Stability and Erosion on Steep Slopes
Constructed by the Forestry Reclamation Approach in the Southern Appalachian Region

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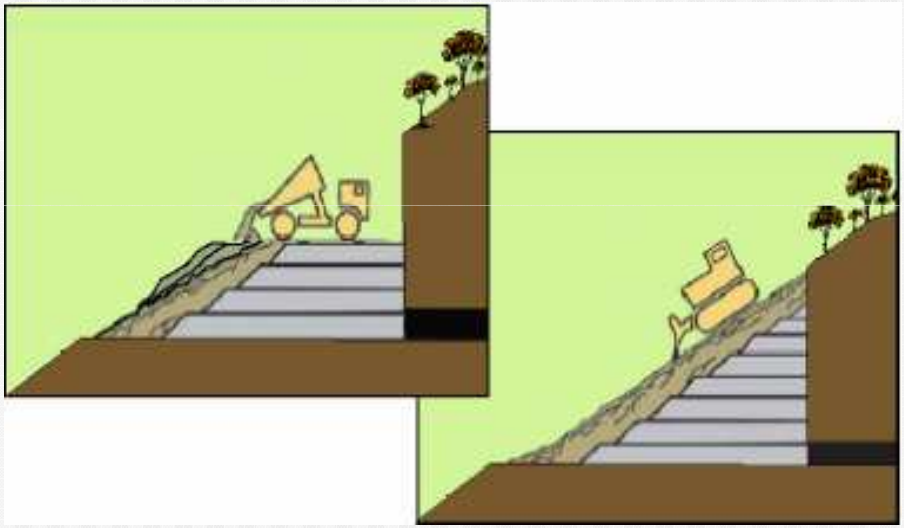
Background: Forestry Reclamation Approach

- Forestry Reclamation Approach (FRA) developed to establish healthy fast-growing, native trees.
  - Low compaction grading of the surface materials (4-6 feet).
  - Soil provides growth medium for trees.
  - Increased root penetration and soil permeability/porosity



Low Compaction Grading Method
(Sweigard et al. 2007)

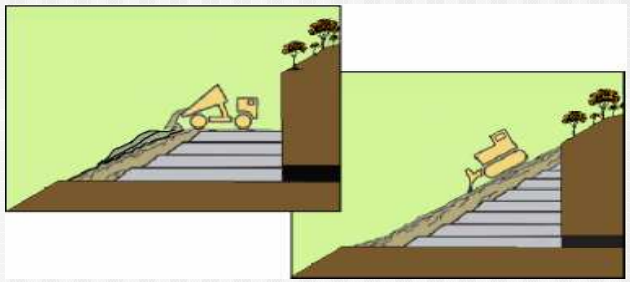
Background: Forestry Reclamation Approach

- However, low density surface materials can be:
  - Lower strength than compacted materials affecting slope stability
  - Less resistant to surface erosion and rill/gully formation
- Prior FRA investigations have included applications on relatively shallow slopes.

Angel, P. C. Barton, R. Warner, C. Agouridis, T. Taylor, and S. Hall (2007)

Research Questions

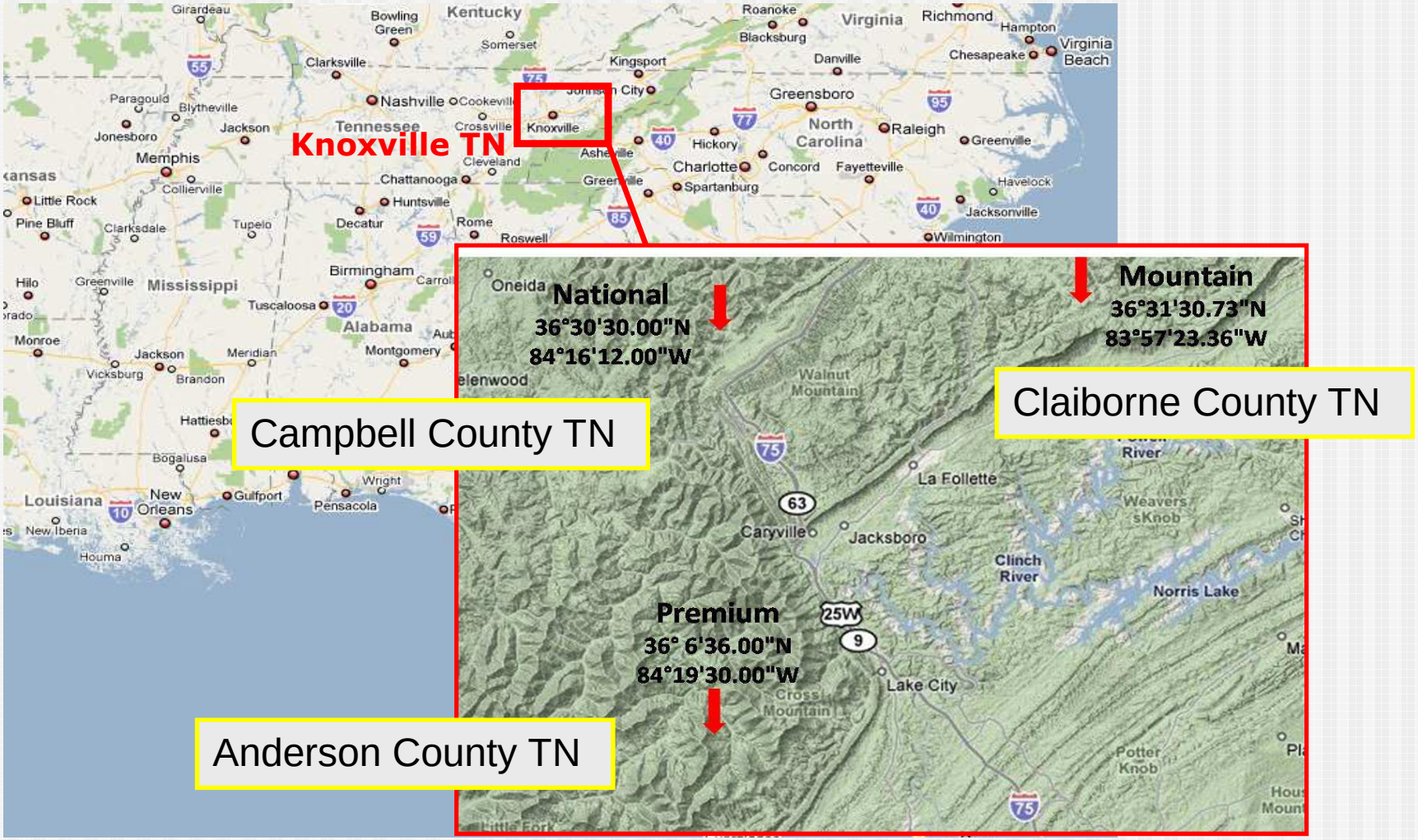
- How does **FRA** perform on "steep" slopes, slopes generally greater than 20 degrees?
- **Slope Stability**
  - How to characterize reclaimed materials for slope stability evaluation?
  - How can geotechnical stability best be evaluated?
- **Surface Erosion and Hydrology**
  - What K factors for erosion resistance, as a function of the R factor should be used for sediment yield models ?
  - What CNs should be used in runoff/sediment yield models?
- Are there additional design considerations when employing FRA in steep slopes as a function of spoil material?



Study Design

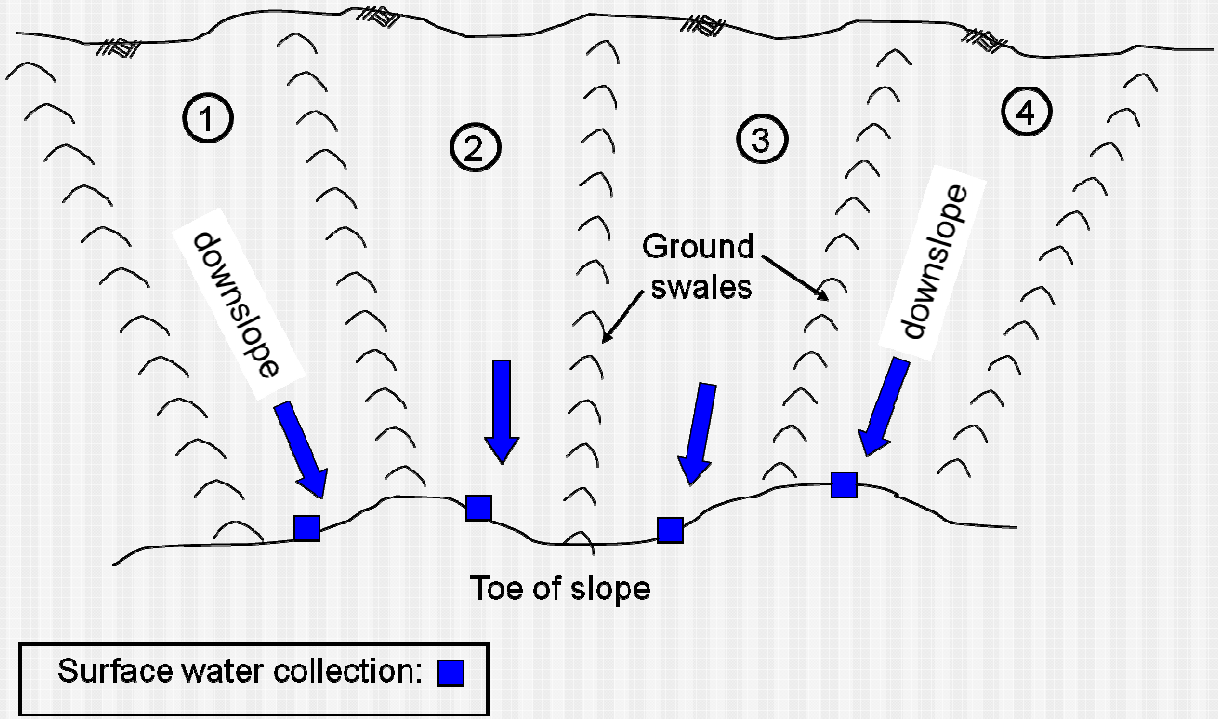
- Select three active surface mining sites in East Tennessee, and work with coal companies to implement FRA on study sites.
- **Slope Stability and Surface Erosion Studies**
  - Characterize geotechnical soil properties on study sites, monitor for slope distress, and perform stability analysis.
  - Install instrumentation to monitor rainfall, runoff, and sediment yield from study sites, four plots per study site.
- **Reforestation**
  - Forest establishment study by UT Forestry Department; reforestation study concurrently implemented by J. Franklin and D. Buckley.
  - Trees planted March 2009.

Study Site Locations



Study Site Development

Elevation view depicting the four reforestation treatment zones, each with a surface water collection point.



Proposed Reforestation Study:
3 ground cover treatment plots and 1 “no cover” plot

Premium Coal Company
March 2009

Premium Coal Company
March 2009

Mountainside Coal Company
March 2009

Mountainside Coal Company
March 2009

National Coal Company
March 2009

Study Sites Characteristics

- Each study site divided into 4 treatment plots
  - Divided by small berms to isolate runoff and sediment yield
  - Surveyed by Trimble™ total station

SITE	Approx Inclination (degrees)	Approx Slope Length (meters)	Approx Width of each plot (meters)	Approx Total Width of each plot (meters)
Premium Coal	28	32	28 top 25 bottom	115 top 100 bottom
Mountainside Coal	28	45	23	90 top 101 bottom
National Coal	20	48	21	84

Spoil material: shales and sandstone mix

Surface Hydrology & Erosion Monitoring Instrumentation

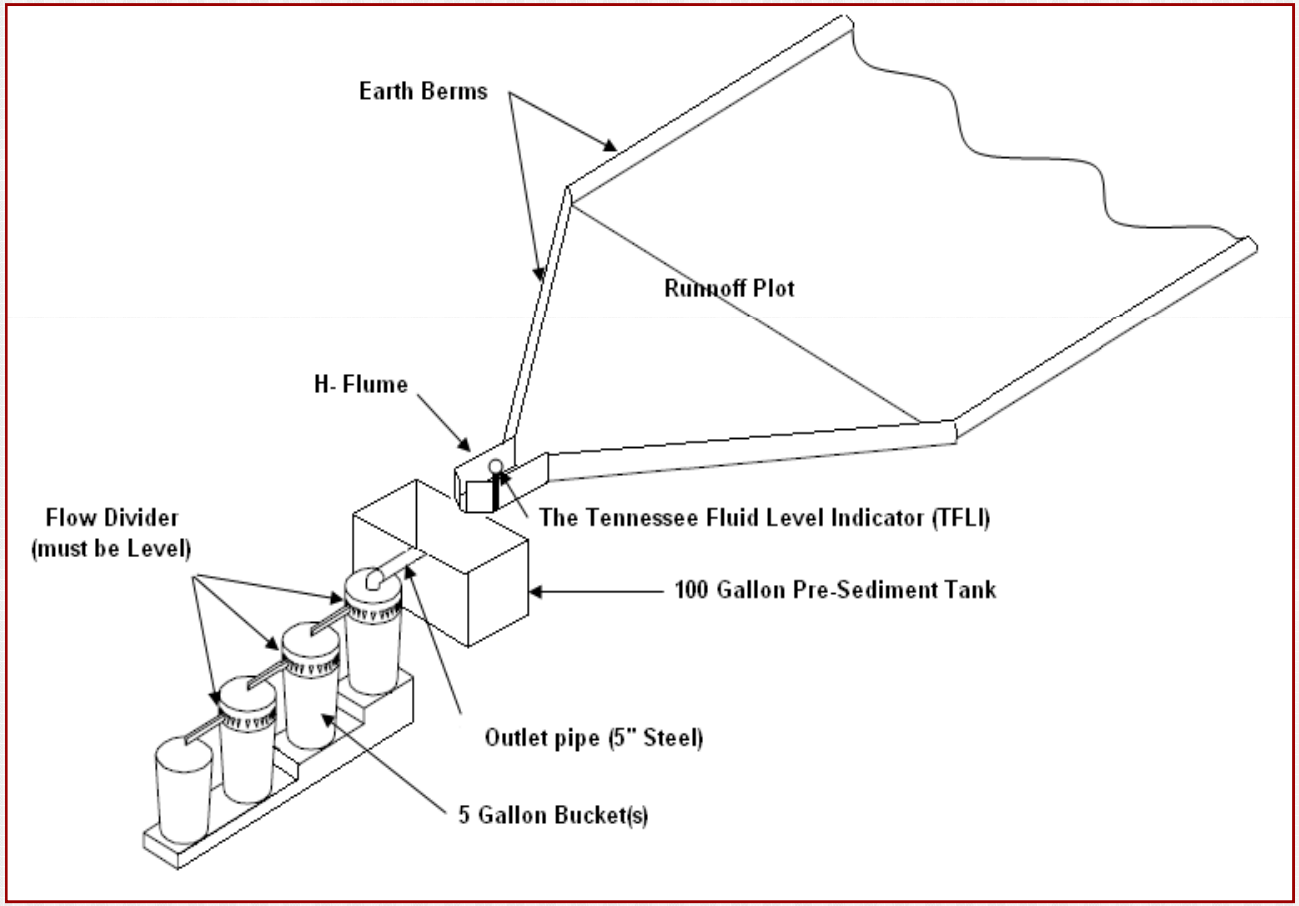
- **Precipitation and Climate**
  - Fully instrumented weather stations per study site
- **Surface Hydrology - Runoff**
  - H-flume, ¾-ft size, Standard USDA design, per plot
  - Stilling well with pressure transducers recording water depth on 5-min intervals.
- **Sediment Erosion and Yield**
  - 100-gal Pre-trap "tank" for coarse sediment collection
  - Multi-slot Dividers for fine sediment collection
    - Design based on Pinson et al. (2004).
  - Requires manual collection following significant precipitation/runoff events.

- Weather Stations
  - Measure rainfall depth on 5-min intervals
  - Measure wind speed and direction, solar radiation, and air temperature

Surface Hydrology & Erosion Monitoring Instrumentation

Detail of surface water collection system installed at each study plot

References:
Pinson et al. 2004; Hoomehr et al. 2010

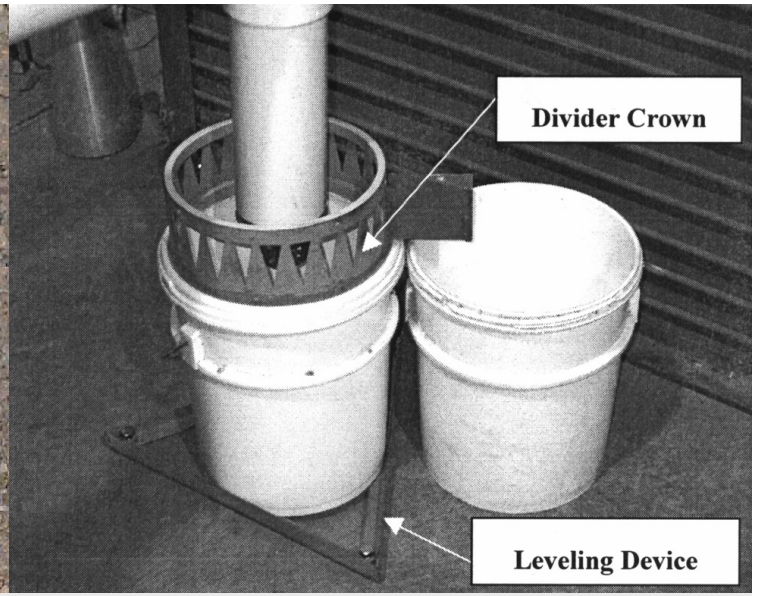


Pinson, W. T., D. C. Yoder, J. R. Buchanan, W. C. Wright, and J. B. Wilkerson (2004) "Design And Evaluation of An Improved Flow Divider For Sampling Runoff Plots" *Applied Engineering in Agriculture,* American Society of Agricultural Engineers, Vol. 20(4): 433−438

Surface Hydrology & Erosion Monitoring Instrumentation

Mountainside Coal Company
March 2009

Modified Flow and Sediment Measurement System (From left): Flume, Sediment Pre-trap (100 Gallon), Flow Dividers with collection buckets.



Divider buckets showing the divider crown on a bucket and the leveling device (from Pinson, 2004).

Geotechnical Characterization

- Reclaimed spoil materials vary significantly in geotechnical properties. **Metrics characterized:**
  - Unit weight
  - Grain size distribution
  - Strength

- **Unit weight** is an important parameter for stability analysis; Unit weight – **2 field measurement approaches**
  - Within 5-m x 5-m grid areas for the entire study site, randomly select areas using 1-m x 1-m locations to take measurements.
    - *Goal:* obtain best estimate of unit weight for each site.
  - Measured entire plot by 3-m x 3-m grid cells **only** in the originally designated "no cover" plot.
    - *Goal:* estimate unit weight variability within plots.

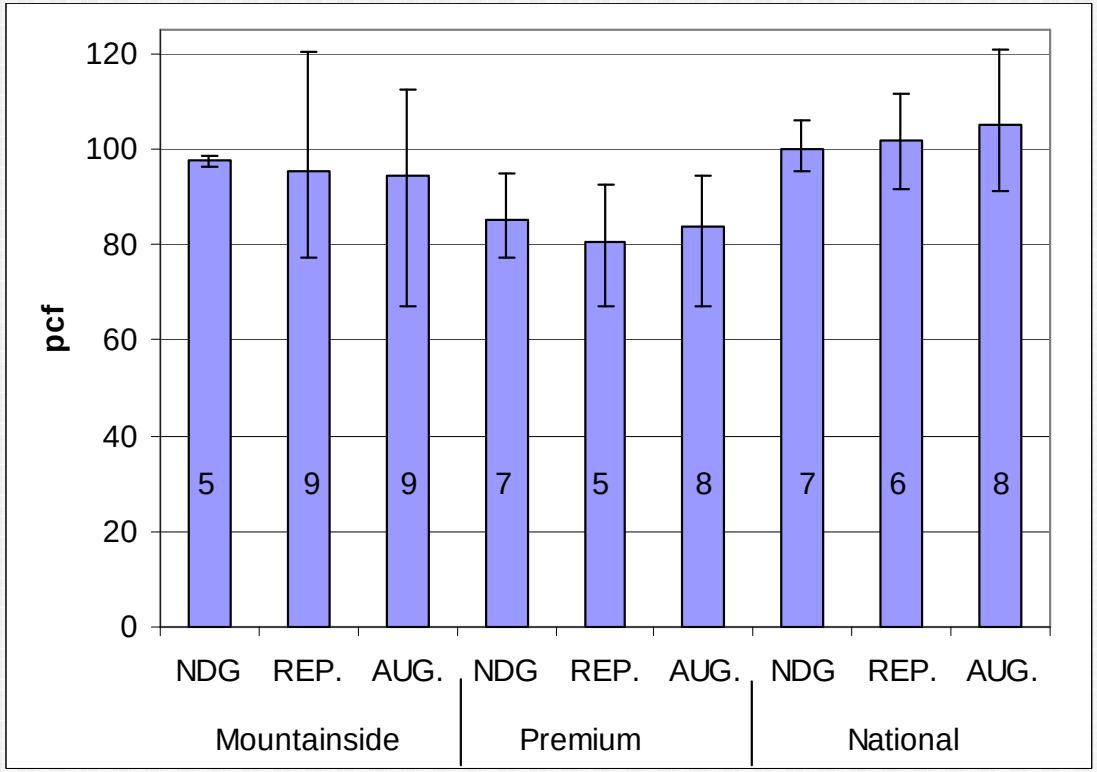
Results: Unit Weight Measurements
Randomly-selected 1-m x 1-m grid cells

- Unit weight measurements: 3 different methods
  - Water Replacement Method
  - Auger Replacement Method
  - Nuclear Density Gauge

Nuclear Density Gauge Testing on 1-m x 1-m grid

Results: Unit Weight Measurements
Randomly-selected 1-m x 1-m grid cells

- **Dry Unit Weight Measurements**
  - **Nuclear Density Gauge (NDG)**
  - **Water Replacement Method (REP)**
  - **Auger Replacement Method (AUG)**



English units
lbs/ft³ (pcf)

Comparison of 3 testing methods: mean value shown with error bars indicating high and low values measured (p = 0.95). Also shown within the bars is the number of samples taken.

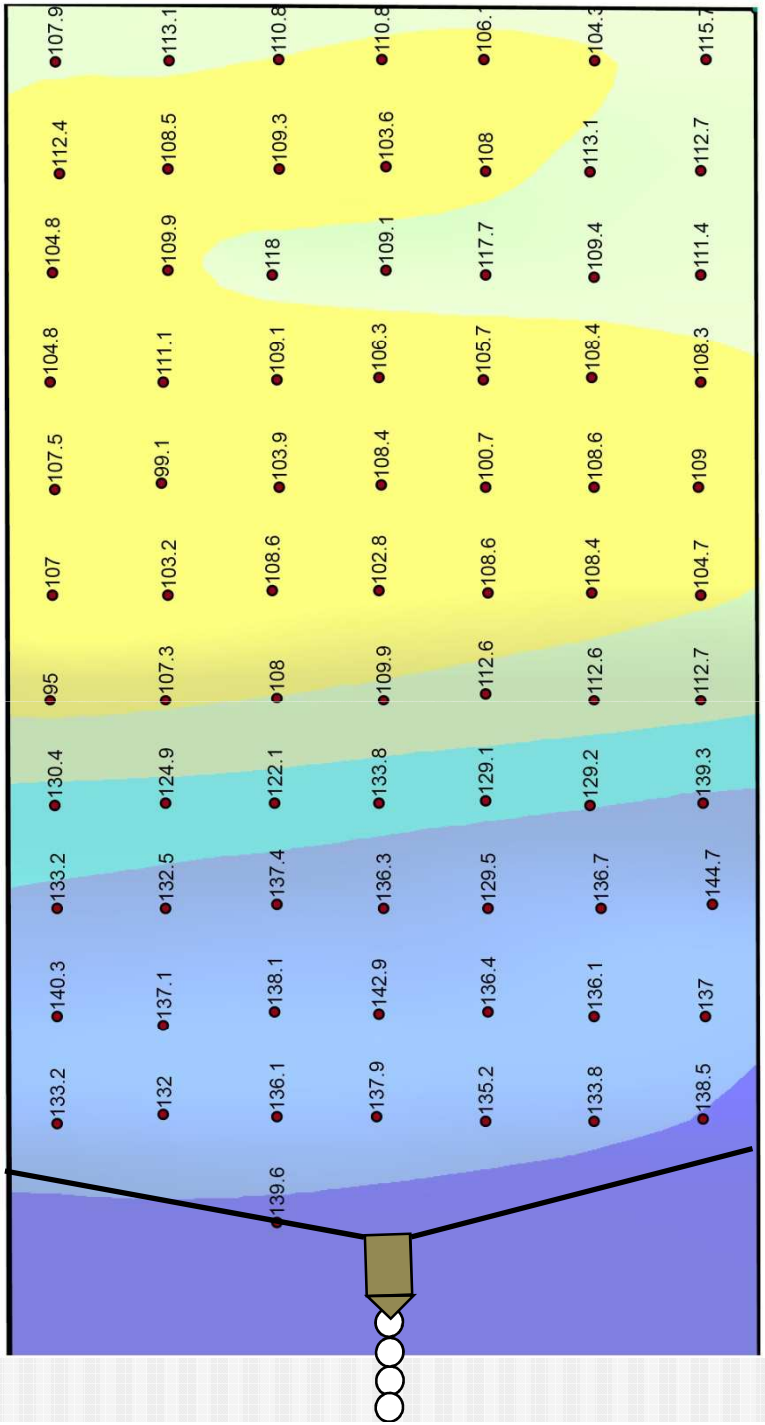
Results: Unit Weight Measurements

Complete Plot 3-m x 3-m grid

- Nuclear density testing over entire "no cover" plot at each study site.
- Plot density variation of greater interest than actual values.
  - Differences likely reflect spoil source and construction procedures.

Results: Dry Unit Weight

- **Example:**
  Site Variability for Mountainside Study Site



Dry Unit Weight Interpolation Map
Mountainside Site

Densities_Mountainside

Ordinary Kriging
Prediction Map
[Densities_Mountainside].[Dry_Densit]

Hillshade

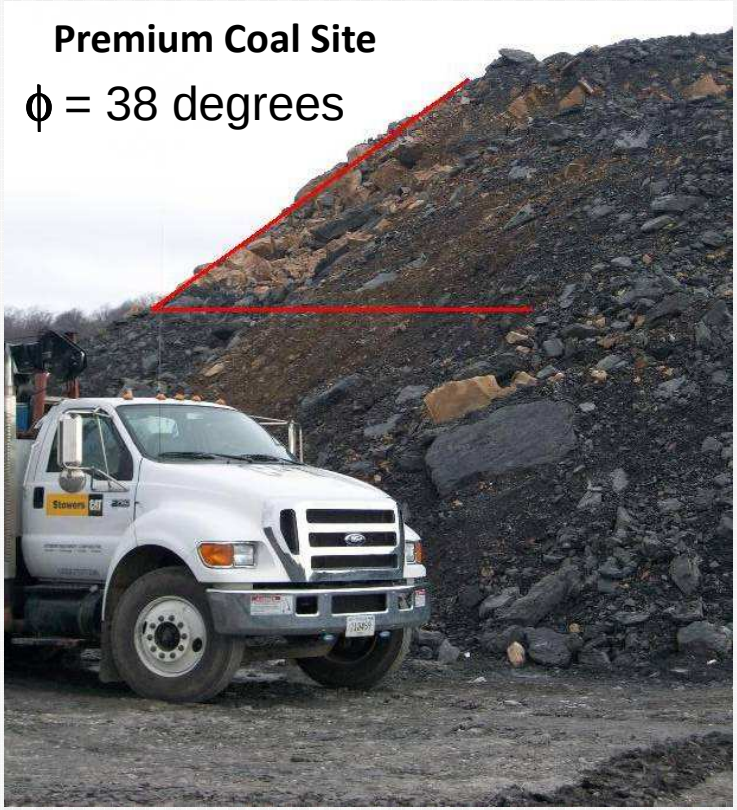
Filled Contours

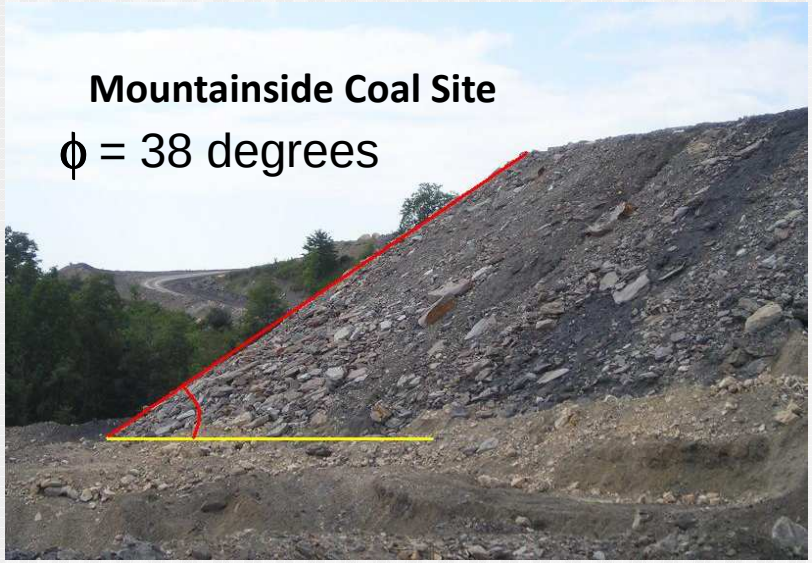
- **80-90 pcf**
- **90-100**
- **100-110**
- **110-120**
- **120-130**
- **130-140**
- **140-150 pcf**

English units lbs/ft³ (pcf)

Results: Strength Determination

Angle of Repose Measurement





Slope Stability:
Infinite Slope Approach

- Assume "infinite slope" *conditions* for Factor of Safety

$$FS_{\text{with no seepage}} = \frac{\tan\phi}{\tan q}$$

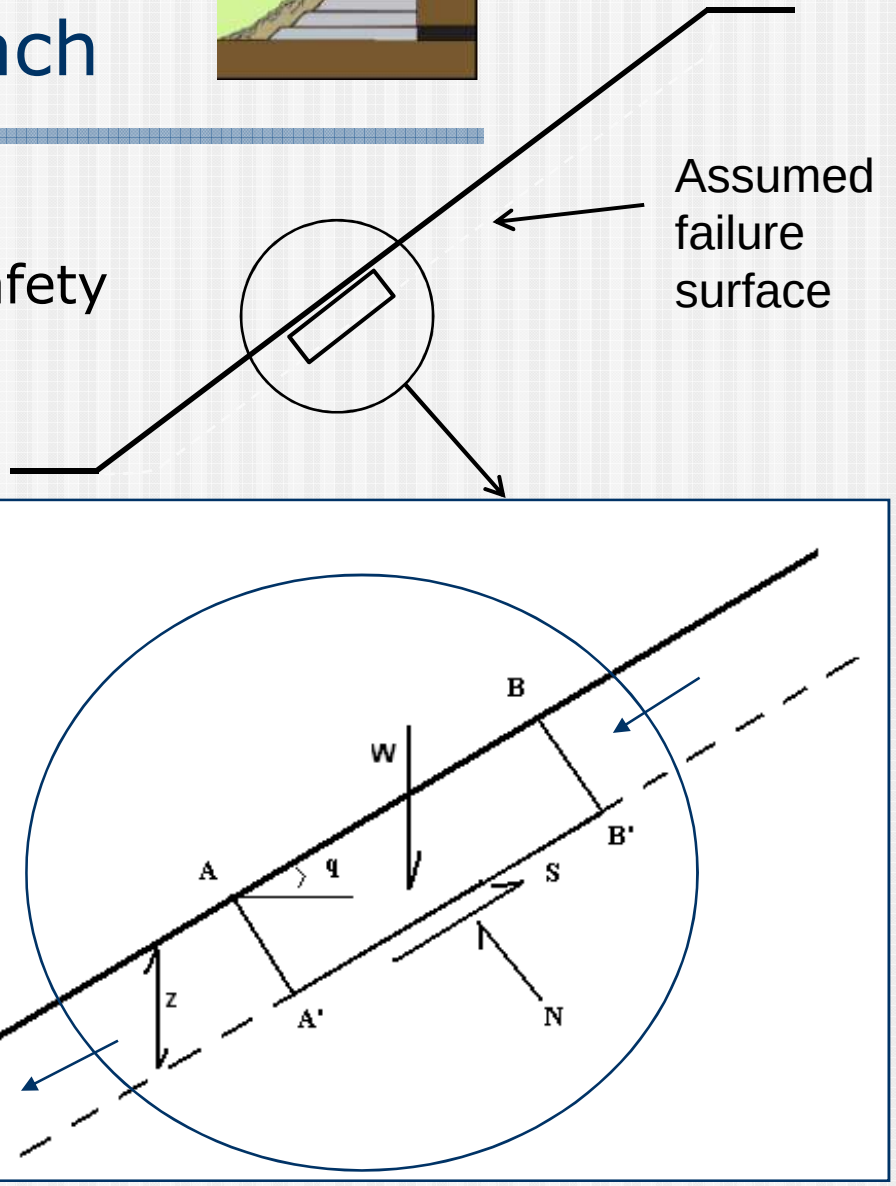
$$FS_{\text{with seepage}} = 0.5\frac{\tan\phi}{\tan q}$$

Where,

ϕ = angle of repose

= friction angle of loose material

q = slope angle



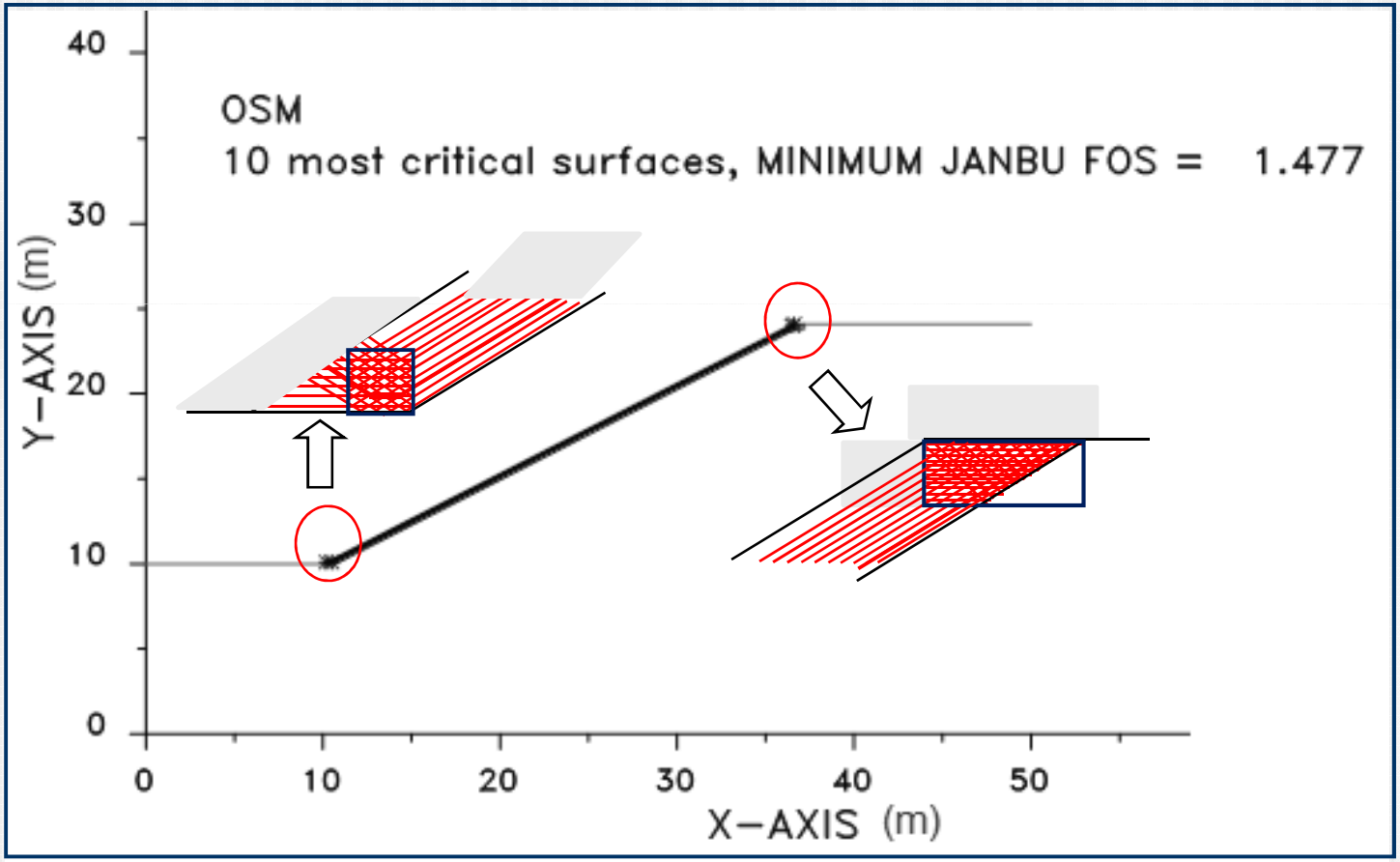
Results:
Factor of Safety for Slope Stability

SITE	Mean Angle of Repose (degrees)	Highest In-Situ Slope Angle (degrees)	Mean Upper Bound FS (no seepage parallel to slope)	Mean Lower Bound FS (with seepage parallel to slope)
Mountainside	38	30	1.4	0.7
National	37	22	1.9	0.95
Premium	38	29	1.4	0.7

$$\boxed{\text{soil strength} = \underbrace{c}_{0} + \sigma \tan \phi}$$

Note: These results assume a conservative (low) value for the strength and would correspond to the “long-term” stability (neglect strength contribution due to cohesion, c)

Results: Computer-based stability analysis



Slip surfaces analyzed with the block search feature of the software XSTABL for the drained analysis. Enlarged areas of the toe (left) and head (right) of the slope are illustrated.

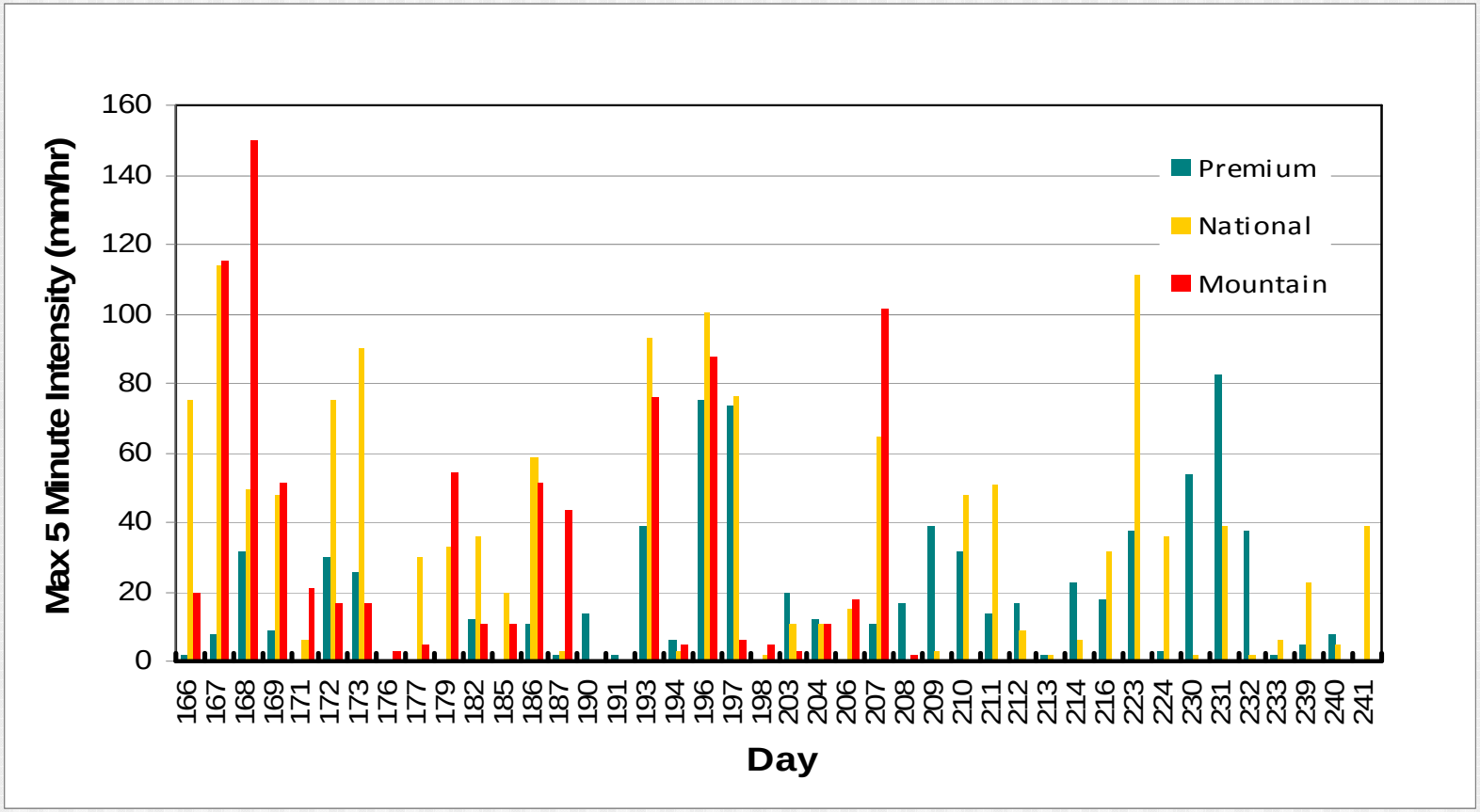
Results: Computer-based stability analysis

Long/Short Term	Slope Stability Method of Analysis	
Sliding mass with planar failure along Loose soil layer (Long Term Analysis)	Search Block (XSTABL) (no seepage effects)	Infinite Slope (no seepage effects)
	1.48	**1.47**

Analysis for a generic site

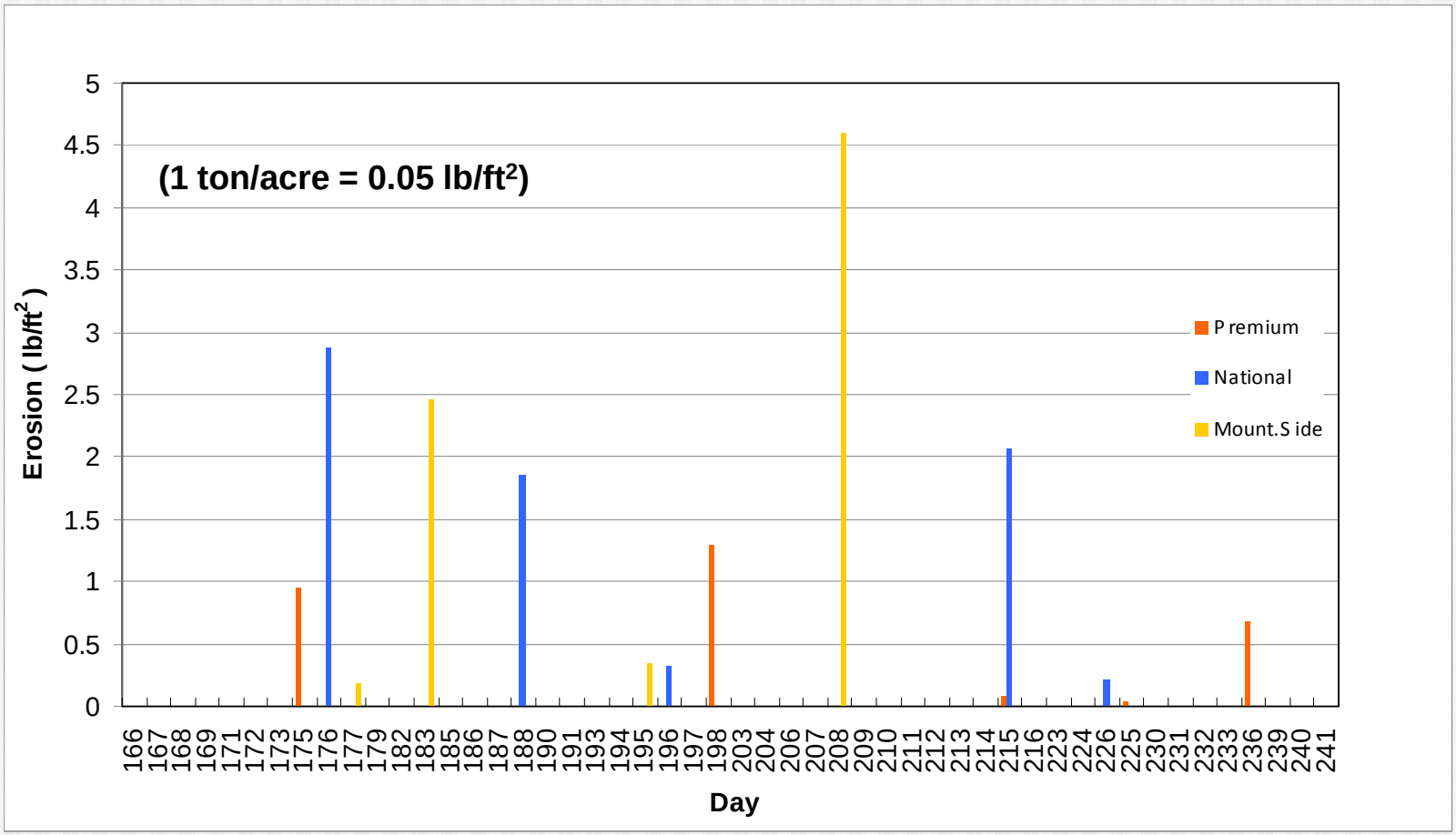
To achieve FS = 1.3:
for **ϕ = 37, inclination should be less than 30 degrees**

Hydrology & Erosion Results: Precipitation



Maximum five minutes rainfall intensity at each site (Hoomehr, 2010)

Results: Erosion (Sediment Yield)



Average erosion rate from each site (Hoomehr, 2010)

Soil Loss & RUSLE

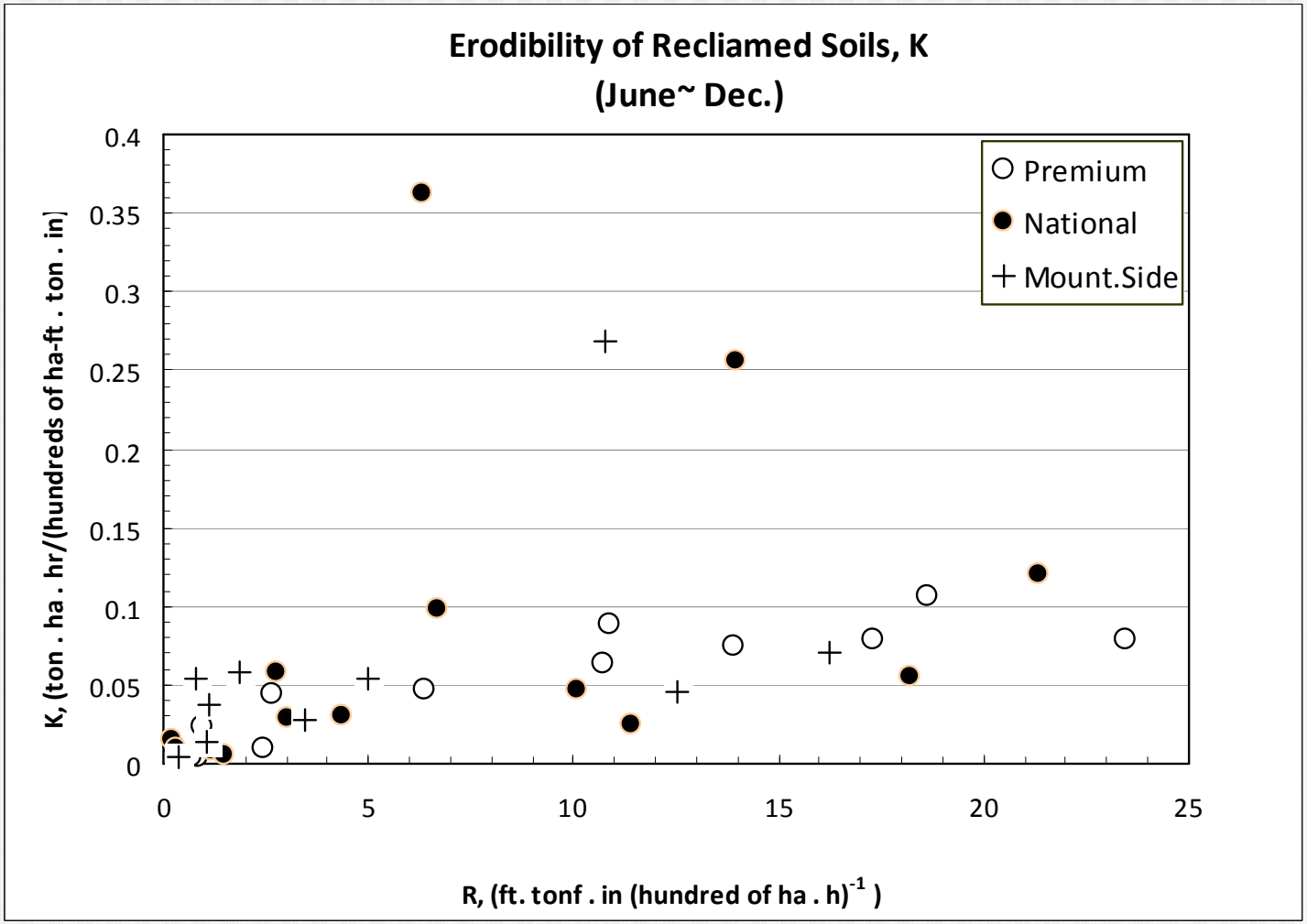
RUSLE (Revised Universal Soil Loss Equation):
Soil Loss equations were developed to extrapolate limited erosion data to the many localities and conditions that have not been directly represented in the research

The major forces driving erosion are from the impact of rain drops and from water flowing over land surface.

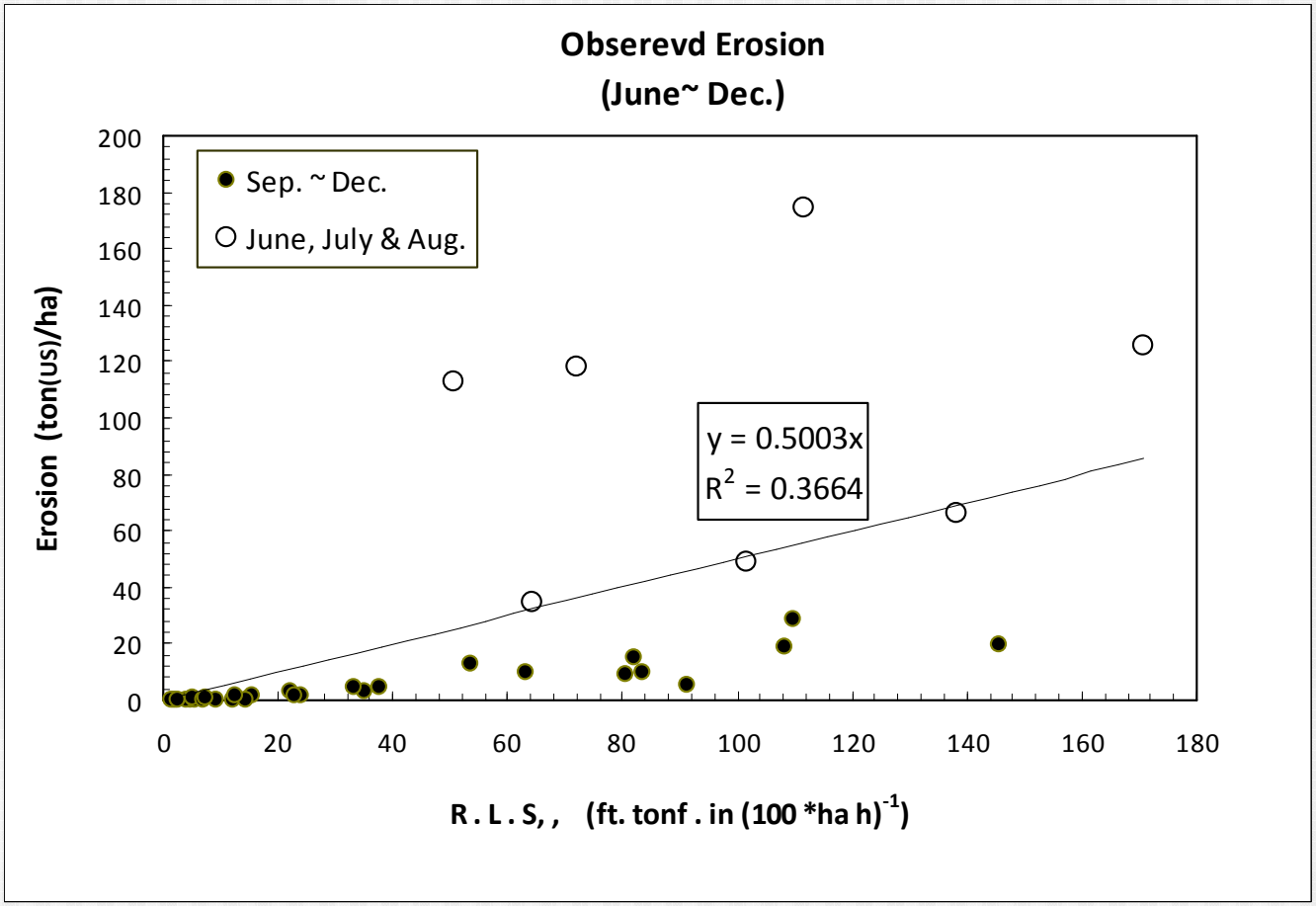
A= R. K. L. S . C . P

A = Amount of erosion occurred ($t \cdot ha^{-1}$)
R = Rainfall and runoff erosivity factor
K = Soil Erodibility factor
LS= Slope length and steepness factor
C = Cover management factor
P = Support practice factor

Results: K Factor



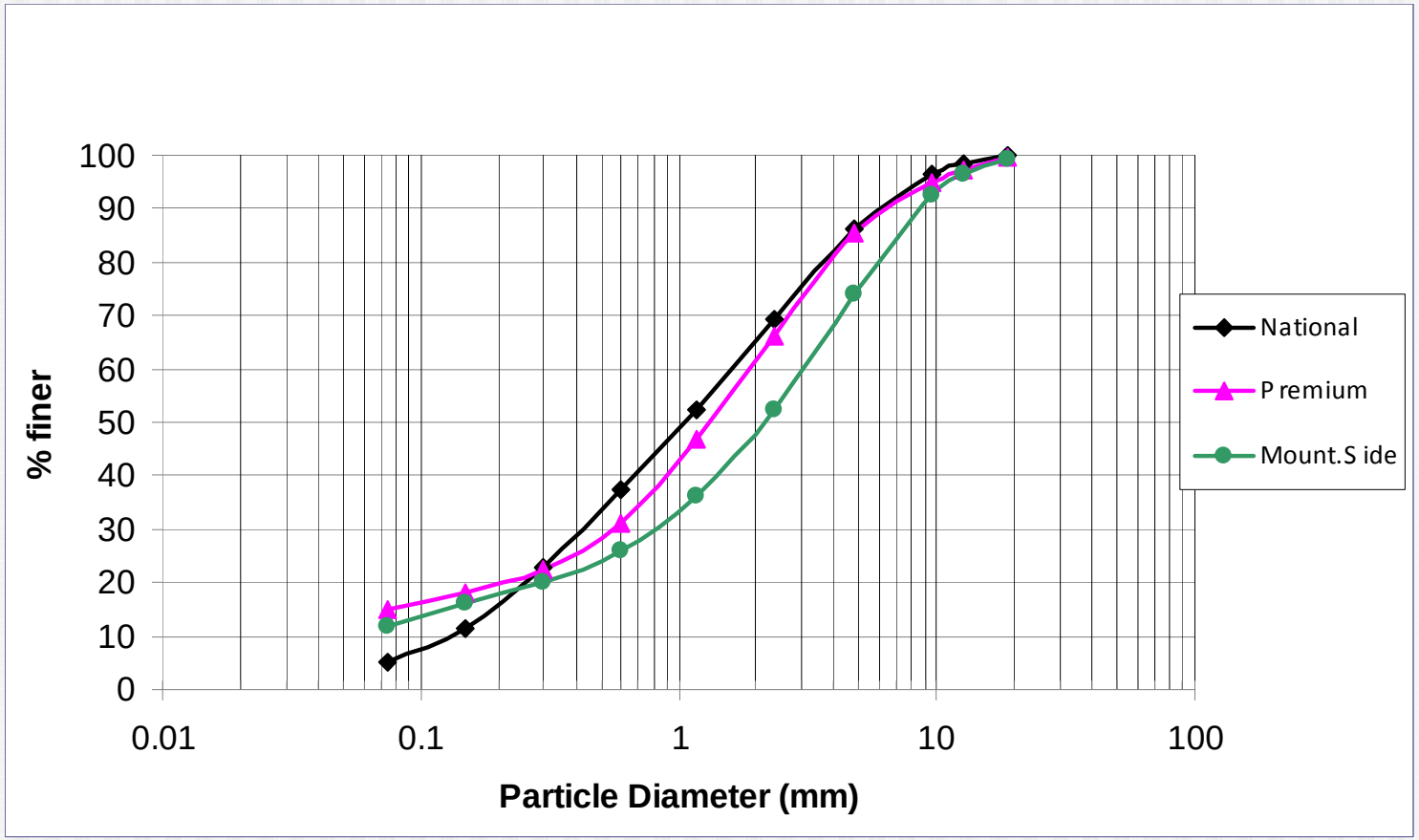
Results: K Factor



The plots constructed early 2009

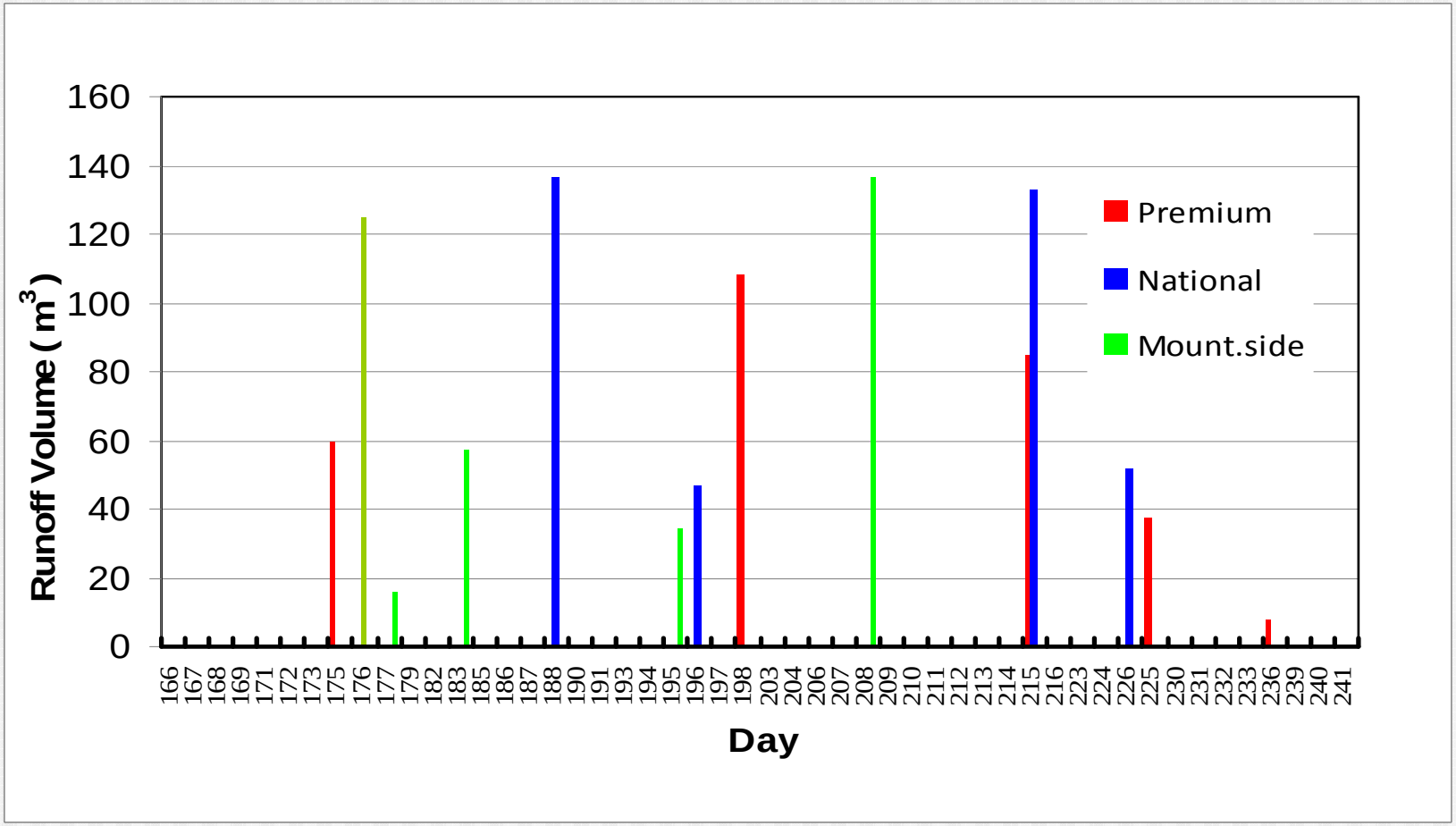
Mountainside: **study plot (left) no cover, established annual ground cover (right)**

Results: Eroded Sediment Particle Sizes



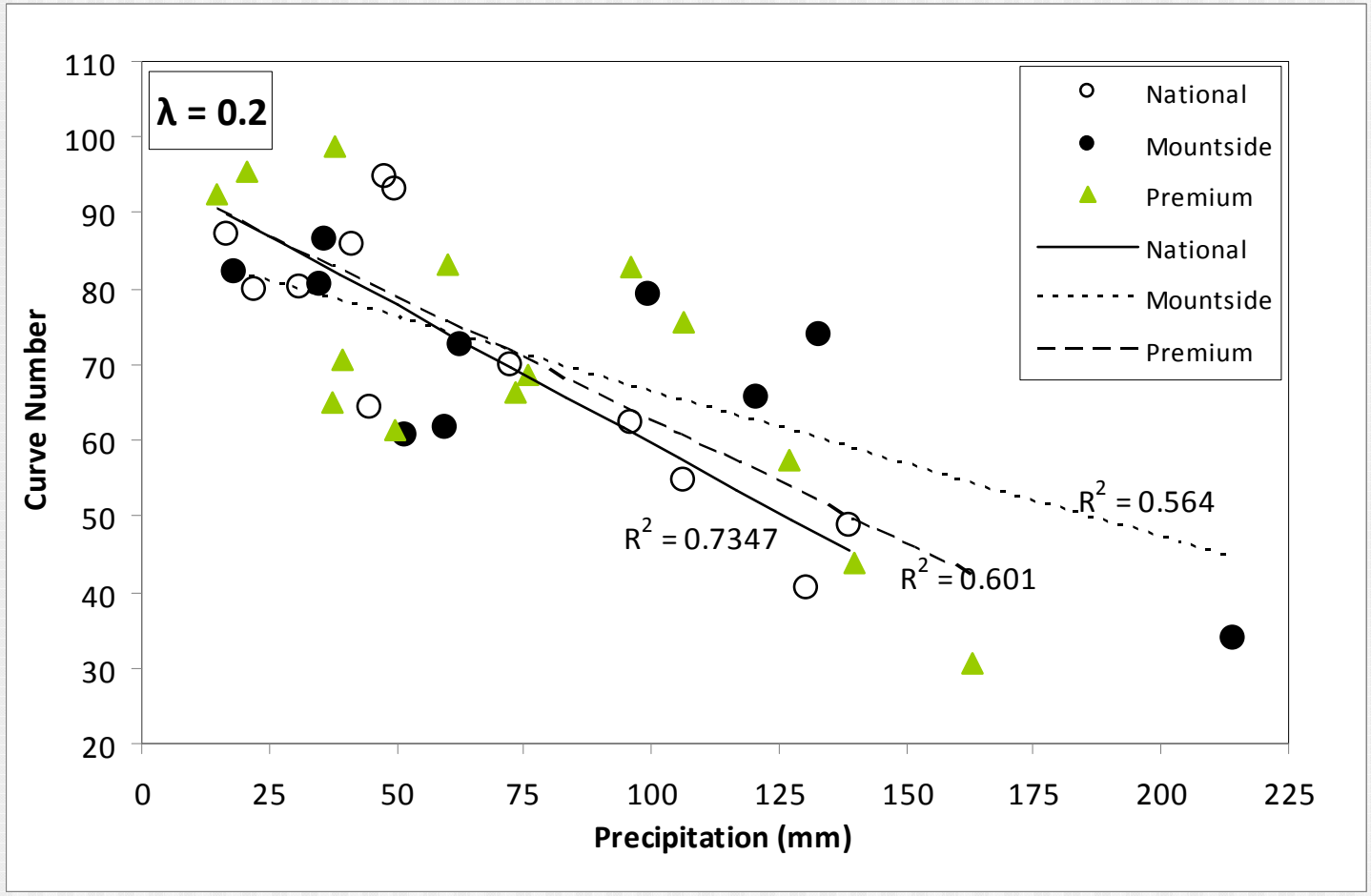
Typical particle size distribution of eroded material (for each site) for first three months after building the plots (June, July and August 2009)

Results: Runoff

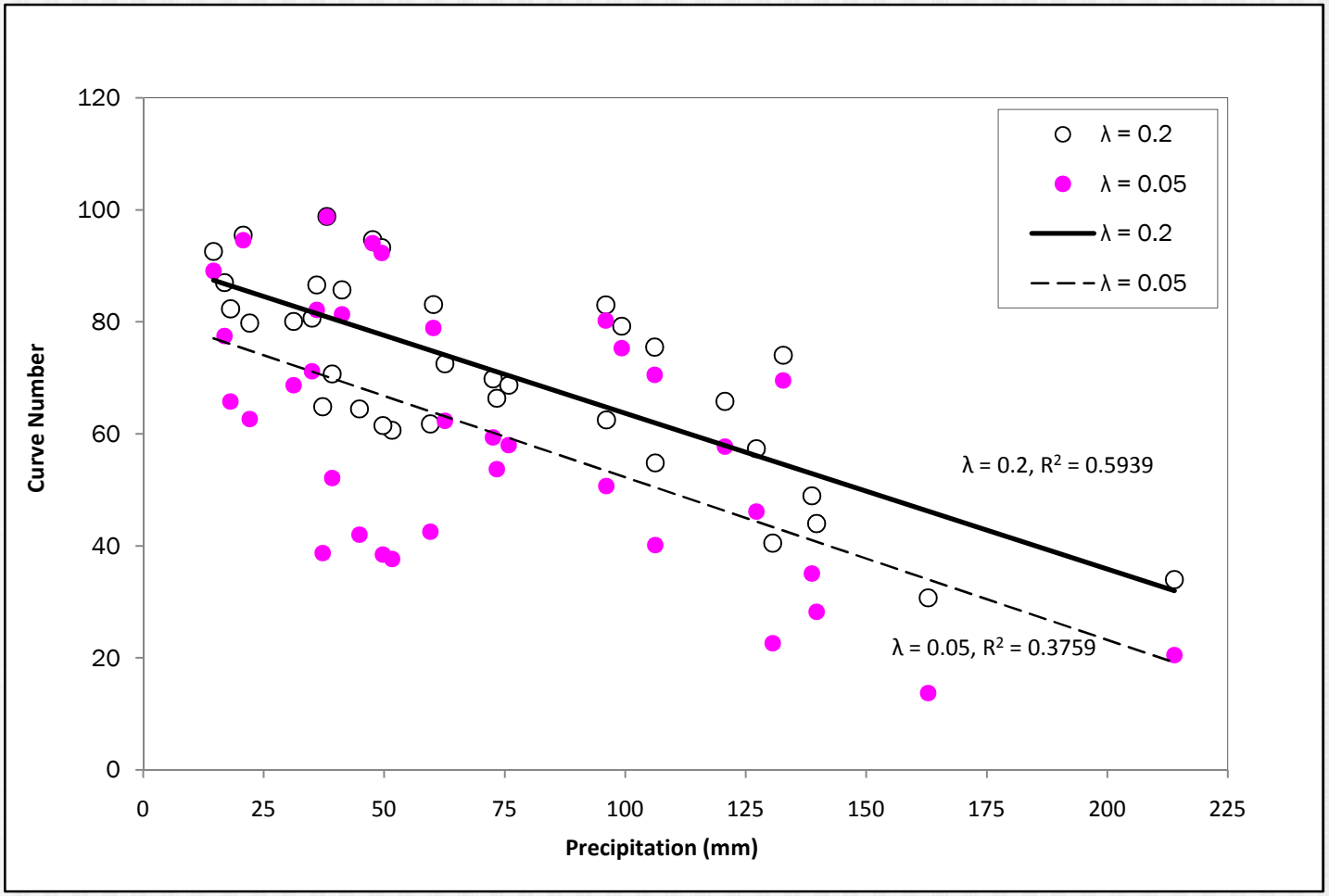


Runoff volume for each site (at each sampling day)

Results: CN


λ = 0.2
National
Mountside
Premium
National
Mountside
Premium
R^2 = 0.7347
R^2 = 0.601
R^2 = 0.564
Curve Number
Precipitation (mm)
110
100
90
80
70
60
50
40
30
20
0
25
50
75
100
125
150
175
200
225

Results: CN


λ = 0.2
λ = 0.05
λ = 0.2
λ = 0.05
λ = 0.2, R² = 0.5939
λ = 0.05, R² = 0.3759
Curve Number
Precipitation (mm)
0
20
40
60
80
100
120
0
25
50
75
100
125
150
175
200
225

Summary Results:
Erosion Sediment Yield and Runoff Curve Numbers

Erodibility of Reclaimed material is variable with time, which can be categorized into three major parts:

1) During formation of rills: $K_{avg.}$= 0.296 (~0.3) $\frac{tonf.ha.hr}{hundreds-of-ha.ft.ton.in}$

2) Transition period: $K_{avg.}$= 0.074 $\frac{tonf.ha.hr}{hundreds-of-ha.ft.ton.in}$

3) When the rills are stabilized: $K_{avg.}$= 0.052 $\frac{tonf.ha.hr}{hundreds-of-ha.ft.ton.in}$

CN values:

For λ = 0.2 has a range of value between 30.7 ~ 98.8 with an average of 71.75

For λ = 0.05 has a range of value between 20.5 ~ 98.76 with an average of 62.22

Conclusions

- Suggested method for evaluation of stability
  - ϕ = about 37 degrees for materials at 3 sites
  - FS > 1.3 provided slope less 30 degrees
- Developed model parameters for SEDCAD for hydrology and sediment yield, critical parameters for BMPs and detention pond designs.

Future Efforts

- Continue monitoring of slope stability condition on sites.
- Complete sediment erosion modeling and parameter sensitivity analysis using SEDCAD.
- Continue site monitoring of rill growth, and erosion yields as cover develops.
- Develop RUSLE C factors for different cover types.

Acknowledgments

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  - Premium Coal Company, Briceville, TN
  - Mountainside Coal Company, Clairfield, TN.
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Applied Science Project:

Reforestation of Steep Reclaimed Slopes: Stability and Sediment Control Considerations

Questions

Wesley Wright's skilled ATV operation; Mountainside Study Site; March 2009