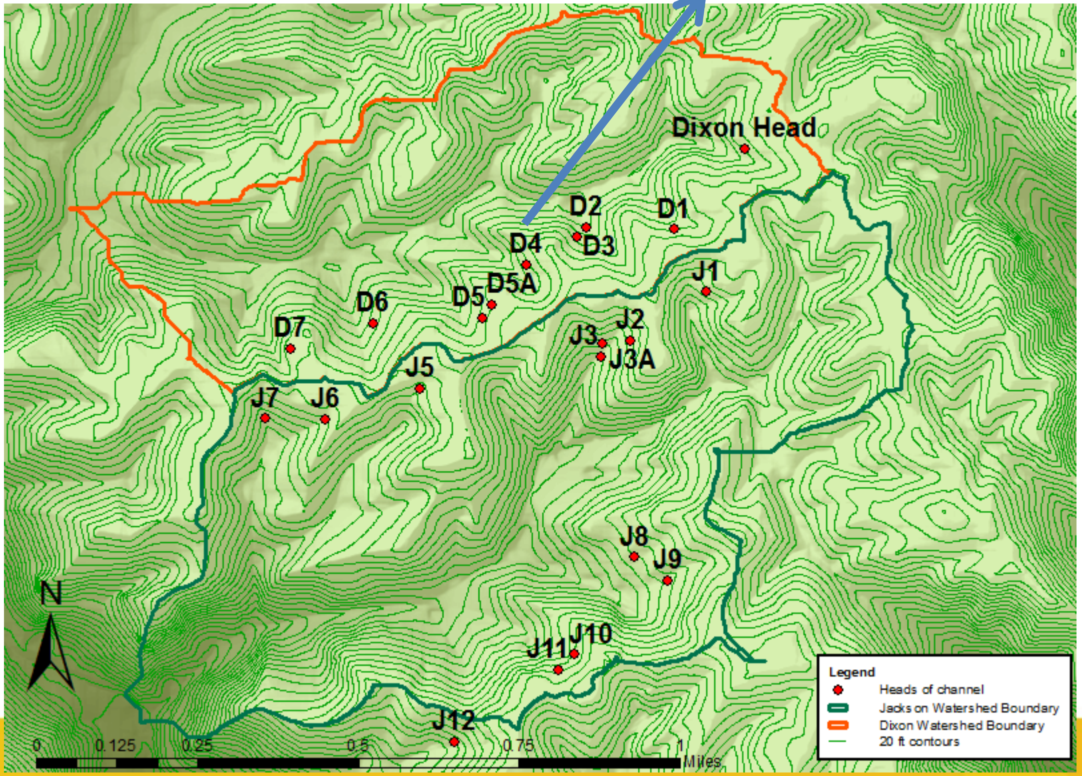


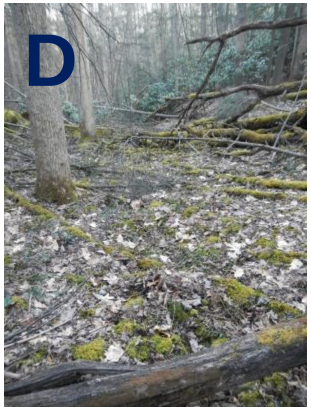
Channel/valley characteristics were defined for each site.

- Channel slope
- Channel cross-section
- Sinuosity
- Discharge
- Grain size
- Vegetation



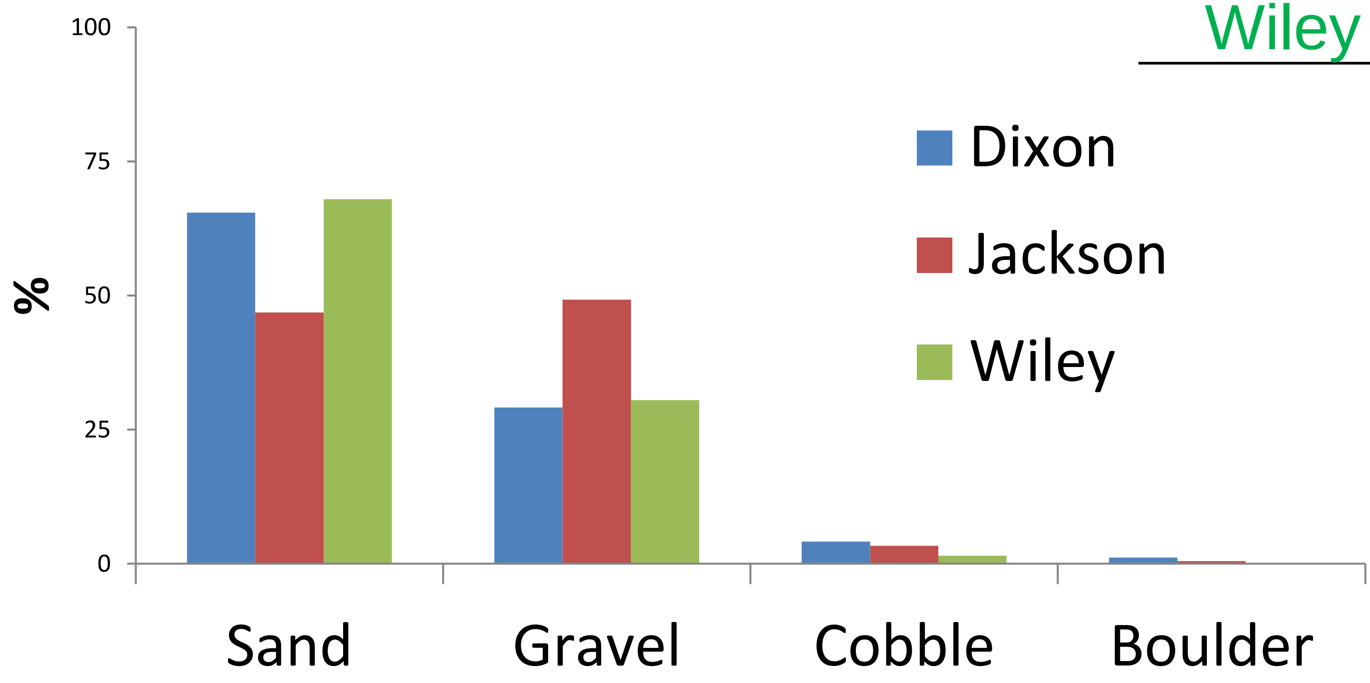
Dixon Watershed



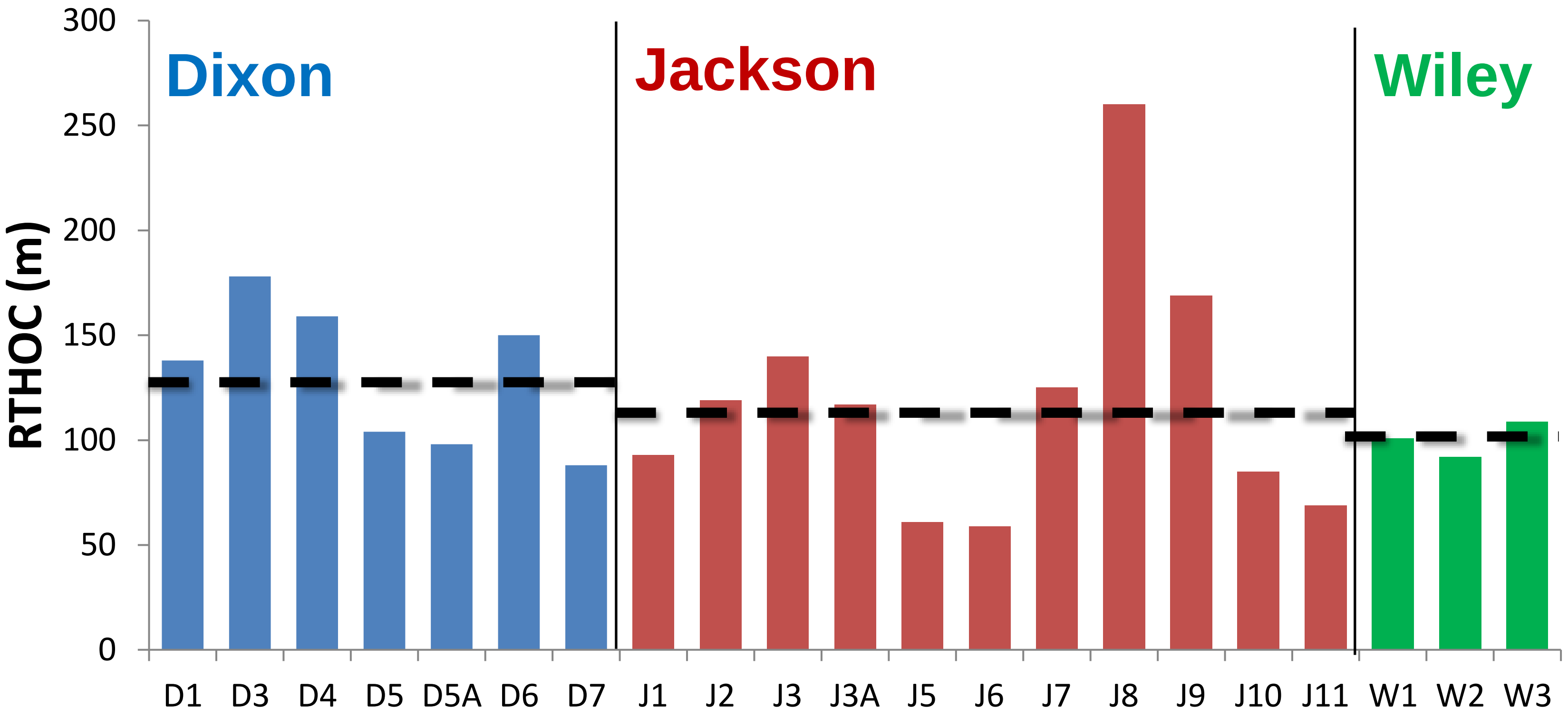


Grain size: Most of the bed material was sand and gravel.

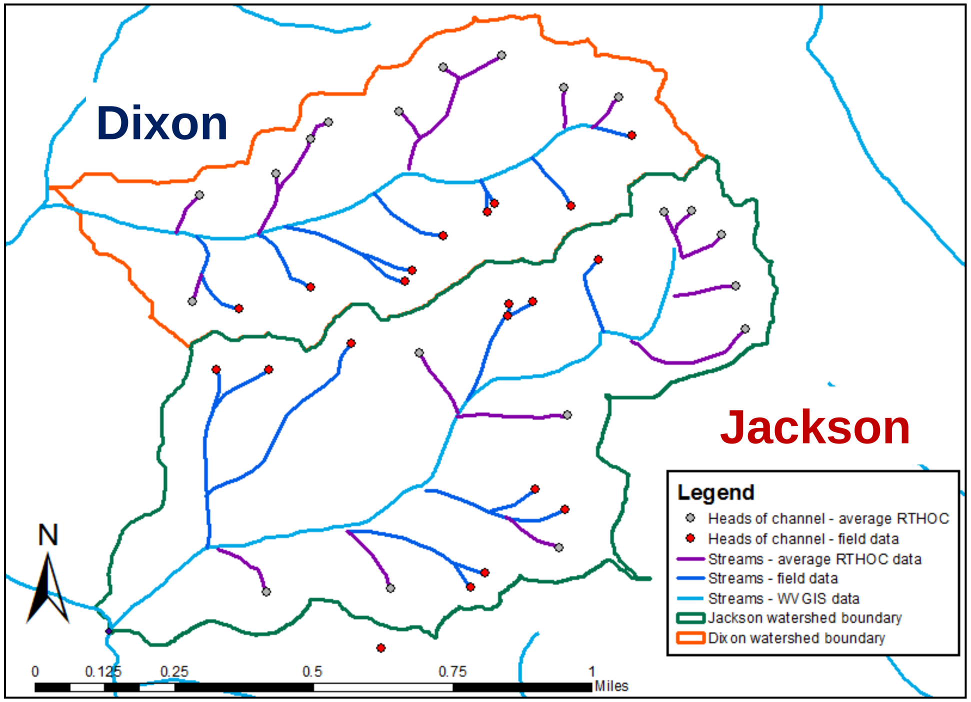
Site	D_{50} (mm)
Dixon	2.8
Jackson	3.7
Wiley	0.8

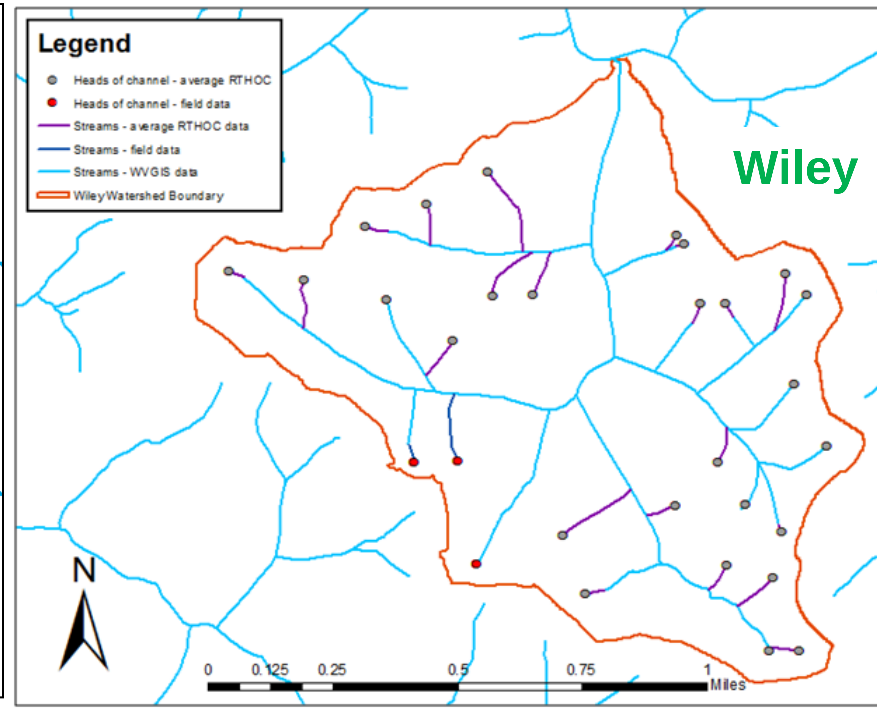


Ridge to head of channel (RTHOC) distance was calculated as the distance from head of channel to associated ridge point.

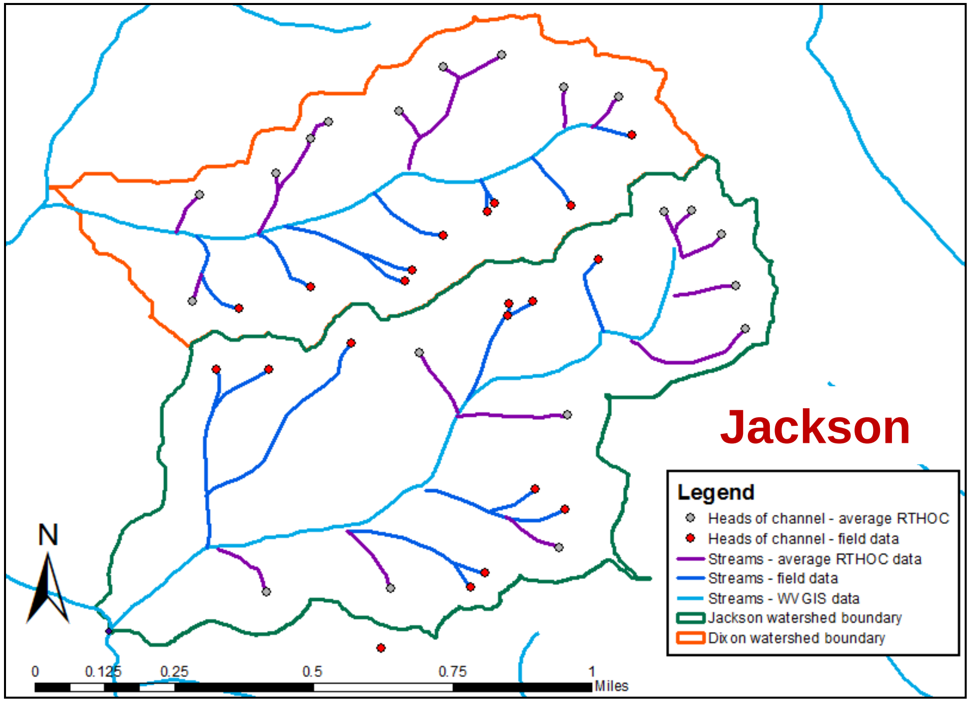


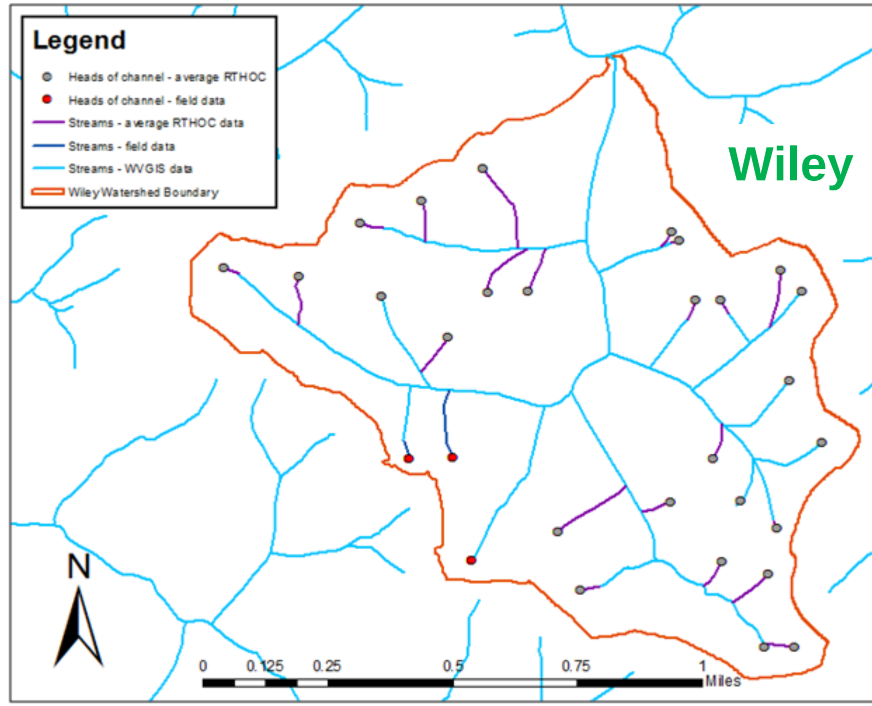
Average RTHOC distance was applied to unmapped valleys.



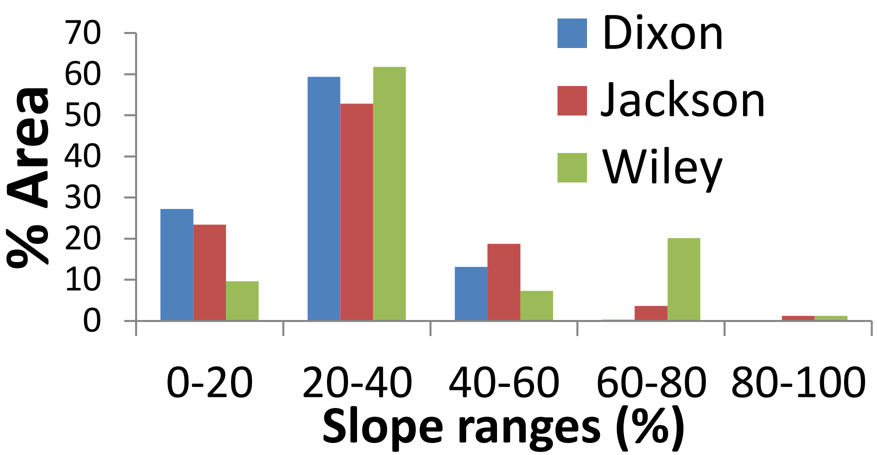


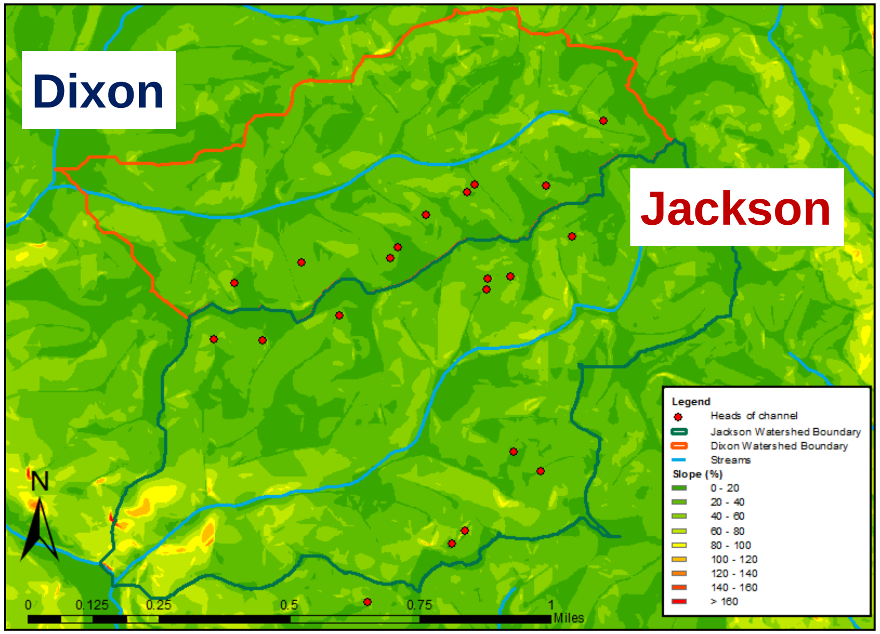
Drainage density was calculated as 61.7 ft/acre (± 23%).

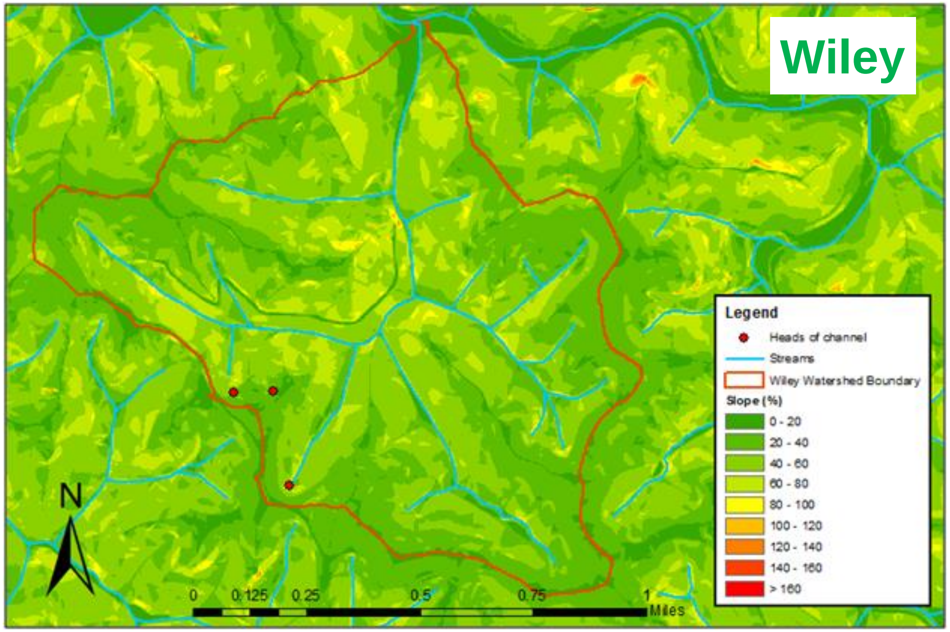




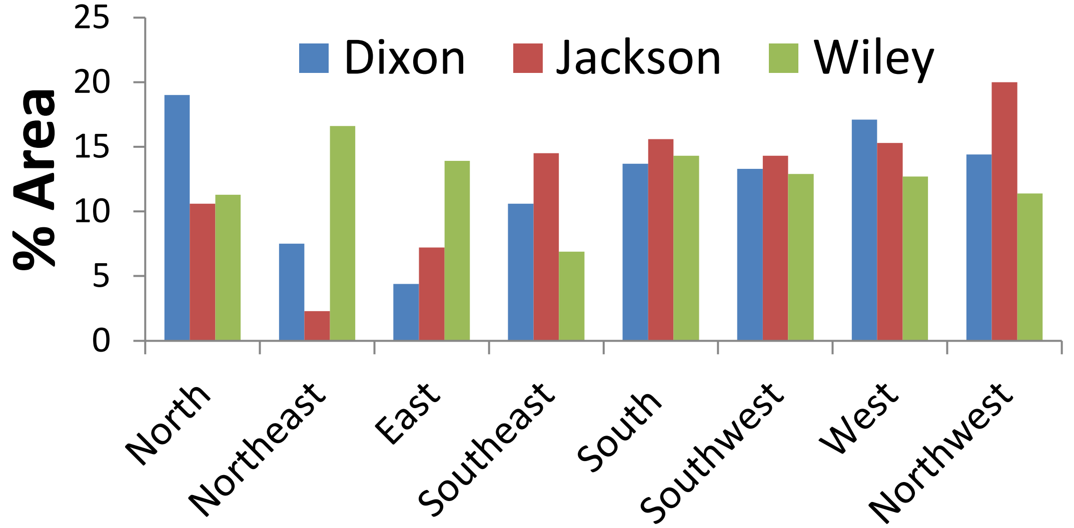
Most of the slopes were in the range of 20-40%.

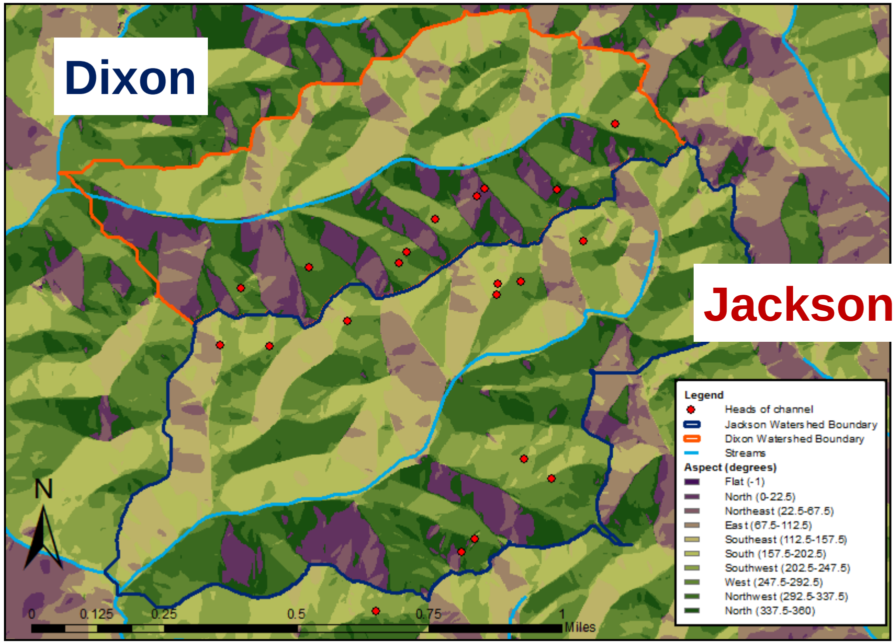


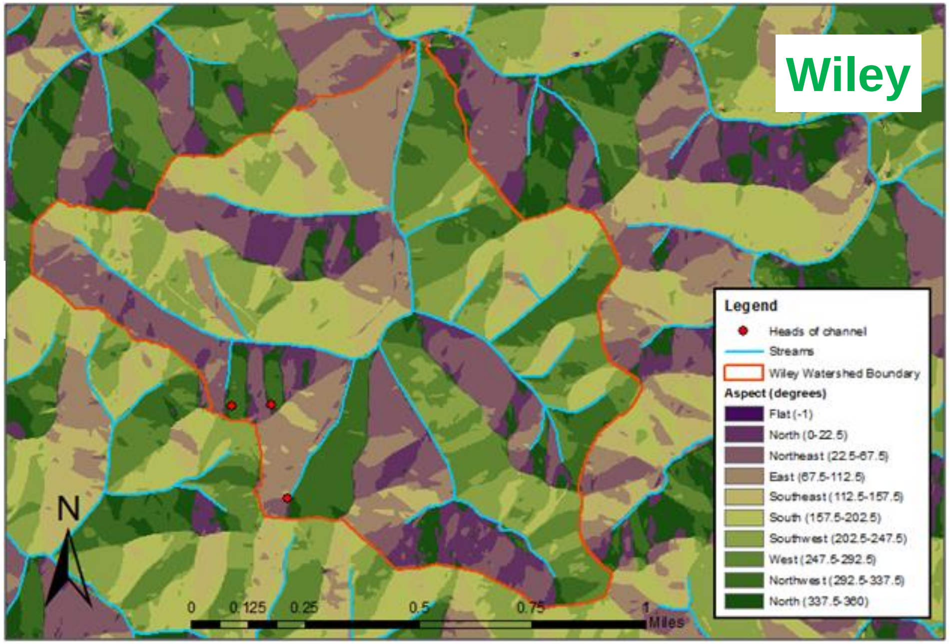




Slopes aspects were well distributed among all directions.







Measured landform characteristic varied from software recommended values.

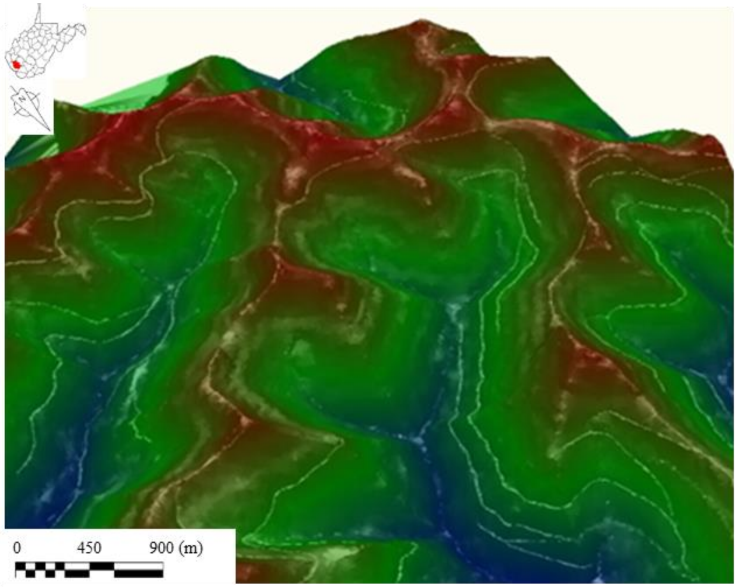
Input	Default	Measured
ROTC (ft)	80	408
Target drainage density (ft/ac)	100	61.7
Target drainage density variance (%)	± 20	± 23
Slope at the mouth of main valley bottom channel (%)	2	3

Contribution

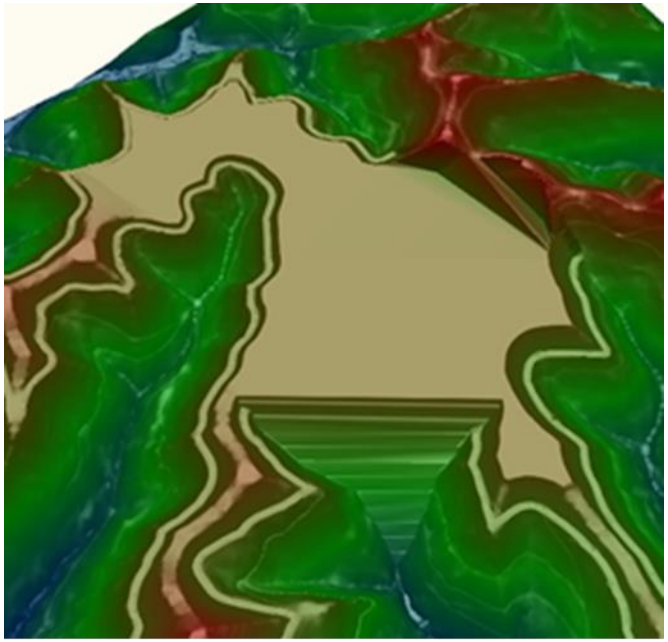
- Confirmed the importance of defining geomorphic properties on a local scale
- Compiled dataset of geomorphic properties (drainage lengths, drainage densities, slopes, aspects, vegetation)
- Methodology can be applied to any geographic area

Can stream mitigation be implemented on surface mine valley-fill sites in Central Appalachia?

Study site

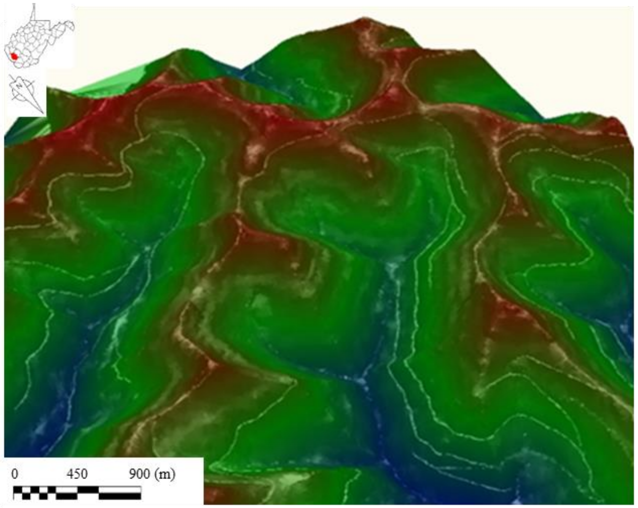


- Undisturbed
  - Logan County, WV
  - Area = 1.4 km^2
  - Compound slope profiles

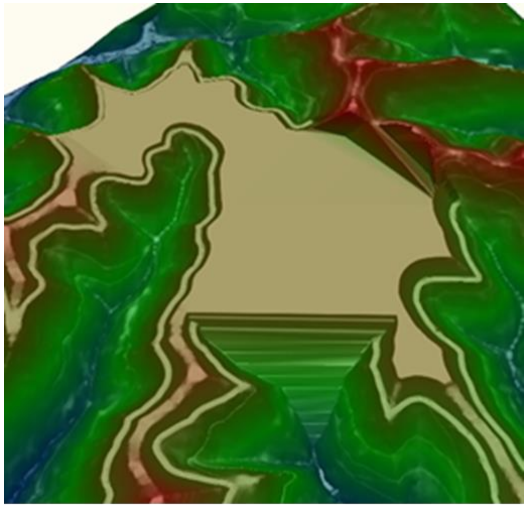


- Valley-fill
  - Permitted AOC variance valley fill
  - Benched fill face
  - 35% area: post-mined land use of forest
  - 65% area: post-mined land use of pasture
  - 1-2% sloping crest
  - SWROA and groin ditches

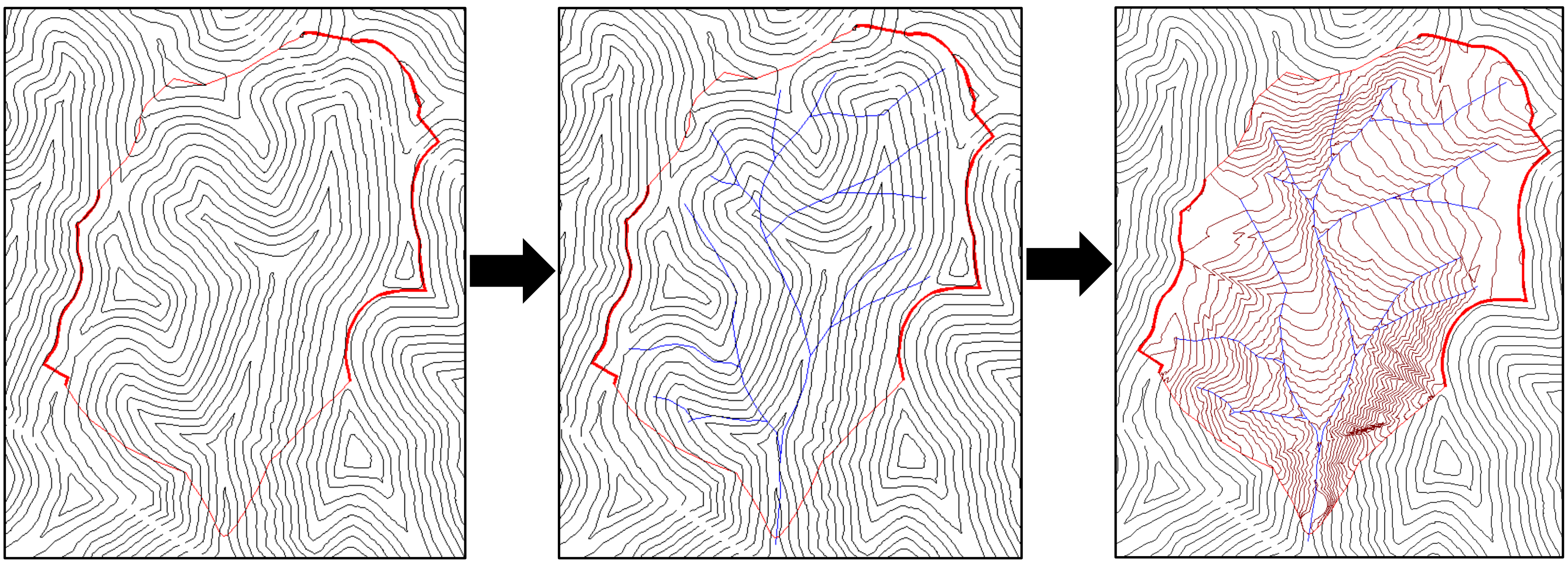
Develop four enhanced valley-fill designs for new and previously constructed valley fills



1. Regional data GLD
2. Bench Pond GLD
3. Valley Pond GLD
4. Retrofit GLD



Regional Data geomorphic landforming methods

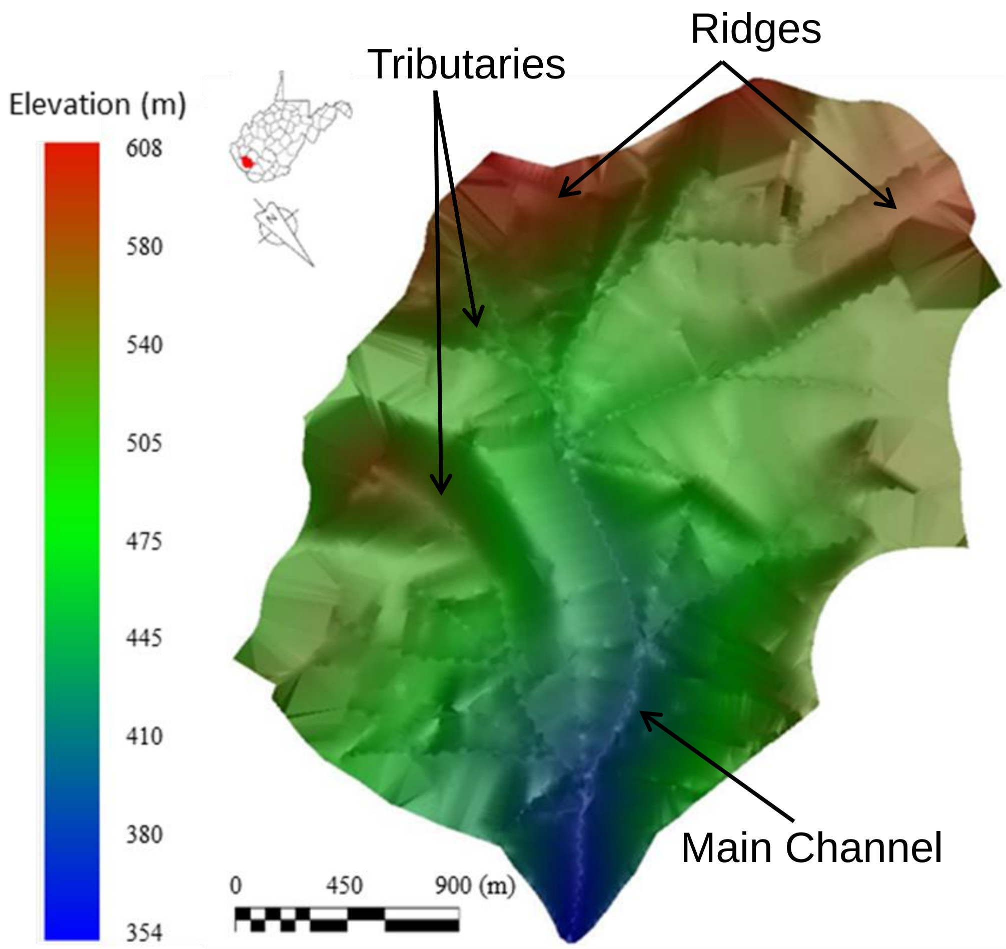


Undisturbed Topography

Created Stream Channels

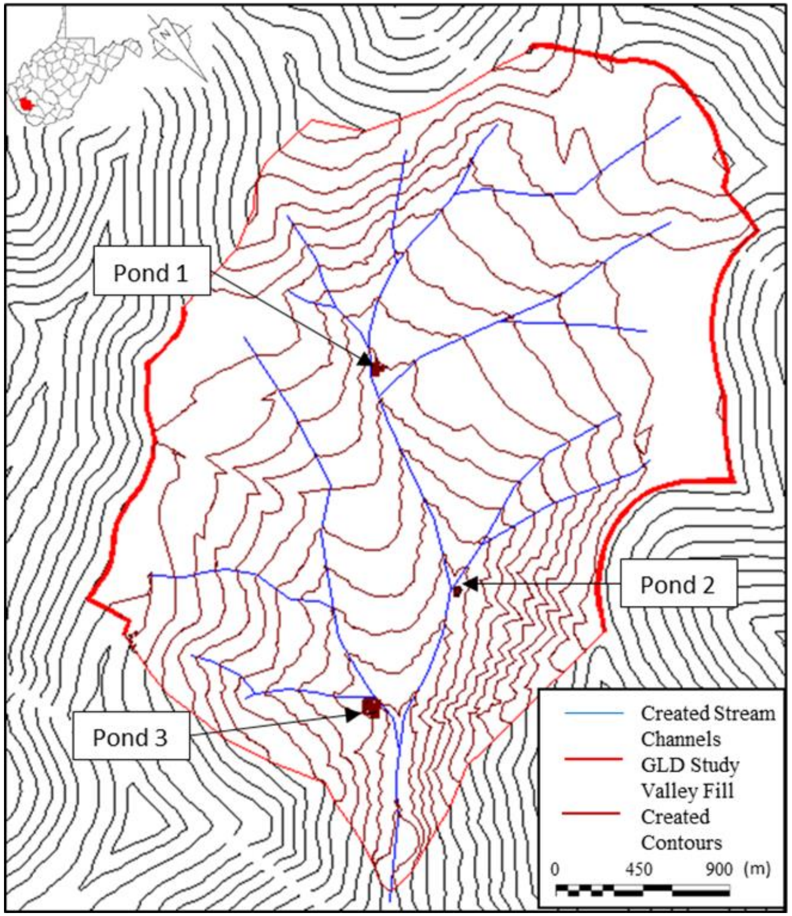
Final Regional Data GLD

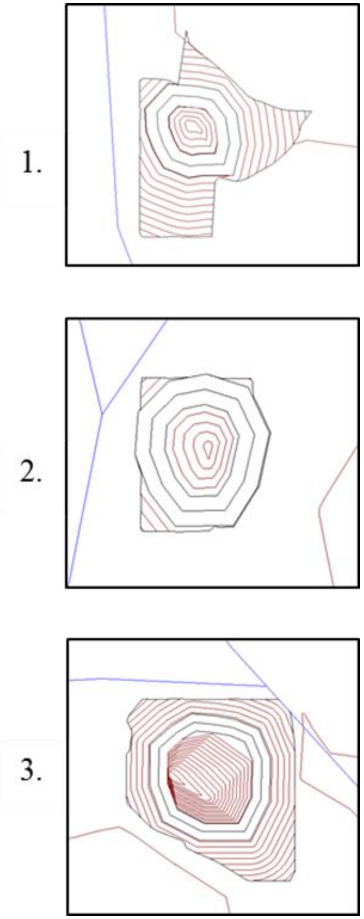
Regional Data GLD



- Imitated undisturbed topography
- Compound slope profiles, ridges, and valleys
- On-site stream mitigation
- Main channel and 12 tributaries
- 5.5 km created stream length

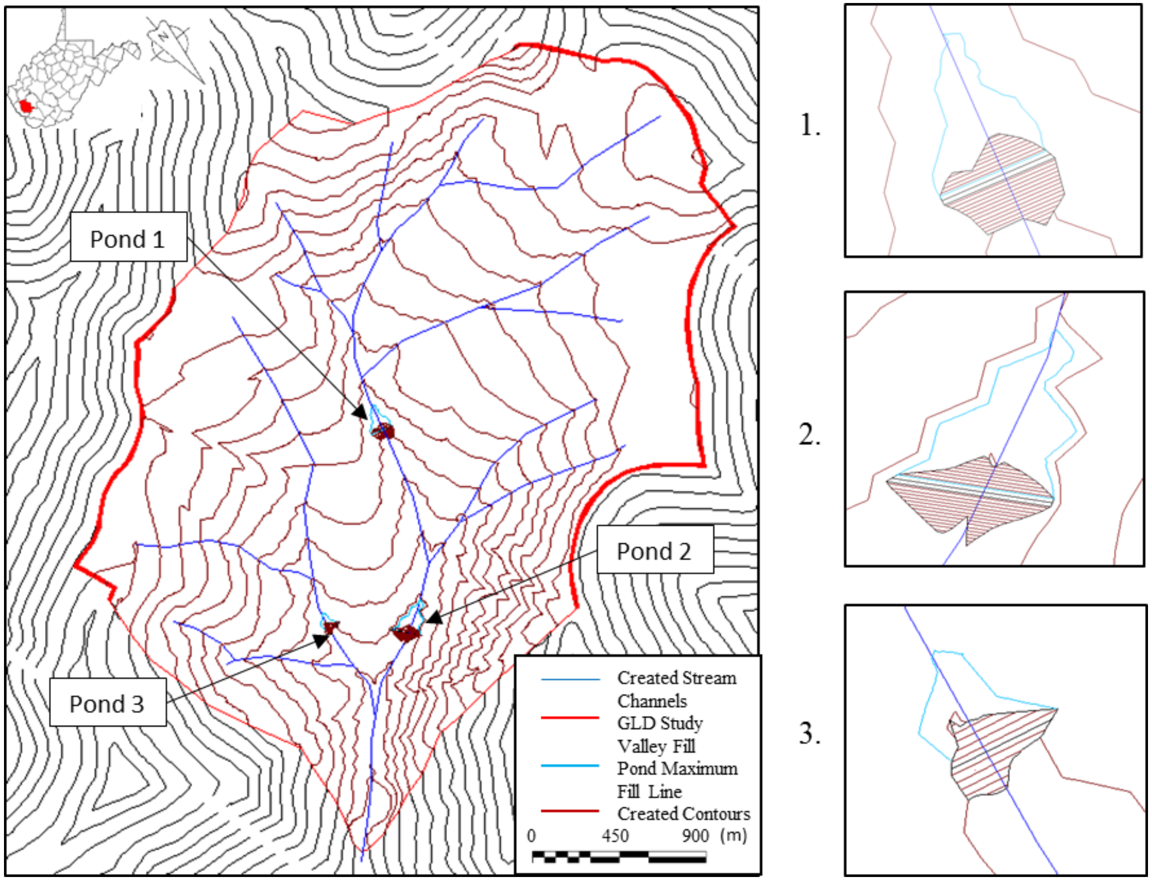
Bench Pond Design





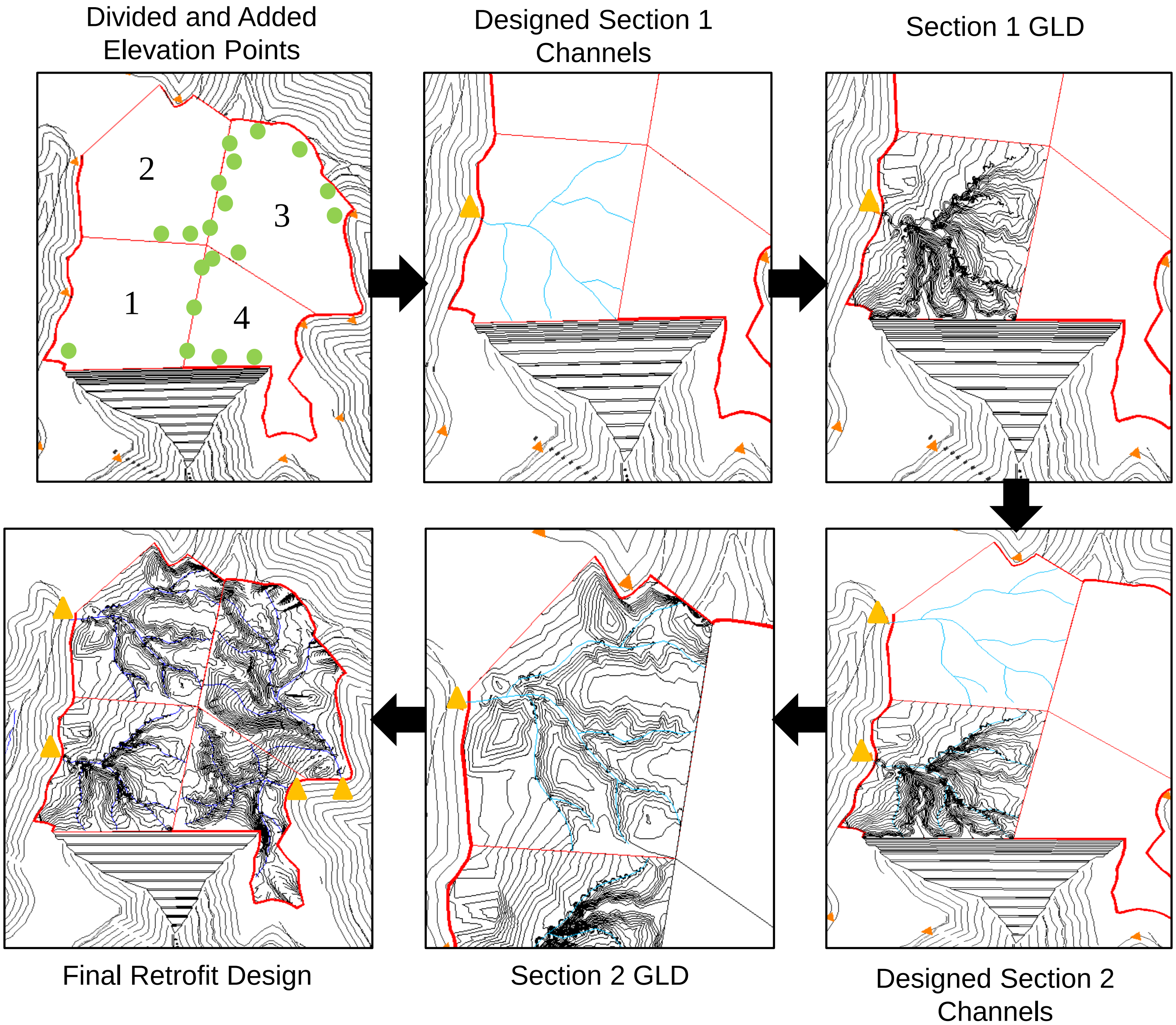
- 3 bench ponds
- Mimic natural wetlands with connection to stream channels
- Potential benefits of regional data GLD with bench ponds:
  - Long-term water source
  - Enhanced vegetative and wildlife habitats

Valley Pond Design

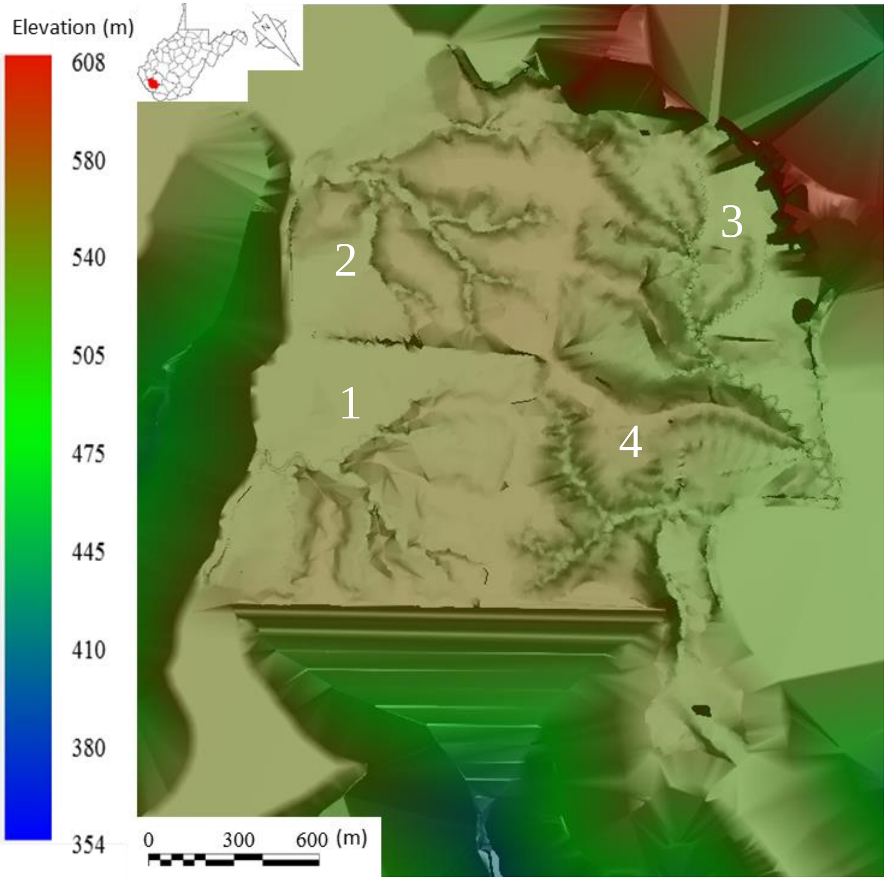


- 3 valley ponds
- Potential benefits of regional data GLD with bench ponds:
  - Extend length of time water is in created channels
  - Long-term water source
  - Enhanced vegetative and wildlife habitats

Retrofit design methods

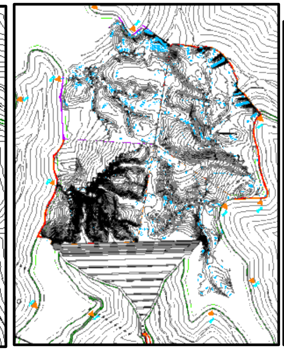


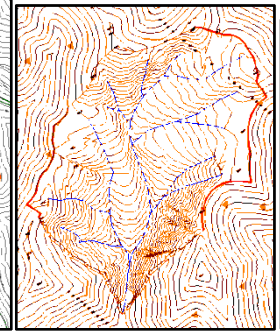
Retrofit Design

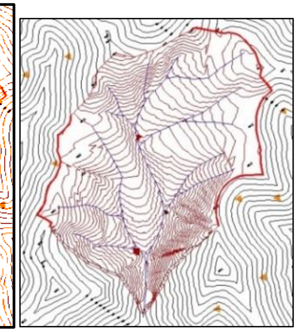


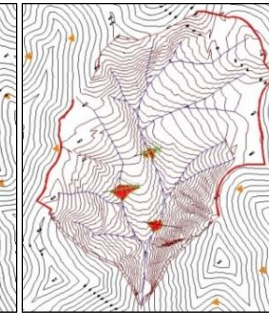
- Stream channels on top of variance fill:
  - On-site stream mitigation
  - 8.4 km stream length added
- Retrofit design enhancements:
  - Topography with compound slopes, ridges, and valleys
  - Pastureland

Design comparison







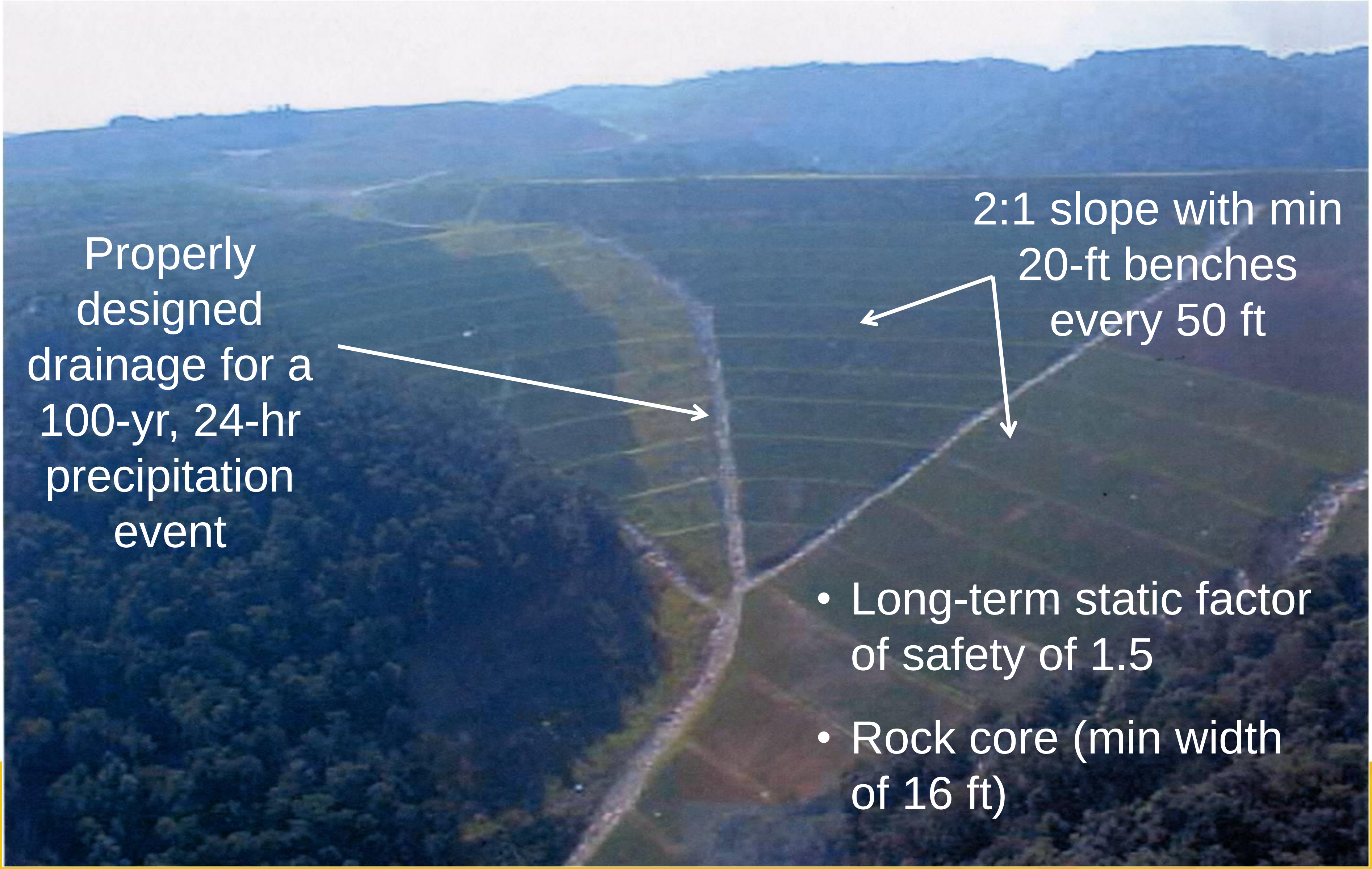


	Traditional	Retrofit GLD	Regional Data GLD	Bench Pond GLD	Valley Pond GLD
Base surface drainage pattern	Dendritic	SWROA	Dendritic	Dendritic	Dendritic
Designed drainage pattern	SWROA	Dendritic	Dendritic	Dendritic	Dendritic
Base surface topography	Steep/Rugged	Steep/Rugged	Steep/Rugged	Steep/Rugged	Steep/Rugged
Designed topography	Benched face/ Level top	Compound slopes	Compound slopes	Compound slopes	Compound slopes
Original stream length, m	3,130	3,109*	3,130	3,130	3,130
Created stream length, m	N/A	8,345	5,466	5,466	5,466

Note: GLD = Geomorphic Landform Design, SWROA = Surface Water Runoff Analysis ditches
*Original stream length was SWROA ditch length

Are geomorphic landform designs geotechnically stable?

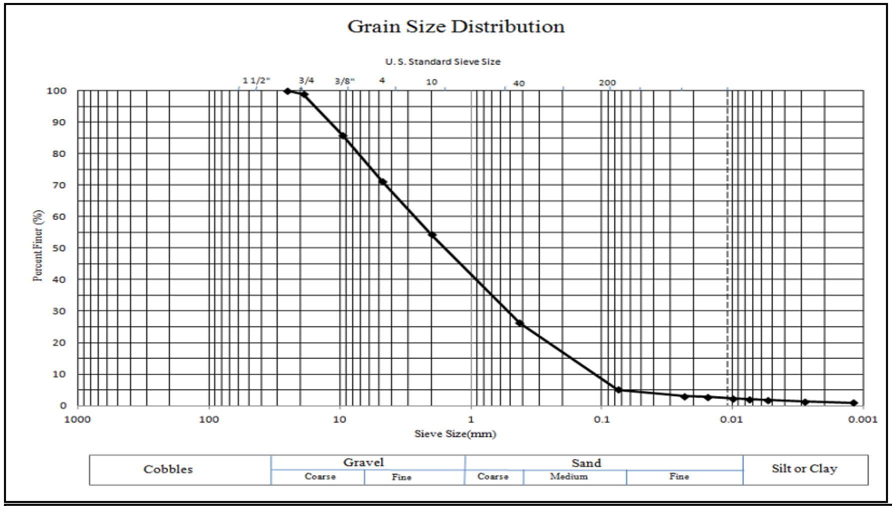
Geotechnical Aspects to GLD Implementation

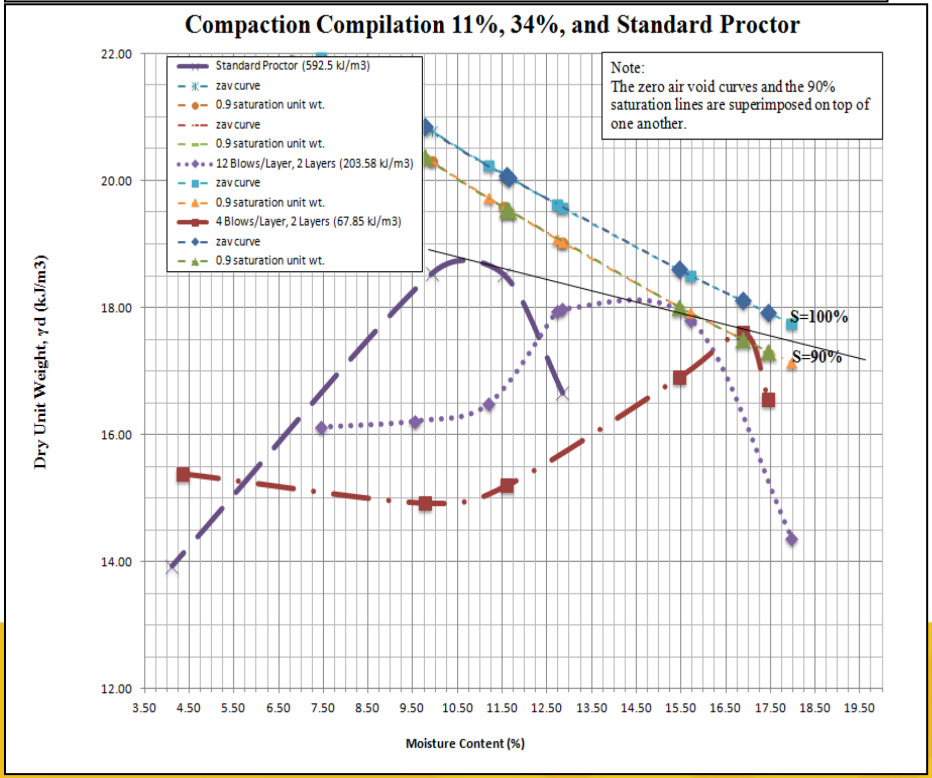


Mine Material Classification and Design

1. Nature of the fill material
   - ASTM Laboratory Testing:
     - Well graded sand w/silt
     - Gs = 2.69
     - Slightly Plastic

2. Construction characteristics
   - Little compaction needed to acquire dense material
   - Moisture conditions should be considered during construction





Strength & Permeability Testing

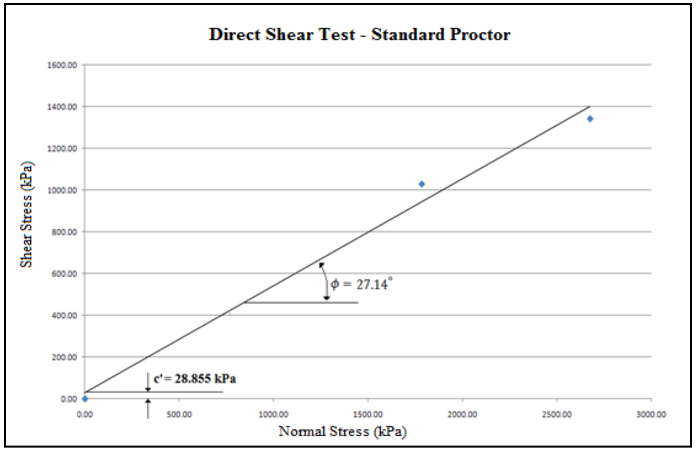
- Target strain at 20% (0.5 in.)
- Friction angle range:
  - 27.7° zero cohesion
  - 22.77° w/ cohesion

- Considerable residual strength is retained at failure

- The hydraulic conductivity (*k*) remained within the same order of magnitude for each specimen at varying compaction:

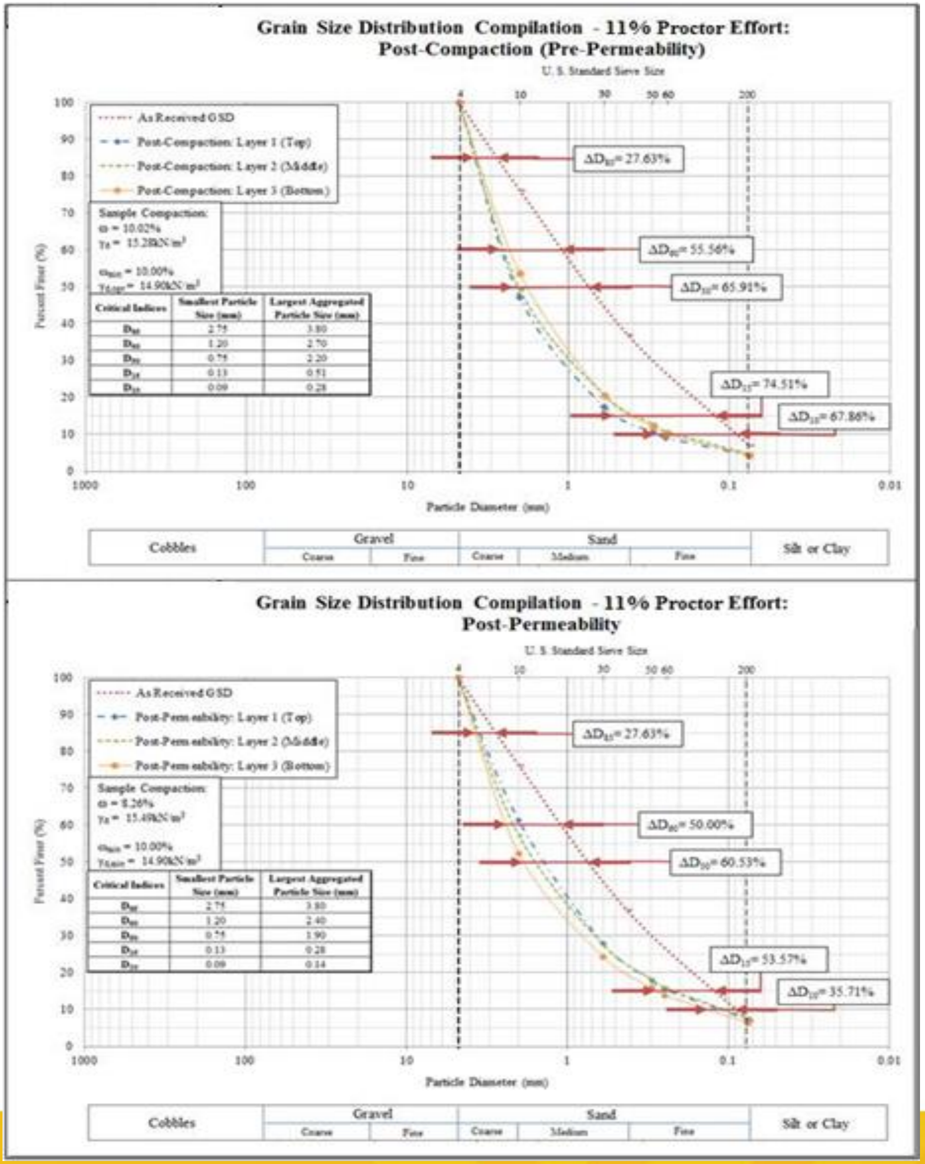
  $k = 5 \times 10^{-7}$ m/s

- Finding: **Material can have good strength and is permeable**



Grading Envelopes and Fine Particle Behavior

- Gradation curves created to investigate particle behavior
- The pre-permeability and post-permeability compared
- Results were material tended to aggregate regardless of compaction, after water permeation
- Outcome is particle aggregation effects durability, permeability conditions



Numerical Slope Stability Modeling

Slope Stability Modeling to evaluate profiles of GLD watershed contours with Geotechnical Slope Stability Requirements

<u>Evaluated</u>

- Three slope profiles were analyzed for a factor of safety

Limit Equilibrium Analysis

$$S_r = s\beta = (c' + (\sigma_n - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b)\beta$$

$$S_m = \tau_m \beta$$

$$S.F. = \frac{\sum S_r}{\sum S_m}$$

- Valley fill design (Planar Profile) vs. Geomorphic Landform Design modeled for three hydrologic conditions:
    1. Initially unsaturated underdrain
    2. Initially saturated underdrain
    3. Initially fully saturated fill body

- An exceedingly steep slope profile was also modeled under two user defined piezometric hydrologic conditions

Site Hydrology

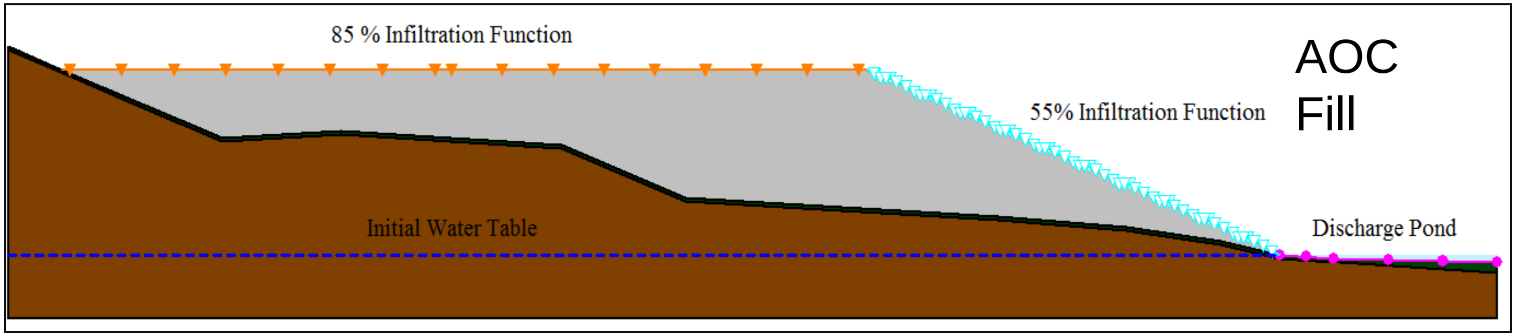
- **Hydraulic Conductivity**
  - $k_{unsat} = 1 \times 10^{-5}$ m/s and $k_{sat} = 1 \times 10^{-7}$ m/s

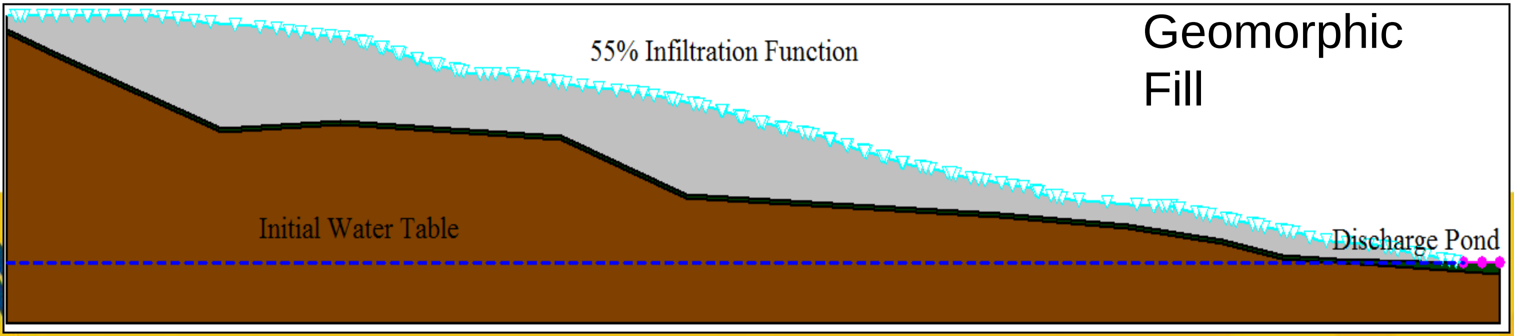
- **Geostudio2007:** SEEP/W: groundwater seepage analysis
  - Saturated and Unsaturated Pore Water analysis
  - Finite element model
  - Discretize geometry
  - Assign material properties
  - Apply boundary conditions

- **Precipitation**
  - National Oceanic and Atmospheric Administration (NOAA)
  - Logan, WV station (closest to surface site)
  - Steady state analysis for 10 individual 1 year time steps
  - Total model time frame: 10 years

Materials

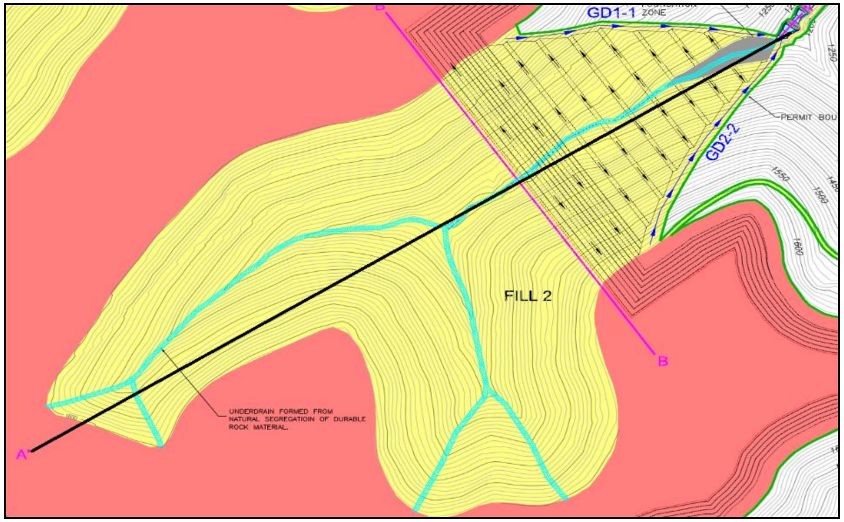
- Three materials were defined similarly for the valley fill and geomorphic design:
  - Overburden Fill
  - Foundation Rock
  - Blocky Core Drain (durable rock underdrain)
  - SEEP/W Boundary Condition Locations



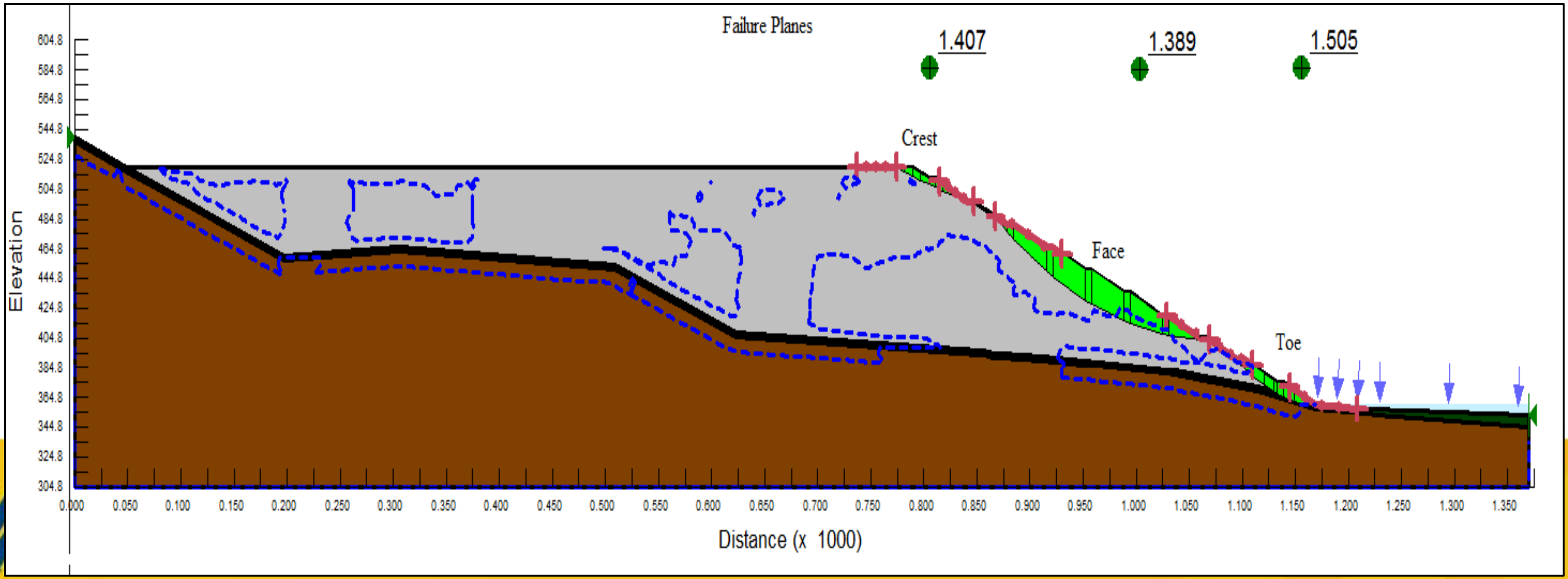


Valley Fill Geometry

Plan View Contours (WVDEP Permit file #S500809)

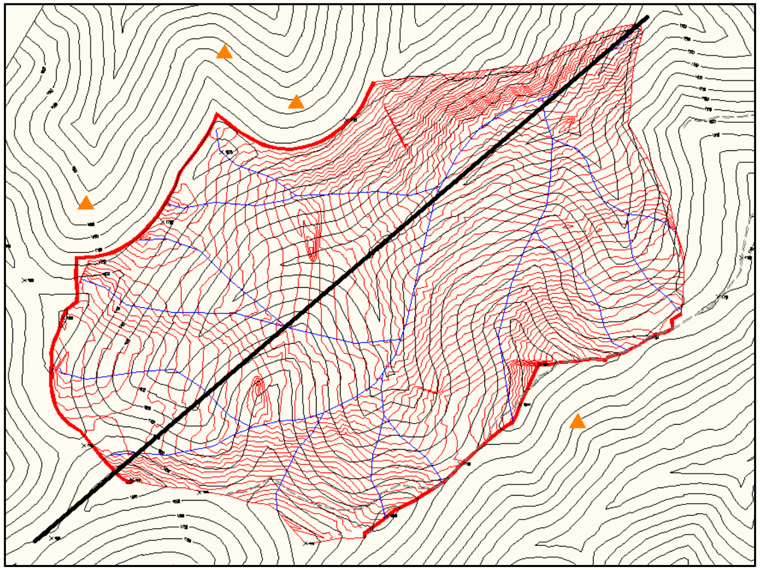


Profile bench and original ground coordinates (WVDEP Permit file #S500809)

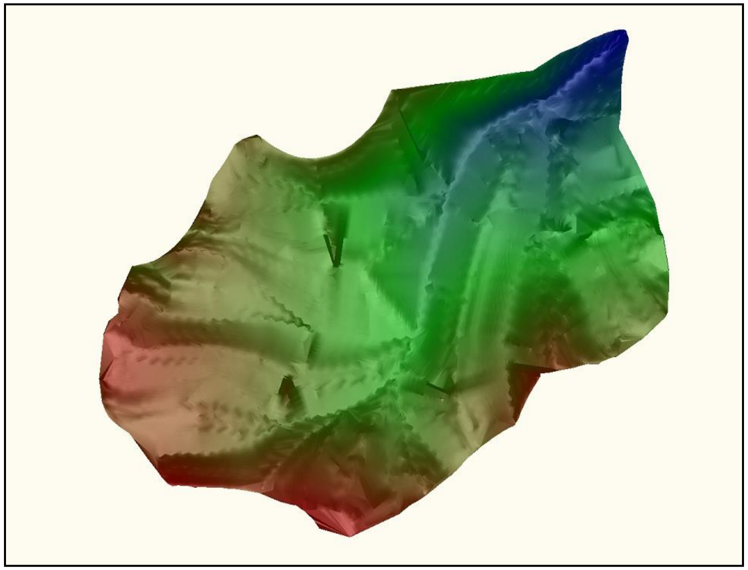


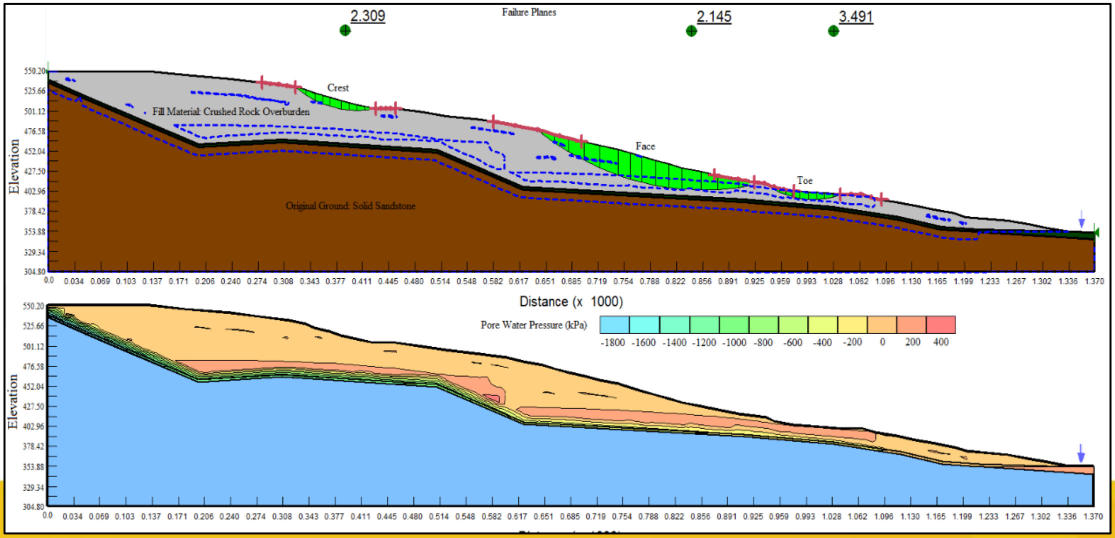
Geomorphic Design Geometry

Plan View Contours (Carlson Natural Regrade)



Plan View Hillshade (Carlson Natural Regrade)





Slope Stability Analysis Findings: Saturated & Unsaturated Conditions

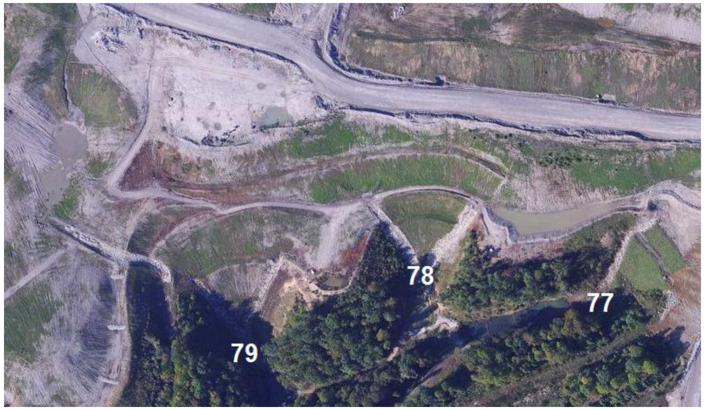
WVDEP requires FS> 1.5

- The AOC valley fill design FS ranged from the highest at 1.80 to the lowest at 1.31
- The geomorphic FS ranged from the highest at 2.41 to the lowest at 2.25

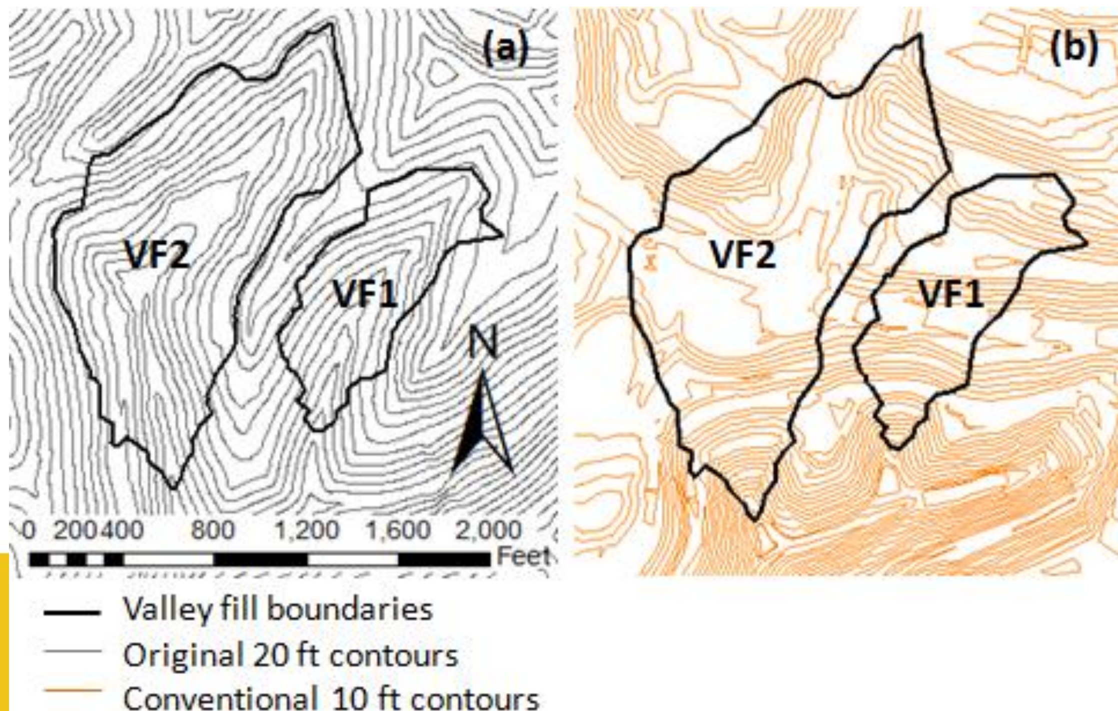
- AOC vs. Geomorphic Slope Stability
  - All geomorphic factors of safety were greater than 2.0 (longer slope lengths)
  - AOC valley fill factors of safety did not all meet the regulation requirement of 1.5 (shorter slope lengths)
  - The AOC design must remain sufficiently drained to meet regulations

Can a stable geomorphic landform be designed as an alternative to a conventional valley fill?

Study site


78
77
79


MINES
078
077
079
072


(a)
(b)
VF2
VF1
N
0 200 400 800 1,200 1,600 2,000
Feet
Valley fill boundaries
Original 20 ft contours
Conventional 10 ft contours

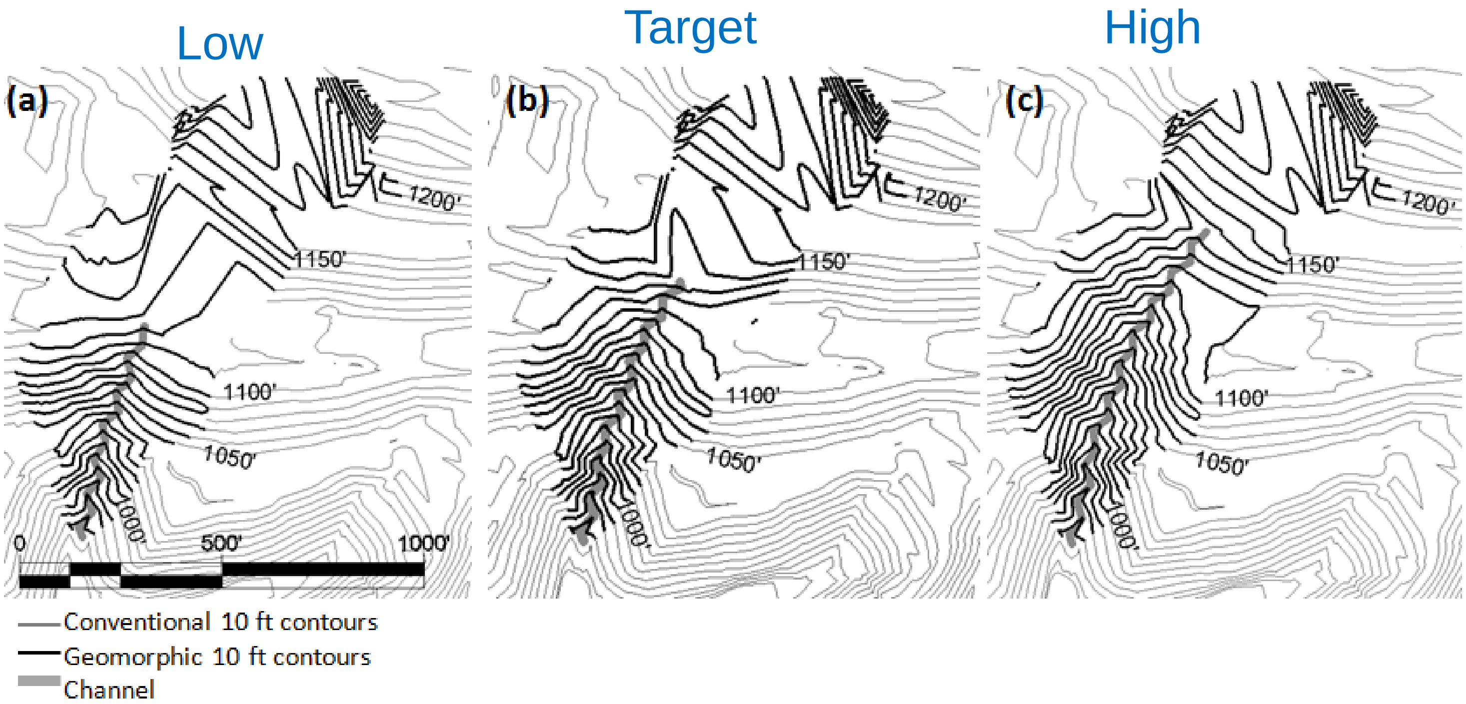
Landforms were analyzed based on stability and material placement

- Channel stability
  - Set shear stress limit for channel bed (4.33 psf; bed particle size: cobble)
- Landform stability
  - Investigated slopes greater than 50% grade (2:1)
- Fill volume
  - Compared geomorphic fill volumes to volume of conventional reclamation

Designs investigated individual and compromised levels of analysis criteria

- Varying drainage density
- Maximizing channel stability
- Maximizing fill volume and hillslope stability
- Compromising stability and fill volume
- Expanding impacted area
- Using default design criteria
- Stability analysis

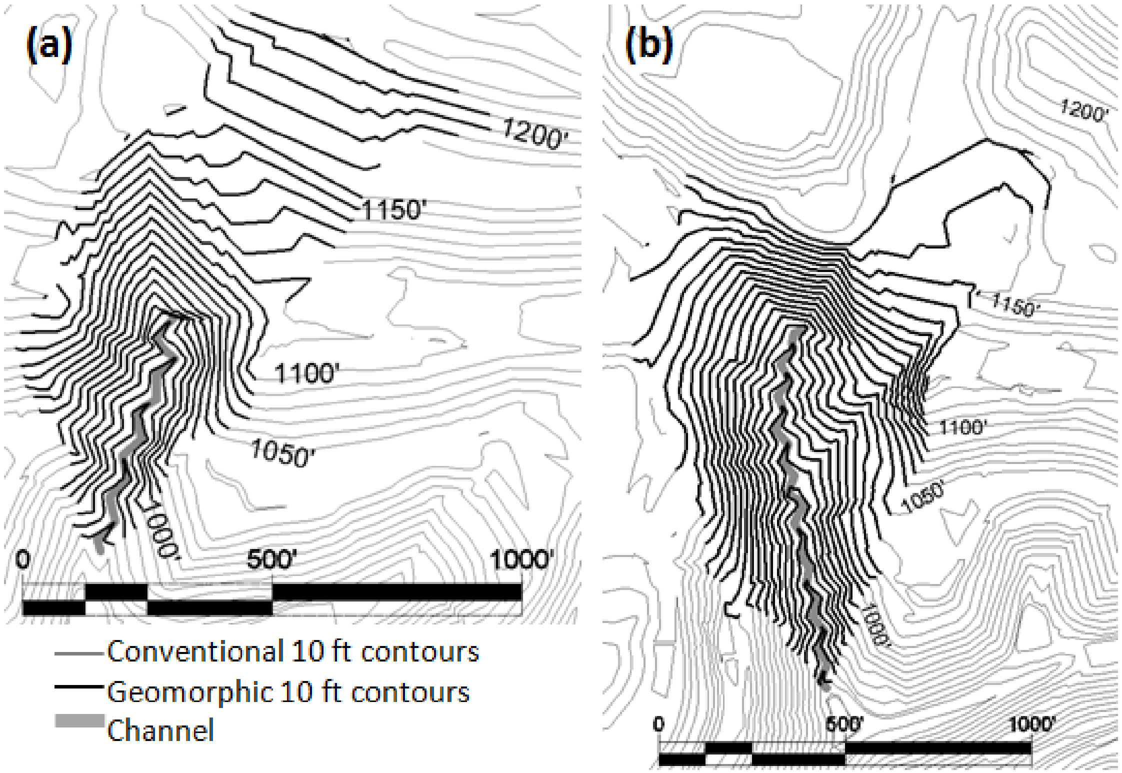
Fill volume decreased with increasing drainage density



Valley fill	DD (ft/ac)	V_{GLD}/V_{CV} (%)
1	48.2	83
1	60.8	73
1	74.8	66
2	48.3	77
2	60.7	63
2	72.4	49

Existing channel could not be preserved due to unstable hillslopes

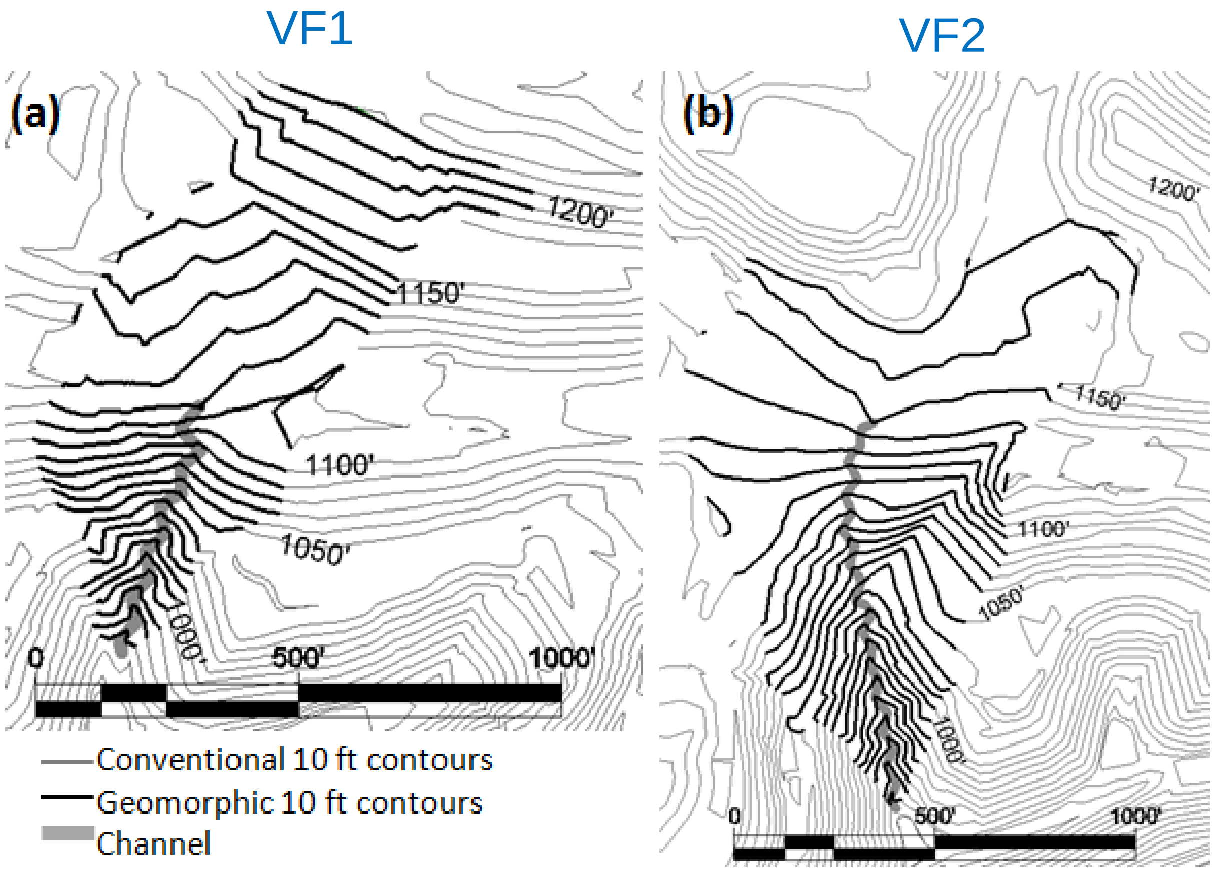
VF1



VF2

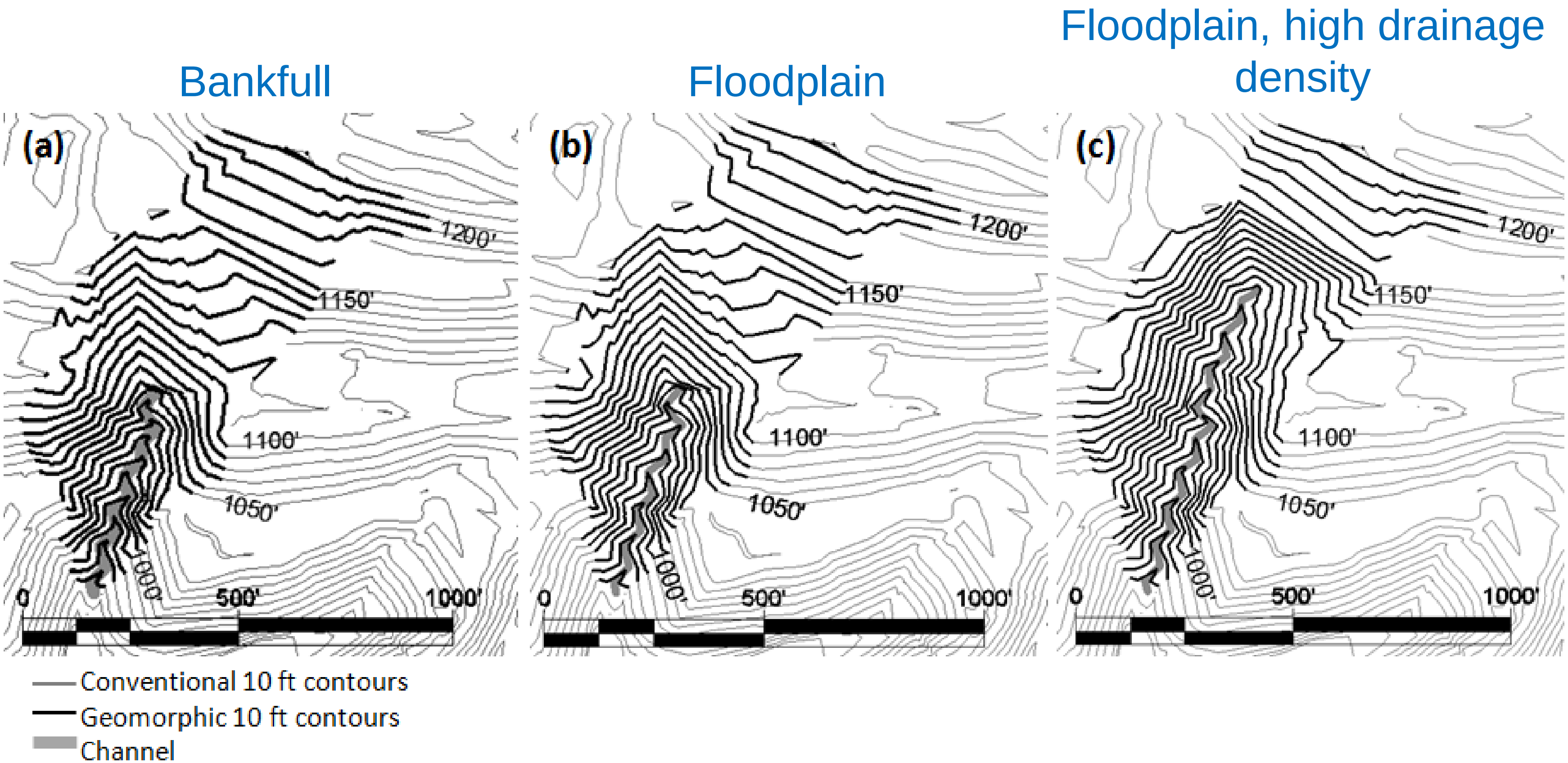
Valley fill	S_C (%)	t_b (psf)	t_f (psf)	P_{HS} (%)	V_{GLD}/V_{CV} (%)
1	6.7-12	2.84	3.67	33	65
2	6.7-12	4.09	5.28	26	53

Maximizing fill volume resulted in unstable channels



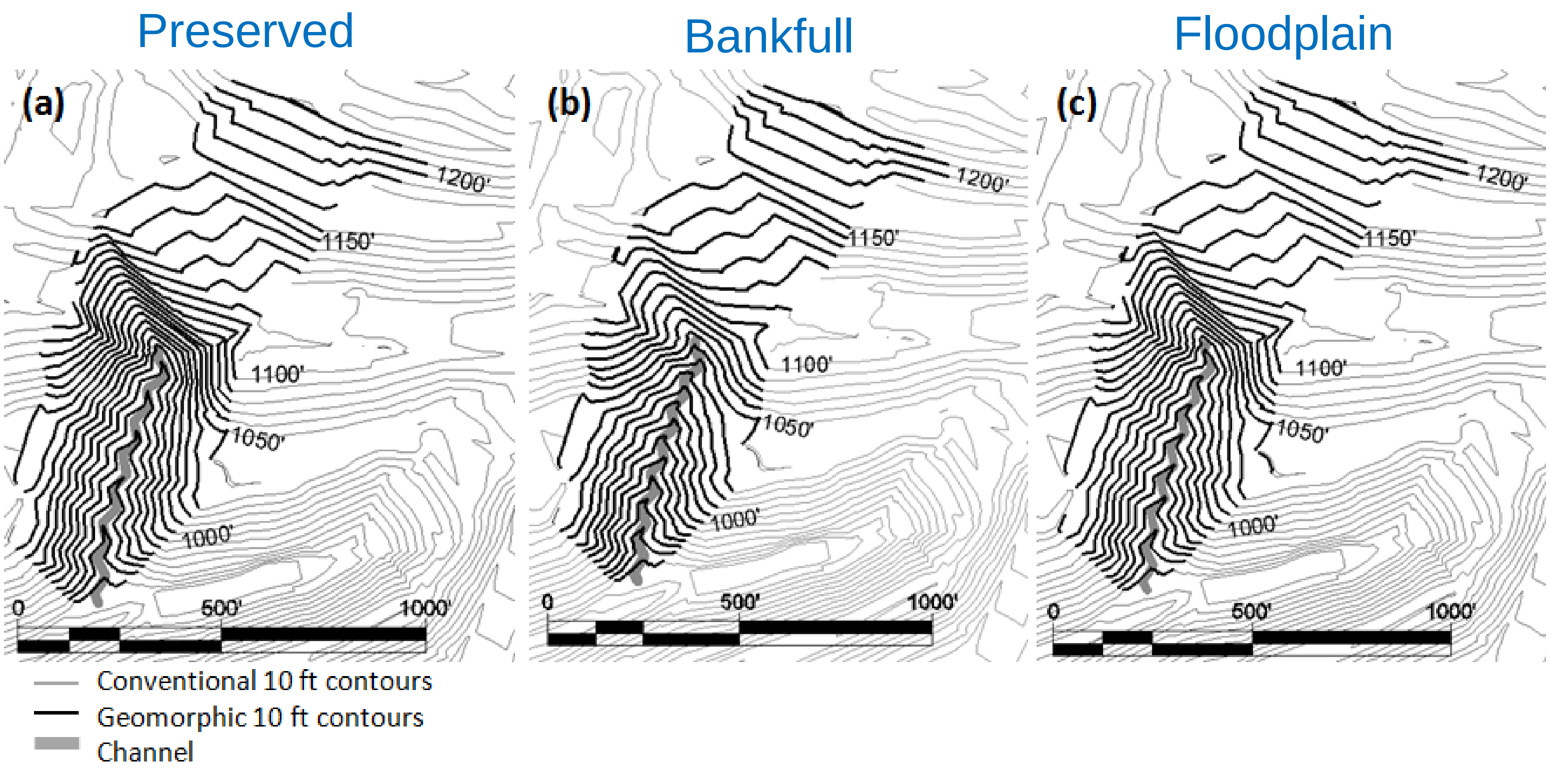
Valley fill	S_C (%)	τ_b (psf)	τ_f (psf)	P_{HS} (%)	V_{GLD}/V_{CV} (%)
1	9.7-35	8.24	10.64	6.1	99
2	8.5-24	8.09	10.45	4.4	85

Design criteria could not be met when area of impact was maintained



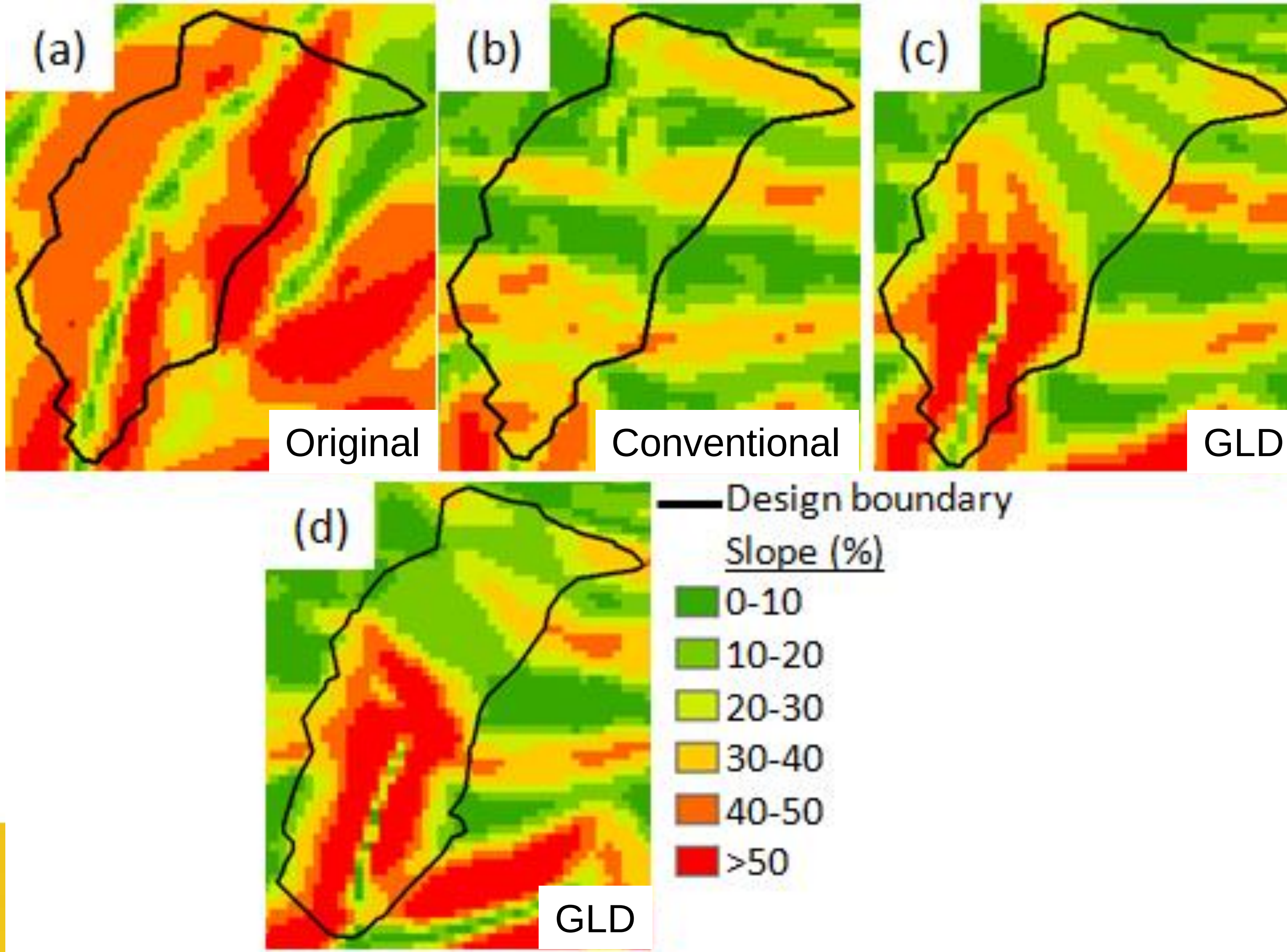
Channel	S_C (%)	τ_b (psf)	τ_f (psf)	P_{HS} (%)	V_{GLD}/V_{CV} (%)
Stable at BF	8.6-18	4.30	5.56	14	78
Stable at FP	8.0-14	3.33	4.30	21	72
Stable at FP with high DD	8.2-13	3.33	4.30	39	54

Expanding area of impact increased likelihood of meeting design criteria

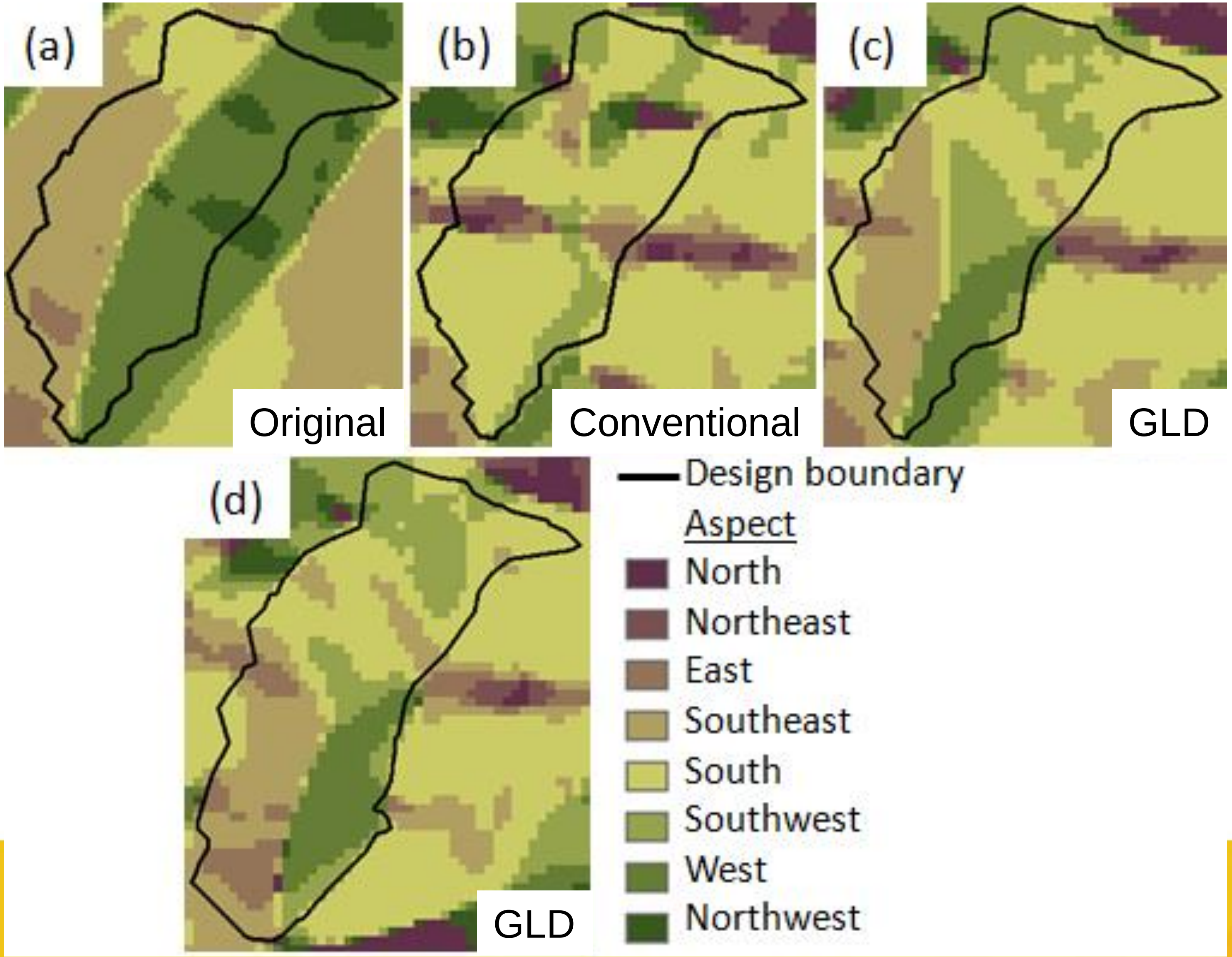


Channel	S_C (%)	τ_b (psf)	τ_f (psf)	P_{HS} (%)	V_{GLD}/V_{CV} (%)
Preserved	6.7-12	3.25	4.19	27	79
Stable at BF	8.2-24	4.33	5.60	9	114
Stable at FP	8.2-12	3.35	4.32	17	102

Slope distribution was more closely mimicked by geomorphic designs



Variability in aspect supports variation in vegetation and habitat diversity



Conclusions

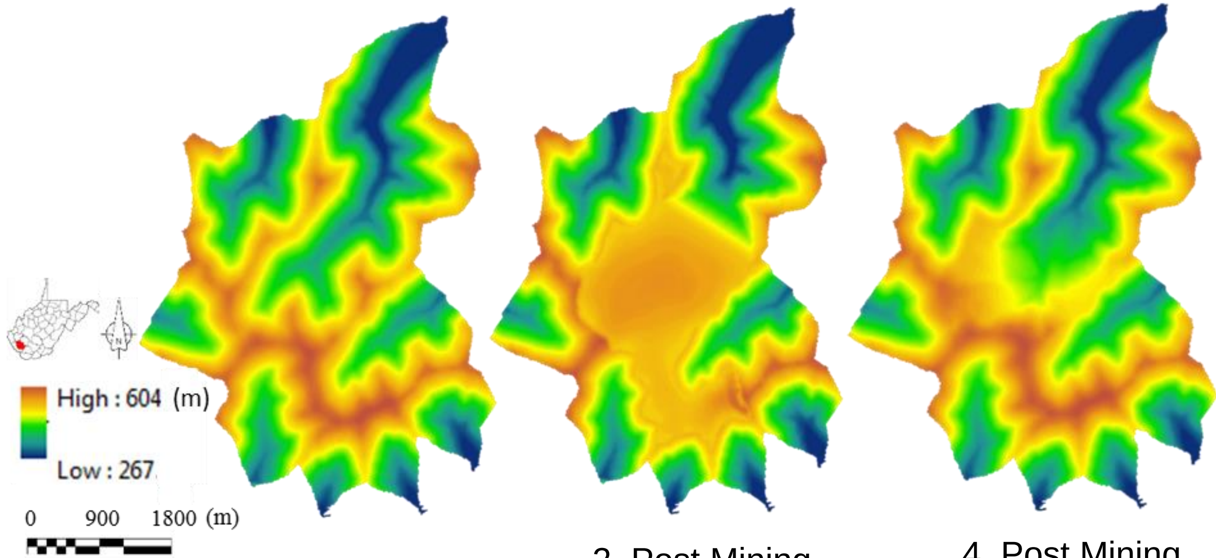
- The existing stream of the pre-mined topography could not be preserved through geomorphic reclamation due to unstable constructed slopes around the channel.
- A geomorphic reclamation could mitigate the burial of the existing channel by creating a stable channel at a higher elevation.
- When the area of impact of the conventional reclamation was maintained, a geomorphic design could not meet the requirements of channel stability, landform stability, and fill volume simultaneously.
- Expanding the area of impact of the fill allowed a geomorphic design to better satisfy all three criteria for a successful design but did not comply with regulations.

Is soil loss altered at the watershed scale by different valley-fill reclamation methods?

Study site and model conditions

- Study site:
  - Permitted valley fill in Logan County, WV
  - Surrounding area
  - Area of 3.5 km^2
- Undisturbed site and two reclaimed sites

Undisturbed **Conventional** **Regional Data GLD**



Design Conditions:

1. Pre-Mining

2. Post Mining Pre-Vegetation

3. Post Reclamation Long Term

4. Post Mining Pre-Vegetation

5. Post Reclamation Long Term

Five design conditions were modeled with Revised Universal Soil Loss Equation (RUSLE) in GIS

A=R*K*LS*C*P

A = average soil loss per unit area

R = rainfall-runoff erosivity factor

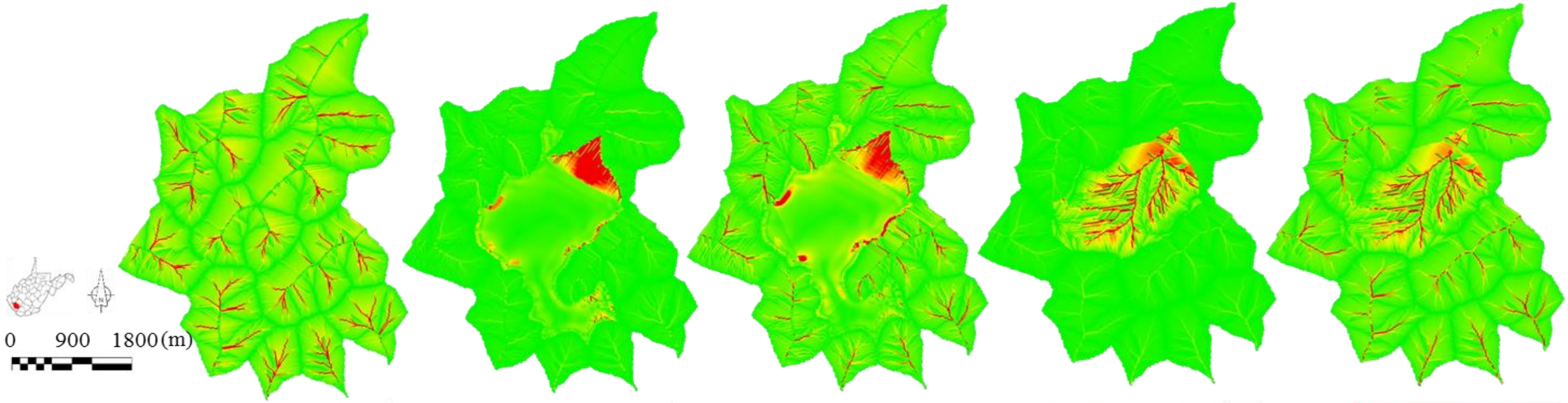
K = soil erodibility factor

LS = slope length/steepness factor

C = cover-management factor

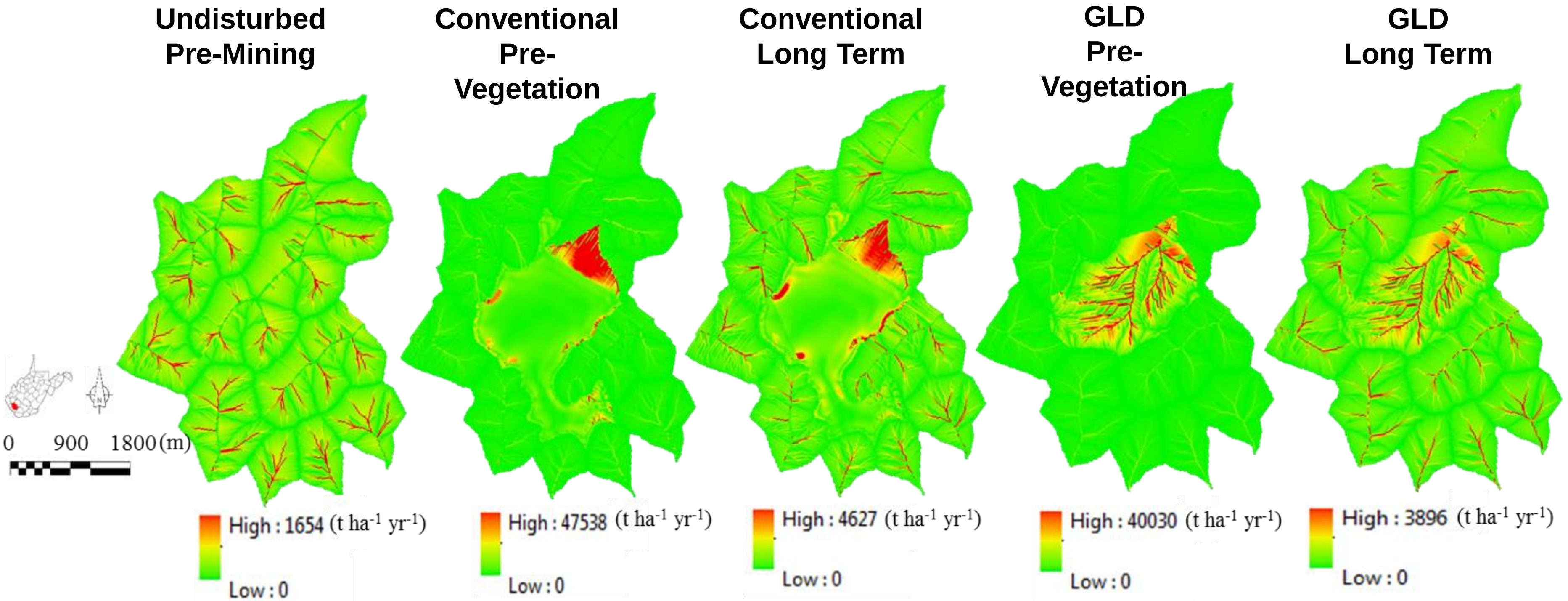
P = supporting practices factor

- Each factor of RUSLE equation became a layer in GIS for each modeled condition
  - R-factor calculated using rainfall data
  - K-factor calculated using soil properties
  - LS-factor calculated in GIS using slopes
  - C-factor calculated using land cover
  - P-factor calculated according to supporting practices implemented



	Undisturbed Pre-Mining	Conventional Pre-Vegetation	Conventional Long Term	GLD Pre-Vegetation	GLD Long Term
Ranges: (t ha^{-1} yr^{-1})	High : 1654 Low : 0	High : 47538 Low : 0	High : 4627 Low : 0	High : 40030 Low : 0	High : 3896 Low : 0
Spatial Means: (t ha^{-1} yr^{-1})	35.4	123.2	35.6	204.3	35.6

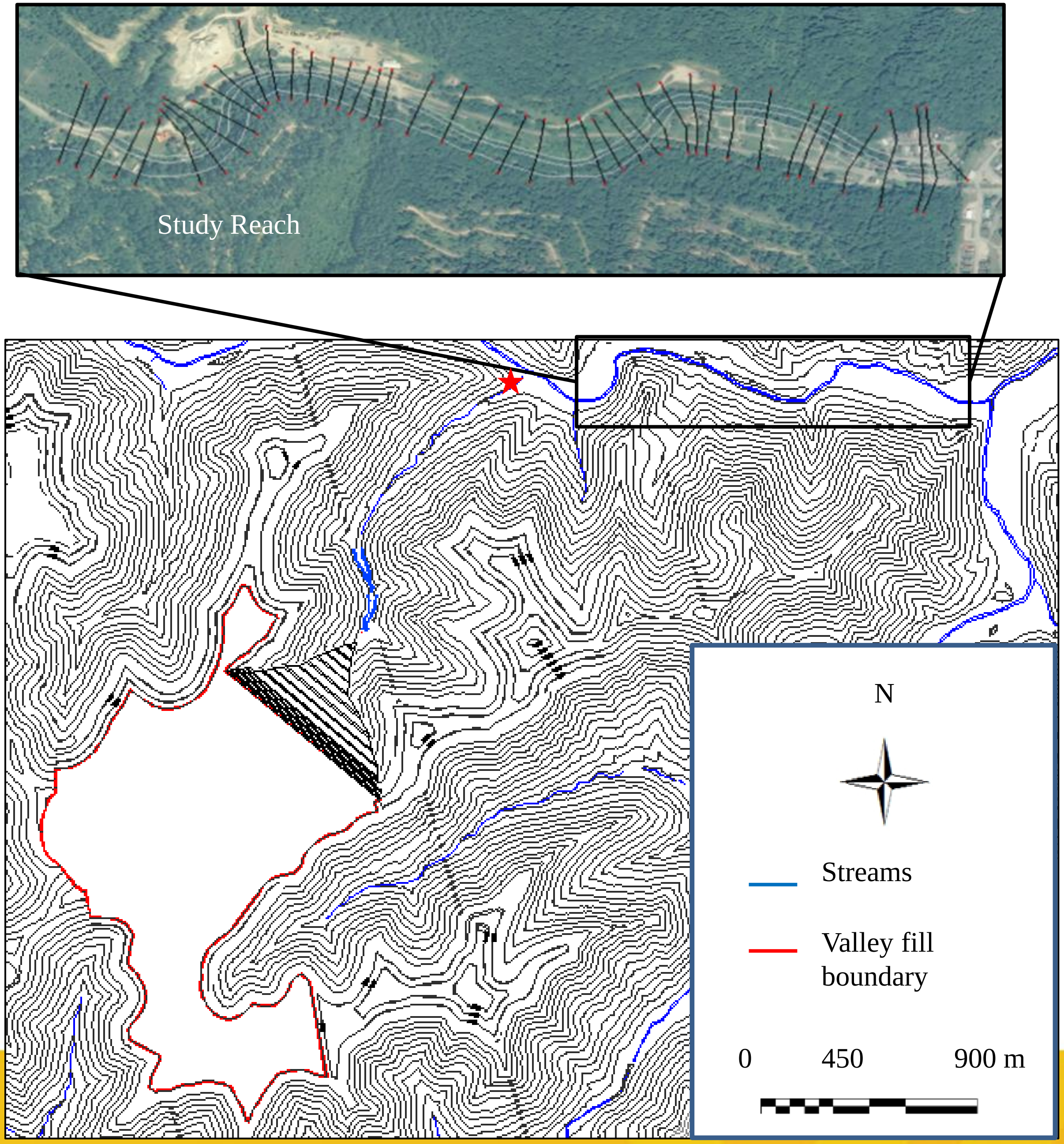
- Average annual erosion rate spatial means:
  - No substantial difference among undisturbed and long term (conventional and GLD) conditions
  - Pre-vegetation conditions substantially higher



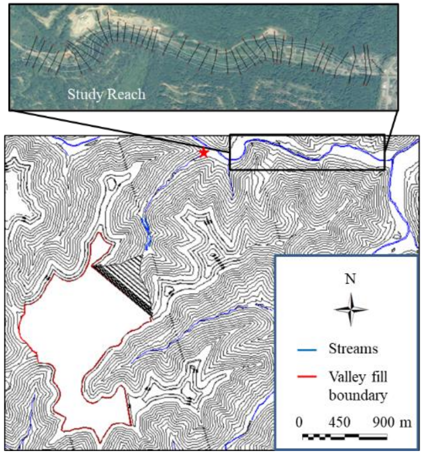
- Low erosion rates spatial distribution:
  - Along ridgelines
  - Valley-fill crest
  - Mimicked locations of lowest LS-factor values
- High erosion rates spatial distribution:
  - Along stream channels
  - Steep areas (slope >50%)
  - Valley-fill face
  - SWROA ditches
  - Mimicked locations of highest LS-factor values

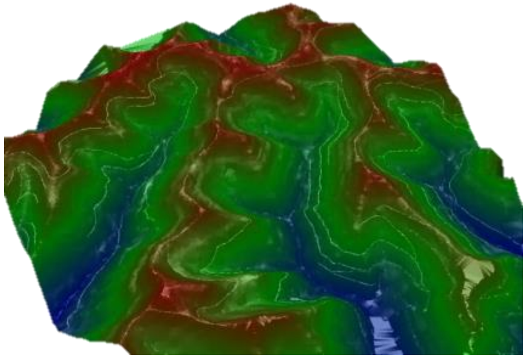
What is the potential hydrologic response?

Study reach

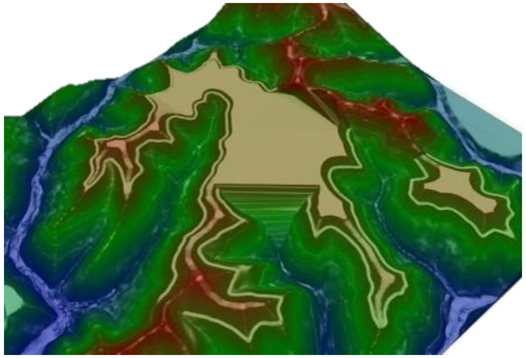


Modeled four conditions

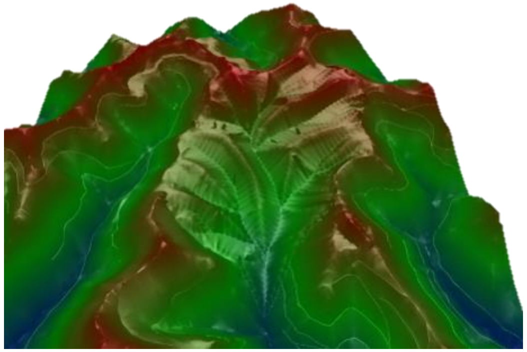




1) Pre-mined



2) Conventional Reclamation



3) GLD-DC (During Construction)
4) GLD-PR (Post reclamation)

Summary of sub-basin characteristics and curve numbers (CN) for each modeling condition.

	PM	CF	GLD-DC	GLD-PR
Contributing watershed area (km^2)	2.1	1.8	2.1	2.1
Number of sub-basins	9	15	9	9
Sub-basin characteristics				
Area (km^2)	0.04-0.66	0.007-0.64	0.03-0.69	0.03-0.69
Length (km)	0.29-1.5	0.03-0.45	0.23-1.4	0.23-1.4
Slope	0.44-0.56	0.16-0.54	0.31-0.59	0.31-0.59
Average overland flow distance (km)	0.09-0.25	0.007-0.21	0.09-0.36	0.09-0.36
Maximum stream length (km)	0.14-1.19	0.03-0.28	0.10-1.11	0.10-1.11
Maximum stream slope	0.03-0.35	0.01-0.33	0.03-0.23	0.03-0.23
CN	66	66-82	84	67

Hydrologic modeling results for each modeling condition.

	Return Period					
	2-yr	**10-yr**	**25-yr**	**50-yr**	**100-yr**	**500-yr**
Pre-mined						
Peak flowrate (m^3/s)	2.94	11.3	16.4	19.2	24.0	36.5
Time to peak (min)	738	738	738	738	738	738
Runoff volume (cm)	0.99	2.8	3.8	1.9	5.2	7.3
Conventional Fill						
Peak flowrate (m^3/s)	0.82	12.1	22.3	26.2	33.1	46.1
Time to peak (min)	757	733	727	726	724	722
Runoff volume (cm)	1.9	4.2	5.1	6.1	7.14	9.6
GLD-During Construction						
Peak flowrate (m^3/s)	19.4	38.8	48.8	53.9	62.4	91.3
Time to peak (min)	732	732	732	732	732	726
Runoff volume (cm)	3.2	6.0	7.5	8.2	9.4	12.2
GLD-Post Reclamation						
Peak flowrate (m^3/s)	3.0	10.5	15.4	18.0	22.5	36.2
Time to peak (min)	750	744	738	783	738	732
Runoff volume (cm)	1.1	2.9	4.0	4.5	5.5	7.7

Average properties of flood events

	PM	CF	GLD-DC	GLD-PR
		2-yr		
Flood Extents (m)	11.7	9.5	19.6	11.6
Cross-sectional flow area (m^2)	4.1	2.3	13.5	4.1
Average velocity (m/s)	1.1	0.9	1.8	1.1
Maximum depth (m)	0.9	0.7	1.7	0.9
Flood surface area (km^2)	23.0	18.4	38.6	23.0
		100-yr		
Flood Extents (m)	21.3	24.7	35.6	20.7
Cross-sectional flow area (m^2)	15.7	19.9	33.7	15.0
Average velocity (m/s)	1.9	2.1	2.4	1.9
Maximum depth (m)	1.9	2.2	3.0	1.9
Flood surface area (km^2)	41.4	47.2	66.5	40.5
		500-yr		
Flood Extents (m)	25.8	29.9	44.8	26.0
Cross-sectional flow area (m^2)	21.0	25.9	47.7	21.3
Average velocity (m/s)	2.1	2.2	2.6	2.1
Maximum depth (m)	2.3	2.6	3.5	2.1
Flood surface area (km^2)	48.9	56.4	85.6	49.2

2-year

Pre-mining

Conventional

GLD (During Construction)

GLD (Post Reclamation)

100-year

Pre-mining

Conventional

GLD (During Construction)

GLD (Post Reclamation)

500-year

Pre-mining

Conventional

GLD (During Construction)

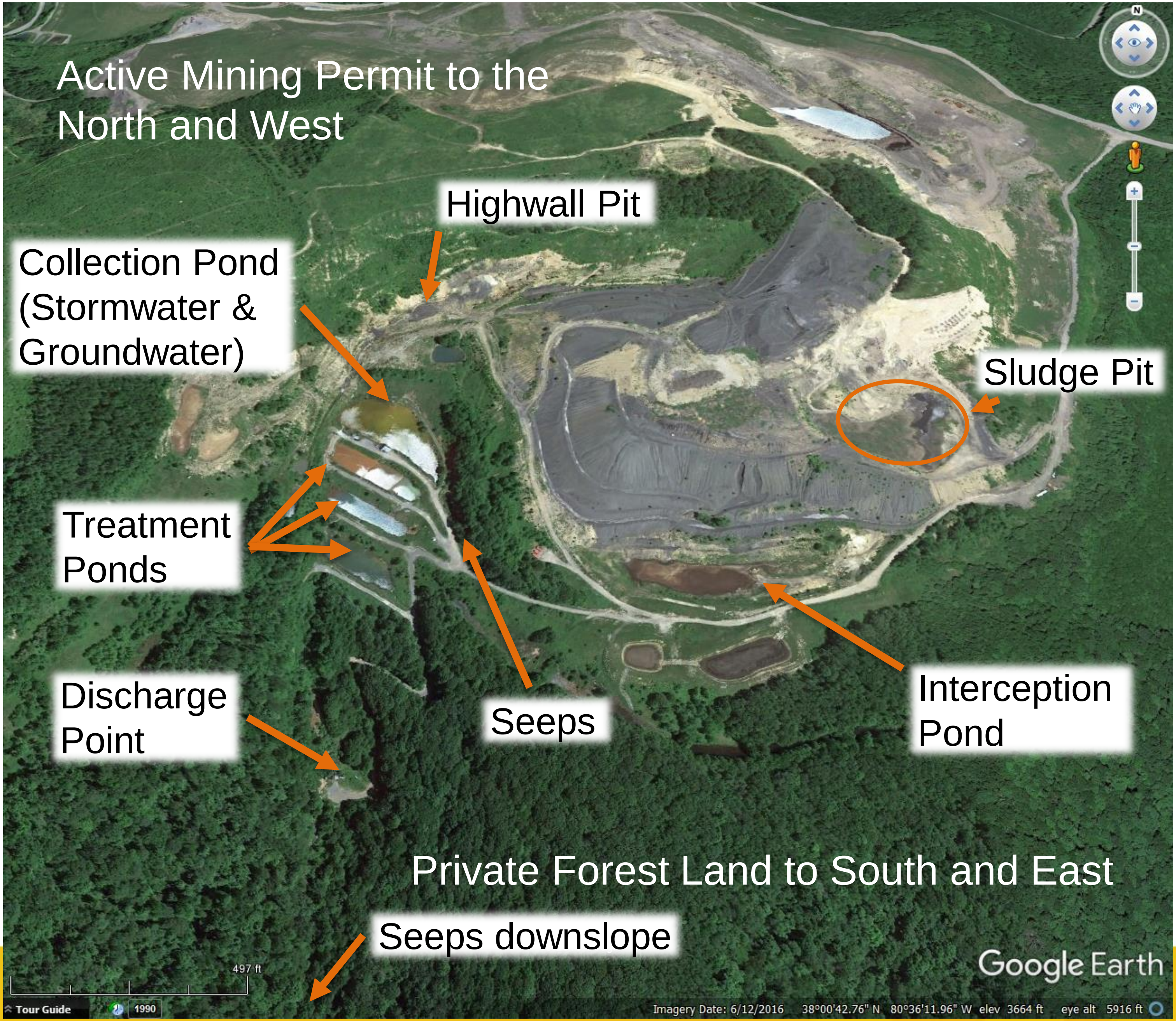
GLD (Post Reclamation)

Conclusions

- The GLD-During Construction condition resulted in peak flowrates that were more than twice the pre-mining condition for all storm events.
- The long-term difference decreased, and the long-term peak flowrates were within 7% of the PM condition.
- These trends were also evident in the downstream flooding impacts.
- The results illustrated that water management structures were necessary during the construction phase of GLD designs. However, this work shows promise that long-term structures will not be needed

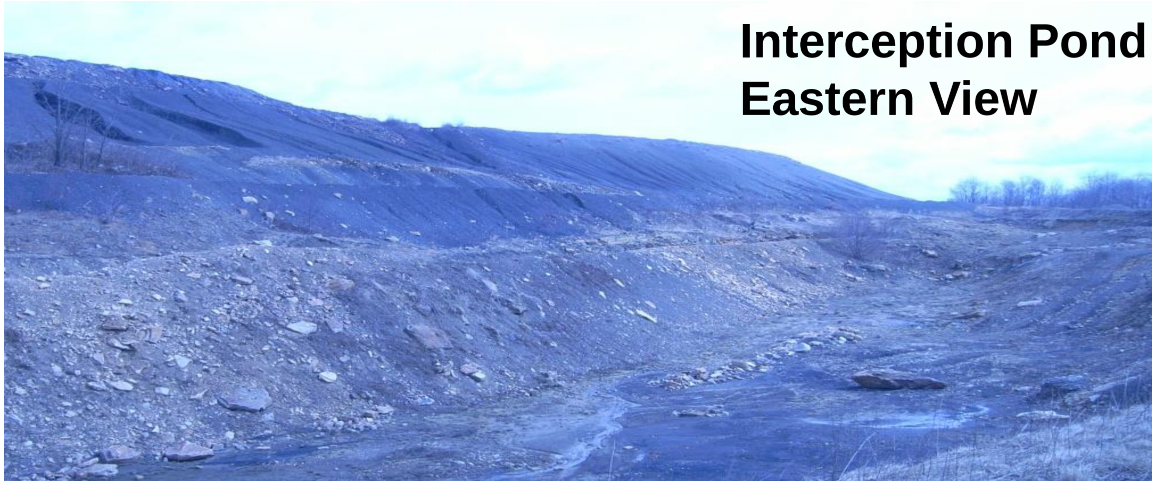
Royal Scot demonstration site

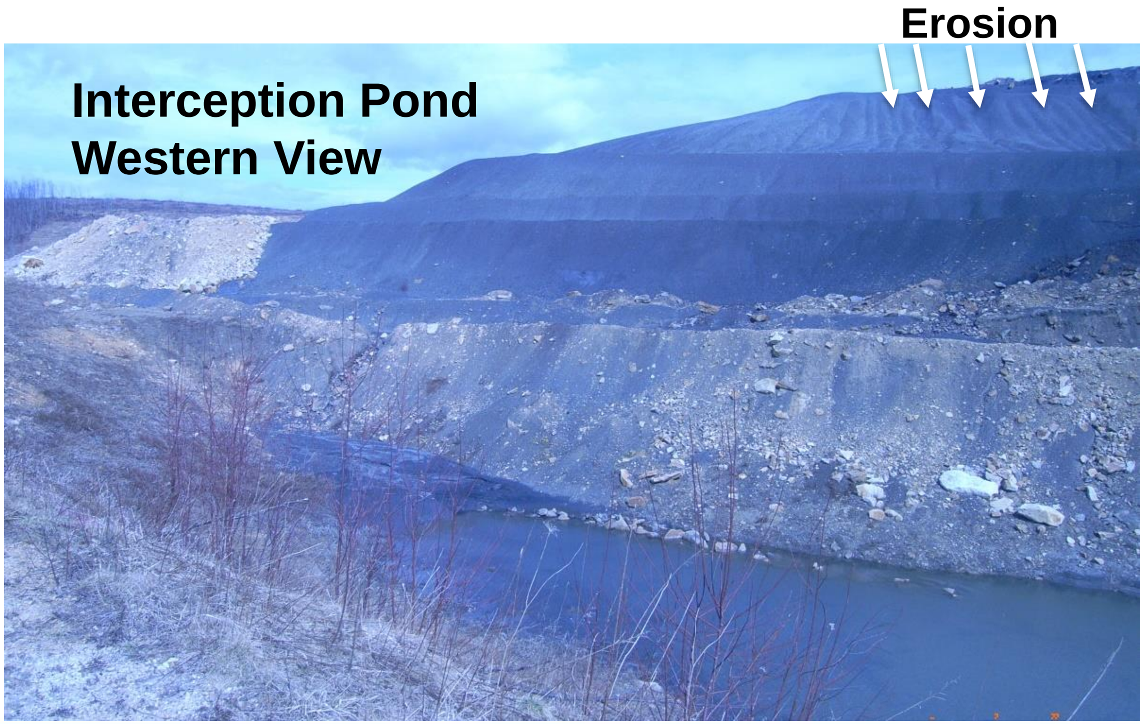
- Greenbrier County, WV
- Coarse coal refuse disposal site
- Abandoned in 2001
- Ridge-top location


Active Mining Permit to the North and West
Highwall Pit
Collection Pond (Stormwater & Groundwater)
Sludge Pit
Treatment Ponds
Seeps
Interception Pond
Discharge Point
Private Forest Land to South and East
Seeps downslope
497 ft
Google Earth
Tour Guide
1990
Imagery Date: 6/12/2016 38°00'42.76" N 80°36'11.96" W elev 3664 ft eye alt 5916 ft

Interception Pond:

- Underdrain is plugged
  - No controlled outlet
- Pond invert is on rock
  - Rock mass is heavily jointed
  - <u>Seepage</u>
- Seep response tests conducted by WV DEP
  - Flow paths
  - Response time





Sludge Pit:

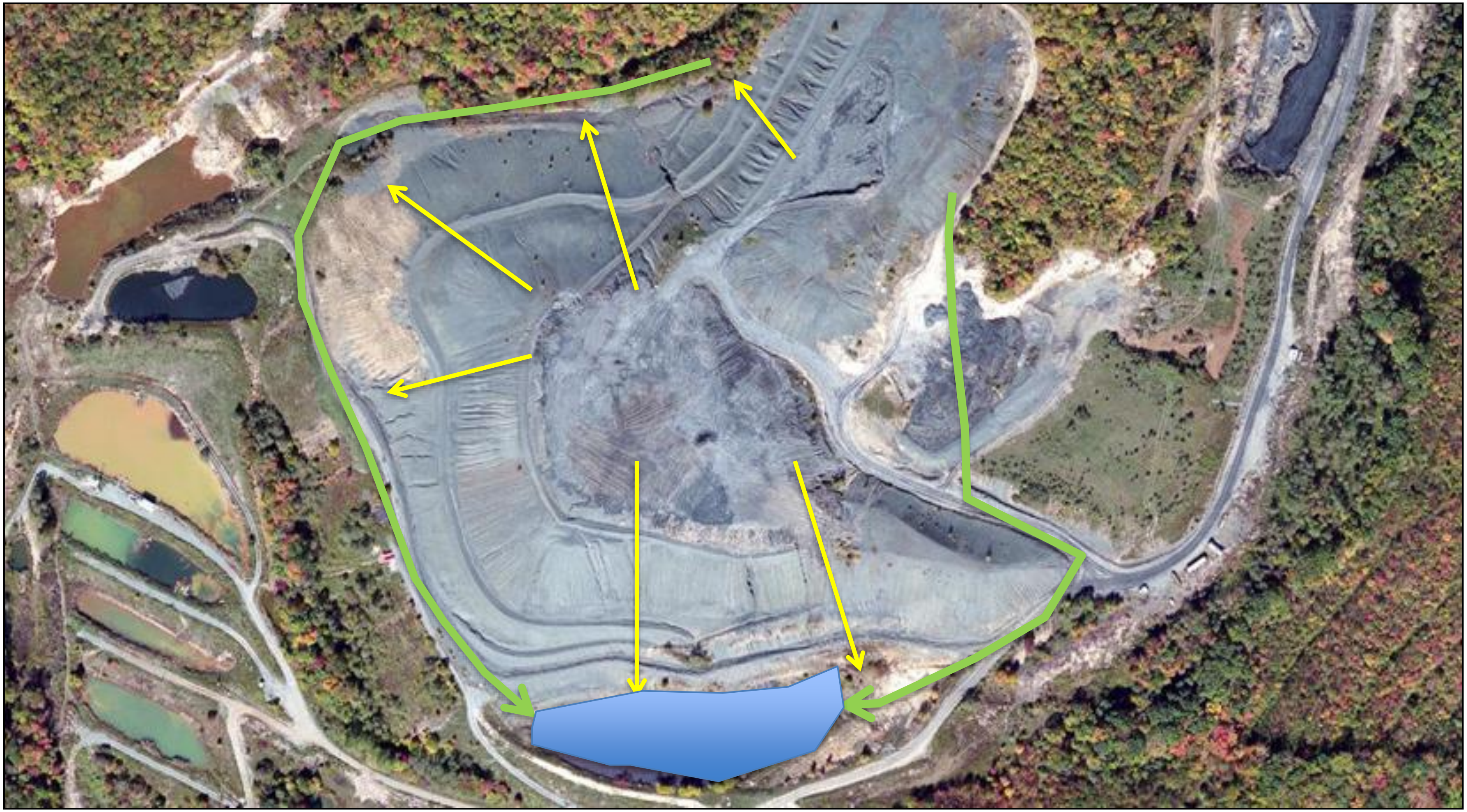
- Disposal of pond sediment
- Air dry sediment in the Sludge Pit
- Sediment contains heavy metals

Royal Scot Reclamation Objective:

Develop a reclamation alternative utilizing geomorphic landform design principles at the Royal Scot Coarse Coal Refuse Facility

1. Reduce stormwater infiltration
2. Segregate stormwater and groundwater flows
3. Minimize construction costs

Basic approach: Regrade site, decrease infiltration, and manage runoff



Final design

- Four geomorphic watersheds
- Connected by benched slopes
- Draining to perimeter channel
- Pond sized for 100-yr event

Geomorphic Channels

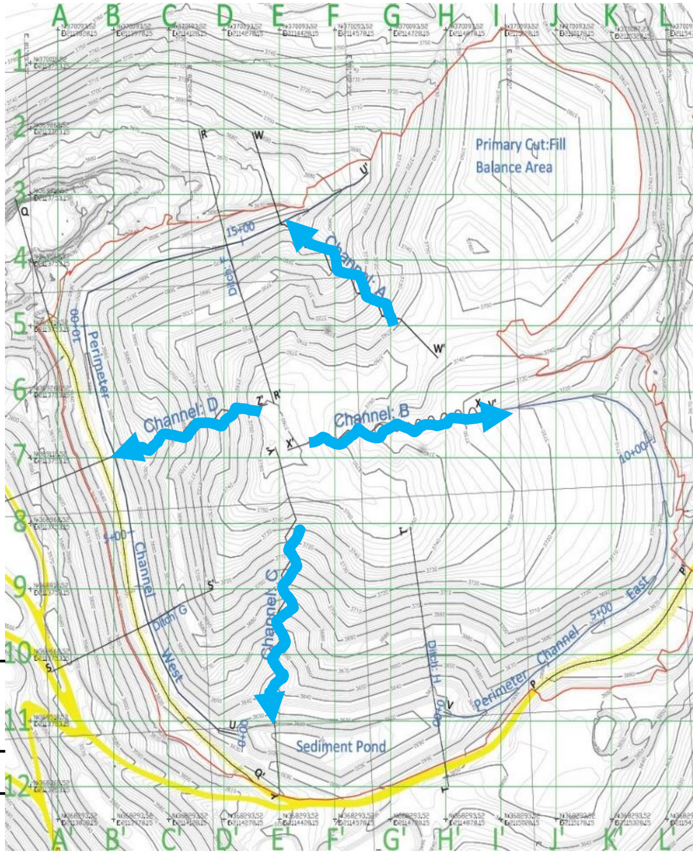
Bed Slope
- Varies

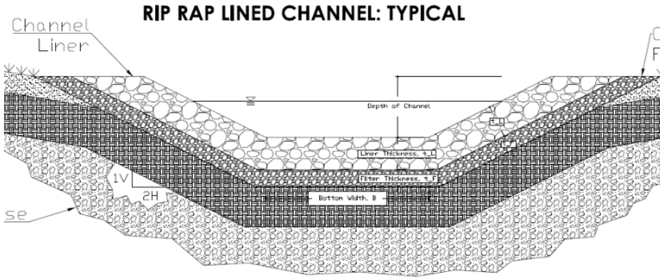
Riprap Liner
- D50: 9.0 to 12.0 inch

Channel Filter
- D50: 3.0 inch

Vegetation Liner
- Type 1 Cap

Flow Reach	Liner	Length	Peak Flow	Bottom Width	Depth	Bed Slope	Bedding D_{50}	Filter D_{50}
[Name]	[Mat'l]	[ft]	[cfs]	[ft]	[ft]	[ft/ft]	[in]	[in]
Channel A – 1	Rip Rap	399	23.4	6.0	0.8	0.12 - 0.20	9.0	3.0
Channel A – 2	Rip Rap	114	5.0	5.0	0.6	0.19	9.0	3.0
Channel B – 1	GRASS	475	19.3	4.5	2.3	0.02 - 0.03	GRASS	
Channel B – 2	Rip Rap	190	11.1	4.0	0.9	0.04 - 0.09	9.0	3.0
Channel B – 3	Rip Rap	67	5.9	3.5	0.7	0.12	9.0	3.0
Channel C – 1	Rip Rap	519	25.9	6.0	0.8	0.12 - 0.24	12.0	3.0
Channel C – 2	Rip Rap	103	3.5	4.0	0.6	0.20	12.0	3.0
Channel D – 1	Rip Rap	313	18.2	5.5	0.8	0.12 - 0.27	12.0	3.0
Channel D – 2	Rip Rap	201	7.0	4.5	0.6	0.26	12.0	3.0





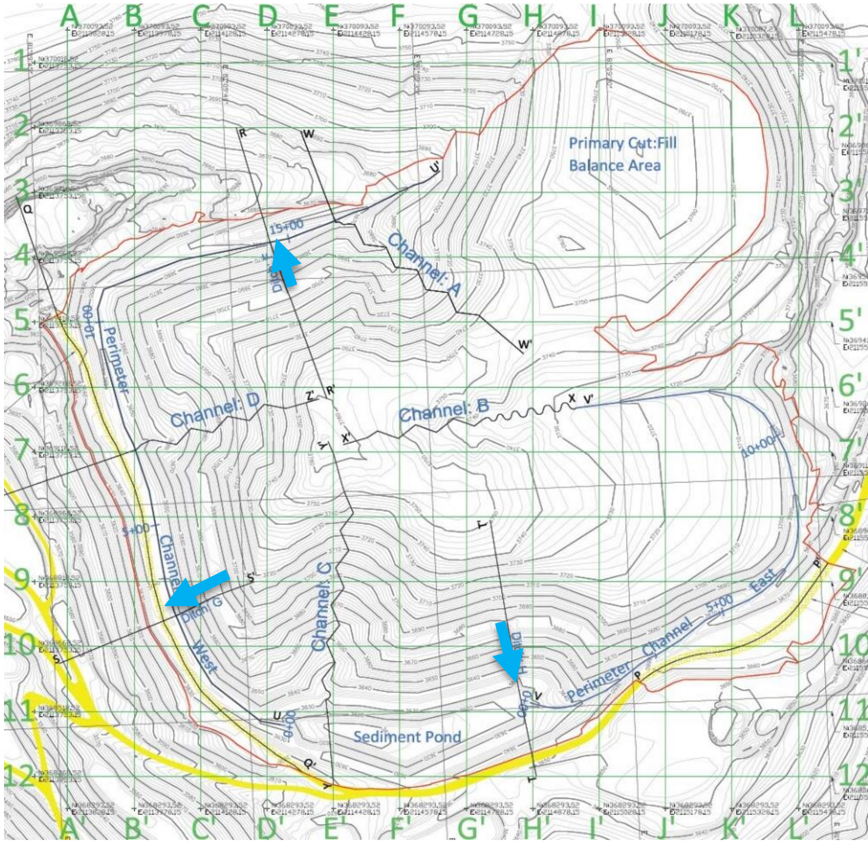
*Channels shown in Blue

Conventional Ditches

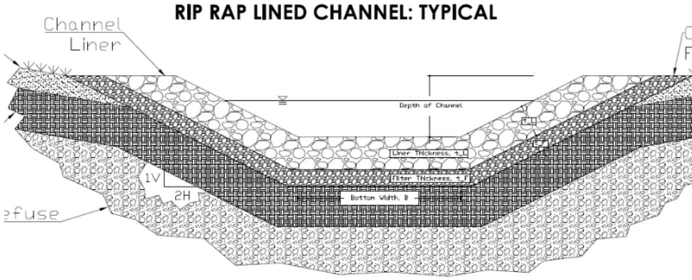
Bed Slope
- 50%

Riprap Liner
- D50: 15.0 to 18.0 inch

Channel Filter
- D50: 3.0 inch



Flow Reach	Liner	Length	Peak Flow	Bottom Width	Channel Depth	Bed Slope	Bedding D_{50}	Filter D_{50}
[Name]	[Material]	[ft]	[cfs]	[ft]	[ft]	[ft/ft]	[in]	[in]
Ditch F	Rip Rap	155	16.9	4.0	1.1	0.50	18.0	3.0
Ditch G	Rip Rap	160	5.9	2.0	1.1	0.50	18.0	3.0
Ditch H	Rip Rap	130	7.8	3.5	1.1	0.50	15.0	3.0



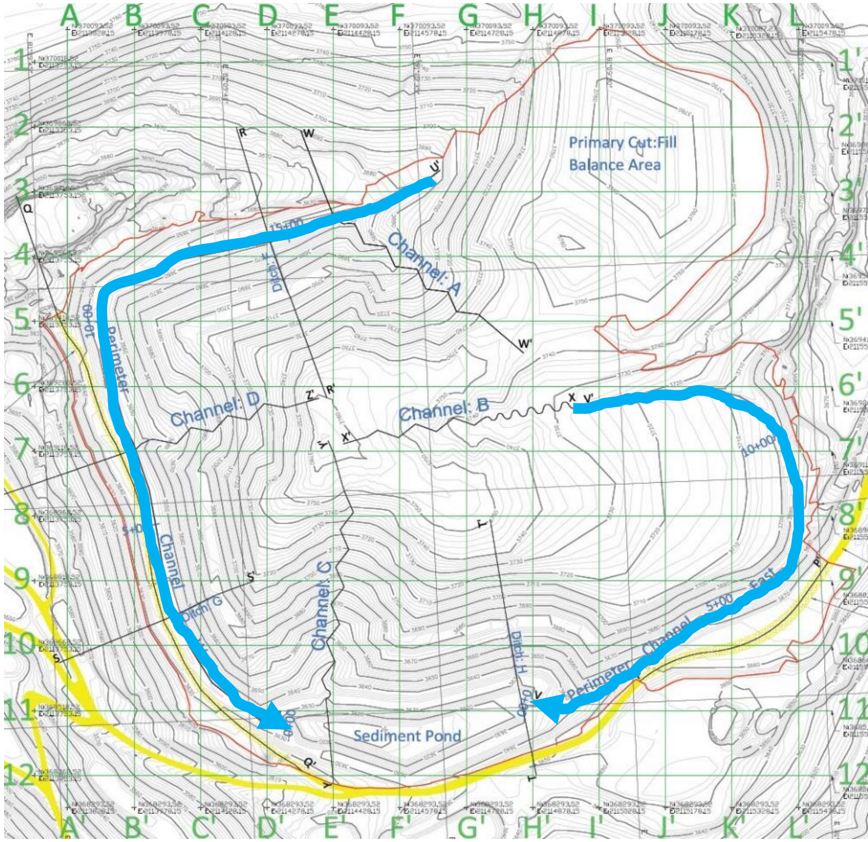
*Channels shown in Blue

Perimeter Ditches

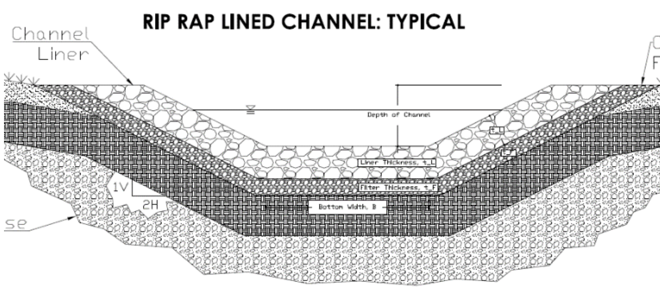
Bed Slope
- 2.0 to 15%

Riprap Liner
- D50: 9.0 to 12.0 inch

Channel Filter
- D50: 3.0 inch



Flow Reach	Liner	Length	Peak Flow	Bottom Width	Channel Depth	Bed Slope	Bedding D_{50}	Filter D_{50}
[Name]*	[Material]	[ft]	[cfs]	[ft]	[ft]	[ft/ft]	[in]	[in]
P. Ch. West - 1	Rip Rap	756	108.8	10.5	1.8	0.02	9.0	3.0
P. Ch. West - 2	Rip Rap	1,514	68.3	7.0	1.8	0.02 - 0.15	9.0	3.0
P. Ch. East - 1	Rip Rap	350	69.6	8.0	1.7	0.10	12.0	3.0
P. Ch. East - 2	Rip Rap	1,142	57.7	8.0	1.7	0.06	9.0	3.0



*Channels shown in Blue

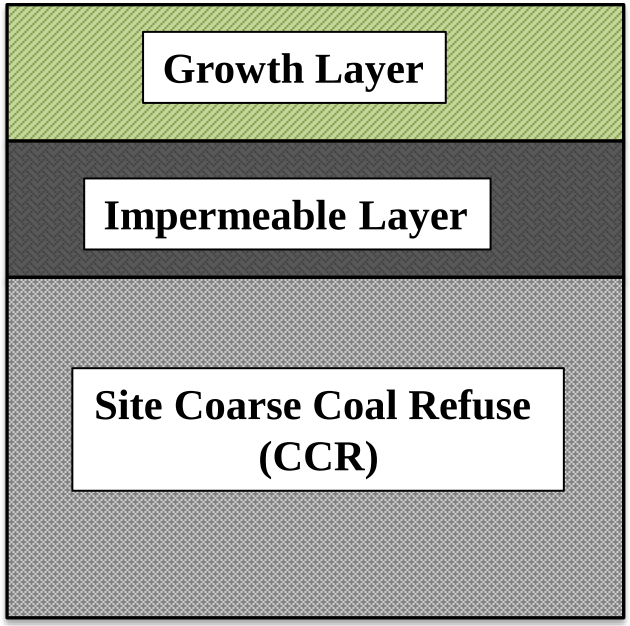
Cap and cover: 2 Layer Design

Growth Layer:
- Mixture of shale and MGro™ in fixed volumetric ratio.
- Initial results from the 60% shale: 40%
- MGro blend have been favorable. (started here)
- 60/40 Mgro Geotechnical properties being defined in laboratory testing
- Proposed thickness = 1 feet

Impermeable Layer
- Intended for seepage infiltration control
- Compacted coarse coal refuse
- Preliminary thickness ranges = 1 – 2 ft

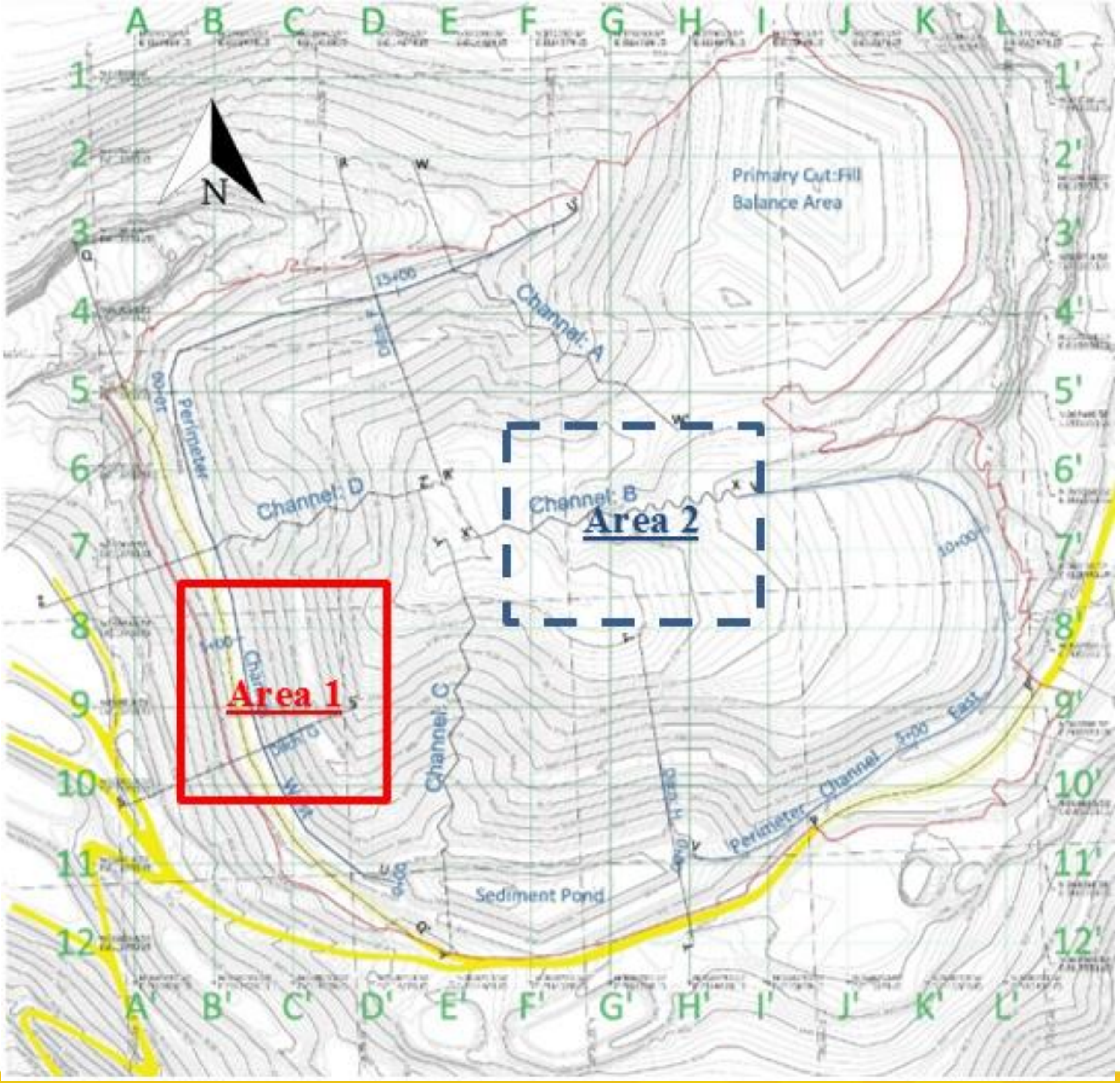
Refuse pile material (Cut / Fill)
- Assess necessary compaction
- Homogeneous
- Source of the acid mine drainage
- Field self weight ranges 80 to 90 pcf.
- Thickness varies 10 ft to 120 ft.

2 Layer Final Cover System



Typical MGro™ sample

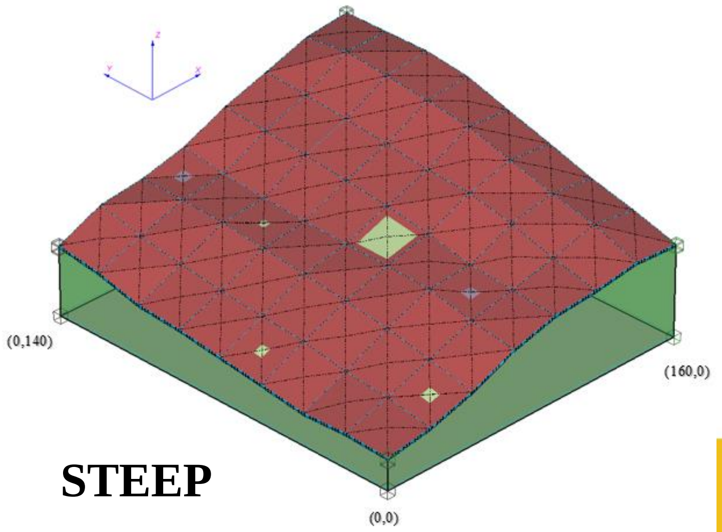
Reclamation Geometry and modeled areas



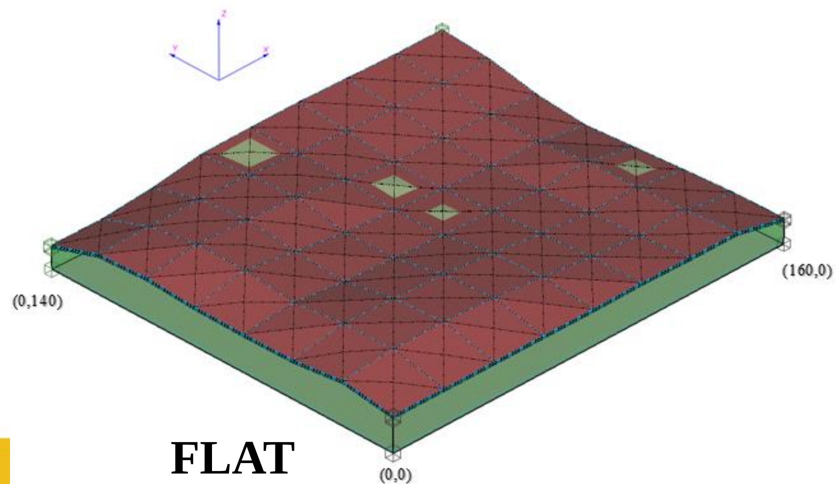
Adapted from Lorimer, 2016

Modeling Cases

- **Soil Vision® geotechnical engineering software**
  - **SVFlux and SVSlope in coupled analysis**
  - **Incorporated unsaturated soil mechanics**
- **Developed precipitation event(s)**
- **Applied Precipitation: 5 year rainstorm, 24 hr duration**
- No evapotranspiration (worst case condition)
- **Case 1: Land Cover reclamation.**
- **Case 2: Hydraulic Barrier using *in situ* material.**
- **Case 3: Hydraulic Barrier with controlled grain size distribution: 60% coarse coal refuse material 40% fines.**
- **Case 3: Hydraulic Barrier with controlled grain size distribution: 80% coarse coal refuse material 20% fines.**



STEEP

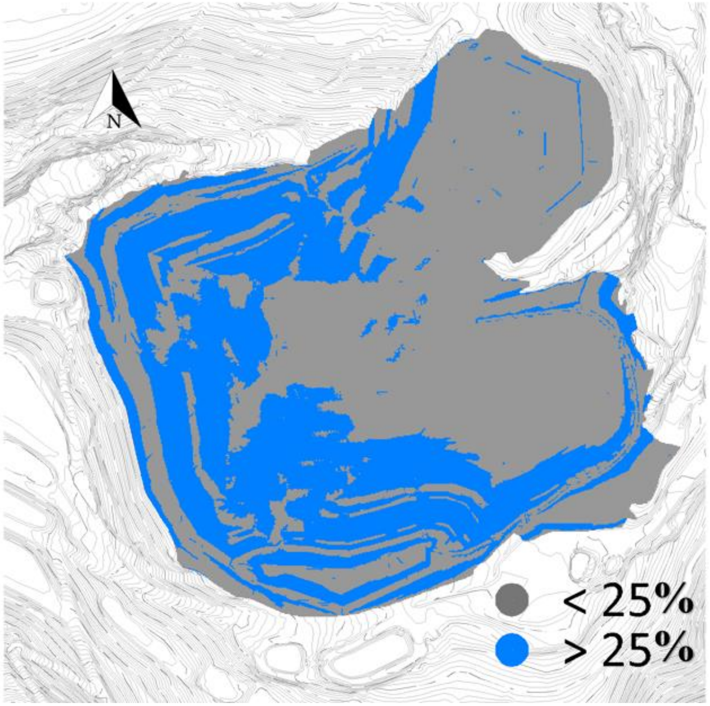


FLAT

Total infiltration calculation

$$Total\ red.(\%) = \frac{\%red.(steep) * area(steep) + \%red.(flat) * area(flat)}{total\ area}$$

Slope definition	% of total area	Area (acres)	Average Slope %
Flat	60.81	28.59	11.1
Steep	39.19	18.43	36.9
Total	100	47.02	

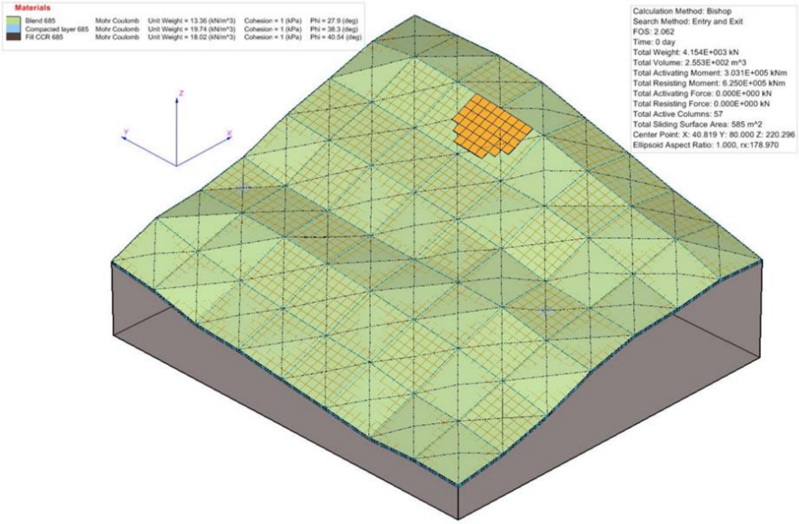


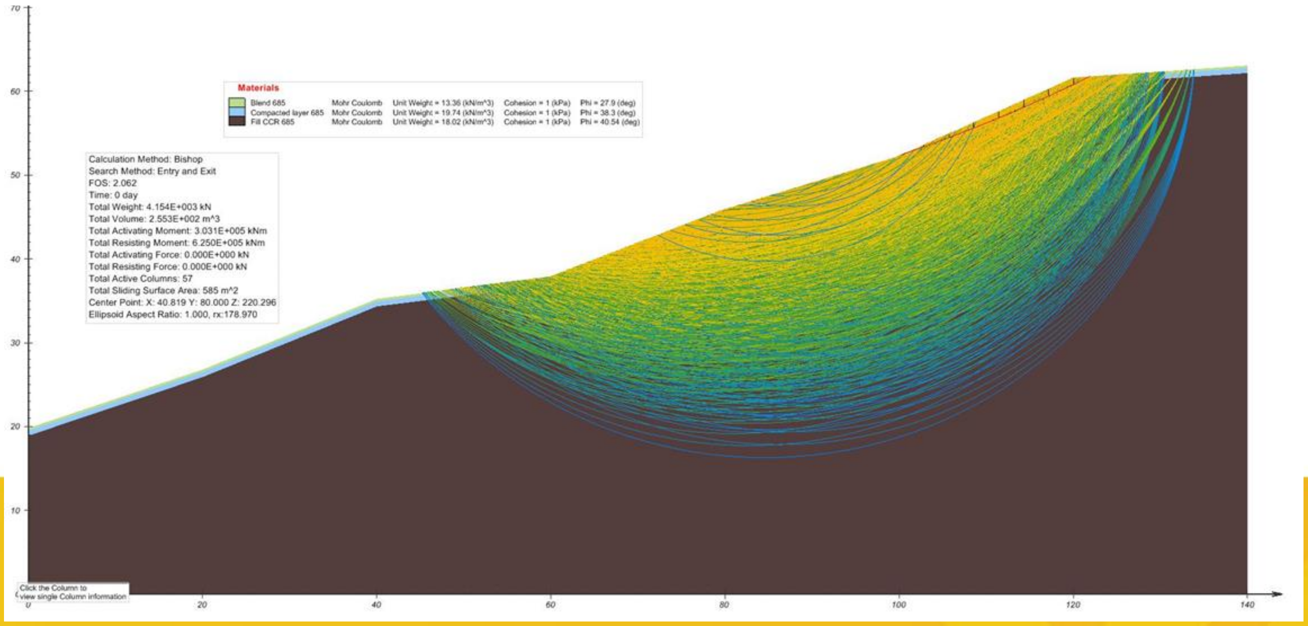
Infiltration Reduction Summary

Design	Precipitation (m^3)	Flow through Surface 2 (m^3)	Reduction (%)	Total design % reduction
CASE 1: No Barrier steep	1993.49	1948.12	2%	0.82
CASE 1: No Barrier flat	1846.04	1898.16	0%	
CASE 2: In situ Barrier steep	1981.05	1920.7	3%	3
CASE 2: In situ Barrier flat	1872.12	1817.17	3%	
CASE 3: 60/40 Barrier steep	2000.16	1362.72	32%	26.11
CASE 3: 60/40 Barrier flat	1856.52	1441.05	22%	
CASE 4: 80/20 Barrier steep	2001.56	1387.50	31%	35.13
CASE 4: 80/20 barrier flat	1936.16	1191.70	38%	

Steep Barrier Design

Calculation Method	GLE
Factor of Safety	**2.06**
Total Weight (kN)	4,154
Total Volume (m^3)	255.30
Total Activating moment (kNm)	3.03×10^5
Total Resisting Moment (kNm)	6.25×10^5
Total Activating Force (kN)	1,554
Total Resistive Force (kN)	3,203
Total Active Columns	57
Total Sliding Surface Area (m^2)	585
Center Point (X,Y,Z)	(40.82,80.00,220.29)
Ellipsoid Aspect Ratio	1.00, rx:178.97





Conclusions

- The Land Cover reclamation did not reduce precipitation infiltration into the refuse layer.
- Hydraulic Barrier cover presented a delay of 20 days for the precipitation completely infiltrate in to the refuse layer on steep slopes and 30 for flat slopes.
- Controlled GSD barriers are more effective than the *in situ.*
- In terms of slope stability both approaches resulted in safe slopes with factors of safety of 2.0.

Conclusions

- **Sustainable landforms**
  - Four geomorphic watersheds
  - Flow shear force is conservatively designed with “self healing” flexible membrane channel lining
- **Stormwater infiltration reduction**
  - Cap Structure Barrier Zones
  - Radial draining, fast but stable channels

Conclusions

- **Segregate stormwater and groundwater**
    - Sludge Pit was capped and the embankment was not included within any excavation
    - Hydraulic network captures 87% of the rainfall
    - Sediment Pond is designed as “dry” and dewaters in 68 hours
- **Minimize construction costs**
    - Earthwork balanced
    - Onsite material used for the Barrier Zone throughout
    - Minimal import for soil amendment
    - Channel liner may be produced onsite

Students

- Graduate students
  - Alison Sears
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  - Harold Russell
  - Jeff Stevens
  - Rogan Park
  - Jeff Lorimer
  - Iuri Santos
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Questions?