Hydraulic Properties of Coal and Related Materials, Northern Great Plains

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ABSTRACT

The hydraulic properties (hydraulic conductivity, specific storage and porosity) of coal and the sediments that surround the coal must be known or estimated to properly evaluate the environmental impact of coal strip mining on ground-water flow systems. Published and unpublished data have been summarized from five study areas in North Dakota, three areas in Wyoming, two areas in Montana and two study sites in Alberta. Coal and sand beds form important aquifers in the region. Both materials have hydraulic conductivities of about 2×10^{-6} m$\cdot$s^{-1} and specific storage values on the order of 5×10^{-6} m^{-1}. Aquitards in the region consist of clayey silt to clay bedrock and pebble-loam (in parts of the region). The aquitards are fractured to varying degrees resulting in a wide range of measured hydraulic conductivity values. The aquitards are, in general, 100 to 1,000 times less permeable than the aquifers. Specific storage values of the aquitard material is on the order of 3×10^{-4} m^{-1}. The hydraulic conductivity of strip mine spoils has a six order of magnitude range with a mean of 8×10^{-7} m$\cdot$s^{-1}. Variability is due to a number of factors including spatial variation of overburden lithology, method of spoil handling and contouring and time of year during which the spoil is handled. The hydraulic conductivity of the coal shows wide spatial variability within a given mine site. Variability of coal hydraulic conductivity between mines within North Dakota is less than within a given mine. Within the Northern Great Plains the permeability of coal may increase slightly from east to west.

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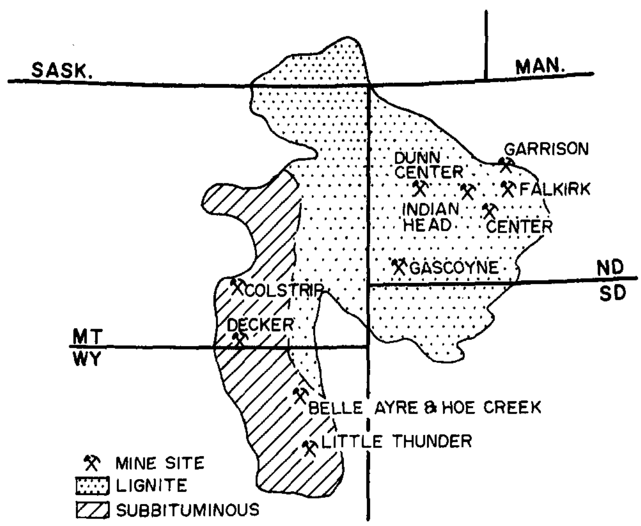

Fig. 1. Location of mine sites discussed in this paper.

INTRODUCTION

With ever-increasing demands for energy has come increased pressure to mine the estimated 10^{12} metric tons (1.1×10^{13} short tons) (USEPA, in preparation) of coal in the Northern Great Plains. Much of the coal, 10^{10} metric tons (1.1×10^{11} short tons) is at shallow enough depths to be extracted by surface or strip mining methods. Low rank lignite and subbituminous coals are found within the Fort Union Group (Paleocene) throughout western North Dakota, eastern Montana, northeastern Wyoming and southern Saskatchewan (Figure 1). The coal beds are on the order of 3 m (10 ft) thick in the eastern portions of the area and up to 25 m (80 ft) thick in the southwest. The coal is interbedded with fluvial deposits of sand, silt and clay which are all slightly to moderately indurated. In the northeastern portion of the area Quaternary pebble-loam (till) deposits overlie the coal-bearing units.

Many questions remain concerning the impacts mining activities will have on physical and social environments. Of particular concern in this semiarid region is the impact strip mining will have on ground-water resources. Proper evaluation of the effects of mining and reclamation on ground-water quantity, availability and quality requires a knowledge of the hydraulic properties of coal and associated sediments. This paper presents data on hydraulic conductivity, storativity and porosity of these materials collected from published and unpublished sources. These data are from sites throughout the Northern Great Plains, with an emphasis on North Dakota.

The absolute values of the hydraulic properties must be understood. In addition, the variability of the parameters must be assessed. On a regional scale, an appraisal of the variability of the hydraulic properties is helpful in evaluating the transferability of site-specific data to other mine sites. On a local scale, the degree of variability of hydraulic properties needs to be considered when designing monitoring networks or developing dewatering operations.

The data presented in this paper were collected from 11 mine sites in North Dakota, Montana and Wyoming (Figure 1) and 2 sites in Alberta, Canada. In Wyoming, the Belle Ayr Mine was evaluated by Davis (1975) and Davis and Rechard (1977) and the Little Thunder Mine by the USEPA (in preparation). The Hoe Creek site was described by Stone and Snoeberger (1977). Mines in the Colstrip and Decker areas of Montana have been investigated by Van Voast (1974), Van Voast and Hedges (1975), Van Voast, Hedges and McDermott (1977) and the USEPA (in preparation). The North Dakota sites have been described in Groenewold and others (1979), Groenewold and Bailey (1979), Moran and others (1978), USEPA (in preparation) and Morin (1979). Data from Alberta were supplied by Moran (personal communication) and Vogwill (1979).

The hydraulic conductivity and storativity values were determined by these authors using several means. The aquifer testing methods included multiple and single-well pumping tests, "slug" tests, permeameter tests, consolidation tests, barometric response analyses, and calibration of numerical ground-water models. No attempt has been made here to assess the relationship between the method of testing and the values of conductivity and storativity derived from these tests.

VARIATIONS BETWEEN LITHOLOGIC UNITS

The hydraulic conductivity values determined by the authors and selected from the literature are summarized in Table 1 and plotted as histograms in Figures 2a through f. This data base includes approximately 420 determinations of hydraulic conductivity.

Sand and gravel of Quaternary and Holocene age show a positively skewed log normal frequency distribution with a geometric mean hydraulic conductivity of 5×10^{-5} $m \cdot s^{-1}$ (2×10^{-4} $ft \cdot s^{-1}$). Geometric means are used to normalize the hydraulic conductivity data from strongly skewed arithmetic distributions. The sand and gravel deposits have a limited areal extent, generally being confined to valleys, but form the best potential ground-water supplies in the Northern Great Plains.

Aquifers in Paleocene sediments consist of coal and sand or sandstone. The frequency distribution of the coal conductivities (Figure 2b) approximates a log normal distribution with a geometric mean of 3×10^{-6} $m \cdot s^{-1}$ (1×10^{-5} $ft \cdot s^{-1}$). The sand and sandstone aquifers (Figure 2c) have virtually the same mean hydraulic conductivity, 1×10^{-6} $m \cdot s^{-1}$ (3×10^{-6} $ft \cdot s^{-1}$), and standard deviation, 10^{-1} $m \cdot s^{-1}$ (3×10^{-1} $ft \cdot s^{-1}$), as the coal but the frequency distribution is more strongly skewed towards low hydraulic conductivities than the coal. Paleocene sand or sandstone is generally quite "dirty" with as much as 15 to 25% silt and clay (USEPA, in preparation). The large number of low conductivity measurements for sand and sandstone probably reflect the presence of sandy silt or sandy clay stringers.

Pebble-loam (till) of Quaternary age covers the bedrock in much of the coal-producing area of North Dakota. This material is not present at the Montana and Wyoming sites. The thickness of the pebble-loam is highly variable, ranging from 0 to 40 metres (0 to 130 ft). The frequency distribution for pebble-loam (Figure 2d) suggests several modes with a mean hydraulic conductivity of 7×10^{-9} $m \cdot s^{-1}$ (2×10^{-8} $ft \cdot s^{-1}$), 100 to 10,000 times less than that of the aquifers.

Aquitards in Paleocene sediments, consisting of silt, clay and shale (Figure 2e), are on the average 100 times less permeable than the bedrock aquifers but four times more permeable than the pebble-loam. The geometric mean hydraulic conductivity of the bedrock aquitards is 3×10^{-8} $m \cdot s^{-1}$ (1×10^{-7} $ft \cdot s^{-1}$). The frequency distribution appears to have two modes at about 3×10^{-7} $m \cdot s^{-1}$ (1×10^{-6} $ft \cdot s^{-1}$) and 5×10^{-9} $m \cdot s^{-1}$ (2×10^{-8} $ft \cdot s^{-1}$).

Both the Paleocene and Quaternary aquitards have a wide range of hydraulic conductivities, approximately six orders of magnitude (Figures 2d and 2e). The spread of values results from the dual permeability and porosity of the aquitards. All of these fine-grained materials have been observed to be fractured on highwalls and in cores. The permeability of fractures is much greater than the permeability of unfractured silt, shale or pebble-loam; therefore, the greater the number of fractures intercepted by a piezometer or a core, the greater the permeability determined by that test. If no fractures are intercepted by the piezometer or core the measured hydraulic conductivity is that of the silt or pebble-loam itself. Because core samples used in laboratory tests are very small, the chances of intersecting fractures are much less than with a 3-m (10-ft) long piezometer tip. Therefore, laboratory tests generally measure the hydraulic conductivity of the unfractured material. The mean hydraulic conductivity of six permeameter tests of bedrock aquitards is 33 times less than that of 14 single-well tests at Dunn Center (Moran and others, 1978).

The coal and sand or sandstone aquifers are also fractured. Both single-well tests and permeameter tests on cores have been carried out on Paleocene sands in the Dunn Center and Falkirk areas of North Dakota. The mean hydraulic conductivity of the sand from single-well tests was only two times greater than the conductivity determined from the laboratory tests. The similarity indicates that the permeability resulting from the fracturing is less important to the bulk hydraulic behavior of sands than for fine-grained sediments.

Fractures are the only cause of permeability in coal. Observations of highwall exposures at the Falkirk Mine indicate fracture spacings of 0.5 to 2 metres (1.6 to 6.6 ft) for the two major, steeply dipping, fracture sets in the coal. This close spacing results in a high probability that a piezometer will intersect at least one fracture. The hydraulic conductivity determined from single-well tests therefore probably applies in many cases to the fracture permeability of the coal rather than the permeability of the coal itself.

Table 1. The Hydraulic Conductivity of the Major Lithologic Units Found in the Northern Great Plains

Quaternary Materials:

	Pebble-loam					Sand & Gravel					
Source*	1	2	3	10	12	1	3	4	7	11	12
N	10	12	1	11	1	4	9	1	6	5	2
log K**	-7.59	-7.39	-6.38	-9.63	-7.00	-4.50	-4.67	-3.25	-4.93	-2.76	-4.37
S	1.12	1.04		0.60		0.23	0.62		0.39	0.42	

Paleocene Materials:

	Silt, Clay or mudstone							Sand or sandstone				
Source	1	2	3	8	9	10	12	1	2	3	9	12
N	8	34	9	1	7	2	2	19	2	23	21	5
log K	-8.39	-7.51	-8.42	-6.04	-6.39	-9.35	-5.17	-6.10	-5.75	-5.84	-5.98	-5.26
S	1.04	0.98	1.69		0.61			1.33		0.99	0.80	0.49

	Coal								
Source	1	2	3	4	5	7	8	12	13
N	52	15	67	9	14	5	4	10	1
log K	-5.89	-5.55	-5.38	-5.61	-5.17	-5.60	-5.49	-5.02	-5.15
S	1.21	0.97	0.92	0.93	0.47	1.21	0.23	0.98	

Spoils

Source	1	4	7	12
N	18	11	2	9
log K	-7.08	-5.62	-5.03	-4.98
S	1.36	0.91		1.11

*Sources:
1. Groenewold & others (1979)
2. Morin (1979)
3. Moran & others (1976)
4. Van Voast, Hedges & McDermott (1977)
5. Van Voast & Hedges (1975)
6. Wyoming data USEPA (in prep)
7. Davis & Rechard (1977)
8. Stone & Snoeberger (1976)
9. North Dakota data, USEPA (in prep)
10. Bara (1953a, b, 1954)
11. Klausing (1974)
12. Moran (personal communication)
13. Vogwill (1979)

** All hydraulic conductivity data presented in terms of $m \cdot s^{-1}$.

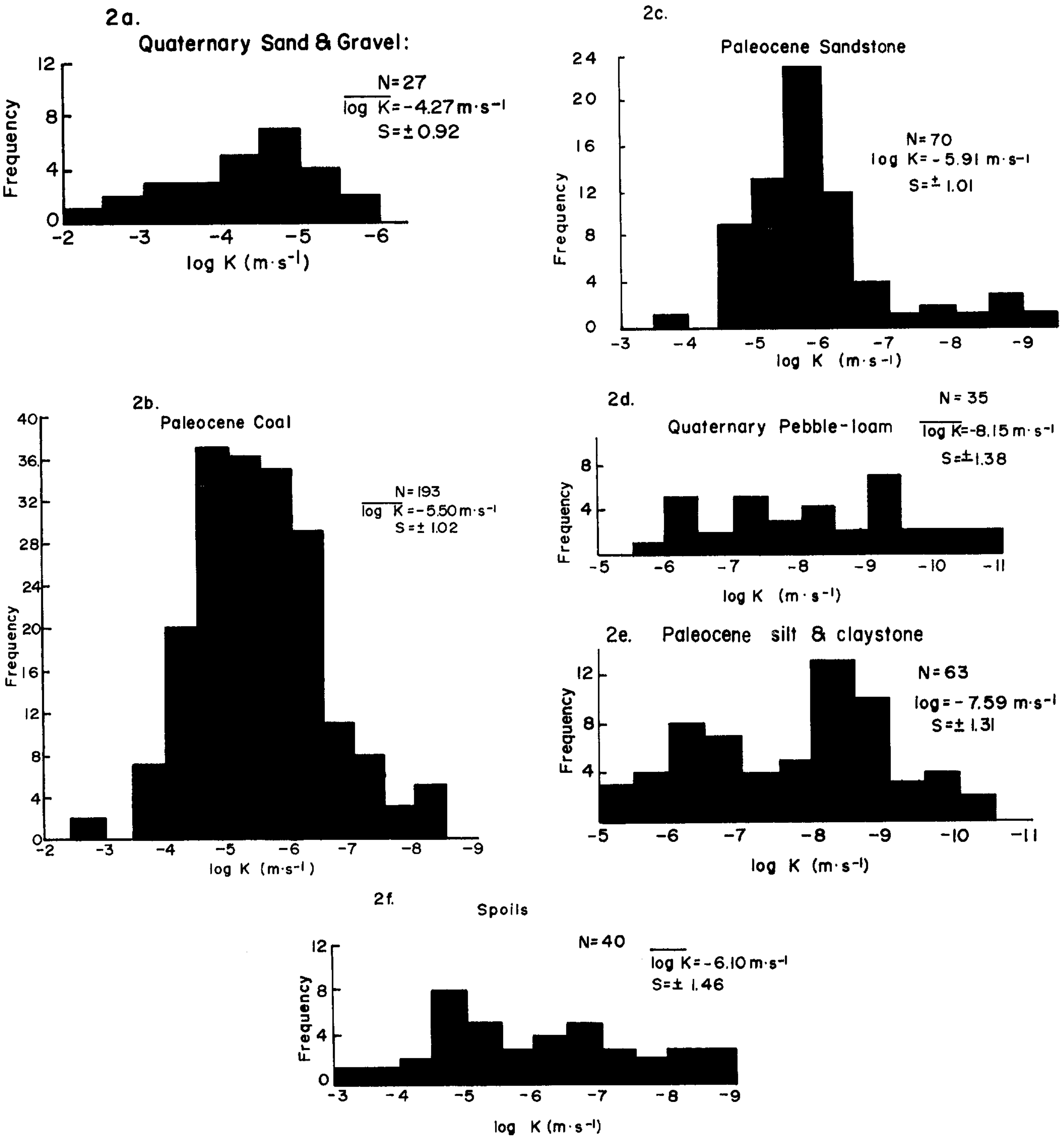

Fig. 2. Histograms of hydraulic conductivity data from the Northern Great Plains.

We have been unable to locate permeameter-derived hydraulic conductivities from the low rank coals found in the Northern Great Plains.

Because the hydraulic conductivity of coal is controlled by fractures, anisotropy is to be expected. Observations of coal in outcrops and oriented cores in Wyoming, Montana and North Dakota all indicate the presence of two principal sets of near-vertical fractures. At the Falkirk Mine the two sets are oriented at approximately N64° E and N30° W. Northeastern Wyoming's sets are oriented at about N70° E and N29° W (Stone and Snoeberger, 1977) with the northeastern group being the more prominent of the two. A primary and a secondary fracture set have been identified in southeastern Montana (Widmayer, 1977). The primary set has an orientation of N55° W and the secondary N40° E. Erickson (1970) found lineaments in the Williston Basin to cluster around two directions: N53° E and N45° W. Stone and Snoeberger (1977) determined the orientations of the principal conductivity axes of coal in northeastern Wyoming using a well-instrumented pump test. The maximum and minimum conductivity axes were oriented at N59° E and N31° W, respectively, very close to the average fracture directions. The maximum and minimum hydraulic conductivities, 3.2×10^{-6} m·s^{-1} (1.0×10^{-5} ft·s^{-1}) and 1.7×10^{-6} m·s^{-1} (5.6×10^{-6} ft·s^{-1}), differ by a factor of 1.9. The maximum and minimum hydraulic conductivity axes for a pumping test conducted at the Falkirk Mine in North Dakota were oriented at N30° E and N60° W and had values of 6.3×10^{-3} m·s^{-1} (2.1×10^{-2} ft·s^{-1}) and 1.3×10^{-3} m·s^{-1} (4.3×10^{-3} ft·s^{-1}). The orientations of the major and minor axes are rotated approximately 23° and 15°, respectively, counterclockwise from the regional lineament orientation found by Erickson (1970).

A third evaluation of coal anisotropy was carried out by Vogwill (1979) near Forestburg, Alberta. The orientation of the hydraulic conductivity axis approximately parallels the regional fracture trends. The major and minor hydraulic conductivity axes were different by a factor of 2.4 with values of 1.0×10^{-5} m·s^{-1} (3.3×10^{-5} ft·s^{-1}) and 4.3×10^{-6} m·s^{-1} (1.4×10^{-5} ft·s^{-1}), respectively.

The hydraulic conductivity of spoils has a six order of magnitude range (Figure 2f). The geometric mean of 40 hydraulic conductivity values from spoils is 8×10^{-7} m·s^{-1} (3×10^{-6} ft·s^{-1}) with a 1.5 order of magnitude standard deviation, the largest standard deviation of all the lithologic units. The large range of measured hydraulic conductivities reflects the highly variable internal structure of the spoils. Spoils consist of a fairly heterogeneous mixture of premining overburden sediments. The overburden is redistributed by blasting and handling by draglines, bulldozers and scrapers. The internal structure of the spoils depends on several factors including the original overburden lithology, methods of stripping the overburden, methods of recontouring the spoils, and the time of year stripping and recontouring take place (Winczewski, 1977 and Groenewold and Bailey, 1979). These factors combine to create a lithologically and texturally heterogeneous mixture. Individual spoil particles range in size from less than one millimetre to several metres in diameter. Slug testing in areas of blocky, loosely consolidated spoils yield hydraulic conductivity values on the order of 10^{-3} or 10^{-4} m·s^{-1} (3×10^{-2} or 3×10^{-3} ft·s^{-1}). In contrast, spoils that were disaggregated or well compacted during the mining and reclamation processes are characterized by hydraulic conductivity values similar to that of the undisturbed fine-grained overburden. Density logs conducted in 44 test holes in spoils at the Indian Head Mine in North Dakota generally substantiate the density or void volume differences indicated by the hydraulic conductivity data (Groenewold and Bailey, 1979).

Since the spoils will replace the coal and sand or sandstone aquifers, the differences in hydraulic conductivity should be noted. Using the average of all permeability values, the spoils in the Northern Great Plains generally have a hydraulic conductivity less than the coal but similar to the silt, sand, sandstone and clay that make up the overburden.

In areas where loosely consolidated and blocky spoils are concentrated, especially where the spoils consist of slightly indurated bedrock as in North Dakota, the hydraulic properties of the spoils are expected to change over time as the spoils consolidate and the voids are filled or lost due to compaction. Evidence for consolidation can be seen in localized and area-wide subsidence and piping of spoils at the Indian Head and Center Mines in North Dakota (Groenewold and Rehm, 1980). The permeability of spoils would be expected to decrease as consolidation continues. Nine piezometers emplaced in spoils at the Indian Head Mine have been tested twice over a period of 17 months. The hydraulic conductivity of 7 of those piezometers has decreased an average of one order of magnitude. The remaining two piezometers indicated a one order of magnitude increase in the hydraulic conductivity of the spoils. This would seem to indicate that in portions of the precontouring valleys the size of the voids are increasing, perhaps as a result of differential settling around the piezometer screen.

Data on the storativity of coal is limited. Van Voast and Hedges (1975) estimated storage coefficients of 2×10^{-5} to 1×10^{-5} [approximate specific storage of 3×10^{-6} m^{-1} (1×10^{-5} ft^{-1})] from the barometric efficiency of wells around the Decker Mine in southeastern Montana. USEPA (in preparation) reports an average storage coefficient of 2×10^{-4} [specific storage of 1×10^{-5} m^{-1} (3×10^{-5} ft^{-1})] of 14 values from pump tests in coal ranging from 8×10^{-8} to 4×10^{-4} m^{-1} (3×10^{-7} to 1×10^{-3} ft^{-1}). The average specific storage determined from a pump test at Dunn Center was 5×10^{-5} m^{-1} (2×10^{-4} ft^{-1}) (Moran and others, 1978). The average specific storage of a pumping test at the Falkirk Mine was 2×10^{-4} m^{-1} (7×10^{-3} ft^{-1}). A pumping test near Forestburg, Alberta yielded an average specific storage of 2×10^{-5} m^{-1} (7×10^{-5} ft^{-1}) (Vogwill, 1979). The mean specific storage value of this data is 6×10^{-5} m^{-1} (2×10^{-4} ft^{-1}) with a standard deviation of approximately one order of magnitude.

Specific yield is important in defining the ground-water flow around a surface mine. Specific yield is equivalent to the effective fracture porosity of the coal. Very few data are available on the fracture porosity of coals in the Northern Great Plains. A specific yield of 0.07 provided the best results in a computer simulation study in Wyoming (USEPA, in preparation). The specific yield from a pump test in an unconfined coal aquifer in North Dakota averages 0.01 (Moran and others, 1978).

The specific storage of the confined bedrock sand aquifers, determined by two pumping tests at Dunn Center (Moran and others, 1978), was 5×10^{-6} m^{-1} (2×10^{-5} ft^{-1}) and 1×10^{-5} m^{-1} (3×10^{-5} ft^{-1}). The specific storage of an earth material can also be calculated from data obtained during consolidation tests. Consolidation data published by Bara (1953b) have been analyzed in this manner. Two cores of Tertiary silty sand in North Dakota were determined to have specific storage values of 2×10^{-4} m^{-1} (7×10^{-4} ft^{-1}) and 3×10^{-4} m^{-1} (1×10^{-3} ft^{-1}).

As surface mining proceeds and ground water begins to discharge from coal aquifers, the aquitards surrounding the coal release water held in storage. Therefore, the specific storage of the aquitards must also be estimated. Three Tertiary silt and clay samples from the Falkirk Mine had specific storage values of 1×10^{-4} m^{-1} (3×10^{-4} ft^{-1}), 5×10^{-4} m^{-1} (2×10^{-3} ft^{-1}), and 1×10^{-4} m^{-1} (3×10^{-4} ft^{-1}). Three pebble-loam (till) samples from the Falkirk Mine had calculated specific storage values of 2×10^{-4} m^{-1} (7×10^{-4} ft^{-1}), 7×10^{-4} m^{-1} (2×10^{-3} ft^{-1}), and 2×10^{-4} m^{-1} (7×10^{-4} ft^{-1}). Two consolidation tests of Tertiary clay and silt, published by Bara (1953b), yielded storativity values of 2×10^{-4} m^{-1} (7×10^{-4} ft^{-1}) and 3×10^{-4} m^{-1} (1×10^{-3} ft^{-1}).

Evidence suggests that spoils can form confined aquifers where coarse, blocky spoils are surrounded by finer spoil material. The barometric response of six piezometers was used to estimate an average storage coefficient of 2.5×10^{-5} in Montana (USEPA, in preparation).

VARIATIONS WITHIN LITHOLOGIC UNITS

The following discussion of variability of hydraulic properties within lithologic units is limited to North Dakota because of the high density of instrumentation at the North Dakota mine sites (approximately 1,200 piezometers) and the authors' greater familiarity with the area.

No strong areal trends have been observed within any single lithologic unit in the intervals between the coal beds. Most variability in permeability in the noncoal sediments results from lateral changes in lithology. The lateral, and vertical gradations from silt and clay to sand are the result of changes in the alluvial-flood plain paleo-depositional environments during the Paleocene (Jacob, 1973).

Individual coal beds, on the other hand, show a great deal of areal variability in hydraulic characteristics. Significant differences in hydraulic characteristics between coal beds are also common. The major bed at the Garrison site splits into an upper and a lower seam (Morin, 1979) (Figure 3). The dashed lines in Figure 3b indicate the approximate location where the lower and upper seams join to form a single coal bed. Through the south-central portion of the study site is an area of very high hydraulic conductivity, greater than 10^{-4} m·s^{-1} (3×10^{-4} ft·s^{-1}) (stippled area of Figure 3). To the north and south the conductivity of this coal decreases by at least two to four orders of magnitude, respectively.

The major coal bed at the Falkirk Mine is extensively instrumented. This coal bed is split into two seams; the main Hagel bed (upper) and the B bed split (lower) (Groenewold and others, 1979). In the south-central portion of the area, the main Hagel bed has a low hydraulic conductivity, 10^{-6} to 10^{-7} m·s^{-1} (3×10^{-6} to 3×10^{-7} ft·s^{-1}) (Figure 4). To the east the conductivity of this bed increases to 10^{-4} m·s^{-1} (3×10^{-4} ft·s^{-1}) whereas to the west the hydraulic conductivity increases one to two orders of magnitude and then decreases again. The B bed split is less well instrumented but generally a trend of declining conductivity is evident to the north (Figure 4b).

The permeability pattern of the main Hagel bed appears to parallel the northeast trending erosional surface of the coal bed and is truncated by the east-west erosional edge on the south side of the coal subcrop. These erosional surfaces are deeply incised pre-Quaternary age valleys. The high permeability zones also roughly parallel regional lineament orientations (Erickson, 1970). The lineaments are probably surface expressions of fracture zones which would have higher permeability than the surrounding rock.

Croft and others (1978) have also noted zones of high coal hydraulic conductivity, 7×10^{-4} m·s^{-1} (2×10^{-3} ft·s^{-1}), in the vicinity of valleys which parallel the regional lineament orientations at the Gascoyne Mine. The hydraulic conductivity of the Harmon lignite bed at the Gascoyne Mine was found to vary between 7×10^{-4} to 4×10^{-6} m·s^{-1} (2×10^{-3} to 1×10^{-5} ft·s^{-1}).

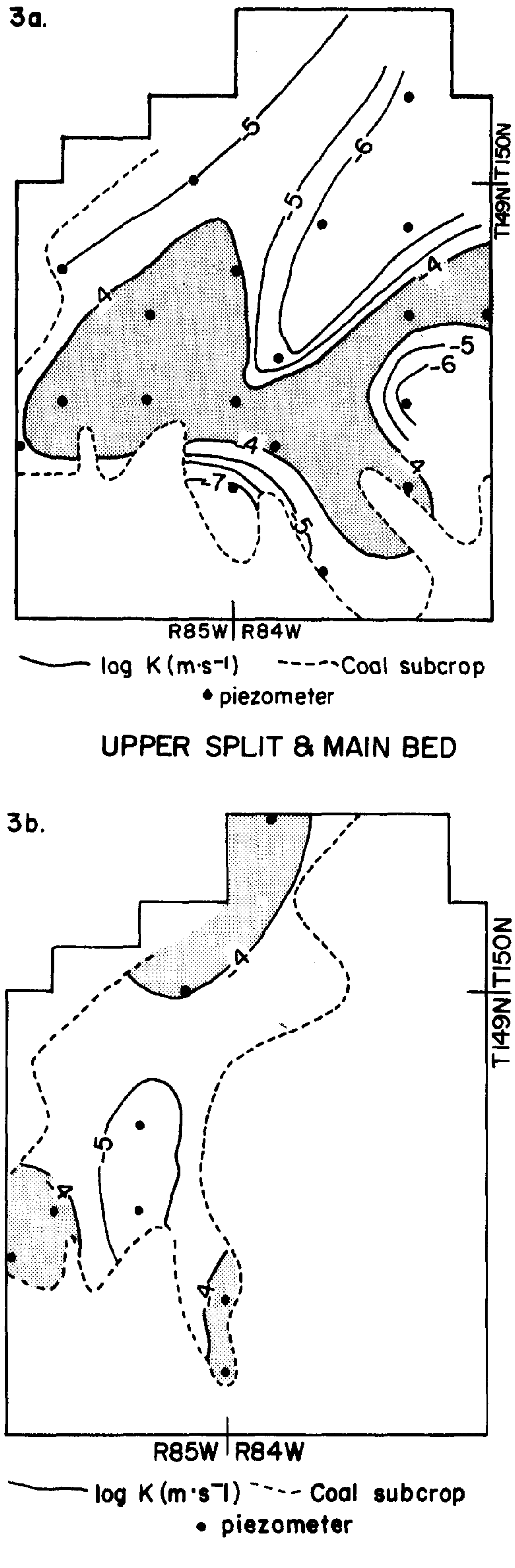

Fig. 3. Areal variations in hydraulic conductivity at the Garrison site, North Dakota.

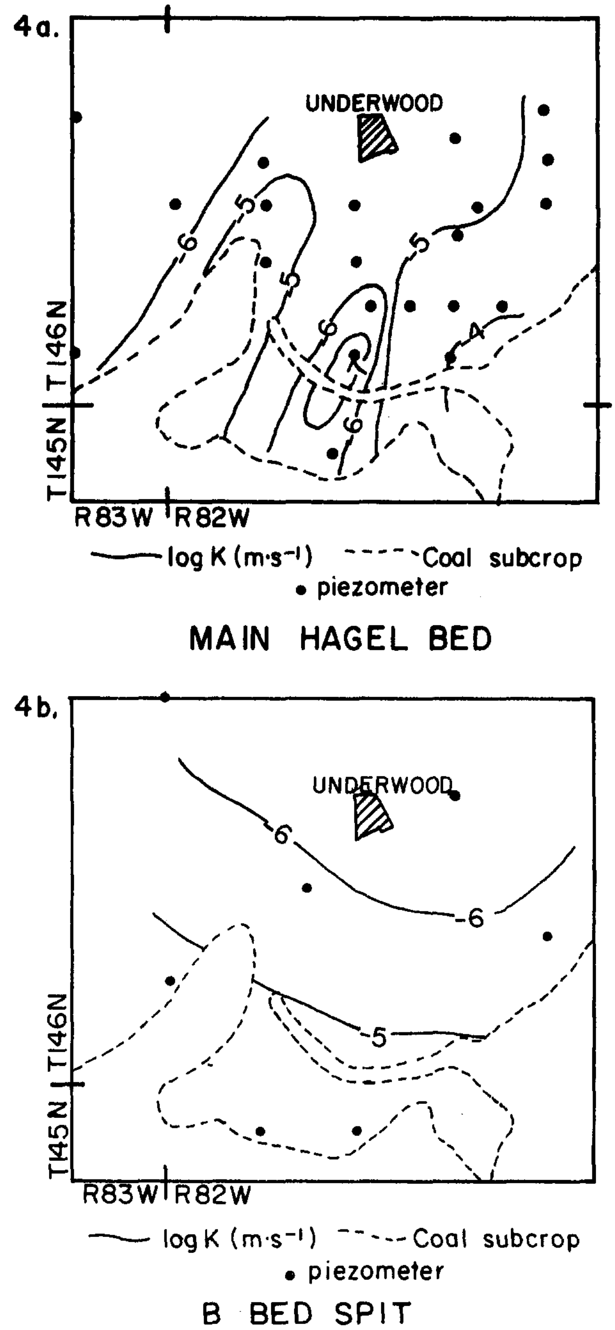

Fig. 4. Areal variations in hydraulic conductivity at the Falkirk Mine, North Dakota.

There is a weak correlation between coal hydraulic conductivity and depth in the Falkirk data with a one order of magnitude decrease in hydraulic conductivity for every 13-m (42-ft) increase in depth. A trend of decreasing permeability with depth is to be expected. Increased depth and confining pressures result in a decrease in the size of the fractures in the coal and thus, a decrease in permeability. Three pump tests at the Dunn Center site, conducted in coal beds at depths of 6, 20, and 47 metres (20, 66 and 154 ft), result in a regression equation of

$$\log K = -2.182 - 0.081\ d \qquad r^2 = 0.996$$

which corresponds to a one order of magnitude decrease in hydraulic conductivity for every 12 m (39 ft) of depth.

At the Center site, the Hagel bed (Groenewold and others, 1979) and the stratigraphically higher Kinneman Creek bed (Groenewold and others, 1979) are instrumented (Figure 5). A pattern of conductivity variation cannot be derived from the seven conductivity measurements made in the Kinneman Creek bed. The Hagel bed is most permeable through the center of the study area and decreases by three orders of magnitude toward the north and south. The mean hydraulic conductivity of the Kinneman Creek bed is approximately 10 times less than that of the Hagel bed. On the basis of a two-tailed

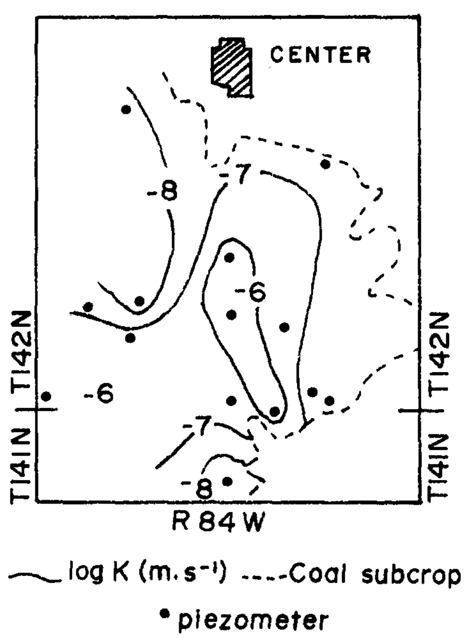

Fig. 5. Areal variation in hydraulic conductivity of the Hagel bed at the Center mine, North Dakota.

t-test this difference in conductivity is significant at the 0.01 and 0.05 levels.

Limited data from spoils at the Indian Head Mine suggest that the hydraulic conductivity of the spoils is related to the methods with which the spoils are handled and the time of year the spoils are leveled for reclamation (Groenewold and Gailey, 1979). Within the spoil ridges, the mean hydraulic conductivity of six single-well response tests is 3×10^{-8} m·s^{-1} (1×10^{-7} ft·s^{-1}) with a range of 3×10^{-7} to 5×10^{-9} m·s^{-1} (1×10^{-6} to 2×10^{-8} ft·s^{-1}). The mean hydraulic conductivity of five single-well response tests from inter-ridge valleys is 2×10^{-7} m·s^{-1} (7×10^{-7} ft·s^{-1}) with a range of 5×10^{-5} to 3×10^{-9} m·s^{-1} (2×10^{-4} to 1×10^{-8} ft·s^{-1}) (Groenewold and Bailey, 1979). The conductivity of the spoils in the valleys has a higher mean and a wider range of values than those of the ridge areas. The difference in permeability between the two prereclamation spoil morphologies is related to their means of emplacement. The ridges were created solely by draglines while the materials in the valleys were handled largely by bulldozers. As the dragline dumps buckets of overburden, the larger blocks of material tend to roll into the valleys between ridges. During the contouring process the bulldozers push the tops of the ridges into the valleys. This action also tends to segregate the large blocks of spoil material in the valleys (Winczewski, 1977; Groenewold and Winczewski, 1977). Large voids are created within this blocky, loosely compacted spoil. The existence of the voids is evidenced by density logs (Groenewold and Bailey, 1979) and by the higher and more variable hydraulic conductivity measurements. Where a piezometer intersects a large number of voids a high hydraulic conductivity is measured. When a piezometer is placed within a spoil block or highly compacted spoil, the measured hydraulic conductivity reflects that of the lithology of the block or of materials having a density very similar to the premining overburden, respectively. The creation of blocky spoils is enhanced when overburden stripping or spoil contouring are carried out during the winter months because the water in the pores of the sediment freezes. The tendency to create permeable, blocky spoils is reduced when the spoils are handled by scrapers. The scrapers break the spoil blocks into smaller pieces when they pick up the material. The scrapers also compact the spoils as they drive over the layers of spoil that have been previously deposited (Groenewold and Winczewski, 1977; Groenewold and Bailey, 1979).

Table 2. Coal Hydraulic Conductivities ($m \cdot s^{-1}$) at North Dakota Mine Sites

	Falkirk	*Garrison*	*Center*	*Indian Head*	*Dunn Center*
N	28	15	20	4	67
$\log_{10}K$	−5.23	−5.55	−6.38	−6.50	−5.38
S	1.39	0.97	1.14	1.34	0.92

VARIATIONS WITHIN NORTH DAKOTA

The similarity of the geometric means of the hydraulic conductivity of the coal at four of the instrumented mine sites (Table 2) has been evaluated using t-tests. At a significance level of 0.01 the mean conductivity of the coal at Center is significantly less than that of the coal at Falkirk, Garrison and Dunn Center. The differences in conductivity are about one order of magnitude. Four values of the hydraulic conductivity of coal from the Indian Head Mine have a mean conductivity value that is over ten times less than those from Falkirk, Garrison and Dunn Center. The reasons for this difference in permeability are currently unknown. The limited data published for the Gascoyne Mine (Croft and others, 1978) indicate that the hydraulic conductivity of coal there is higher than that found at the other North Dakota mines.

VARIATIONS WITHIN THE NORTHERN GREAT PLAINS

Permeability of coal averaged by State and Province (Table 3) indicates that within the Northern Great Plains and Alberta the geometric mean hydraulic conductivity is not significantly different from one area to another at a 99% confidence level. However, a trend in the hydraulic conductivity of coal is evident within the small range of conductivity variations. The coal hydraulic conductivity increases from North Dakota to Montana to Wyoming to Alberta by about half an order of magnitude. The trend may be due to increasing coal rank, lignite in North Dakota and subbituminous in the other areas or increased fracturing resulting from varying degrees of tectonic activity. The hydraulic conductivity of spoils also appears to increase along the same regional trend as the coal hydraulic conductivity. This change may reflect the degree of induration of the overburden or varying methods of spoil handling and recontouring. Further research is needed to evaluate the significance of this trend.

Table 3. Hydraulic Conductivities ($m \cdot s^{-1}$) of Coal and Spoils Averaged by State and Province

Coal	*North Dakota*	*Montana*	*Wyoming*	*Alberta*
N	128	23	22	10
$\log_{10}K$	−5.55	−5.34	−5.27	−5.02
S	1.16	0.70	0.85	0.98
Spoils	*North Dakota*	*Montana*	*Wyoming*	*Alberta*
N	18	11	2	9
$\log_{10}K$	−7.08	−5.62	−5.03	−4.98
S	1.36	0.91		1.11

CONCLUSIONS

Hydraulic properties of shallow coal-bearing units in the Northern Great Plains not only vary from one lithologic unit to another but spatially within and between mines for the coal beds and temporally for strip mine spoils. Generally only the variation of hydraulic conductivity and specific storage between lithologic units has been used in evaluating the impacts of strip mining on ground-water flow systems. The analytical solutions used by some investigators (Moran and Cherry, 1978; and Van Voast, 1974) cannot handle heterogeneous porous media. Numerical models can generally accommodate a heterogeneous media but many studies (Hamilton and Wilson, 1977; Wilson and Hamilton, 1978; and Warner and others, 1978) assume the coal or spoils to be homogeneous.

Disregard for the heterogeneities of a coal aquifer at a specific mine site can result in problems in the development of a dewatering plan and in correct prediction of the effect of the mine on local water supply wells. The main Hagel bed at the Falkirk Mine (Figure 4) can be used as an example. For purposes of illustration we will assume that the thickness, specific storage and potentiometric surface of the coal bed are constant, and ground-water flow above the bed is everywhere vertical and constant. If the mine begins in the south-central portion of the coal bed the "drawdown cone" around the mine will be steep and extend only a relatively short distance from the mine. The mine will encounter minor problems with pit dewatering. If, on the other hand, the mine were to begin along the eastern subcrop of the coal where the hydraulic conductivity is 100 times greater the "drawdown cone" will be much flatter and it will extend much further from the mine than in the previous case. The mine will also face much greater problems in pit dewatering. As the active mine pit moves across the area the reaction of the ground-water flow system will vary between these extremes.

The evaluation of postmining ground-water flow systems can become very complex since the hydraulic properties of the spoils will vary both over the area of reclaimed land and with time at a point within the reclaimed area. In past studies of postmining flow systems the reclaimed spoils have been treated as homogeneous masses (Hamilton and Wilson, 1977). A more accurate representation of spoils may consist of parallel bands of high and low hydraulic conductivity that are perpendicular to the direction in which the mine highwall(s) advanced. The average horizontal flow rate through the spoils would then depend not only on the low mean hydraulic conductivity found within the prereclamation spoil ridges, but also on the orientation of the ridges relative to the regional ground-water flow direction. Minimum flow rates would occur when the ridges are perpendicular to the flow direction. When the ridges are parallel to the regional flow direction the maximum flow rates through spoils will be controlled by the higher hydraulic conductivity of the material in the precontouring valleys.

In areas such as North Dakota, where overburden consists of predominantly nonindurated sediments, it is probable that the permeability of spoils will decrease with time. Over a period of years, spoils which are initially relatively permeable, may approach the intergranular hydraulic conductivity of the predominant lithology of the premining overburden. If the overburden consists mostly of sand or soft sandstone the spoils may continue to function as aquifers over the long term. If silt, clay and shale predominate in the overburden, the hydraulic conductivity may decrease to a value similar to that of premining aquitards.

Many other scenarios can be devised. This paper has demonstrated the fact that the areal and temporal variability in hydraulic conductivity (and probably specific storage and porosity as well) within a given lithostratigraphic unit is important in evaluating the impact of surface mining and reclamation on ground water and the impacts of ground water upon mining. In areas where data is lacking or for general nonsite-specific studies, the mean values and their respective standard deviations and ranges are available to derive approximate solutions to problems. The variability of the hydraulic properties then can be used to evaluate qualitatively the uncertainty in applying those solutions.

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