times an error in design acceptance will occur. Selecting an alpha of 0.1 means there is a 10 percent probability of accepting a reclaimed channel design that does not meet the test criteria.

3.0 RESULTS

Based on the results of the inventory and the field investigation, reclaimed and natural channel characteristics were compiled for the two selected study sites. Results of the regression analysis indicate certain relationships between channel and drainage basin parameters predict ephemeral channel configuration. Three important channel design parameters were incorporated into a long-term stability evaluation.

3.1 Reclaimed Channel Characteristics

3.1.1 Rock Springs

The twenty reclaimed channels at the Colony and Rainbow mines south of Rock Springs form broad, shallow swales (Figure 4). Flow depths associated with the 10-year, 1-hour design event range from 0.1-0.3 feet deep, and top widths range from 5-7 feet (Tables A-1 through A-4). Minor incision of 1-4 inches was observed during field work in channel bottoms at the two abandoned mines (Figure 4). Design flow hydraulics described in AML reports accounted for a pilot channel, but it was not constructed as part of reclamation.

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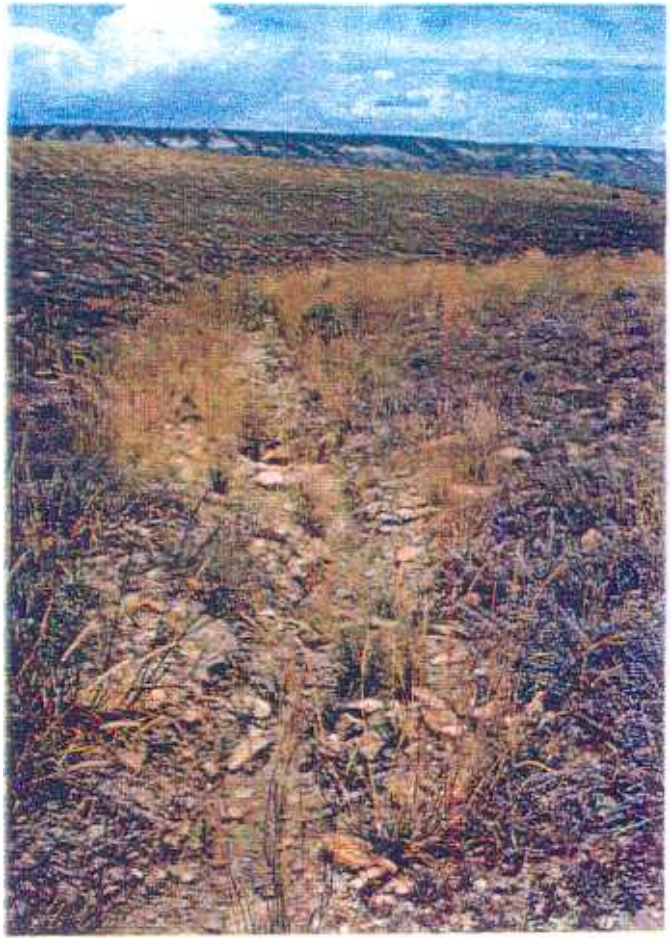

FIGURE 4 RECLAIMED CHANNEL AT COLONY MINE AML 6C–8 SOUTH OF ROCK SPRINGS, WYOMING.

3.1.2 Hanna

Information in AML files on reclaimed channels in the Hanna area was not complete. A single channel slope of 0.049 feet/feet and overall drainage basin area of 154 acres was reported for AML 7-26 (Table A-1 - A-4).

3.2 Natural Channel Characteristics

3.2.1 Rock Springs

Natural channels studied within the vicinity of Rainbow and Colony mines south of Rock Springs are largely alluvial, and have narrow, deep, V-shaped cross sections (Figure 5), a sharp contrast to the shallow swales at reclaimed sites. Local bedrock control is exerted in several of the unmined basins studied, where sandstone slabs crop out or armor channel bottoms. Mature sagebrush line all natural drainage courses, anchoring channel top banks and largely stabilizing against bank sloughing and lateral channel migration. Natural channel slopes are relatively steep, ranging from 0.03 to 0.13 feet/feet, with a mean of 0.0747 (Tables 2 and 3). Flow velocities associated with the 10-year, 1-hour flood events vary from 3.7 to 7.6 feet/second with a mean of 5.06 feet/second. Depths and top widths for 10-year, 1-hour discharges within the natural channels studied vary from 0.1-1.3 feet and 1.2-6.2 feet, respectively. A complete tabulation of unmined basin and channel characteristics for the Rock Springs study site is provided in Appendix B, Table B-1

Regression results indicate strong correlation between flow depth, flow area, hydraulic depth, hydraulic radius and Area Gradient Index (AGI) for unmined channels at Rock Springs

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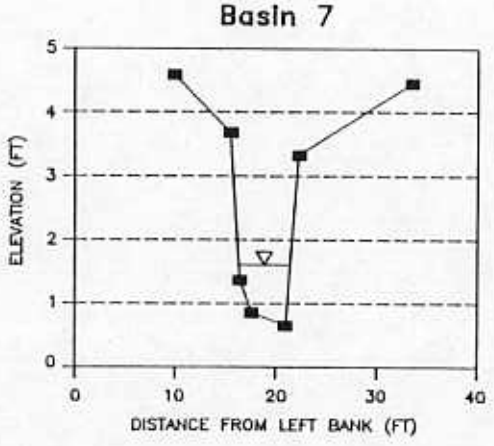
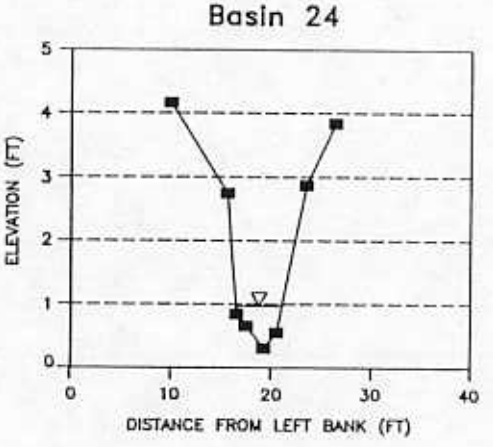
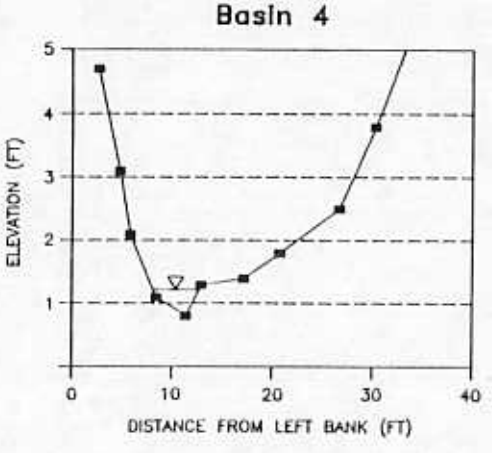
ROCK SPRINGS





HANNA



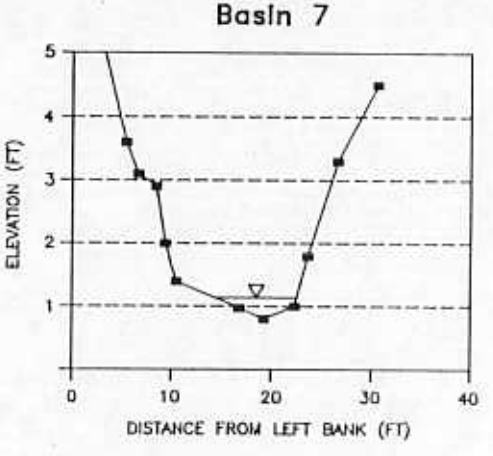


FIGURE 5: UNMINED CHANNEL CROSS SECTIONS

Table 2. Channel Slope and Flow Velocity Test Statistics for 10-yr, 1-hr Design Event, Rock Springs Study Site

Unmined Basin	AGI	Channel Slope (ft/ft)	10-yr Flow Velocity (ft/sec)	100-yr Flow Velocity (ft/sec)
3	1.06	0.072	4.03	3.7
4	4.51	0.077	6.97	9.85
5	2.78	0.134	7.60	10.9
6	6.30	0.038	6.16	8.53
7	6.82	0.051	6.64	9.64
7a	0.33	0.070	3.86	5.87
7'	2.42	0.048	4.83	6.95
12a	0.43	0.128	4.56	6.72
12b	0.07	0.131	2.99	4.42
13	1.70	0.087	5.86	8.36
15	3.16	0.049	5.84	8.21
16	4.92	0.026	4.68	5.36
16a	2.16	0.058	4.05	5.92
24	2.39	0.049	4.84	7.27
25	0.99	0.100	5.47	8.04
28	1.41	0.078	3.98	6.38
31	0.52	0.075	3.66	5.37
Mean	2.47	0.0747	5.06	7.15
Stand. Dev	2.07	0.0325	1.29	1.98
n	17			
(Sx)^2	1762.12			
S(x^2)	172.27			
Sum of Squares for Error				
SSE=		0.0170	26.6506	
Se=		0.0326	1.2906	

Reclaimed Basin		AGI	Channel Slope (ft/ft)	Flow Velocity (ft/sec)	Case 1: Is Channel Slope< Upper Limiting Slope	Case 1: Is Velocity <Upper Limiting Velocity	Case 2: Is Channel Slope< Upper Limiting Slope	Case 2: Is Velocity <Upper Limiting Velocity
Upper Limiting Value:					0.0642	4.64	0.0543	4.25
6C-2 Rainbow Mine	1	0.19	0.02	2.35	Yes	Yes	Yes	Yes
	2	0.16	0.02	2.18	Yes	Yes	Yes	Yes
	3	0.09	0.02	1.94	Yes	Yes	Yes	Yes
	4	0.20	0.03	2.49	Yes	Yes	Yes	Yes
	5	0.11	0.02	1.83	Yes	Yes	Yes	Yes
	6	0.09	0.03	1.97	Yes	Yes	Yes	Yes
	7	0.25	0.03	2.61	Yes	Yes	Yes	Yes
	8	0.08	0.06	1.97	Yes	Yes	No	Yes
	9	0.21	0.03	2.31	Yes	Yes	Yes	Yes
	10	0.16	0.04	2.23	Yes	Yes	Yes	Yes
	11	0.20	0.05	2.45	Yes	Yes	Yes	Yes
	12	0.21	0.08	2.57	No	Yes	No	Yes
	13	0.17	0.07	2.27	No	Yes	No	Yes
	14	0.08	0.02	1.83	Yes	Yes	Yes	Yes
	15	0.05	0.02	1.67	Yes	Yes	Yes	Yes
	16	0.30	0.04	2.75	Yes	Yes	Yes	Yes
6C-8 Colony Mine	I	0.39	0.075	2.75	No	Yes	No	Yes
	II	0.82	0.048	2.92	Yes	Yes	Yes	Yes
	III	0.38	0.04	2.52	Yes	Yes	Yes	Yes
	IV	0.09	0.01	1.50	Yes	Yes	Yes	Yes

Stability Analysis for Channel Slope and Flow Velocity:

Confidence Interval:

$$\textit{Upper Limit} = \bar{x} - t_{\alpha,n-1} s \sqrt{\frac{1}{n}}$$

case 1: $t = 1.337$ *for* $\alpha = 0.10$

case 2: $t = 2.585$ *for* $\alpha = 0.01$

Table 3. Flow Area Test Statistics for 10-yr, 1-hr Design Event, Rock Springs Study Site

Unmined Basin	AGI	Flow Area (sqft)
3	1.06	0.70
4	4.51	2.41
5	2.78	1.10
6	6.30	3.73
7	6.82	3.39
7a	0.33	0.56
7'	2.42	1.41
12a	0.43	0.31
12b	0.07	0.10
13	1.70	0.92
15	3.16	2.34
16	4.92	3.76
16a	2.16	0.92
24	2.39	1.70
25	0.99	0.68
28	1.41	1.29
31	0.52	0.37

Reclaimed Basin		AGI	Actual Flow Area (sqft)	Pred. Flow Area (sqft)	Case 1: Lower Limit Flow Area 1.341	Case 1: Is Flow Area > Lower Limiting Area	Case 2: Lower Limit Flow Area 2.602	Case 2: Is Flow Area > Lower Limiting Area
6C-2 Rainbow Mine	1	0.19	1.23	0.26	0.44	Yes	0.62	Yes
	2	0.16	1.05	0.24	0.43	Yes	0.60	Yes
	3	0.09	0.78	0.20	0.39	Yes	0.57	Yes
	4	0.20	0.92	0.26	0.45	Yes	0.62	Yes
	5	0.11	0.71	0.21	0.40	Yes	0.58	Yes
	6	0.09	0.56	0.20	0.39	Yes	0.57	No
	7	0.25	0.96	0.29	0.47	Yes	0.65	Yes
	8	0.08	0.30	0.20	0.39	No	0.57	No
	9	0.21	0.78	0.27	0.45	Yes	0.63	Yes
	10	0.16	0.53	0.24	0.43	Yes	0.61	No
	11	0.20	0.53	0.26	0.45	Yes	0.62	No
	12	0.21	0.35	0.27	0.45	No	0.63	No
	13	0.17	0.35	0.24	0.43	No	0.61	No
	14	0.08	0.71	0.20	0.39	Yes	0.57	Yes
	15	0.05	0.60	0.18	0.37	Yes	0.56	Yes
	16	0.30	0.84	0.32	0.50	Yes	0.67	Yes
6C-8 Colony Mine	I	0.39	0.62	0.37	0.54	Yes	0.71	No
	II	0.82	1.06	0.60	0.76	Yes	0.91	Yes
	III	0.38	0.95	0.36	0.54	Yes	0.71	Yes
	IV	0.09	1.33	0.20	0.39	Yes	0.57	Yes

Population Statistics:

Mean	2.47	1.51
n	17	
(Sx) ^ 2	1762.1	
S(x ^ 2)	172.3	
S(X-Xavg)	68.62	
Sum of Squares for Error (SSE)		2.1541
Mean Square Error (MSE)		0.3790

Flow Area vs. AGI

Regression Output:

Constant	0.1515
Std Err of Y Est	0.3790
R Squared	0.9062
No. of Observations	17
Degrees of Freedom	15
X Coefficient(s)	0.5506
Std Err of Coef.	0.0457

Stability Analysis for Flow Area:

Confidence Interval:

$$\textit{Lower Limit} = \hat{y} + [t_{\alpha,n-2}(S\sqrt{\frac{1}{n} + \frac{n(x_o-\bar{x})^2}{n\Sigma x_i^2 - (\Sigma x_i)^2}})]$$

case 1: t = 1.341 *for* α = 0.10

case 2: t = 2.602 *for* α = 0.01

(Table 4). AGI was developed as a proxy-measurement for total stream power, and is calculated as the product of drainage area and channel slope (Schumm et al., 1984). In this study, mean basin slope was substituted for channel slope in the determination of AGI, such that the independent variable (AGI) consists solely of the more inflexible elements of reclamation design (drainage basin area, mean basin slope) that are easily derived from topographic maps. Reference to AGI herein is the product of drainage basin area and mean basin slope, rather than channel slope. (Mean basin slope is measured from topographic maps as the length of the longest stream divided by change in elevation from top of basin to mouth). Strong correlation between 10 and 100-year discharge and AGI, and poor correlation between stream power or shear stress and AGI indicates that, for purposes of this study, AGI is a surrogate measure of flow magnitude. Thus, AGI was selected as the primary independent variable because it correlates most strongly with hydraulic variables.

By definition, flow area is related to flow depth, hydraulic depth, and hydraulic radius. It was decided to use flow area singularly in the statistical analysis with AGI because it is a standard variable in engineering channel design. Multiple regression was not conducted to avoid covariation amongst dependent variables. A plot of channel flow area for the 10-year, 1-hour event versus AGI is provided in Figure 6. It is evident from Figure 6 that reclaimed channel flow areas are greater than corresponding unmined channels in the Rock Springs area.

3.2.2 Hanna

Unmined channels studied are north-northeast of Hanna, and are largely alluvial. Numerous headcuts and vertical channel adjustments were observed in every basin assessed.

Table 4. Regression Equations with $R^2 > 0.60$ for Unmined Channels, Rock Springs and Hanna Study Sites

Rock Springs

10-Year Event

Depth (ft.)	= 0.129 (AGI) + .27	$R^2 = 0.76$
Flow Area (ft.^{2})	= 0.552 (AGI) + .16	$R^2 = 0.91$
Hydraulic Radius (ft.)	= 0.075 (AGI) + .15	$R^2 = 0.90$
Hydraulic Depth (ft.)	= 0.087 (AGI) + .16	$R^2 = 0.90$

100-Year Event

Depth (ft.)	= 0.225 (AGI) + .49	$R^2 = 0.84$
Flow Area (ft.^{2})	= 1.311 (AGI) + .56	$R^2 = 0.82$
Hydraulic Radius (ft.)	= 0.117 (AGI) + .27	$R^2 = 0.86$
Hydraulic Depth (ft.)	= 0.145 (AGI) + .30	$R^2 = 0.85$

Hanna

10-Year Event

Depth (ft.)	= 0.098 (AGI) + .20	$R^2 = 0.88$
Flow Area (ft.^{2})	= 0.401 (AGI) + .29	$R^2 = 0.88$
Hydraulic Radius (ft.)	= 0.038 (AGI) + .15	$R^2 = 0.68$
Hydraulic Depth (ft.)	= 0.066 (AGI) + .12	$R^2 = 0.91$

100-Year Event

Depth (ft.)	= 0.166 (AGI) + .35	$R^2 = 0.85$
Flow Area (ft.^{2})	= 1.163 (AGI) + .52	$R^2 = 0.88$
Hydraulic Radius (ft.)	= 0.077 (AGI) + .23	$R^2 = 0.81$
Hydraulic Depth (ft.)	= 0.084 (AGI) + .27	$R^2 = 0.79$

Note: AGI = Area Gradient Index (Drainage Area * Mean Basin Slope)

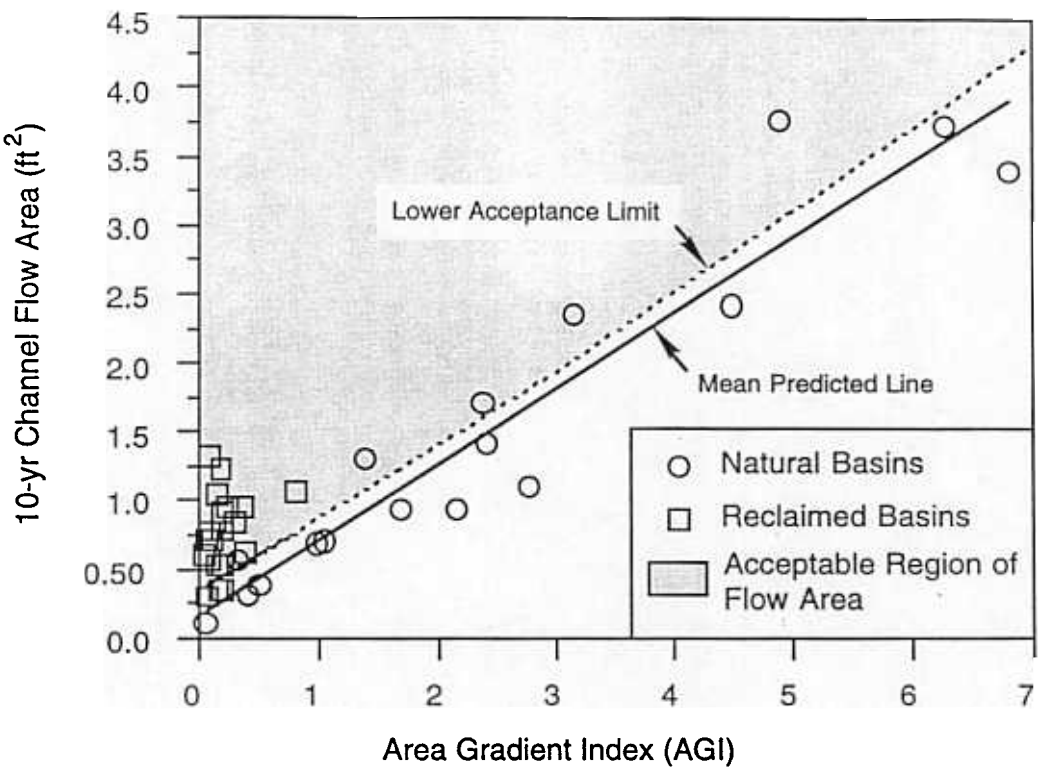


Figure 6. Limiting Flow Area for $\alpha = 0.10$, Rock Springs Study Site.

Channels are less entrenched than at Rock Springs, with larger cross sectional areas (Figure 5), and sagebrush is less important in bank stabilization. It was difficult to find truly undisturbed areas adjacent to AML site 7-26 due to continued active mining in the area, and dated maps and aerial photographs. As a result, only a limited number of basins were judged as undisturbed and actually measured. Channel slopes of the Hanna drainages are steeper than Rock Springs, ranging from 0.02 to 0.198 feet/feet, and 10-year flow velocities vary from 3.1 to 6.8 with a mean of 5.4 feet/second (Table 5). Regression relations of flow depth, flow area, hydraulic depth, and hydraulic radius on AGI produced strong correlation (Table 4), consistent with the Rock Springs findings. The fact that similar parameters produced high correlation coefficients indicates AGI (between 0 and 9 acres) predicts channel characteristics of flow area, flow depth, hydraulic radius and hydraulic depth for the southern Wyoming region from Rock Springs to Hanna.

3.3 Risk-based Stability Evaluation

A stability evaluation of reclaimed channels at the Rainbow and Colony mines was developed using the three channel parameters judged most useful in engineering channel design; channel slope, flow velocity for the design event, and cross sectional flow area. The risk-based approach allows user flexibility in choosing levels of error, and two cases involving different risk levels where evaluated: 1) Case 1, a less stringent test with higher alpha (0.10), and 2) Case 2, a more stringent evaluation with lower alpha (0.01).

Table 5. Flow Area, Channel Slope, and Flow Velocity, Unmined Basins, Hanna Study Site

Unmined Basin	AGI	10-Year Flow Area (ft2)	Channel Slope (ft/ft)	10-Year Flow Velocity (ft/sec)	100-Year Flow Velocity (ft/sec)
1	5.30	3.31	0.016	3.91	5.11
1a	0.84	0.34	0.106	5.26	7.20
2	9.18	3.36	0.047	6.80	9.56
3	3.46	1.64	0.082	6.24	9.31
4	2.14	1.09	0.109	6.17	7.29
5	3.71	2.09	0.057	6.30	9.60
6	1.73	0.77	0.198	6.40	9.75
7	3.45	1.86	0.090	5.28	7.58
8	0.19	0.32	0.053	3.11	4.40
9	0.18	0.23	0.097	4.46	6.20
Population Statistics:					
Mean	3.02	1.50	0.0854	5.39	7.60
Standard Dev.	2.73	1.17	0.0494	1.22	1.94
n	10				
(Sx) ^ 2	910.89				
S(x ^ 2)	158.29				
Sxx	67.20				
Sum of Squares for Error (SSE)		1.45			
Mean Square Error (MSE)		0.43			
Area Gradient Index vs. Flow Area - Regression Output:					
Constant					
Std Err of Y Est			0.289		
R Squared			0.426		
No. of Observations			0.882		
Degrees of Freedom			10		
X Coefficient(s)		0.401			
Std Err of Coef.		0.052			

Limiting Values:

	Acceptable Alpha Error Levels	
	0.10	0.01
Flow Area	See Figure 7	
Channel Slope (ft/ft)	0.0638	0.0413
10-Year Velocity (ft/sec)	4.86	4.30
100-Year Velocity (ft/sec)	6.75	5.86

3.3.1 Channel Slope

Over the range of natural data collected, channel slope does not correlate with drainage area or AGI. Since channel slope directly influences flow velocities in both reclaimed and natural channels, and hence affects erosion potential, it is included in this evaluation of channel stability. Due to poor correlation, channel slope was tested for randomness, and can be considered to have a normal distribution. Channel slope is thus treated as a random variable with confidence intervals about the mean of natural data calculated using Equation 1. Results of the statistical test for reclaimed channel slope are provided in Table 2.

Channel slope for all but reclaimed Basins 12 and 13 at the Rainbow mine, and Basin I at Colony Coal mine are less than the upper confidence limit of 0.0642 feet/feet for alpha=0.10, the Case 1 error selected. By increasing the confidence level to 99% (alpha=0.01), as in Case 2, fewer reclaimed channel slopes are shallower than the more stringent slope limit of 0.0543 feet/feet (Table 2). Four of the 20 reclaimed channels at Rainbow and Colony mines fail the stability test for channel slope using alpha at 0.01. Channel slopes steeper than the mean of natural analog sites will generate higher-than-normal flow velocities and undesirable erosion will likely result.

3.3.2 Flow Velocity

Similar to channel slope, natural channel flow velocity is poorly correlated with drainage basin parameters. Flow velocity is assumed to be normally distributed and Equation 1 applies for calculating confidence intervals. Results of the evaluation indicate all of the reclaimed 10-year channel flow velocities are acceptable below the limit of 4.64 feet/second for Case 1 (Table

2). Designed flow velocities for the reclaimed channels are consistently less than 3 feet/second, and pass the stability evaluation at both the 90% and 99% confidence levels for Cases 1 and 2.

3.3.3 Flow Area

Equation 2 was used to compute confidence limits for analog channels at Rock Springs. Equation 2 is applicable to relations with strong correlation such as between flow area and AGI. The 10-year, 1-hour channel flow areas for reclaimed drainages at the Rainbow and Colony mines are acceptable in Case 1 except for reclaimed Basins 8, 12, and 13 (Table 3). Acceptable flow areas include those greater than or equal to the lower limit established by unmined data at alpha=0.1 (Figure 6). Flow area varies as a function of basin parameters (AGI) and, therefore, the lower limiting flow area is a range of values, depicted as the lower limit on Figure 6, and depends on AGI.

In Case 2, using an alpha level of 0.01, which indicates a 99% assurance that the mean flow area of unmined channels is greater than the limiting value, and that a Type I error will only occur 1 in 100 times, 7 of the 20 reclaimed flow areas are rejected, in that the flow areas are too small (Table 3). Wider confidence bands at alpha=0.01 encompass more points between the mean and limiting lines. Flow areas smaller than the lower limit or the rejection region of natural analog areas may produce higher velocities and a greater potential for erosion.

As is clear, a lower alpha (0.01) provides a more conservative approach to evaluating design flow areas by accepting only those greater than the 99% confidence level about the mean flow area established by natural analog channels. Depending on the application, a lower alpha may be better suited for evaluating recently constructed channels where vegetation is sparse or

non-existent. Differences in soil compaction, general disturbance of the soil substrate due to mining, and the lack of vegetation are factors that may warrant a more stringent stability test for proposed channel reclamation or recently constructed channels. The one-tailed statistical test accepts shallower channel slopes or larger flow areas than natural channel systems, desirable conditions that minimize flow velocity within a channel and favor more conservative designs. The risk-based approach of selecting acceptable error adds an additional level of flexibility for regulatory design review and channel stability evaluations.

While the design event at the Rainbow and Colony mines is the 10-year, 1-hour, results of the 100-year, 1-hour are useful because it is the more commonly selected design event. Channel slopes, and flow velocities for the 100-year, 24-hour event are reported in Appendix B (Tables B-1 and B-2).

3.4 Application of Risk-based Method

Dual application of the risk-based stability evaluation is illustrated using the Hanna study site. First, this stability test can function as a tool by which AML or DEQ/LQD personnel evaluate channel designs. With limited data on unmined basins near Hanna (Table 5), designed flow areas submitted to DEQ/LQD or AML for approval that are greater than the lower limit depicted on Figure 7 would be determined stable over the long-term, provided AGI falls between 0 and 9, the constraints of the data set. Likewise, channel slopes and flow velocities less than 0.0638 feet/feet and 4.86 feet/second, respectively, (Table 5) are determined as limiting values for the Hanna area at alpha=0.10. For a more conservative test (alpha=0.01), channel slopes less than 0.0413 feet/feet and flow velocities less than 4.30 feet/second would be acceptable

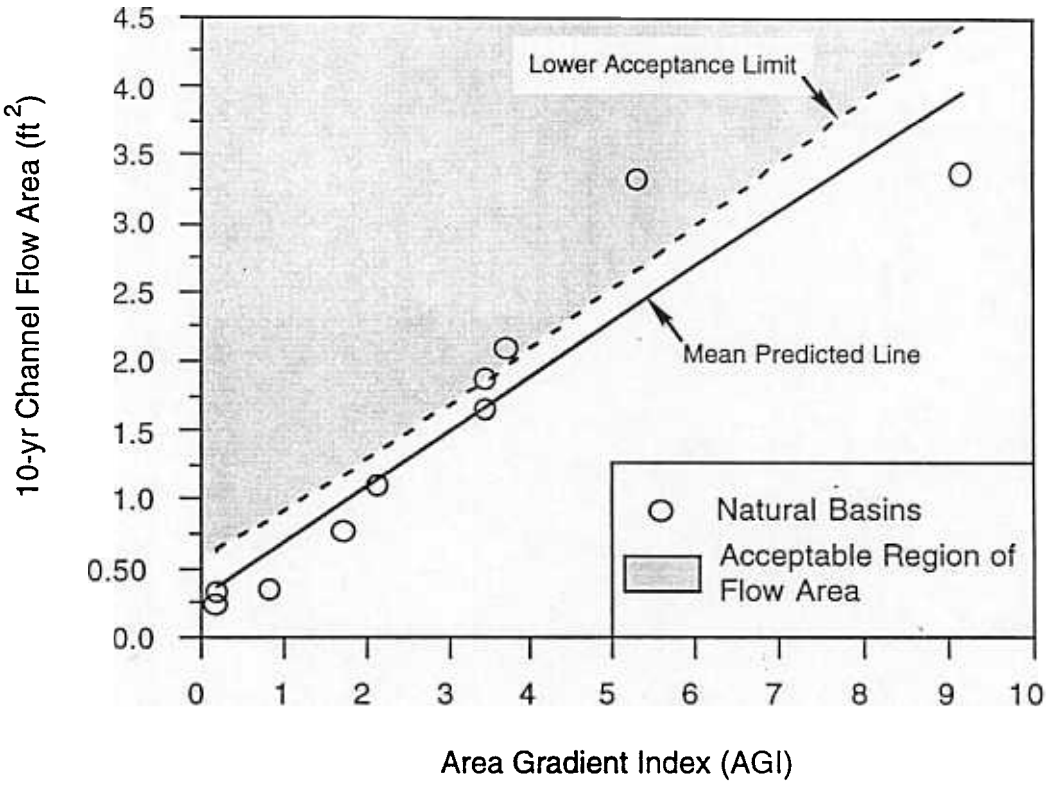


Figure 7. Limiting Flow Area for $\alpha = 0.10$, Hanna Study Site.

acceptable within the Hanna area. Designed channels that have had limited time of exposure to surface water flow, or design plans submitted for initial approval, may be more conservatively evaluated using a smaller alpha level (0.01 vs. 0.1) when vegetation is immature, recently seeded, or nonexistent.

Secondly, reclamation specialists can use this risk-based stability evaluation for designing channels in a particular area of interest. If natural analog data are available for the site, the technique of balancing channel cross sectional area (flow area) and channel slope to attain a permissible velocity can target limiting slope and velocity values developed for unmined areas. In these cases, an acceptable alpha level should be established that suits both designer and design reviewer, and is appropriate for the application.

Use of the three parameters (flow area channel slope, and flow velocity), to judge channel stability is advised such that a minimum of two out of the three tests are satisfied prior to design acceptance. Since channel slope and flow velocity data from unmined drainages at Rock Springs and Hanna are random, based on a test for normality, the three stability tests function independently. This is in contrast to the actual process of engineering design where channel slope and flow area are linked to velocity via Manning's equation. For example, reclaimed Basin 12 at the Rainbow Mine has a steeper channel slope (Table 2) and a smaller flow area (Table 3) than adjacent natural areas at the 90% confidence limit. Flow velocity within Basin 12 is acceptable, however, at the 90% confidence limit, a result that contradicts the flow area and channel slope tests. The large standard deviation (1.29 feet/second) about the mean flow velocity (Table 2) means that a much wider range of velocities are accepted for a

given alpha. We recommend using discretion in selecting which stability tests best serve the situation and selecting a satisfactory risk level.

3.5 Geographic Transferability

A test was conducted to assess the differences between mean channel slope and flow velocity for natural analog data from Rock Springs and Hanna. There is no statistical difference between mean values of channel slope and flow velocity between the two sites, indicating similar ephemeral channel controls and influences for basins 0.5 to 78 acres in size within southwestern and south central Wyoming.

The stability tests were recalculated using the Hanna and Rock Springs population mean values of 0.0787 feet/feet and 5.18 feet/second for channel slope and flow velocity, respectively. Upper limiting channel slope increased slightly and limiting velocity decreased slightly for the Rock Springs study site, and the Hanna data changed in the reverse, decreased channel slope and flow velocity. No changes occurred to the acceptance or rejection of the channel designs, however.

Although the data collected and evaluated herein are limited to a small region, larger areas with abundant coal mining such as the Powder River Basin of northeastern Wyoming could benefit from a stability analysis. The potential exists to further expand the applicability of the proposed stability tests by utilizing data available in mine permit applications. It would be instructive to determine if similar flow area and AGI relationships exist over large geographic regions with different climatic and geologic controls.