LONG-TERM STABILITY OF DESIGNED EPHEMERAL CHANNELS AT RECLAIMED COAL MINES, WYOMING

May 25, 1993

Final Technical Report
for
Abandoned Coal Mine Lands
Research Program

Submitted By:

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ABSTRACT

Restoring the landscape to a stable configuration is central to the reclamation of abandoned coal mines in Wyoming. Reclamation efforts seek to reestablish long-term channel stability by efficiently routing surface water and sediment, while minimizing erosional processes. Evaluating the long-term performance and success of channel reclamation is a great challenge for government regulatory personnel because major channel adjustments typically occur in response to large, infrequent flood events. A risk-based channel stability analysis is presented to facilitate regulatory decisions and engineering design by statistically comparing reclaimed channel designs with natural analog areas. An inventory of reclaimed channel information was compiled for AML coal sites in Wyoming. Natural data for 17 basins adjacent to the Rainbow and Colony mines in south central Wyoming were collected in the field. For purposes of this study natural, undisturbed drainage basins adjacent to the mined areas are considered stable. Three channel parameters that are important channel design elements (channel slope, flow velocity, channel flow area) comprise separate long-term stability tests. One-tailed confidence intervals calculated about the mean predicted channel slope, flow velocity, and flow area from the natural data indicate that 18 out of 20 reclaimed channels at the Rainbow and Colony mines are stable at a risk level or alpha=0.1. Alpha is the risk associated with accepting a channel design that does not meet the stability test criteria. A more stringent stability test, alpha=0.01, indicates that 16 out of the 20 reclaimed channels are stable. Those channels that do not satisfy the stability test either have steeper channel slopes or smaller flow areas than the mean from adjacent natural channels, aspects that enhance erosion potential. User flexibility in choosing an acceptable alpha, and any combination of the three tests, allows modifications to suit the application. If channel reclamation truly intends to replicate a natural drainage system, then reclaimed channel designs should be judged based on geomorphic characteristics and relations established from natural areas.

Long-term Stability of Designed Ephemeral Channels at Reclaimed Coal Mines, Wyoming

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1.0 INTRODUCTION

Surface coal mining continues to be an important cornerstone of fossil fuel extraction in Wyoming. Associated with the extraction of coal is the disturbance of surface drainage networks. Natural channels may become blocked by spoils, rerouted, or unearthed during the surface mining process, thus, an important aspect of mined land reclamation is the restoration of surface drainage systems.

Reclamation seeks to reestablish long-term channel stability by efficiently routing surface water and sediment, while minimizing erosional processes. The goal of attaining long-term stability of ephemeral channels in semi-arid environments is particularly challenging because natural sediment yields are normally high, and ephemeral streams may, by nature, undergo cycles of cutting and filling (Schumm and Hadley, 1957).

Evaluating the long-term performance of designed ephemeral channels at reclaimed coal mines in Wyoming is difficult because major channel adjustments in semi-arid regions typically occur in response to infrequent, large floods. Complete certification and bond release issues are management and regulatory decisions that involve evaluating long-term performance of reclaimed channels, but the rarity of the channel-changing discharges and the short time since reclamation construction completion poses a great challenge to Abandoned Mine Land (AML) and Department of Environmental Quality/Land Quality Division (DEQ/LQD) personnel. At

present, many of these decisions are based on the short-term observations provided by post-construction monitoring or annual permit application information. There is a need to derive a means of evaluating long-term channel stability that is not limited by short-term monitoring. The specific objectives of this research are:

- To understand previous channel design practices at reclaimed abandoned coal mine sites in Wyoming through an inventory of engineering design reports and plans;
- To determine characteristics that contribute to ephemeral channel stability by conducting field investigations of natural, unmined channels and drainage basins, and;
- To derive a risk-based stability evaluation for reclaimed channels using statistical comparisons of channel design criteria from reclaimed AML coal sites with adjacent, natural surface drainage systems.

1.1 Definition of Channel Stability

A major premise of this research is that natural alluvial channels represent long-term stability because their deformable boundaries allow channel geometry adjustments to accommodate water and sediment discharges, a self-regulating process known as dynamic equilibrium (Hack, 1960). In addition, natural channels have evolved over long periods of time with channel cross section parameters of width, depth, and slope reflecting prevailing climatic and hydrologic conditions. By this definition natural channels are stable, whether aggrading or degrading, a temporally independent definition that evaluates reclaimed channel stability solely on how closely reclaimed channels resemble unmined, natural drainages. Reclaimed channels that are properly integrated into the surrounding landscape, specifically the drainage basin, will respond to large flows in a manner that is similar to channels upstream or downstream of the mined areas. Degradation and\or aggradation that occurs on a basin-wide scale and migrates

headward or downstream into the reclaimed reach is considered to be within the natural evolution of drainage basins and stream channels. Initiation of headcuts, knickzones, or deposition within the reclaimed channel reach, however, would be indicative of an instability, or a design failure.

Undisturbed areas adjacent to mined lands provide natural analogs of pre-disturbance conditions, or stable channels. Given the absence of premining baseline information at AML sites, and the limited time of exposure of reclaimed channels at active mines, it is generally accepted that stable, natural channels should be used as analogs for designing reclaimed channels (Stiller et al., 1980; Bishop, 1981; Wells and Potter, 1986; Lidstone and Anderson, 1989; Erion, 1991; Waldo, 1991).

2.0 METHODS

Research methods to evaluate long-term, ephemeral channel stability utilized two data sources; 1) an inventory of existing information on channel reclamation design from reports and plans in the AML library, and 2) field-derived measurements consisting of geomorphic parameters of unmined ephemeral channels in natural analog sites adjacent to mined lands. Regression analyses and statistical evaluation were used to develop a risk-based stability test to serve as a channel design and a regulatory evaluation tool. In this way, reclaimed channel designs can be quantitatively compared to adjacent, stable unmined areas.

2.1 Inventory

Mined lands disrupted prior to the 1977 enactment of the Surface Mine Reclamation Control Act qualify for AML reclamation funding and oversight. Under the guidance of Wyoming's AML program, approximately 125 abandoned coal mine sites have been reclaimed. Of these 125 sites, 14 entailed channel reclamation and engineering design of earthen channels (Table 1).

A review of consultant's reports, engineering design plans, construction as-builts, and AML site files for the 14 AML sites with channel restoration was completed. Information was readily available in the AML library, Herschler Building, Cheyenne, Wyoming, and from the AML archives. Compiled data included channel design criteria, specific channel and basin characteristics, and final design features of top soil depths and surface amendments. Information from sites reviewed during the inventory are tabulated in Appendix A (Table A-1 through A-4).

The inventory was further embellished by adding information that was easily measured from topographic maps and design plans, or calculated using Manning's equation. As an example, where channel geometry was not fully reported, Manning's equation was used to calculate the missing parameters, based on available information. These calculations helped verify reported channel design hydraulics. In addition, drainage basin information was estimated, where possible, using topographic maps and design plans (e.g. mean basin slope).

2.2 Study Area

Results of the inventory indicated that AML projects 6C-2 and 6C-8, the Rainbow and Colony mine sites, south of Rock Springs, are the only reclamation sites with a complete suite

Table 1. Abandoned Coal Mine Land Projects With Channel Reclamation

Project	County	Reclamation Work/Comment	Owner	Certified Complete
6C-2 Rainbow Mine	Sweetwater	Large site, abundant channel reclamation, rolling mature topography	Sweetwater, Upland Resources, BLM	1991
6C-4 College Hill	Sweetwater	Deeply incised drainage with bedrock grade control, joins Bitter Creek	Jessica Longston	1991
6C-8 Colony Coal Co.	Sweetwater	Abundant, variable topography; anomalously stable due to lack of vegetation	Upland Resources, W.R. Grace & Co.	Under project 17B
7B-1 Elk Mtn. area	Carbon	Abundant large drainages, impoundments, steep slopes	Edison Corp.	1991, with continued transect monitoring
7-26	Carbon	Impoundment with riprapped spillway, designed channel pattern	BLM	1991, with continued transect monitoring
7-28 Toilet Bowl	Carbon	Underground mine with surface drainage work, rock gallery	Union Pacific Railroad	1988
8-8	Johnson	Large gully reclaimed with riprap	Collins Ranch, Inc	1991
8-13 Mine Fire Site	Sheridan	Large drainage, gentle slope, riprap used	Big Horn Coal	Certification pending
8-19 Hidden Waters	Sheridan	Surface drainage work	Padlock Ranch et al.	Transect monitoring continued
8-23 Hidden Waters	Sheridan	Reclaimed drainage washed out, migrating under boundary fence	Annakersten Randall	Remediation pending
8-24	Sheridan	Underground mine with surface drainage work, subsided drainage reclaimed	United Mine Workers	Certification pending
9B-15	Fremont	Underground mine with surface drainage work	BLM	1989
15A-22 Kaycee Site	Sheridan	Reestablished northward drainage; recent minor settling below highwall	William Welch	Certification pending
15A-24 Pugsley Mine	Johnson	Small 5-acre site, minor drainage work	Winter Gardens Prod. Credit Assoc	Certification pending

(modified from Appendix C, AML 1990 Reclamation Monitoring Summary)

of design information (Table A-1 - A-4). Our research into channel stability has thus focused on this area near Rock Springs, encompassing the Rainbow and Colony mines which were recently reclaimed by AML (Table 1). In addition, Hanna was chosen as a test site to apply the stability analysis developed using the Rock Springs unmined and reclaimed channel data. Abundant active mining continues in the Hanna area, and one abandoned mine site (AML 7-26) has been reclaimed in the vicinity of Hanna, although complete design information is lacking. Figure 1 illustrates the selected study locations.

2.2.1 Rock Springs

In general, the Rock Springs study area occupies a semi-arid climatic zone where ephemeral streams dissect horizontally-bedded sedimentary rocks, forming buttes with variable, steep topographic relief. Elevation of the area ranges between approximately 6,500 and 6,700 feet above mean sea level. Precipitation in Rock Springs ranges between 7 and 9 inches per year, a majority of it falling in spring and early summer. Most streams flow only in response to precipitation events. Grasses and woody vegetation (sagebrush, rabbitbrush) provide the most common types of ground cover in the area. Near surface geology of the Rock Springs study site is the Cretaceous-age Mesa Verde formation, a heterogeneous unit comprised of sandstone interbedded with shale, siltstone and coal lenses.

2.2.2 Hanna

The Hanna study area lies within an intermontane structural basin. The elevated flanks of the basin receive approximately 12-16 inches of yearly precipitation (Richter, 1981).

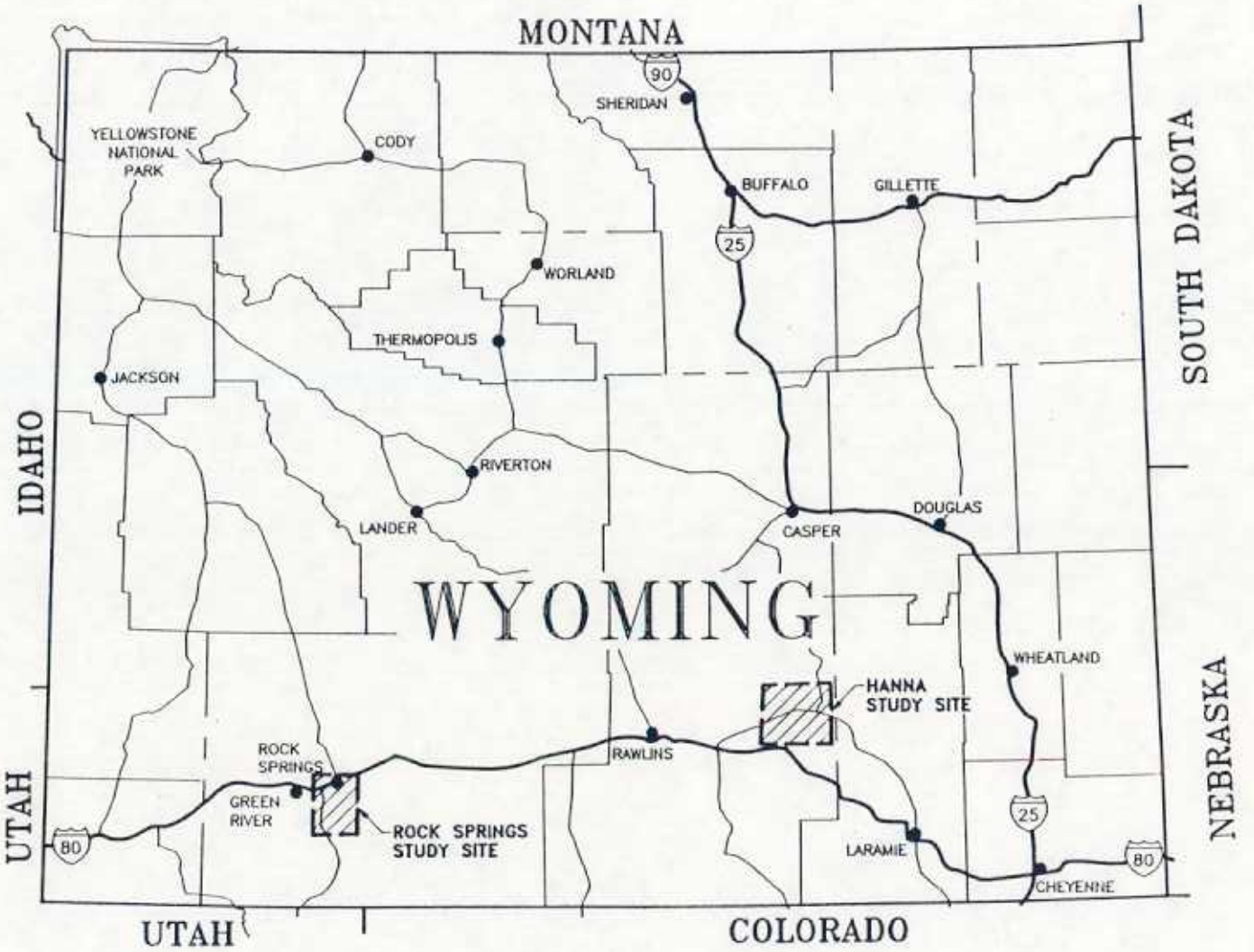


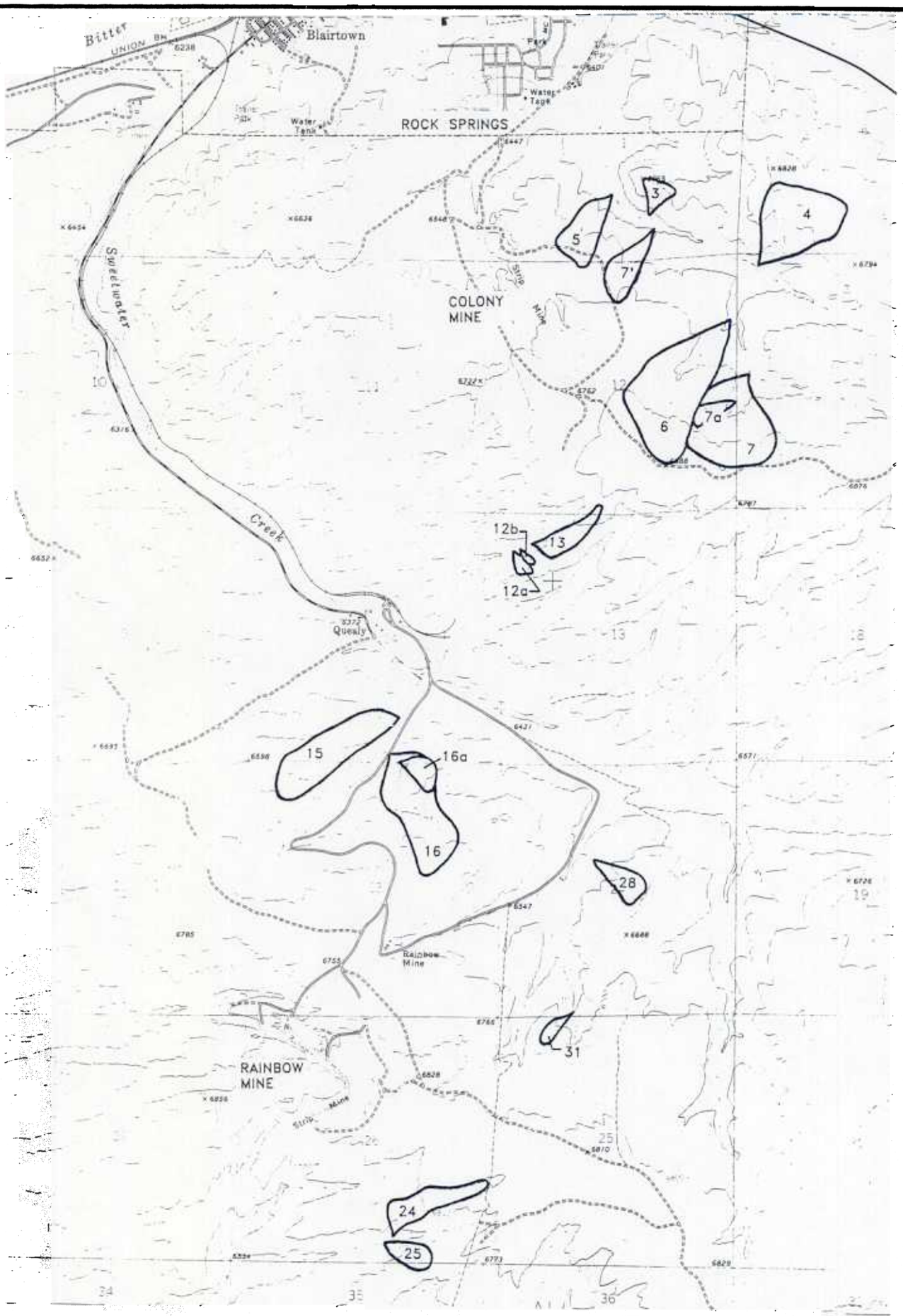
FIGURE 1. NATURAL ANALOG STUDY SITES BASED ON LOCATIONS OF RECLAIMED COAL MINES WITH CHANNEL RESTORATION

Elevation of the drainage basins studied at the Hanna site range from 6,800 to 7,200 feet above mean sea level. Streams are ephemeral, and climate is less arid than at Rock Springs. Vegetation in the basins spans the sagebrush and juniper-woodland communities. Drainage basin geology is dominantly Eocene Hanna formation of variable lithology including sandstone, siltstone, shale and coal beds. Numerous northwest-southeast trending faults are noted within the Hanna formation (Love and Christiansen, 1985) near the towns of Hanna and Elmo.

2.3 Natural Analogs

Data from natural, unmined drainage basins within the study sites were initially collected from topographic maps and aerial photographs. The natural analog channels were selected based on overall similarity to reclaimed basins. Basins with similar geology, basin size, and shape, were selected for study when possible. Basins were chosen for study only if no obvious anthropogenic influence such as roads, utilities, buildings, or channelization was evident. This was verified in the field during reconnaissance work locating selected analog channels.

In the field, a channel cross section was surveyed at the mouth of each unmined basin along with a local channel slope at the cross section. The perimeter of several small basins was surveyed at the Rock Springs study site to increase the overlap of data from the small reclaimed basins (< 10 acres); unmined small basins are difficult to define on topographic maps. In addition, the general condition of each surveyed natural channel was described, noting the presence of bedrock influence, headcuts or knickzones, and bank sloughing or undercutting. A Total Station was used to survey 17 unmined channels south of Rock Springs (Figure 2),



0 2000 FT.
SCALE

FIGURE 2

UNMINED DRAINAGE BASINS, ROCK SPRINGS STUDY SITE

ABANDONED COAL MINE LAND RESEARCH PROGRAM

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whereas, a rod, level and tape proved sufficient to survey 10 analog channels within the Hanna study site (Figure 3). Photographs were taken at each unmined basin measured.

A visit was made to the reclaimed Rainbow and Colony Mine sites (Figure 2) to document site-wide conditions 3 years after construction. Likewise, reclaimed AML site 7-26 near Hanna was observed during field work. No measurements were made at the three reclamation sites, but photographs were taken, and design plans visually compared to constructed topography.

To derive a data set for the natural analogs similar to that compiled from the inventory for reclaimed channels, drainage basin area was determined for unmined channels using U.S.G.S. 1:24,000 topographic quadrangles, and other parameters were estimated using available software. Data tables for the analog sites were developed using both the 10-year and 100-year, 1-hour precipitation event. The 10-year, 1-hour event was selected by the consultant as the design event for reclamation of the Rainbow and Colony mine sites. A computerized version of NOAA's Atlas (PREFREE) was used to determine 10-year precipitation quantities. The SCS Triangular Hydrograph method (TRIHYDRO is a computerized version) was applied to natural analog channels to determine peak discharges. Manning's equation, available in a program called OPEN, was utilized to determine hydraulic parameters (flow velocity, flow area, depth, top width, hydraulic radius) associated with the design discharge and the surveyed cross-section and channel slope.

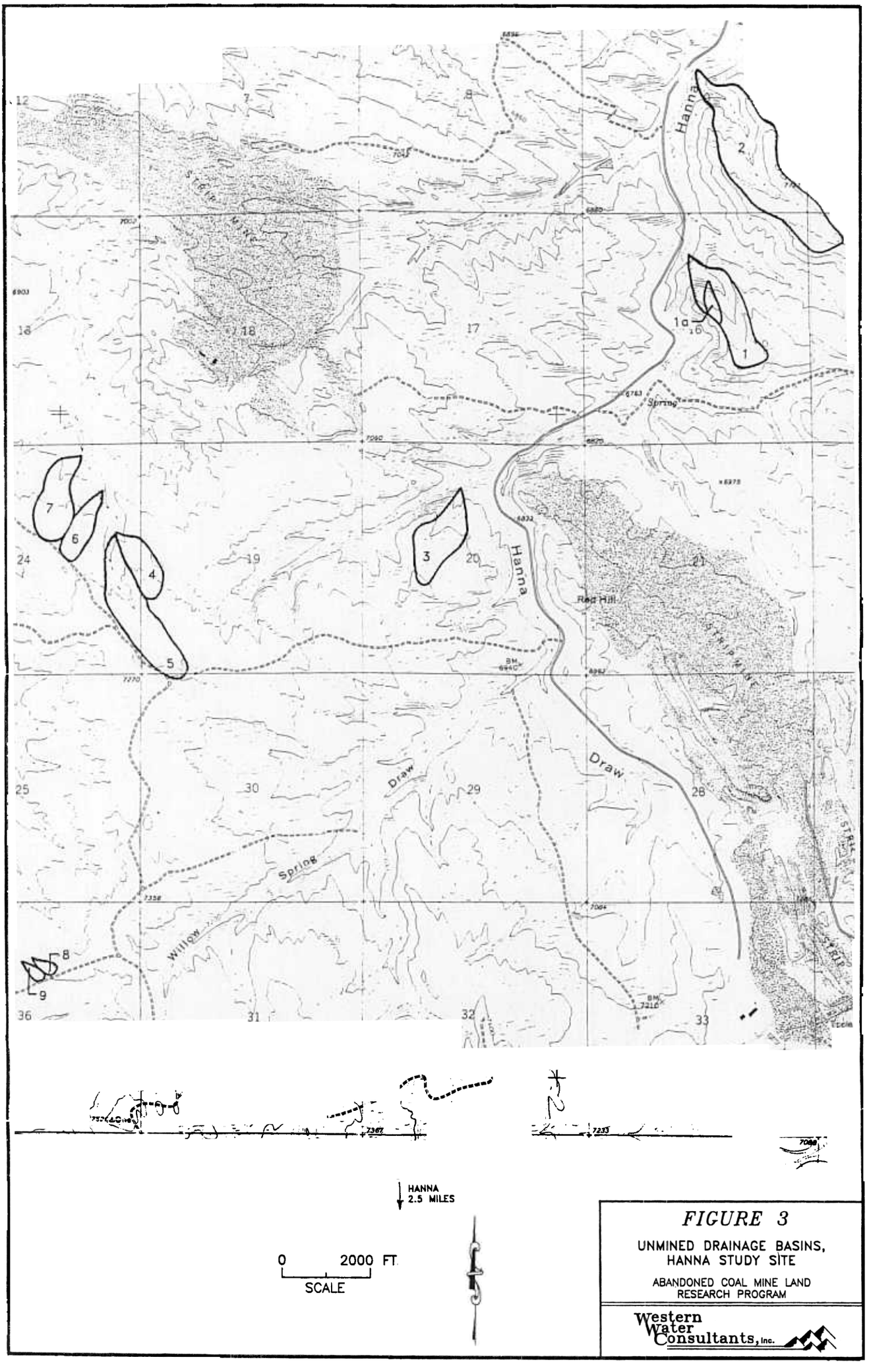

FIGURE 3

UNMINED DRAINAGE BASINS,
HANNA STUDY SITE

ABANDONED COAL MINE LAND
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2.4 Statistical Evaluation

During reclamation channel design, hydraulic properties of the channel (cross sectional flow area, channel slope, flow depth, hydraulic radius, etc.) are manipulated by reclamation planners until an acceptable reclaimed design is achieved. In contrast, drainage basin area and mean basin slope, characteristics of the drainage basin, are difficult and cost prohibitive to freely modify during engineering design and construction. However, these rather fixed basin parameters are relatively easy to measure from topographic maps, and provide easily obtained, useful information on geomorphic properties. A major emphasis of this research project was to develop relationships between basin parameters and channel hydraulic parameters that are most important to designing channels and influencing ephemeral channel stability. These relationships could then be used to assess channel stability and as a guide for future channel reclamation.

Research regarding long-term channel stability has centered around geomorphic thresholds (Schumm, 1973), a concept describing the landform change resulting from a change in internal or external controls. Previous channel stability studies in Wyoming and surrounding states developed threshold or empirical relationships to predict channel instabilities such as gully initiation (Hadley and Schumm, 1961; Patton and Schumm, 1975; Elliot, 1990). Other studies were specifically directed at developing design equations for reclaimed channels within the actively mined Powder River Basin (Rechard and Hasfurther, 1980; Divis, 1982; Bergstrom, 1985). The utility of previously established regression equations, although based on measurements of natural systems, is limited to the specific drainage basins for which the relationships were developed. Application to channels and basins other than those evaluated,

such as the Rock Springs and Hanna areas, is possibly a misuse of the regression data (Williams, 1983).

For this project, surveyed field data on natural channels, and map-derived data on the drainage basins within the Rock Springs and Hanna areas were analyzed by regression analysis. Regression analysis is intended to identify the relationship between two (or more) variables such that information about one of them allows knowledge or prediction of the other. The regression relations between drainage basin and hydraulic parameters were then used to develop a risk-based channel stability test based on the variation exhibited by natural channels about a mean predicted value. The stability assessment provides a quantitative way to evaluate discrepancies between natural analog channels and reclaimed or designed channels.

2.4.1 Confidence Intervals

A method for evaluating the uncertainty in the regression relations for natural channels, or the variance about a mean predicted value, involves the development of confidence intervals. Confidence intervals were calculated using Student's t distribution (Ott, 1984, p. 128). The Student's t distribution is a variation of the normal distribution adjusted to account for small sample sizes. Using this distribution, a confidence interval about the mean value of an independent random sample is calculated as follows:

$$\bar{x} \pm t_{a,n-1} s \sqrt{\frac{1}{n}} \qquad (1)$$

where $\bar{x}$ is the sample mean, $t_{\alpha,n-1}$ is the test statistic from standard tables for a specified error level (alpha) with n-1 degrees of freedom, s is the standard deviation, and n is the sample size. The error level (alpha) is related to the confidence level as follows:

$$\text{confidence interval} = 100\ (1-\alpha)\%$$

Estimation of a population mean can become more involved if the variable of interest is correlated with one or more independent variables. Inferences concerning the population mean for data showing strong correlation coefficients were treated by calculating confidence intervals using the Student t distribution (Devore, 1982; p. 443) as follows:

$$\hat{y} \pm [t_{\alpha,n-2}(s\sqrt{\frac{1}{n} + \frac{n(x_o-\bar{x})^2}{n\Sigma x_i^2 - (\Sigma x_i)^2}})] \tag{2}$$

where $\hat{y}$ is the predicted value of the dependent parameter, $t_{\alpha,n-2}$ is the test statistic from standard tables for a specified alpha and n-2 degrees of freedom, s is the sample standard deviation, n is the sample size, x_0 is the independent variable, and $\bar{x}$ is the mean of the independent parameter.

2.4.2 Limiting Type I Error

An important component in statistical testing is specifying an acceptance level to control the probability of an erroneous result. Typically, the user chooses an acceptable Type I error, or alpha level, in this case specifying the amount of acceptable risk associated with approving a given channel design; herein lies the risk-based approach to this channel stability evaluation. Alpha typically is selected at either 0.1 and 0.01, and indicates the probability or percentage of

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.

D:\WORK\2029\FIG4 03/08/93 11:29

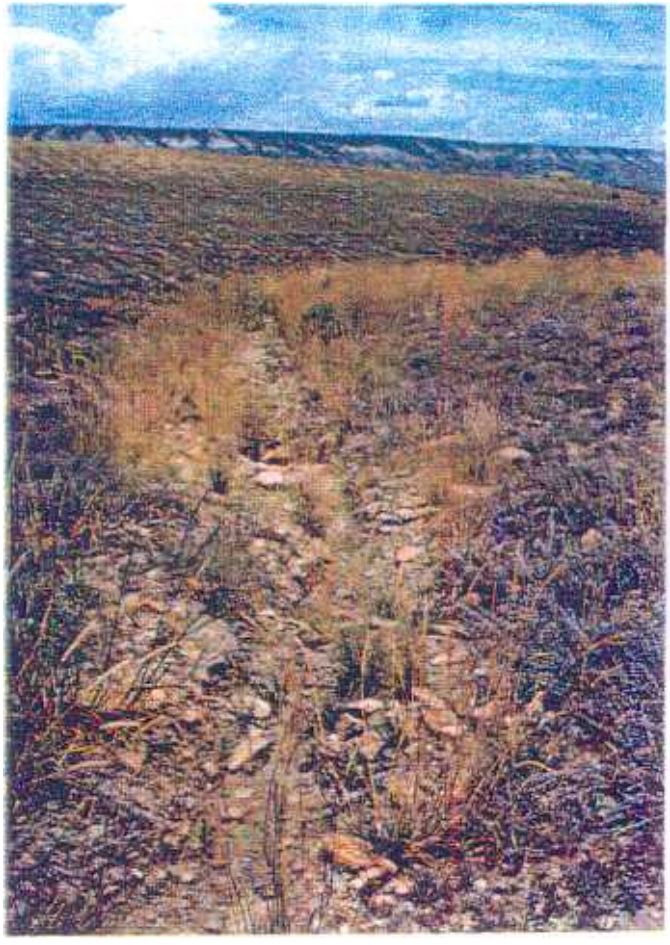

FIGURE 4 RECLAIMED CHANNEL AT COLONY MINE AML 6C–8 SOUTH OF ROCK SPRINGS, WYOMING.

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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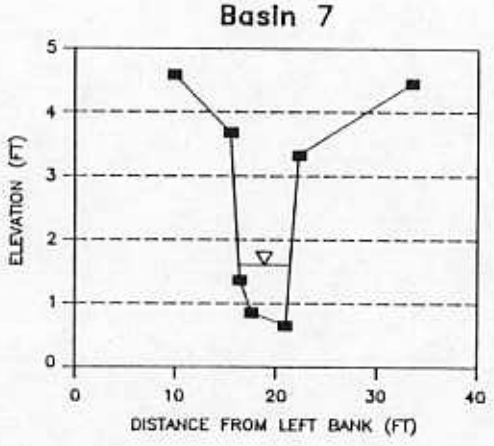
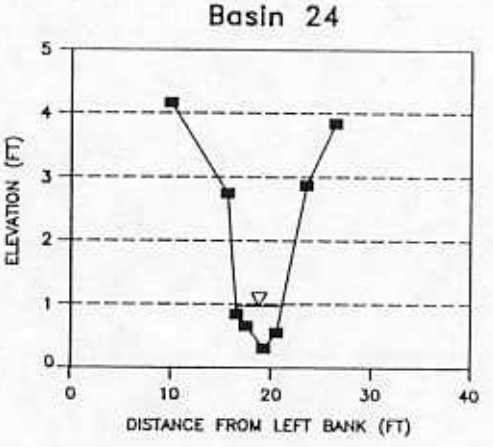
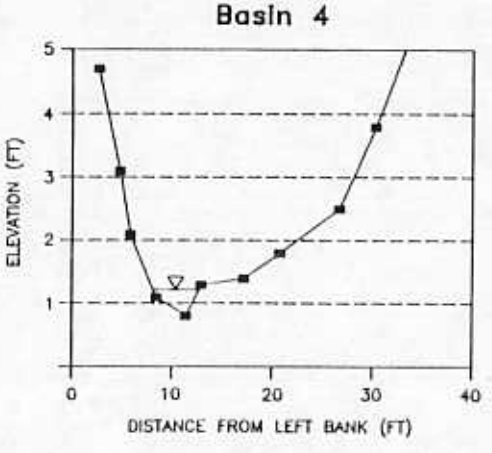
ROCK SPRINGS





HANNA



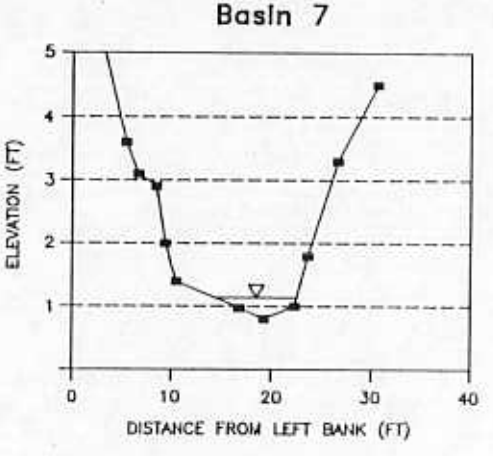


FIGURE 5: UNMINED CHANNEL CROSS SECTIONS

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)

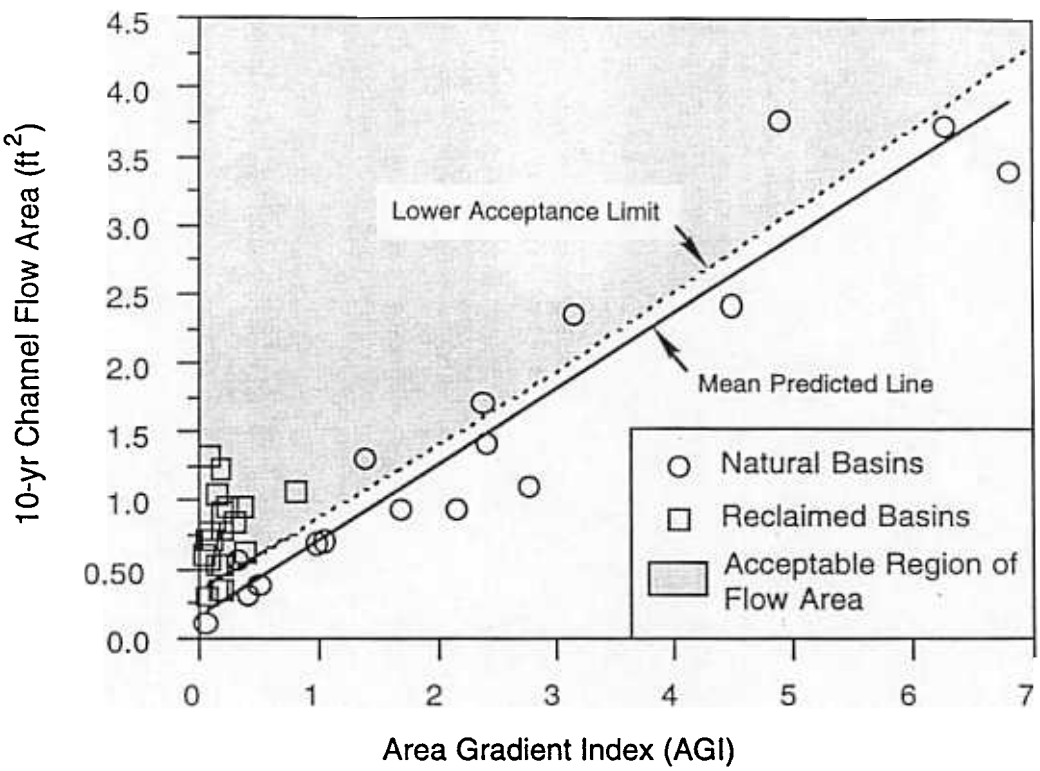


Figure 6. Limiting Flow Area for $\alpha = 0.10$, Rock Springs Study Site.

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

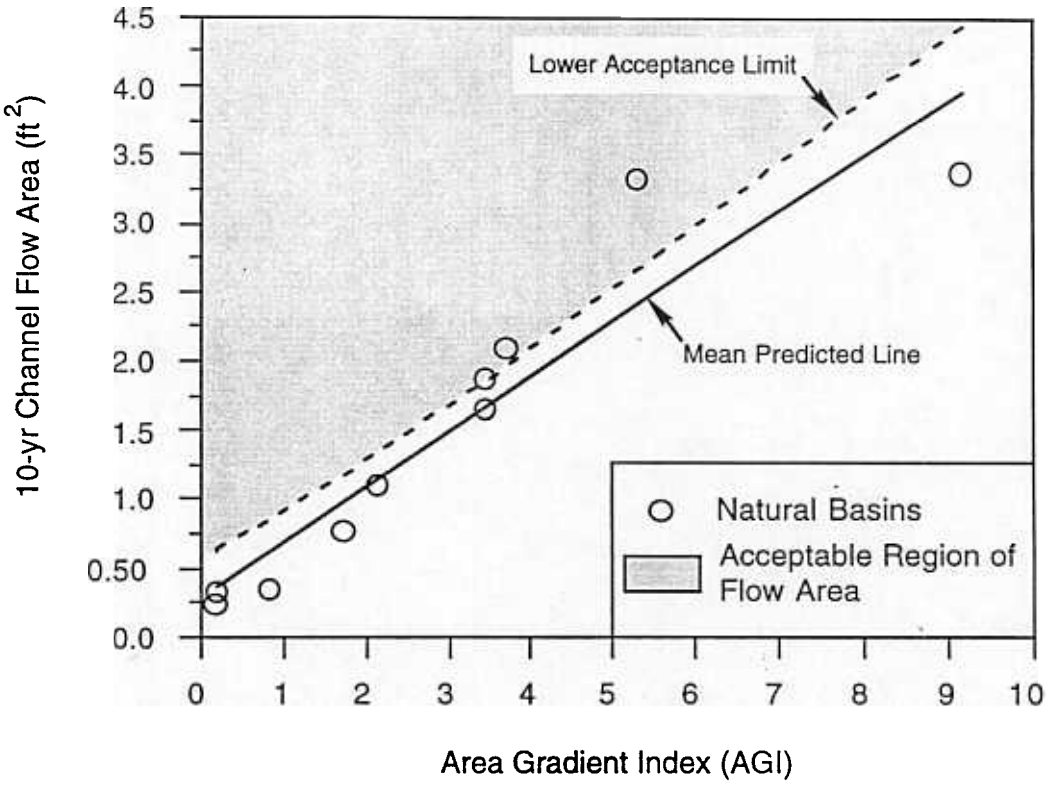


Figure 7. Limiting Flow Area for $\alpha = 0.10$, Hanna Study Site.

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.

4.0 DISCUSSION AND CONCLUSIONS

There is a general lack of information on channel and basin characteristics for reclaimed channels at abandoned coal mines in AML library reports and plans. While the success of locating consultant's reports, design plans, and other information on reclamation was high during the inventory, finding specifics regarding channel design criteria and other information was low. The most frequently lacking piece of information was drainage basin area, and it was rarely possible to accurately measure this from available design plans. It is suspected that although a rainfall-runoff analysis was undoubtedly completed for each basin reclaimed, the delineated basin areas were not reported in the submitted documents.

Projects 6C-2 and 6C-8, the Rainbow and Colony mines, are the only sites with complete design information available in AML reports and files. At a minimum, drainage basin area, channel cross sectional geometry, runoff information, and design flow recurrence interval need to be available to reproduce reclamation design and evaluate stability of channels at reclaimed and active coal mines.

From the design information available, it is evident that a wide range of design criteria (design event, Manning's n, curve number, etc.) exist for the 14 reclaimed mines inventoried. It is likely that AML will continue to develop standards for all phases of channel design (Koopman, 1991) to limit the wide range of design variability and reclamation procedures.

The product of drainage basin area and mean basin slope (AGI) influences or correlates strongly with natural channel characteristics of flow depth, channel flow area, hydraulic radius, and hydraulic depth for the Rock Springs and Hanna areas. Natural drainage data show AGI correlates well with flood magnitude.

Reclamation designs for 18 out of the 20 constructed earthen channels at the Rainbow and Colony mines satisfy the recommended two out of three stability tests at alpha=0.1 Channel slopes for all reclaimed basins except 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, passing the stability test for channel slope. Reclaimed channel slopes less than the upper limit imply a gentler slope than what exists in the vicinity naturally. The 10-year, 1-hour channel flow areas for reclaimed channels at the Rainbow and Colony mines are acceptable except for reclaimed Basins 8, 12, and 13. Acceptable flow areas include those greater than or equal to the lower limit established by unmined data at alpha=0.1 (Figure 5). At alpha = 0.01, 16 out of the 20 reclaimed channels are stable over the long-term using the two out of three stability test criteria.

Although complete design criteria were not available for the Hanna site, confidence intervals were developed for natural analog areas. The statistical limits can serve to facilitate engineering channel design, and to evaluate design plans for bond release or construction purposes within the vicinity of Hanna. Limiting channel slope and 10-year flow velocity for the Hanna area are 0.0683 feet/feet and 4.86 feet/second, respectively.

Channel slope and flow velocity data from natural basins near Rock Springs and Hanna are not statistically different. Stability analyses for channel slope and flow velocity can thus be applied to the southwestern and south central portions of Wyoming. Further geographic transferability has not been tested but may be important in limiting data requirements and increasing the application of channel stability tests.

Stability tests, if incorporated into regulatory decisions, can quantify differences between reclaimed channel characteristics and natural, adjacent unmined areas. A standardized, quantitative approach will help maintain consistency within a process that has been historically rather subjective, and reviewer-specific. A minimum of work is necessary to develop the requisite data set: 1-2 days of surveying, depending on the desired number of data points, and a relatively basic statistical analysis.

Channel adjustment within reclaimed basins does not necessarily mean instability, and nonerosive conditions for reclaimed earthen channels do not exist. Engineered channels will approach the configuration of natural channels over time, and if designers and regulators have an idea of the direction of adjustments within natural settings, they can better evaluate the success of a designed channel to accommodate regional changes. In addition, natural resource regulators may be better able to recommend steeper slopes to minimize fluvial adjustments if natural systems are known, a priori, to be steeper. If channel reclamation truly intends to replicate natural drainage systems, then it follows that the designs should be judged based on the geomorphic characteristics and relations established in natural areas.

5.0 RECOMMENDATIONS

1. Establish permanent survey locations to monitor changes in channel cross section and longitudinal profiles of reclaimed channels. The cross sections could be resurveyed annually during the 3 year post-construction monitoring.

2. Investigate the geographic variability of relations that show strong correlation within the Rock Springs and Hanna areas. Additional work could verify application of AGI and channel hydraulic parameters to other regions of the state with active or abandoned coal mining.

3. Determine optimal sample size associated with defining relationships that influence ephemeral channel stability. This study shows 10-17 data points are acceptable but the lower limit has not been defined.

4. Investigate the role of pilot channels on designed stability. Pilot channels have formed in the bottoms of reclaimed channels at the Rainbow and Colony mines. If pilot channels are shown to develop naturally, then including them in channel designs may be unnecessary. Conversely constructing pilot channels will ensure they occur in desirable locations (not up against a bank), and of an adequate size determined by hydraulic calculations.

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APPENDIX A

INVENTORY TABLES

TABLE A-1. DESIGN CRITERIA, RECLAIMED AML COAL SITES, WYOMING

Reclamation Site	County	Precipitation and Storm Distribution	Runoff Curve Number	Design Flow Recurrence Interval	Permissible Velocity (ft per sec)	Mannings 'n'	Method	Comment
6C-2 Rainbow Mine	Sweetwater	0.9 in short duration advanced type storm	83	10-yr, 1-hr	3-4	0.035	SCS Triangular Hydrograph	Critical shear limit of 0.2-0.5 lb/ft2
6C-4 College Hill	Sweetwater	1.3 in	c=0.4	10-yr, 1-hr 100-yr, 24-hr	8	0.040	Rational Formula	2 ft freeboard on 100-yr channel
6C-8 Colony Coal Co.	Sweetwater	0.9 in	83	10-yr, 1-hr	3-4	0.035	SCS Triangular Hydrograph	Critical shear limit of 0.60 lb/ft2
7-26	Carbon		NA	100-yr, 24-hr	8.9 for riprap		Craig and Rankl (1977)	
7-28 Toilet Bowl	Carbon							
7B-1 Elk Mtn. area	Carbon		80	2-yr 100-yr	3.7-4.1 9.3-10.6	0.030	SCS Triangular Hydrograph	
8-8	Johnson	2.3 in Type II	70	100-yr, 2-hr		0.038	SCS Triangular Hydrograph	Riprapped channel
8-13 Mine Fire Site	Sheridan		72	100-yr, 24-hr				
8-19 Hidden Waters	Sheridan							
8-23 Hidden Waters	Sheridan							
8-24	Sheridan							
9B-15	Fremont							Minor channel design
15A-22 Kaycee Site	Sheridan		80s				SCS Triangular Hydrograph	
5A-24 Pugsley Mine	Johnson		80s	10-yr, 24-hr	5		SCS Triangular Hydrograph	

TABLE A-2. DESIGNED CHANNEL CHARACTERISTICS, RECLAIMED AML COAL SITES, WYOMING

Site	Sub Basin	Drainage Area (acres)	Design Event	Design Discharge (cfs)	Velocity (fps)	Bottom Width* (ft)	Top Width* (ft)	Flow Depth (ft)	Top Width/ Depth	Channel Slope* (ft/ft)	Shear Stress (lb/ft2)	Hydraulic Length+ (ft)	Channel Depth (ft)	Side Slopes (H:V)	X-Sec Shape	Long Profile Shape	Pilot Channel	Comment
6C-2 Rainbow Mine	1	9.6	10-yr, 1-hr	2.9	2.35	3.04	4.90	0.31	15.81	0.020	0.39	1420		3:1	trap		2-4' wide	
	2	7.8		2.3	2.18	3.09	4.71	0.27	17.44	0.020	0.34	1330						
	3	4.3		1.5	1.94	2.87	4.19	0.22	19.05	0.020	0.27	730						
	4	6.7		2.3	2.49	3.11	4.55	0.24	18.96	0.030	0.45	860						
	5	5.3		1.3	1.83	2.95	4.15	0.20	20.75	0.020	0.25	1100						
	6	3.1		1.1	1.97	3.01	3.97	0.16	24.81	0.030	0.30	560						
	7	8.4		2.5	2.61	2.91	4.47	0.26	17.19	0.030	0.49	1580						
	8	1.4		0.6	1.97	3.11	3.65	0.09	40.56	0.060	0.34	440						
	9	7.1		1.8	2.31	3.07	4.33	0.21	20.62	0.030	0.39	1800						
	10	4.1		1.2	2.28	2.83	3.79	0.16	23.69	0.040	0.40	1150						
	11	3.9		1.3	2.45	3.08	3.98	0.15	26.53	0.050	0.42	870						
	12	2.6		0.9	2.57	2.86	3.52	0.11	32.00	0.080	0.55	950						
	13	2.4		0.8	2.27	3.21	3.81	0.10	38.10	0.070	0.44	860						
	14	4.0		1.3	1.83	2.95	4.15	0.20	20.75	0.020	0.25	1010						
	15	2.7		1.0	1.67	3.02	4.04	0.17	23.76	0.020	0.21	650						
	16	7.5		2.3	2.67	3.14	4.46	0.22	20.27	0.040	0.55	1100						
6C-4 College Hill	0 to 2		10-yr, 24-hr		4.7	10		1.8		0.010				1:1	trap	stepped	no	bedrock control
	2 to 2.75				7.4			1.2		0.040								
	2.75 to 4				5.5			1.6		0.016								
	4 to 4.6				5.6			1.5		0.017								
	4.6 to 7				4.3			1.9		0.008								
6C-6 Colony Mine	I	5.2	10-yr, 1-hr	1.7	2.8	4.17	5.34	0.13	41.08	0.075	0.55	700		4.5:1	trap	convex-concave	to form naturally, assumed 4' wide w/ 4.5:1 side slopes	
	II	17.0		3.1	2.9	4.12	6.01	0.21	28.62	0.048	0.53	1000						
	III	9.6		2.4	2.5	4.17	5.88	0.19	30.95	0.040	0.41	1000						
	IV	8.7		2.0	1.5	3.96	6.30	0.26	24.23	0.010	0.13	900						
7-26		154	100-yr, 24-hr	200		8				0.049		3925		4:1	trap		no	
7-28 Toilet Bowl										0.005				3:1				rock gallery
7B-1 Elk Mtn. area	SE Site					2				0.050				4:1	V in trap	concave-convex	3' deep	meandering plan

TABLE A-2. DESIGNED CHANNEL CHARACTERISTICS, RECLAIMED AML COAL SITES, WYOMING (cont.)

Site	Sub Basin	Drainage Area (acres)	Design Event	Design Discharge (cfs)	Velocity (fps)	Bottom Width* (ft)	Top Width* (ft)	Flow Depth (ft)	Top Width/ Depth	Channel Slope* (ft/ft)	Shear Stress (lb/ft2)	Hydraulic Length+ (ft)	Channel Depth (ft)	Side Slopes (H:V)	X-Sec Shape	Long Profile Shape	Pilot Channel	Comment
8-8							40						~4	5:1	V		no	riprapped
8-13 Mine Fire Site			100-yr, 24-hr	350						0.005						concave & convex		
8-19 Hidden Waters	Channel 1						72							20:1	V in V		12' wide 4:1	
	Channel 2						40			0.027				15:1	V in V		10' wide 5:1	
8-23 Hidden Waters	Type A						30			0.020			2.5	10:1	V in V		10' wide 1.5' deep	
	Type B						15			0.005			1.25	6:1	V		no	
8-24							40			0.030				20:1	V in V		8' wide 4:1	
9B-15							8			0.130			2	2:1	V ditch			
15A-22 Kaycee Site	Type I Grassed		10-yr, 24-hr		5	12	28	2 min		0.004				4:1	V in trap		1' deep 2:1	
	Type III							2 min						3:1	V			
15A-24 Pugsley Mine	Type I	5.3	10-yr, 24-hr		5	12	28	2 min		0.022				4:1	V in trap		' deep 2:1	

Notes:

* Calculated using FlowMaster and available design information, or estimated from design plans
At Rainbow and Colony Mines, top width indicates flow top width associated with design event, all others are channel top width.
Design plans for Colony Mine indicate a 12' bottom width for reclaimed channels, whereas calculation indicate 3-4'.

\+ Hydraulic Length is straight line length along basin (TR55 input)

TABLE A-3. DRAINAGE BASIN CHARACTERISTICS, RECLAIMED AML COAL SITES, WYOMING

Reclamation Site	Sub Basin/ Station	Drainage Area (acres)	Basin Slope	Drainage Density* (ft/acre)	Constant of Channel Maintanence (acre/ft)	Stream Order	Transition Zones	Basin Shape	Basin Aspect
6C-2 Rainbow Mine	1	9.6	0.27	147.92	0.007	1st	transition channels designed to route drainage offsite	elongate	south
	2	7.8	0.22	170.51	0.006	1st			south
	3	4.3	0.21	169.77	0.006	1st			south
	4	6.7	0.23	128.36	0.008	1st			south
	5	5.3	0.06	207.55	0.005	1st			south
	6	3.1	0.12	180.65	0.006	2nd			south
	7	8.4	0.29	188.10	0.005	1st			north
	8	1.4	0.21	314.29	0.003	2nd			north
	9	7.1	0.21	253.52	0.004	1st			north
	10	4.1	0.19	280.49	0.004	1st			north
	11	3.9	0.20	223.08	0.004	1st			north
	12	2.6	0.28	365.38	0.003	1st			north
	13	2.4	0.25	358.33	0.003	1st			north
	14	4.0	0.22	252.50	0.004	1st			north
	15	2.7	0.24	240.74	0.004	1st			north
	16	7.5	0.18	146.67	0.007	1st			west
6C-4 College Hill	0 to 2	~100							east
	2 to 2.75								
	2.75 to 4								
	4 to 4.6								
	4.6 to 7								
6C-8 Colony Mine		5.2	0.12	134.36	0.007	1st	transition channels		north
	II	17.0	0.05	58.82	0.017	1st			
	III	9.6	0.07	104.38	0.010	2nd			
	IV	8.7	0.04	104.05	0.010	1st			
7-26		154	0.10	25.49	0.039	1st		elongate	south
7-28 Toilet Bowl						1st			north
7B-1 Elk Mtn. area	SE Site					1st			west/ south
8-8						1st			
8-13 Mine Fire Site									
8-19 Hidden Waters	Channel 1								
	Channel 2					2nd			
8-23 Hidden Waters	Type A								
	Type B								
8-24									
9B-15									
15A-22 Kaycee Site	Type I					1st			
	Type II								
15A-24 Pugsley Mine	Type I	5.3				1st			

* Drainage density does not strictly apply to 1st order streams, however, it was used to calculate constant of channel maintenance. Constant of channel maintenance describes the number of acres required to sustain a foot of channel.

TABLE A-4. MISCELLANEOUS DESIGN FEATURES AND MONITORING INFORMATION, RECLAIMED COAL SITES, WYOMING

Reclamation Site	Depth of Top Soil	Surface Amendments	Surface Manipulations	Revegetation Success*
6C-2 Rainbow Mine	top soil not used on reclaimed site		pitted	
6C-4 College Hill	12"		mulched pitted	
6C-8 Colony Hill Mine				
7-26	8" min 12" max	fertilizer mulch	disced crimped fenced	good 80% veg cover
7-28 Toilet Bowl				good 60% veg cover
7B-1 Elk Mtn. area	8"	mulch fertilizer	scarified disced straw dikes crimped	
8-8			pitted	good 80% cover
8-13 Mine Fire Site				
8-19 Hidden Waters		mulch	chiseled	good 90% cover
8-23 Hidden Waters		mulch	chiseled	good 90% cover
8-24				poor to good
9B-15				
15A-22 Kaycee Site				
15A-24 Pugsley Mine		chemical		

* Compiled from various AML Monitoring Summary Reports

APPENDIX B

UNMINED CHANNEL AND DRAINAGE BASIN DATA

ROCK SPRINGS AND HANNA STUDY SITES

Table B-1. Natural Channel and Basin Characteristics, Rock Springs Study Site

					10-year, 1-hour Event								100-year, 1-hour Event							
Basin	Drainage Area (acres)	Mean Basin Slope	Area Gradient Index	Channel Slope	Peak Discharge (cfs)	Velocity (fps)	Depth (ft)	Flow Area (ft2)	WP (ft)	TW (ft)	Hydr. Radius (ft)	Hydr. Depth (ft)	Peak Discharge (cfs)	Velocity (fps)	Depth (ft)	Flow Area (ft2)	WP (ft)	TW (ft)	Hydr. Radius (ft)	Hydr. Depth (ft)
3	6.6	0.16	1.06	0.07	2.81	4.03	0.36	0.70	3.31	3.30	0.21	0.21	10.33	3.70	0.66	2.79	14.60	14.00	0.19	0.20
4	46.5	0.10	4.51	0.08	16.81	6.97	0.79	2.41	5.29	4.92	0.46	0.49	56.11	9.85	1.34	5.70	7.52	6.72	0.76	0.85
5	21.4	0.13	2.78	0.13	8.36	7.60	0.68	1.10	3.21	2.60	0.34	0.42	28.96	10.90	1.18	2.66	4.65	3.42	0.57	0.78
6	77.8	0.08	6.30	0.04	22.99	6.16	0.99	3.73	5.79	5.21	0.64	0.72	74.95	8.53	1.82	8.79	8.40	7.12	1.05	1.23
7	59.3	0.12	6.82	0.05	22.51	6.64	0.90	3.39	5.88	5.08	0.58	0.67	74.30	9.64	1.70	7.71	7.62	5.78	1.01	1.33
7a	4.8	0.07	0.33	0.07	2.15	3.86	0.35	0.56	2.77	2.55	0.20	0.22	8.04	5.87	0.63	1.37	3.62	3.19	0.38	0.43
7'	16.6	0.15	2.42	0.05	6.82	4.83	0.82	1.41	3.76	3.33	0.38	0.42	23.92	6.95	1.32	3.44	5.42	4.62	0.63	0.74
12a	3.3	0.13	0.43	0.13	1.42	4.56	0.24	0.31	1.89	1.65	0.16	0.19	5.42	6.72	0.48	0.81	2.72	2.48	0.30	0.33
12b	0.5	0.15	0.07	0.13	0.30	2.99	0.14	0.10	1.17	1.16	0.09	0.09	1.28	4.42	0.28	0.29	1.88	1.57	0.15	0.18
13	14.2	0.12	1.70	0.09	5.42	5.86	0.55	0.92	2.89	2.58	0.32	0.36	19.16	8.36	1.00	2.29	4.20	3.44	0.55	0.67
15	46.5	0.07	3.16	0.05	13.67	5.84	0.77	2.34	4.76	4.34	0.49	0.54	45.63	8.21	1.39	5.55	6.61	5.99	0.81	0.93
16	56.5	0.09	4.92	0.03	17.60	4.68	1.26	3.76	6.83	5.72	0.55	0.66	58.22	5.36	2.08	10.9	14.94	13.51	0.73	0.80
16a	8.1	0.27	2.16	0.06	3.74	4.05	0.47	0.92	3.68	3.50	0.25	0.26	13.60	5.92	0.79	2.30	5.22	4.89	0.44	0.47
24	19.9	0.12	2.39	0.05	8.24	4.84	0.65	1.70	4.60	4.31	0.37	0.39	28.64	7.27	1.12	3.94	5.92	5.28	0.67	0.75
25	9.0	0.11	0.99	0.10	3.70	5.47	0.39	0.68	2.59	2.23	0.26	0.30	13.38	8.04	0.78	1.66	3.58	2.91	0.46	0.57
28	12.8	0.11	1.41	0.08	5.13	4.66	0.23	1.10	6.53	6.20	0.17	0.18	18.23	6.38	0.50	2.86	7.16	6.70	0.40	0.43
31	3.3	0.16	0.52	0.08	1.37	3.66	0.36	0.37	2.12	1.88	0.17	0.20	5.23	5.37	0.61	0.97	3.11	2.68	0.31	0.36

Note: WP = Wetted Perimeter
TW = Top Width
Hydraulic Radius = Flow Area/Wetted Perimeter
Hydraulic Depth = Flow Area/Top Width

Table B-2. Natural Channel and Basin Characteristics, Hanna Study Site

					10-year, 1-hour Event								100-year, 1-hour Event							
Basin	Drainage Area (acres)	Mean Basin Slope	Area Gradient Index	Channel Slope	Peak Discharge (cfs)	Velocity (fps)	Depth (ft)	Flow Area (ft2)	WP (ft)	TW (ft)	Hydr. Radius (ft)	Hydr. Depth (ft)	Peak Discharge (cfs)	Velocity (fps)	Depth (ft)	Flow Area (ft2)	WP (ft)	TW (ft)	Hydr. Radius (ft)	Hydr. Depth (ft)
1	44.3	0.12	5.30	0.02	12.94	3.91	0.90	3.31	6.65	6.44	0.50	0.51	46.38	5.11	1.58	9.46	12.37	11.48	0.76	0.82
1a	4.6	0.18	0.84	0.11	1.78	5.26	0.33	0.34	1.82	1.63	0.19	0.21	5.75	7.20	0.56	0.80	2.68	2.13	0.30	0.38
2	101.0	0.09	9.18	0.05	22.84	6.80	1.07	3.36	7.94	4.58	0.42	0.73	92.26	9.56	1.78	9.65	11.35	9.89	0.85	0.98
3	33.3	0.10	3.46	0.08	10.26	6.24	0.45	1.64	5.63	5.49	0.29	0.30	37.57	9.31	0.82	4.04	7.58	7.14	0.53	0.57
4	19.4	0.11	2.14	0.11	6.75	6.17	0.42	1.09	4.72	7.80	0.23	0.14	23.40	7.29	0.70	3.21	10.78	10.42	0.30	0.31
5	53.9	0.07	3.71	0.06	13.14	6.30	0.63	2.09	5.32	5.00	0.39	0.42	52.02	9.60	1.18	5.42	7.57	6.71	0.72	0.81
6	14.2	0.12	1.73	0.20	4.92	6.40	0.27	0.77	4.90	3.33	0.16	0.23	17.12	9.75	0.45	1.76	5.95	4.00	0.30	0.44
7	30.3	0.11	3.45	0.09	9.81	5.28	0.38	1.86	8.77	6.43	0.21	0.29	35.14	7.58	0.63	4.63	12.67	12.47	0.37	0.37
8	2.7	0.08	0.19	0.05	1.00	3.11	0.23	0.32	2.26	2.22	0.14	0.15	3.30	4.40	0.40	0.75	3.12	3.00	0.24	0.25
9	2.7	0.07	0.18	0.10	1.02	4.46	0.27	0.23	1.46	1.27	0.16	0.18	3.25	6.20	0.46	0.52	2.05	1.66	0.25	0.31

Note: WP = Wetted Perimeter
TW = Top Width
Hydraulic Radius = Flow Area/Wetted Perimeter
Hydraulic Depth = Flow Area/Top Width

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