Unsupervised SPOT Classification and Infiltration Rates on Surface Mined Watersheds, Central Pennsylvania

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ABSTRACT: Unsupervised minimum distance classification of digital SPOT data (Systeme Probatoire d'Observation de la Terre) provides a spatially extensive and detailed characterization of surface properties on spatially complex surfaces of four mined areas and surrounding nonmined land in central Pennsylvania. SPOT imagery identifies seven distinct spectral classes that are related to differences in surface rock type and vegetation cover. Eighty-eight dripping infiltrometer tests were conducted on surfaces of the mined and nonmined land. These data, combined with 50 previously completed tests on mined land, were used to relate infiltration capacity to mine surface properties of surface rock type and vegetation cover. Infiltration capacity generally increases as lithologic composition of the dominant rock fragments on the reclaimed surface varies from sandstone to shale to siltstone, and as vegetation increases on surfaces of similar rock type. The seven spectral classes have steady-state infiltration capacities ranging from 1.7 cm/hr to 5.8 cm/hr and are placed into categories of low (2.3 ± 1.2 cm/hr), moderate (3.8 ± 1.9 cm/hr), and high (5.8 ± 0.7 cm/hr) infiltration capacity.

The surface mining and reclamation process greatly increases the potential for surface runoff of mined land, making the mined site, and downstream channels, susceptible to high erosion rates. Infiltration rate controls, to a large degree, the volume of surface runoff from a surface mined watershed, and is, itself, controlled by surface physical properties. Accurate correlation of infiltration rate to surface physical properties allows SPOT data to have important potential in hydrologic forecasting of surface mined watersheds.

INTRODUCTION

SURFACE MINING for coal in central Pennsylvania dramatically alters the surface spectral characteristics of the disturbed area and the hydrology of the disturbed watershed. The process of vegetation and topsoil removal, postmine backfilling, retopsoiling, and revegetating alter many physical properties of the mine surface material (Jansen, 1981), greatly increasing the potential for runoff on the surface (Jorgensen and Gardner, 1987). Increased runoff makes the mined site susceptible to high rates of erosion, both as gullies on the disturbed land (Gryta and Gardner, 1983) and as changes in channel geometry in the watershed downstream (Touysinhthiphonexay and Gardner, 1984).

Infiltration of rainfall into mined surfaces is an important factor controlling the quantity of surface runoff from surface-mined lands (Figure 1) (Frickel *et al.*, 1981; Lemieux, 1987). Infiltration capacities of a mined surface must be known to accurately predict the surface hydrologic response (Jorgensen, 1985; Lemieux, 1987). However, as a result of reclamation methods, surface mines are complex, exhibiting significant spatial variation in surface physical properties and hence in infiltration capacities both across one mine and between mines (Jorgensen and Gardner, 1987).

The classification accuracy for remotely sensed data of such a surface of high spatial variability depends greatly on the spatial resolution of the sensor. For example, by isolating the effects of three sensor characteristics (data quantization, spectral band configuration, and spatial resolution) on Landsat TM classification of an area of extensive surface coal mining, it was shown that data quantization and spectral band configuration did not significantly affect classification accuracy. However, the decrease in spatial resolution from 30 m to 80 m resulted in an average 17.8 percent decrease in classification accuracy (Irons and Kennard, 1986). Thus, where spatial discrimination and ground resolution are important, such as on spatially complex mine surfaces, the greater spatial resolution of SPOT (10-m ground resolution in the panchromatic band and 20-m ground resolution in the three multispectral bands) should allow for even greater correct classification than the TM imagery (30-m ground resolution).

Remote sensing data has been used in the study of water resources, including watershed discharge analysis. Surface features that control the infiltration capacity (vegetation, soil texture and lithology, surface morphology, and antecedent moisture) also control the spectral reflectance detected by remotely sensed data (Figure 1) (Engman, 1981). Surface remote sensing data have been applied to hydrologic modeling by estimating the runoff curve number (CN) (Rango, 1985; Bondelid *et al.*, 1981), which is based on the land surface properties of land-cover and soil type. Land cover is an important aspect of hydrologic processes, particularly the processes of infiltration, erosion, and evapotranspiration (Engman, 1981). Accurate correlation of measured infiltration rates to the surface features controlling the spectral response allows the infiltration capacity of land surfaces to be indirectly identified from remote sensing data.

This research describes the unsupervised spectral feature classes produced from SPOT, for surface mined watersheds in humid temperate climates, and the infiltration capacities (which regulate runoff) associated with these spectral classes. This relationship is developed through three objectives. The first objective explores the relationship between mined surface features and SPOT spectral response, through development of a contingency matrix between a SPOT unsupervised minimum distance classification map and a ground truth map. The second objective explores the relationship between infiltration capacity and the mined surface features controlling the spectral response of the surface, namely, surface rock type and vegetation cover. This relationship will be shown through the correlation of dependent infiltration variables and independent surface feature variables, and through a trend analysis of infiltration capacity to surface features. The third objective explores the relationship between SPOT spectral response and infiltration capacity by calculating, for each spectral class, the infiltration capacity and two surface feature variables controlling both infiltration capacity and spectral response.

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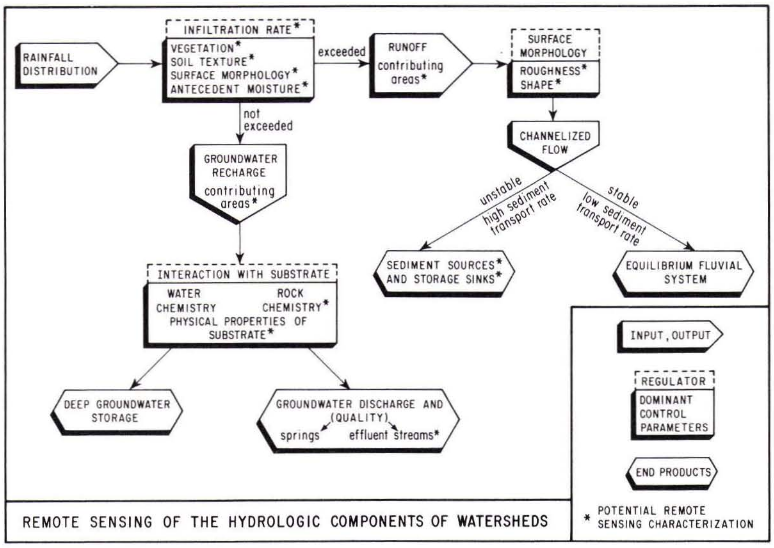

FIG. 1. Flow diagram of water movement within a watershed, including parameters of potential remote sensing characterization (from Connors *et al.*, 1986).

To achieve these objectives, four reclaimed surface mines located in northwestern Centre County, Pennsylvania (Figure 2) ranging in size from 25 to 300 hectares and in age from 2 to 20 years since reclamation, were selected for their variation in surface features of rock type and vegetation cover. In addition, data from 50 previously completed infiltration tests were available for these mines (Jorgensen and Gardner, 1987), and two of the mines had been investigated with simulated SPOT data (Connors, 1985; Connors *et al.*, 1986; Parks *et al.*, 1987).

The four mines are underlain by Pennsylvania age rocks of the Allegheny Group (Figure 3), which averages 85 metres in thickness, and consists of six cyclic zones of fine grained sandstone, siltstone, and shale as the predominant rock types, and coals, underclays, and limestones constituting a minor part (Dutcher *et al.*, 1959).

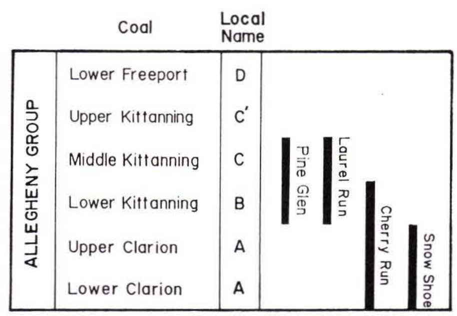

FIG. 3. Stratigraphic location of coals at each mine site.

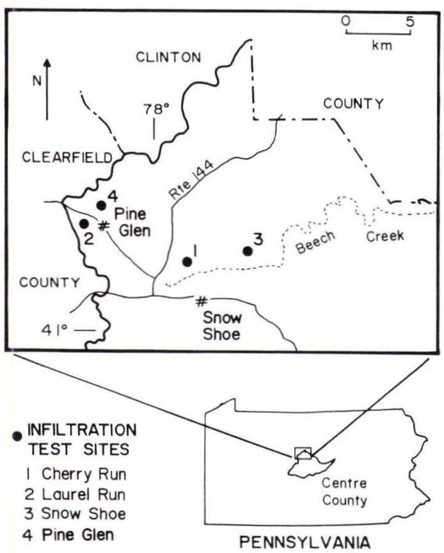

FIG. 2. Location of four mine sites (after Jorgensen and Gardner, 1987). UTM coordinates: Cherry Run = 4549000N, 257000E; Laurel Run = 4549500N, 250200E; Snow Shoe = 4553000N, 744200E; Pine Glen = 45547000N, 746500E.

SPOT CLASSIFICATION ON MINED WATERSHEDS

Data from SPOT was acquired on 29 October 1986 at 1615 GMT, when first available for central Pennsylvania. Because the four mines are located up to 10 km apart (Figure 2), the mines and a section of nonmined land were subset from the SPOT data set (CUTTER and SUBSET programs (ERDAS, 1985)). This subset data set (1.1×10^5 pixels) contains approximately 40 percent mined land and 60 percent nonmined land. The fall acquisition date limits the detectable spectral differences of vegetation in the near infrared range (band 3). The mean reflectance values of the four spectral bands (Table 1) show that the sensors had an inappropriate gain setting for reflectance of surface mined land. The low standard deviations reduce the amount of information available on each band. The small separation between mean reflectance values of the bands may increase the possible overlap between spectral signatures of different features. The result is decreased ability to observe small differences in the spectral signatures of various mined surfaces.

TABLE 1. MEAN REFLECTANCE VALUES FOR FOUR SPOT SPECTRAL BANDS FOR THE SUBSET DATA SET (40% MINED, 60% NONMINED).

Channel	1 (XS)	2 (XS)	3 (XS)	4 (PAN)
Spectral Range (micrometres)	0.51-0.59	0.61-0.68	0.79-0.89	0.51-0.73
Mean Reflectance Value (0-255)	27.0	19.8	31.0	27.0
Std. Deviation	3.6	3.8	6.1	4.7

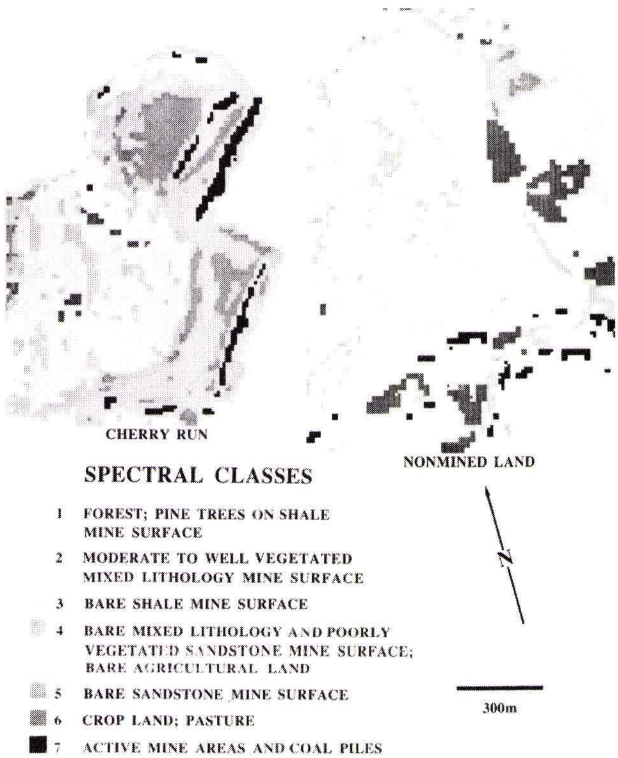

FIG. 4. Cherry Run mine and a portion of nonmined land from the unsupervised minimum distance classification map for the mined and nonmined land subset data set.

A cubic clustering criterion (SAS, 1982) was used on the subset data to determine the number of clusters that maximize the total variance to within-group variance. The optimum number of clusters was interpreted as seven. An unsupervised minimum distance classification was performed to create a spectral class map (seven classes) for the mined and non-mined land subset data set (see Figure 4) (Table 2) (CLUSTR program (ERDAS, 1985)). The spectral classes consist of class 1: forest and pine trees on shale-dominated mined surfaces; class 2: moderate to well vegetated, mixed lithology mined surfaces; class 3: bare, shale-dominated mined surfaces; class 4: bare, mixed lithology and poorly vegetated sandstone-dominated mined surfaces and bare agricultural land; class 5: bare, sandstone-dominated mined surfaces; class 6: crop land and pasture; and class 7: active mine areas and coal piles.

Field observation of surface rock type and vegetation type and percent cover at 200 points across the surfaces of the four mines were recorded on low altitude black-and-white aerial photographs (scale = 1:9000) taken with a 70-mm format Hasselblad camera. Surface rock type was recorded as a visual estimation of the percentages of sandstone, siltstone, and shale

TABLE 2. MEAN REFLECTANCE VALUES FOR FOUR SPOT SPECTRAL BANDS FOR EACH CLASS OF THE UNSUPERVISED MINIMUM DISTANCE CLASSIFICATION FOR SEVEN SPECTRAL FEATURES CLASSES.

Spectral Class	1	2	3	4	5	6	7
% of total area	46.8	20.3	7.1	13.3	6.8	4.3	1.4
Band							
1	24.5	27.9	28.3	30.4	34.9	29.6	22.9
2	17.5	20.2	20.4	23.1	29.4	21.0	13.6
3	28.7	37.6	24.5	31.0	32.6	47.1	11.8
4	24.1	28.0	28.0	31.2	37.6	29.8	20.2

rock fragments present at the surface. Vegetation was recorded as a visual estimation of areal percentage grass cover. Seed mixtures for revegetation consist of 75 pounds/acre of "standard strip mixture": 30 percent Kentucky 31, 27 percent annual Rye, 10 percent Timothy, 10 percent Alsike Clover, 10 percent Import Birdsfoot Trefoil, 10 percent Empire Birdsfoot Trefoil, and 3 percent Redtop. In addition, 5 pounds/acre of crownvetch and one bushel/acre of wheat were applied. Trees, where planted, consist of Red Pine, White Pine, Australian Pine, Black Locust, or Japanese Larch (Mike Talapa, R.S. Carlin Inc., Snowshoe, Penna., personal communication). The two hundred ground observations and photointerpretation of the aerial photographs were used to determine the surface properties (rock type and vegetation), boundaries, and classification accuracy of the seven spectral classes from the unsupervised minimum distance classification. Class boundaries were transferred to a contrast stretched image of the raw data used for the unsupervised classification. This step allowed digitizing the ground truth data into a raster file with the same dimensions and cell size (10 m) as the spectral class map (DIGPOL, MAKEFIL, and GRDPOL programs (ERDAS, 1985)). The ground-truth data set was then registered to the spectral class map (SUBSET program).

Comparison of the digitized ground truth map and the spectral class map (SUMMARY program (ERDAS, 1985)) produced a summary of classification accuracy in the form of a contingency matrix (Table 3). The diagonal elements are percentages of correctly classified pixels. The weighted average of the diagonal elements represents an overall classification accuracy of 70 percent. The off-diagonal elements represent percent errors of omission and commission. For example the element in row 2, column 1 is the percentage (14.8 percent) of ground-truth class 2 (moderate to well vegetated, mixed lithology mined surfaces) incorrectly classified as spectral class 1 (forest and pine trees on shale-dominated mined surfaces). This represents an omission error for the well vegetated mine class and a commission error for the forest and pine trees on shale class.

These errors are not surprising, given the high spatial variability of mined surface features, the similarity in surface properties of the confused classes, the fall acquisition date, and the poor gain setting on the sensor. Some errors in classification also occurred because of shadows on north facing slopes.

INFILTRATION ON MINED WATERSHED SURFACES

Eighty-eight infiltration tests were conducted on the surfaces of the four mines (Figure 2) and on surrounding bare agricultural land, pasture, crop land, and forest. Sites were chosen to encompass the range of surface feature classes defined from field observations. Tests were completed with a Jorgensen-modified Alderfer-Robinson dripping infiltrometer using the procedure established by Jorgensen (1985) which gives consistent, reproducible results and which allows for comparison to

TABLE 3. CONTINGENCY MATRIX FOR GROUND TRUTH CLASSES VERSUS SPECTRAL CLASSES

GROUND TRUTH CLASSES		SPECTRAL CLASSES 1	2	3	4	5	6	7	
	% of total	46.8	20.3	7.1	13.3	6.8	4.3	1.4	100.0
1	51.9	80.4	10.3	4.0	3.1	0.3	0.5	1.4	100.0
2	22.0	14.8	56.2	5.5	16.4	1.5	5.7	0.0	100.0
3	5.1	7.9	2.8	48.8	32.7	6.2	0.1	1.6	100.0
4	5.4	4.7	6.8	3.9	73.5	10.8	0.3	0.0	100.0
5	7.4	1.1	2.9	3.2	21.6	68.9	2.4	0.1	100.0
6	6.5	12.1	27.6	5.1	10.2	5.2	39.8	0.1	100.0
7	1.2	5.5	0.3	33.1	6.8	4.3	0.0	50.0	100.0
	100.0	126.5	106.9	103.6	164.3	97.2	48.8	53.2	total %

Class 1—Forest and pine trees on shale-dominated mined surfaces
Class 2—Moderate to well vegetated, mixed lithology mined surfaces
Class 3—Bare, shale-dominated mined surfaces
Class 4—Bare, mixed lithology and poorly vegetated sandstones-dominated mined surfaces and bare agricultural land
Class 5—Bare, sandstone-dominated mined surfaces
Class 6—Crop land and pasture
Class 7—Active mine areas and coal piles

50 previously completed infiltration tests for the mines (Jorgensen, 1985).

Infiltration rate was calculated by subtracting runoff rate from rainfall rate:

$$F_t = RF_t - RO_t \qquad (1)$$

where F_t = infiltration rate during a specified time interval, t (cm/hr),
RF_t = rainfall intensity over t (cm/hr), and
RO_t = runoff rate over t (cm/hr).

Cumulative volume of runoff was measured approximately 50 times during each 30-minute test.

Use of Equation 1 introduces small errors in the infiltration curve, because, from the mass balance equation

$$F = RF - RO - E - I - Sd - Ss \qquad (2)$$

several rainfall abstractions that do not infiltrate or runoff are incorrectly included in the infiltration volume. These abstractions include evaporation (E), interception by vegetation (I), depression storage (Sd), the amount of water trapped in surface depressions, and surface storage (Ss), the amount of water that must build up on the surface to provide enough depth (head) to initiate runoff (Linsley *et al.*, 1975). These errors result in overestimation of the initial infiltration rate and the rate of decrease to the steady-state infiltration rate.

Evaporation and interception abstractions are assumed to be minimal on poorly vegetated mined surfaces and on pasture and crop land. Evaporative losses are reduced by placing sun/wind screens around the plot and by the short duration of the test. The depth of water intercepted by an area of 100 percent grass vegetation ranges from 0.5 to 1.0 mm (Beasley and Huggins, 1980). The lack of abundant vegetation on most test plots makes interception volumetrically insignificant (1 to 2 percent of the rainfall). Infiltration tests on forested land were run below the forest canopy and thus may overestimate runoff. Estimated depression storage volumes may be up to 500 cm^3 (3 to 5 percent of the rainfall) (Jorgensen, 1985), but are immeasurable because it remains trapped on the plot surface after the test. However, surface storage volume can be calculated and subtracted from infiltration to produce an adjusted curve of infiltration rate as a function of time (Sharp and Holtan, 1940).

From the adjusted infiltration curve, two measured parameters are commonly used to characterize the infiltration capacity of the soil: the steady state infiltration rate (FC) and the thirty-minute volume (V30). The steady-state infiltration rate is the final constant infiltration rate in the Horton (1933) curve, corresponding to the saturated hydraulic conductivity of the soil (Rubin and Steinhardt, 1963). It is calculated in this study as the average infiltration rate (cm/hr) during the 20- to 30-minute period of each test. Thirty-minute volume is the total volume of water infiltrated during the thirty-minute test, calculated as the area under the infiltration curve and measured as the total depth of water infiltrated over the 0.4-m^2 plot. Given a high correlation (r=0.92) between FC and V30, and because FC is not affected by surface storage curve adjustments, FC is used as a dependent variable in subsequent analyses.

Relationships between dependent infiltration variables and independent surface feature variables (Table 4) were explored by use of Pearson Correlation Coefficients (SAS Institute, 1982) (Table 5).

The time since reclamation (AGE) has the highest correlation with FC of any independent variable (r=0.40). Jorgensen and Gardner (1987) found, on three of the four mines, that surfaces during the first year after reclamation have an infiltration capacity which is almost an order of magnitude lower than typical surrounding undisturbed forest soils. However, by the fourth year after reclamation, some mined surfaces have had a significant recovery of infiltration capacity to premining levels in response to physical redistribution, chemical alteration, and vegetation growth (Jorgensen and Gardner, 1987). This explains the positive correlation between AGE and FC. However, infiltration data are not subset by AGE because the time since reclamation is not directly related to the spectral properties of the mined surface.

Increased vegetation (VG) on mine surfaces, in general, increases infiltration capacity. The correlation between FC and VG (r=0.37) is positive and strong relative to other independent variables. Vegetative growth increases soil structure, reduces bulk density, increases soil porosity, and adds surface litter and plant roots, all causing an increase in the infiltration capacity

TABLE 4. DEFINITION OF DEPENDENT INFILTRATION VARIABLES AND INDEPENDENT SURFACE FEATURE VARIABLES USED TO CORRELATE INFILTRATION CAPACITY TO MINE SURFACES FEATURES.

	SYMBOL	DESCRIPTION	METHOD OF MEASUREMENT	UNITS	RANGE
DEPENDENT	FC	Steady-state infiltration rate; maximum final inf. rate	infiltration rate from 20-30 minutes of curve of infil. capacity	vol/time (cm/hr) over known plot area	0.5-6.7
DEPENDENT	V30	thirty minute vol., vol. of water infil. during 30 min. test	total runoff volume subtracted from total rainfall minus ab stract.	volume (cm) over known area	0.4-3.3
INDEPENDENT	AGE	age of mine surface after reclamation	from date of reclamation	years	2-20
INDEPENDENT	RAIN	rate of simulated rainfall applied to test pilot	by linear interpolation of two rate tests, one before and one after test	vol/time (cm/hr)	6.2-8.3
INDEPENDENT	VG	areal percentage of vegetation cover	visual estimation at test site and photointerp.	percentage (%)	0-100
INDEPENDENT	SS	percent of surface composed of sandstone	visual estimation at test sites and random locations	percentage (%)	0-95
INDEPENDENT	ST	percent of surface composed of siltstone	visual estimation at test sites and random locations	percentage (%)	0-90
INDEPENDENT	SH	percent of surface composed of shale	visual estimation at test sites and random locations	percentage (%)	5-90

TABLE 5. PEARSON CORRELATION COEFFICIENTS FOR INFILTRATION AND SURFACE FEATURE VARIABLES.

		DEPENDENT	INDEPENDENT					
		V30	AGE	RAIN	VG	SS	ST	SH
DEPENDENT	FC	0.92 0.0001 138	0.40 0.0001 121	−0.04 0.6575 138	0.37 0.0001 135	−0.36 0.0000 121	0.24 0.0068 121	0.18 0.0481 121
INDEPENDENT	AGE				−0.22 0.0134 121	−0.42 0.0001 121	0.04 0.6721 121	0.60 0.0001 121
INDEPENDENT	VG					−0.02 0.7883 121	0.19 0.0312 121	−0.27 0.0029 121
INDEPENDENT	SS		r= prob= n=				−0.80 0.0001 121	−0.30 0.0001 121
INDEPENDENT	ST							−0.33 0.0002 121

of the mined surface (Jorgensen and Gardner, 1987). Grass vegetation growth increases dramatically on reclaimed surfaces during the first three years.

In 1977, federal law first required mine sites to be regraded to approximate original contour and topsoil to be stockpiled and redistributed over the surface after regrading (Surface Mining Control and Reclamation Act, 1977). The perimeters of all four mines were mined before 1977, and, therefore, have no topsoil cover, but are shale-dominated surfaces with sparse pine tree and grass cover. Because of the early mining date, the lack of abundant vegetation, and the shale dominated surfaces, these surfaces cause a high positive correlation between AGE and SH ($r=0.60$) and a negative correlation between VG and SH ($r=-0.27$) (Table 5). The larger central portions of the remined areas are dominated by either sandstone or siltstone or both, with small amounts of shale. This leads to a negative correlation between SS and ST ($r=-0.80$) because one becomes more dominant at the expense of the other.

The correlation between FC and rainrate (RAIN) is very low ($r=-0.03$) because variation in rainfall intensity was intentionally limited by experimental design in order to decrease the effect of variable rainfall rate on infiltration.

Infiltration tests are initially divided into six groups, based on the predominance of the three main rock types present on the mined surface (sandstone, siltstone, and shale), and four nonmined groups based on agricultural practices (Figure 5). The mined groups were further subdivided by breaks in the histogram into groups of increasing percent vegetation cover of 0 to 25 percent, 25 to 45 percent, 45 to 65 percent, and 65 to 100 percent (Figures 5 and 6).

The trend of increasing FC with increasing vegetation is clearly visible on the sandstone, sandstone-siltstone, and siltstone dominated surfaces. The general trend of FC versus rock type indicates that surfaces dominated by rock fragments of sandstone or sandstone-shale have lower FC values than surfaces dominated by rock fragments of sandstone-siltstone, siltstone,

TABLE 6. SURFACE FEATURES AND INFILTRATION CAPACITY OF SPOT SPECTRAL CLASSES.

Spectral Class	Surface*	Surface Feature Variables in % (± 1 std. dev.) VG	SS	ST	SH	FC (cm/hr) (± 1 std.dev.)
4	M(8) B(3)	4.7 ± 6.1	32.0 ±12.4	20.0 ±20.3	43.8 ±17.1	1.7 ±1.1
5	M(20)	8.1 ± 4.7	77.5 ±15.1	8.0 ±11.2	14.5 ±10.7	2.2 ±1.0
3	M(8)	0.0 ± 0.0	5.0 ± 0.0	10.0 ± 0.0	85.0 ± 0.0	2.5 ±0.8
2	M(32) P(3)	59.8 ±24.5	47.8 ±30.2	43.9 ±32.0	8.3 ± 3.4	2.7 ±1.5
6	P(5) C(3)	96.3 ± 4.0	NA#	NA	NA	3.8 ±1.9
1	M(3) F(3)	87.5 ±12.5	0.0 ± 0.0	25.0 ± 0.0	75.0 ± 0.0	5.8 ±0.7

*Infiltration tests (number in parenthesis) located on surface of:
B = bare agricultural C = crop F = forest M = mined surface
P = pasture
# Not applicable

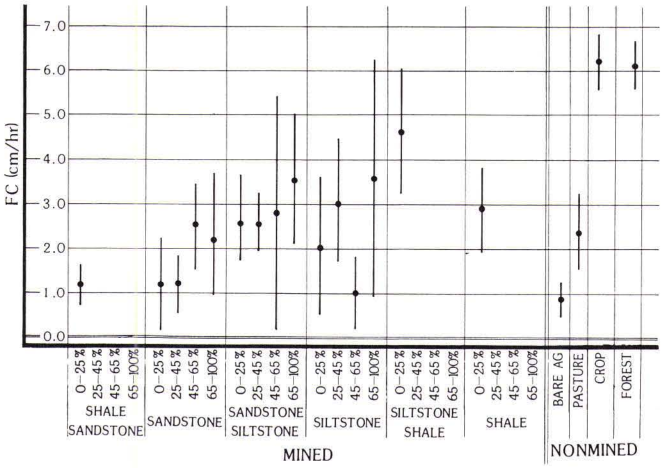

FIG. 5. Plot of infiltration capacity (FC) of six mined groups, based on the surface rock type, and four nonmined groups. The mined groups are subdivided by percent vegetation cover. The mean and ± one standard deviation are indicated by the dot and bar.

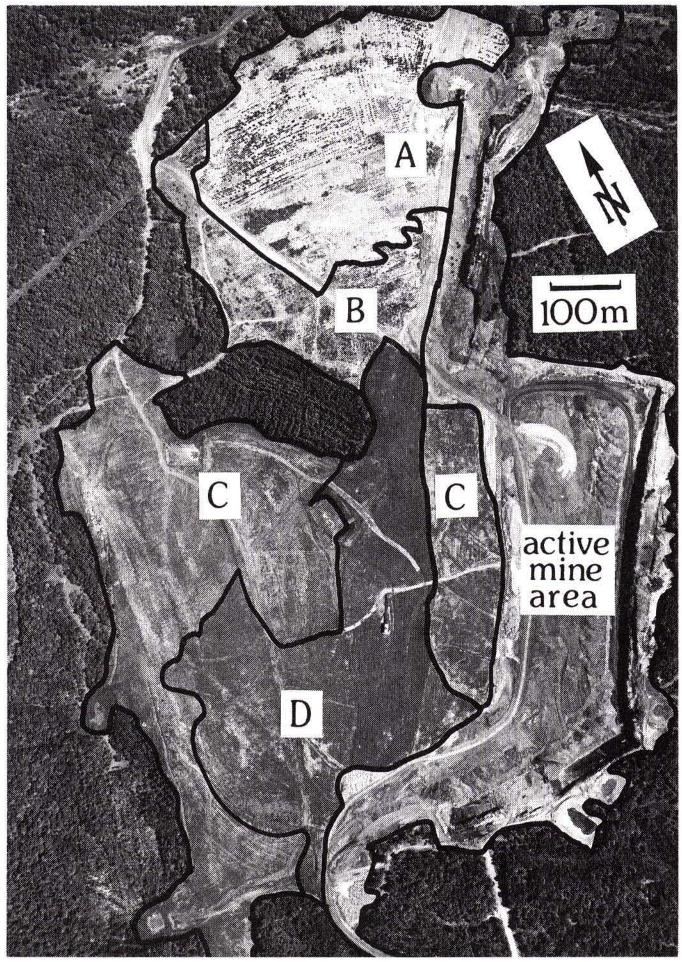

FIG. 6. Percent vegetation cover on Cherry Run mine. A = 0-25 percent; B = 25-45 percent; C = 45-65 percent; D = 65-100 percent.

or siltstone-shale. The siltstone-shale dominated surfaces have the highest FC values. No infiltration tests were run on surfaces dominated partially or totally by shale (siltstone-shale, shale, or sandstone-shale) with greater than 25 percent vegetative cover because of their areal insignificance. The absence of shale dominated surfaces with greater than 25 percent vegetation may be evidence that the highly toxic chemistry of the fissile shales (Jorgensen and Gardner, 1987) prevents more than 25 percent grass cover and only supports pine trees that are more able to tolerate the acid soil. The large scatter in the infiltration data may result from inherent variation in infiltration within each subgroup, not subsetting the data by age, and instrument error.

In conclusion, two properties on mined surfaces that are capable of being remotely sensed—surface rock type and vegetation cover—contribute to the variation of infiltration capacity of mined surfaces. Changes in infiltration due to rock types are most evident on surfaces of less than 25 percent vegetation cover, with siltstone-shale dominated surfaces having the highest infiltration capacities. For mined surfaces of each rock type, infiltration capacities increase with increasing vegetative cover.

INFILTRATION CAPACITIES ON SPOT SPECTRAL CLASSES

It would be useful, for hydrologic studies, to develop a relationship between SPOT spectral classification and infiltration capacity. This relationship will allow the use of remotely sensed data in extrapolation of point infiltration data over an entire watershed. On spatially complex surface mined watersheds, this more spatially extensive and detailed characterization of infiltration rates should contribute to the accuracy and ease of prediction of hydrologic processes, such as water and sediment discharge and groundwater recharge. To develop this relationship, each infiltration test was placed into one of the seven spectral classes by plotting its ground location on the classification map. In addition, each test was labeled according to the type of ground surface (mined, bare agricultural, pasture, crop land, or forest) on which the test was completed. Values for surface features (VG, SS, ST, and SH) and infiltration capacity (FC) entered for each infiltration test were averaged for each spectral class (Table 6). The surface features sensed by SPOT in each spectral class are indicated by the calculated values for the surface feature variables. However, due to the variability in the relationship between FC and surface features (Figure 5), FC valsurface feature variables. However, due to the variability in the relationship between FC and surface features (Figure 5), FC values in each spectral class have large standard deviations relative to the separation of means. Because of this, the SPOT spectral classes for this section of mined and nonmined land are generalized into three groups of low, moderate, and high infiltration, based on the infiltration capacities associated with each class. From Table 6, the class of low infiltration capacity (FC = 2.3 ± 1.2 cm/hr) represents spectral class 4 (bare, mixed lithology and poorly vegetated sandstone-dominated mined surfaces and bare agricultural land), class 5 (bare, sandstone-dominated mined surfaces), class 2 (moderate to well vegetated mixed lithology mined surfaces), and class 3 (bare, shale-dominated mined surfaces). The class of moderate infiltration capacity (FC = 3.8 ± 1.9 cm/hr) represents spectral class 6 (pasture and crop land). The class of high infiltration capacity (FC = 5.8 ± 0.7 cm/hr) represents spectral class 1 (forest and pines on shale-dominated mined surface).

This grouping of spectral classes yields average numerical values of low infiltration capacity for areas disturbed by surface mining and bare agricultural land, moderate infiltration capacity for areas of crop land and pasture, and high infiltration capacity for undisturbed forest and pine trees on old, shaly mined surfaces. This scale of evaluation is useful for hydrologic studies of watersheds containing each of these land-surface types.

CONCLUSIONS

Using SPOT data, an unsupervised minimum distance classification was produced for seven distinct spectral classes on four reclaimed mines and surrounding nonmined land in central Pennsylvania. The spectral classes consist of class 1: forest and pine trees on shale-dominated mined surface; class 2: moderate to well vegetated, mixed lithology mined surface; class 3: bare, shale-dominated mined surface; class 4: bare, mixed lithology and poorly vegetated, sandstone-dominated mined surfaces and bare agricultural land; class 5: bare, sandstone-dominated mined surfaces; class 6: crop land and pasture; and class 7: active mine areas and coal piles.

In this geologic and climatic setting, it is possible to characterize the infiltration capacities of disturbed watersheds by remotely sensed data. Both infiltration capacity and spectral reflectance are related to mined land surface properties of rock type and percent vegetation cover. Infiltration capacity on mined surfaces generally increases as rock type varies from sandstone to shale to siltstone and as vegetation increases on surfaces of similar rock type.

Average rates of infiltration capacity can be determined for each of the seven spectral classes. Because of the variability in the relationship between infiltration capacity and surface features observed by SPOT (vegetation and rock type), the spectral classes are generalized into groups of low (FC = 2.3 ±1.2 cm/hr), moderate (FC = 3.8 ±1.9cm/hr), and high (FC = 5.8 ±0.7 cm/hr) infiltration capacity.

Determination of the relationship between SPOT spectral classes and infiltration capacity illustrates an analytic routine, established in general, for characterizing infiltration rates of disturbed watersheds by remotely sensed data, which can be reapplied under new spectral and field derived infiltration data sets.

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REFERENCES

Beasley, D. B., and L. F. Huggins, 1980. *ANSWERS Users Manual* Lafayette, Department of Agricultural Engineering, Purdue University, Lafayette, Indiana, 55p.

Bondelid, T. R., T. J. Jackson, and R. H. Mc Cuen, 1981. Estimating runoff curve numbers using remote sensing data, *Applied Modeling in Catchment Hydrology (Proceedings of the International Symposium on Rainfall-Runoff Modeling)*. Water Resources Publications, Littleton, Colo., pp. 519–528.

Connors, K. F., 1985. *Simulated SPOT Imagery for the Investigation of Geomorphic Features and Hydrologic Processes*, M.S. Thesis, Pennsylvania State Univ., University Park, Penna., 147 p.

Connors, J. F., T. W. Gardner, G. W. Petersen, 1986. Digital analysis of the hydrologic components of watersheds using simulated SPOT imagery, *Hydrologic Applications of Space Technology*, IAHS Publ. No. 160, pp. 355–365.

Dutcher, R. R., J. C. Ferm, N. K. Flint, and E. G. Williams, 1959. The Pennsylvanian of western Pennsylvania, *Guidebook for Field Trips, Pittsburg Meeting, 1959*, New York, Geological Society of America, pp. 61–113.

Engman, E. T., 1981. Remote sensing application in watershed modeling, *Applied Modeling in Catchment Hydrology (Proceedings of the International Symposium on Rainfall-Runoff Modeling)*. Water Resources Publications, Littleton, Colo., pp. 473–494.

ERDAS, 1985. *ERDAS PC and PC-Kit Image Processing System*, Earth Resources Data Analysis System.

Frickel, D. G., L. M. Shown, L. F. Hadley, and R. F. Miller, 1981. *Methodology for Hydrologic Evaluation of a Potential Surface Mine; The Red Rim Site, Carbon and Sweetwater Counties, Wyoming*. U.S. Geological Survey Water Resource Investigations OF-81-75, 65p.

Gryta, J. J., and T. W. Gardner, 1983. Episodic cutting and filling within gully-fan systems in disequilibrium. *Geological Society of America Abstracts with Programs*, Vol. 15, p. 587.

Horton, R. E., 1933. The role of infiltration in the hydrologic cycle. *American Geophysical Union Transactions*, Vol. 14, pp. 446–460.

Irons, J. R., and Kennard, R. L., 1986. The utility of thematic mapper sensor characteristics for surface mine monitoring. *Photogrammetric Engineering and Remote Sensing*, vol. 52(3), pp. 389–396.

Jansen, I. J., 1981. Reconstructing soils after surface mining of prime agricultural land. *Mining Eng.*, Vol. 33(3), pp. 312–314.

Jorgensen, D. W., 1985. *Hydrology of Surface Mined Land: A Determination of Minesoil Control on Infiltration Capacity, and Runoff Modelling of Disturbed Watersheds*. M.S. Thesis, Pennsylvania State University, University Park, Penna., 127 p.

Jorgensen, D. W., and T. W. Gardner, 1987. Infiltration capacity of disturbed soils: temporal change and lithologic control *Water Resources Bulletin*, Vol. 23(6), pp. 1161–1172.

Lemieux, C. R., 1987. *Infiltration characteristics and hydrologic modeling of disturbed land, Moshannon, Pennsylvania*. M.S. Thesis, Pennsylvania State University, University Park, Penna., 142 p.

Linsley, R. K., M. A. Kohler, and J. L. Paulhus, 1975. *Hydrology for Engineers*: New York, McGraw-Hill, 482p.

Parks, N. F., G. W. Petersen, and G. M. Baumer, 1987. High resolution remote sensing of spatially and spectrally complex coal surface mines of central Pennsylvania: A comparison between simulated SPOT MSS and Landsat-5 Thematic Mapper. *Photogrammetric Engineering and Remote Sensing*, Vol. 53, pp. 415–420.

Rango, A., 1985. Assessment of remote sensing input to hydrologic models. *Water Resources Bulletin*, Vol. 21(3), pp. 423–432.

Rubin, J., and R. Steinhardt, 1963. Soil water relations during rain infiltration. *I. Theory: Soil Science Society of Amer. Proc.*, Vol. 27, pp. 246–251.

SAS (Statistical Analysis System) Institute Inc., 1982. *SAS Users Guide; Statistics*, 1982 edition: North Carolina, SAS Institute Inc., 584p.

Sharp, A. L., and H. N. Holtan, 1940. A graphical method of analysis of sprinkled-plat hydrographs. *Am. Geophysical Union Transactions*, Vol. 21, pp. 558–570.

Surface Mining Control and Reclamation Act, 1977. *Pub. L. 95–87, 91 Stat. 45* (30 U.S.C. Section 1201 et. seq.).

Touysinhthiphonexay, K. C., and T. W. Gardner, 1984. Threshold response of small streams to surface coal mining, bituminous coal fields, Central Pennsylvania. *Earth Surface Process and Landforms*, Vol. 9, pp. 43–58.

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