Chapter 3

HYDROGEOLOGIC CHARACTERISTICS OF SURFACE-MINE SPOIL

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Introduction

An understanding of the hydrology of surface mine spoil is important in predicting mine drainage quality. However, it is poorly understood and one of the least analyzed aspects of mine drainage prediction. Groundwater is a integral chemical component in acid mine drainage (AMD) formation and it serves as the contaminant transport medium. Therefore, prediction of postmining drainage quality requires the inclusion of a surface mine spoil groundwater hydrology component in the process.

The nature, degree, and duration of groundwater and spoil interactions need to be factored into any comprehensive mine drainage predictive method or model. Recharging waters, moving through the unsaturated portion of backfill, will have intermittent episodes where discrete areas of the spoil are briefly contacted, whereas groundwater within the saturated zone will have a considerably more consistent and longer contact time with that portion of the spoil. Groundwater within the zone of water table fluctuation will contact nearly all of that spoil zone periodically during brief episodes when water levels rise. Groundwater will, in both the unsaturated and saturated zones, chemically and physically react with the spoil material that it contacts. However, mine drainage quality prediction is often based on the assumption of uniform contact with 100 percent of the spoil material and does not take into consideration that groundwater only contacts a limited fraction of the spoil. Also, under differing hydrologic conditions, the sections of the spoil contacted by groundwater can change. It is important to determine what portions of the spoil are contacted by the groundwater and what is the nature of this contact. Spoil excavations and aquifer testing indicate that there are areas within backfills that, because of very low permeability, allow very little groundwater flow through them. These relatively "dead" areas contribute little to the groundwater system and to the associated mine drainage quality.

Characteristics of Mine Spoil Groundwater Flow Systems

In the past, the groundwater flow regime in surface mine spoil of the Appalachian coalfields has generally received little attention and study. Most individuals have made the assumption that ground-water flow in mine spoil is a porous media system, similar to flow through unconsolidated alluvium. Recent field work and testing of surface mine spoil indicate that this assumption is not completely valid.

Caruccio et al. (1984) noted that groundwater flow in the backfill of a surface mine in central West Virginia was highly channelized and that it was not observed until one of these randomly located channels was intercepted. Based on their physical observations during excavations in mine spoil, they referred to the groundwater flow regime as pseudokarst, where groundwater flows mainly through large voids and conduits. Pseudokarst hydraulic characteristics are similar to the characteristics observed in some karst (carbonate underlain) terrains, however, the mechanism of channel and void formation differs. These types of systems are more discriptively defined by the term double-porosity.

Hawkins and Aljoe (1990) noted that mine spoil exhibits characteristics of both porous medium and double-porosity aquifers. Under steady-state conditions spoil behaves mainly as a porous medium aquifer. For example, the presence of a relatively continuous water table in the backfill and perennial consistent-flowing mine discharges are indicative of an overall porous media system. Hydraulic conductivity values measured in mine spoil are substantially below values expected for open conduit flow.

Conversely, when a spoil aquifer is stressed (for example, during an aquifer test) or subjected to transient conditions, double-porosity characteristics become more pronounced and can briefly dominate the hydrologic regime. For example, multiple water tables and temporary flowing artesian conditions have been observed during substantial recharge events (Hawkins and Aljoe, 1990). Monitoring and testing indicate that

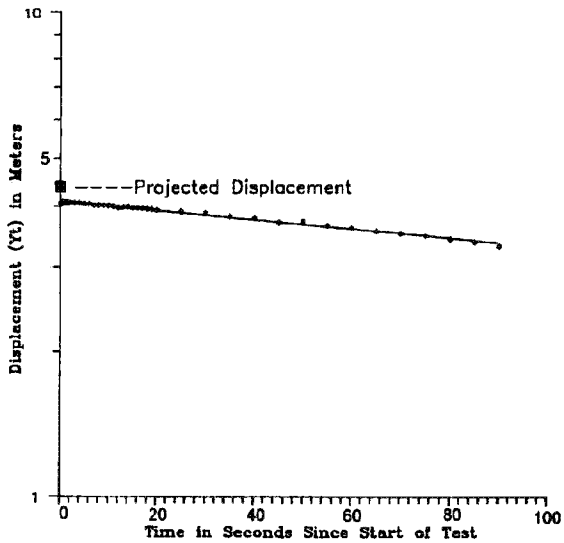

Figure 3.1(a) Slug test exhibiting a "typical" porous media type response. The actual displacement and the projected are nearly the same, because the flow from the well into the aquifer is gradual and diffuse.

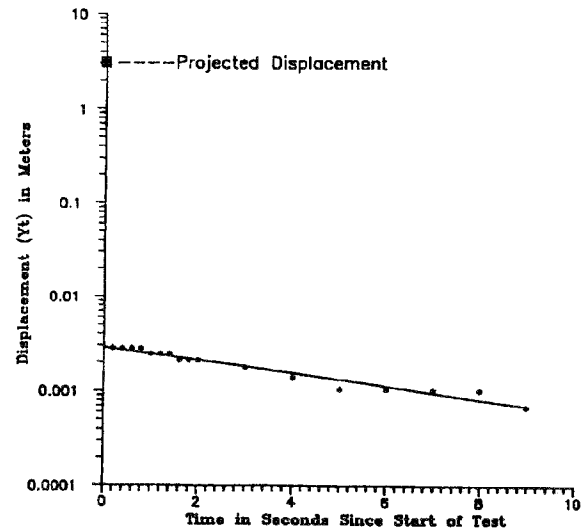

Figure 3.1(b) Slug test exhibiting an "atypical" double-porosity type response. The actual displacement is much lower than the projected displacement, because large voids very quickly accept some of the displaced water. Once the voids are full, a gradual and diffuse flow from the well into the aquifer occurs.

groundwater is stored in and flows through large voids or conduits in spoil; however, these voids are not always well interconnected across a mine site. Therefore, diffuse groundwater flow through the interstices of the fine-grained material between the voids exerts significant control on the overall site hydrology. Slug tests performed in wells penetrating surface mine spoil empirically illustrate the bimodal nature of the groundwater flow regime. These tests yield two distinctly different types of responses in mine spoil (Fig. 3.1(a) and (b)). One type (Fig. 3.1(a)) of response is indicative of a porous media system. The actual displacement and the projected displacement are similar, indicating gradual and diffuse flow from the well into the aquifer as expected in a porous medium. The second type indicates the presence of large voids and conduits of a double-porosity system. The actual displacement is substantially less than the projected displacement, indicating large voids adjacent to the well rapidly fill with water flowing from the well. Once the voids are filled, there is a gradual and diffuse flow from the well into the spoil (Hawkins, 1993). The projected displacement in Figures 3.1(a) and 3.1(b) is determined from the known slug volume.

These dual aquifer flow characteristics exist because mine spoil is an extremely heterogeneous and anisotropic material. The heterogeneities are created by the processes of mining and reclamation. During mining and subsequent reclamation, spoil becomes sorted to some extent. When dumped by a rock truck or dragline and regraded by bulldozers, the larger spoil particles tend to roll toward the base of the spoil ridges into the valley between the ridges, while the midsized and smaller fragments tend to stay on the sides and top of the spoil piles (Rehm et al., 1980). Figure 3.2, a photograph of spoil at an active surface mine in central Pennsylvania, illustrates the results of this process. Groenewold and Bailey (1979) observed that in western North Dakota, monitoring wells completed in the spoil valleys exhibit more variable hydraulic conductivity than wells completed in the spoil ridges. Aquifer testing (constant-discharge tests) of spoil in northern West Virginia and western Pennsylvania indicates that linear zones of high hydraulic conductivity tend to parallel spoil ridge orientation. Hydraulic conductivity perpendicular to the spoil ridges appears to be significantly lower (commonly by several orders of magnitude) than that parallel to the ridges (Hawkins and Aljoe, 1991).

Factors Influencing Hydraulic Characteristics

Lithologic Controls

Lithology of the spoil can influence the hydraulic conductivity in reclaimed mines. Parent rock (overburden) of surface mine spoil in northern Appala-

chia is comprised primarily of sandstone, siltstone, and shale. In some areas, limestone may occur in significant quantities, as may glacial sediments.

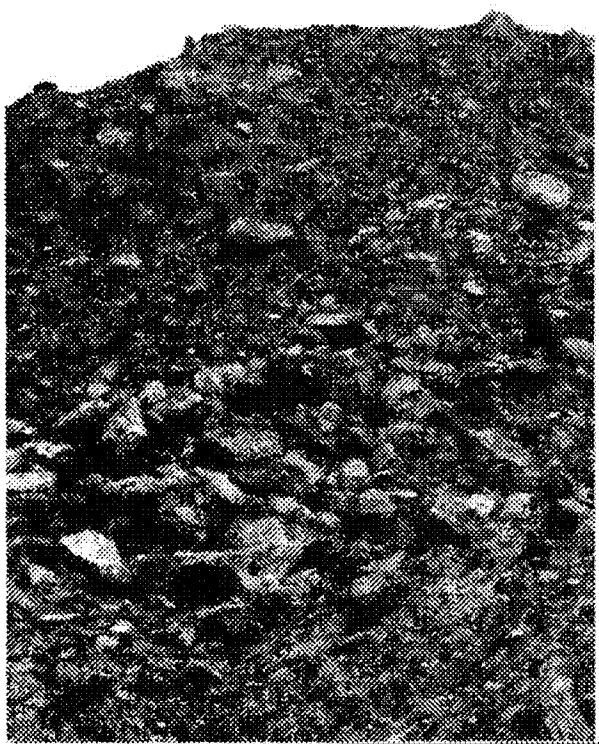

Figure 3.2 Spoil ridge exhibiting fragment size sorting during mining. The sandstone boulders in the foreground are approximately 1 m across and the material in the background is chiefly shale 5 cm or less across.

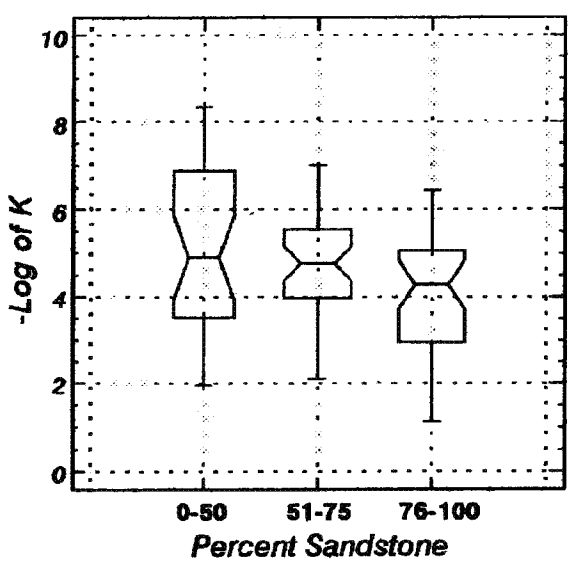

Figure 3.3 Notched box-and-whisker plot illustrating the relationship of spoil lithology to hydraulic conductivity.

Figure 3.3 indicates that increasing percentages of sandstone (and decreasing percentages of shales) in mine spoil appear to yield higher median hydraulic conductivity values and a narrower range of values (Aljoe and Hawkins, 1994). However, the median hydraulic conductivity increases observed were not statistically significant. The apparent trend is explained by the hydraulic properties of the different lithologies and by mechanisms of mining and reclamation. Sandstone-rich spoil zones tend to have larger fragments than shale-rich zones. This is because sandstones of this region tend to be well cemented and are better able to resist breakage and weathering. Shales tend to break into smaller fragments during mining and more readily weather and break down to silt- and clay-sized particles, which decreases the hydraulic conductivity (Aljoe and Hawkins, 1994). An accumulation of clay and silt toward the base of the spoil is often observed in monitoring wells that are purged (pumped or bailed) infrequently, confirming the breakdown.

The processes of mining and reclamation may further facilitate spoil heterogeneity by creating zones comprised predominantly of one lithology. During mining, a dragline or frontend loader often will remove the overburden in layers, spoiling strata composed mainly of one lithology at a time. Monolithic zones are also created by the tendency of large spoil fragments (mainly sandstone) to roll to the base of spoil ridges, while the medium and smaller fragments (shale and some sandstone) tend to remain on the sides and top (Fig. 3.2). This appears to account for the observation of Groenewold and Bailey (1979) that spoil valleys had a higher mean and greater range of hydraulic conductivity than the ridge areas in the northern Great Plains. A test well drilled randomly into spoil with a lithology of 50 percent sandstone and 50 percent shale should have an equal chance of intersecting a shale-rich or a sandstone-rich saturated zone. Therefore, the hydraulic conductivity is expected to range more widely when the sandstone content is 50 percent than when it approaches 100 percent. As the sandstone content of spoil increases, the number of wells that will intersect sandstone-rich zones likewise increases, thus causing the median hydraulic conductivity to increase (Fig. 3.3).

Phelps (1983) observed that spoil bulk density generally decreases with depth. This appears to be caused by the creation of a significant volume of interstitial

voids when the large spoil fragments, commonly sandstone, roll to the bases of spoil piles.

Mining Methods and Topography

Because, surface mine spoil is a highly heterogeneous and anisotropic medium, groundwater flow paths are difficult to determine. However, some general trends have been identified and a few assumptions can be made concerning groundwater flow through mine spoil.

Topography influences groundwater flow in surface mine spoil, because groundwater flows down the hydraulic gradient and topography directly influences the hydraulic gradient. Although, spoil aquifers can exhibit multiple water tables for brief periods under transient conditions (Hawkins and Aljoe, 1990), surface mine spoil generally exhibits a single continuous water table with a moderate hydrologic gradient. Thus, the water table tends to reflect the overlying topography. However, the water table is also influenced by other geologic and hydrologic conditions, such as permeability variations, local structure, and the adjacent unmined areas.

The structural dip of the pit floor is a major influence on the direction of groundwater flow in spoil aquifers. Groundwater tends to flow down dip and perpendicular to the strike of the pit floor. Toe-of-spoil discharges will commonly form at the structural low point of the pit floor outcrop.

Influences from the groundwater system in adjacent unmined areas can cause groundwater in spoil to disregard structural dip and other hydrologic factors. Localized rolls or swales in the pit floor can affect the direction of groundwater flow. When the strata dip toward the final highwall, the groundwater tends to saturate spoil behind the highwall. This is because the hydraulic conductivity of the undisturbed aquifer in the highwall is commonly at least 2 orders of magnitude less than in the spoil and the pit floor material usually has significantly lower permeability than the spoil (Hawkins, 1995). Groundwater impounding at the highwall may flow in any of several directions. Depending on the hydraulic gradient, groundwater may enter the unmined strata and flow down the structural dip, or it may flow laterally, parallel to the highwall, and discharge where the pit floor is exposed at the surface along the structural strike. The spoil may become sufficiently saturated to permit discharges to emanate at the topographic low point of the mine along the original coal cropline, opposite to the dip direction (Fig. 3.4). Depending on the permeability, significant amounts of groundwater may leave the backfill by downward flow through the pit floor. Depending on the configuration and size of adjacent unmined areas, the groundwater gradient may cause flow from the highwall into the spoil, regardless of the structural dip.

Direction of mining and the configuration of the backfill can dramatically impact the direction of groundwater flow. The highly permeable zones that

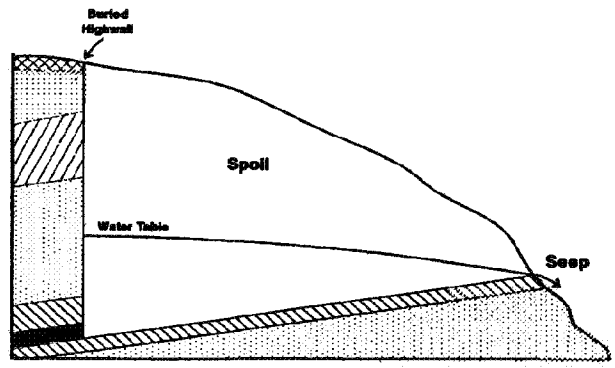

Figure 3.4 A schematic cross section of a reclaimed surface mine with saturated spoil behind the highwall and a seep emanating at the topographic low point opposite the structural dip.

form in the valleys between spoil ridges permit substantial groundwater flow parallel to the ridges. Because groundwater tends to follow the path of least resistance, groundwater flow perpendicular to the spoil ridges is considerably less than flow parallel to them. Constant-discharge testing in a reclaimed surface mine in central West Virginia, conducted by the author, indicates that the hydraulic conductivity difference between buried spoil valleys and ridges can exceed 2 orders of magnitude. Groenewold and Winczewski (1977) observed that the surface over these highly transmissive spoil valleys is more susceptible to subsidence from piping of fine grained spoil materials because of the substantial amount of groundwater movement.

The location of haul roads across the backfill also can influence groundwater flow (Robert S. Evans, personal communication). Spoil underlying haul roads can become highly compacted (less transmissive) from the traffic of vehicles and heavy equipment. The spoil on each side of the haul road will be substantially more transmissive than the spoil under the haul road. The level of spoil compaction is related to the lithology of the spoil material and the amount of equipment traffic.

Groundwater may flow along the road edge until a pathway through exists or impound behind these haul roads which may be buried and hidden in the reclaimed backfill.

Impacts of Spoil Age

Shortly after regrading of the spoil, differential settling and piping of the finer material begin in the backfill (Groenewold and Bailey, 1979). These subsequent processes contribute greatly to the heterogeneity of spoil and are facilitated by infiltrating surface waters and the water table re-establishment. The "uplift" pressure provided by the rebounding groundwater table may aid the shifting and repositioning of spoil fragments (Sweigard, 1987). Sweigard observed significant settling within a year after reclamation on Illinois surface mines and noted that considerable settling may continue at least 2 to 3 years after reclamation. Aquifer testing by the author indicates that settling within spoil continues, apparently at a lesser rate, even 12 years after reclamation.

Hydraulic conductivity has been observed to change as the age of the spoil increases. Aljoe and Hawkins (1994) observed that reclaimed surface mine spoil that was 30 months or less old had a significantly lower (95 percent confidence level) median hydraulic conductivity than reclaimed mine spoil that was over 30 months old (Fig. 3.5). The manner by which hydraulic conductivity increases with time may be caused by the improved interconnectedness of the voids that were created during backfilling. Piping and differential compaction of fine-grained spoil material in response to vertical movement of recharging waters through the unsaturated portion and horizontal movement of groundwater in the saturated portion of the spoil may be the cause of increased void communication. Bulk density also may change as the spoil settles and fine grained materials migrate toward the base of the spoil.

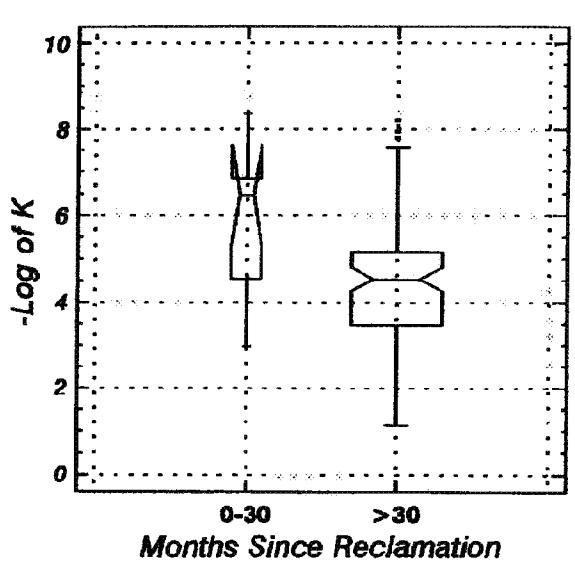

Figure 3.5 Notched box-and-whisker plot illustrating the relationship of spoil age to the hydraulic conductivity.

Changes in hydraulic conductivity in spoil are directly related to the mechanisms and timing of the postmining water table re-establishment. In eastern Ohio, water table re-establishment at three reclaimed surface mines was observed to be nearly complete approximately 22 months after reclamation was completed, (Helgesen and Razem, 1980). Based on the authors experience, recovery of the water table after mining may take 24 months or longer in Pennsylvania. The rate of water table recovery is related to several factors including the precipitation rate, recharge and discharge rates, porosity, topography, and geologic structure.

Rehm et al. (1980) and Moran et al. (1979) stated that spoil permeability decreases with age. This may be caused by differences in physical and chemical properties of the rock units that they encountered in the coalfields of the northern Great Plains compared to the units of the eastern coal fields. Overburden for the western coal fields are mainly comprised of weakly cemented units, which tend to form few large voids. Permeability may be further decreased by swelling clays common to overburden in the northern Great Plains. In the northern Great Plains, postmining hydraulic conductivity values are very similar to premining values (Rehm et al., 1980).

Reported Values of Hydraulic Parameters

Hydraulic conductivity and transmissivity

Performing aquifer tests to determine hydraulic properties (hydraulic conductivity and transmissivity) of spoil can be a difficult procedure. Assumptions must be made as to the homogenity and isotropic nature of the aquifer. However, testing indicates that spoil is highly heterogeneous and anisotopic. Therefore, the values presented below must be viewed in this context. Hawkins (1993) detailed some of the problems incurred while conducting slug tests and during the subsequent data analysis to determine the hydraulic properties of surface mine spoil. Large voids within mine spoil may permit rapid, possibly turbulent groundwater flow during aquifer testing. If turbulence

actually occurs, Darcian methods of data analysis cannot be used. Additional problems are created because the unknown surface area of the adjacent voids is added to the known surface area of test well. This situation can cause the hydraulic conductivity to be overestimated. Conversely, aquifer modeling (MINEFLO AND MODFLOW) of mine spoil indicates that the effective site hydraulic conductivity may be 1 to 2 orders of magnitude higher than the field determined values at individual test wells. This was determined by error reduction during model calibration. The modifications to the hydraulic conductivity may vary substantially under differing hydrologic conditions because of extreme heterogeneity and anisotropy common to reclaimed mine spoil (Hawkins and Aljoe, 1990; Hawkins, 1994). Despite the problems involved in conducting aquifer tests, aquifer testing to determine hydraulic properties is still an integral part of the hydrologic characterization of mine spoil. The hydraulic conductivity and other site-specific hydrologic data can be used to predict the postmining water table elevation within the spoil, which in turn is important for alkaline addition and special handling techniques. Transmissivity, in the strictest sense, refers only to confined aquifers. However, many researchers have reported transmissivity for mine spoil which is mainly unconfined. These values are included below. These hydraulic parameters are important for mine drainage prediction because they are used to determine groundwater velocity, water table fluctuation, groundwater storage turnover rates as well as other factors influencing groundwater contact within different zones in the spoil. Knowledge of these and other hydrologic parameters is especially important to special handling and alkaline addition techniques and other aspects of mine drainage prediction.

Hydraulic conductivity and transmissivity of surface mine spoil exhibit a very broad range of values from location to location and within a mine site. Table 3.1 illustrates the range of hydraulic conductivity and transmissivity values in different regions of North America. Hydraulic conductivity values generated from testing of 103 monitoring wells from 15 surface mines in northern West Virginia and western Pennsylvania ranged from 4.2×10^{-9} to 7.6×10^{-2} m/s (Table 3.1). The data exhibited a geometric mean of 2.5×10^{-5}, a median of 2.8×10^{-5}, and a standard deviation of 9.6×10^{-3} m/s. Hydraulic conductivity within a single mine site ranged over 5 orders of magnitude (6.6×10^{-9} to 9.3×10^{-4} m/s). Hydraulic conductivity ranges exceeding 3 orders of magnitude within a mine site were common when more than 4 wells were tested. Aquifer testing of the 15 mine sites exhibited a range of transmissivity values exceeding 8 orders of magnitude (1.2×10^{-9} to 2.0×10^{-1} m^2/s).

Similar values have been reported by others working with surface mine spoil in the Appalachian coalfields. Weiss and Razem (1984) noted hydraulic conductivity values ranging from 1.13×10^{-6} to 1.89×10^{-5} m/s in a surface mine located in eastern Ohio

Table 3.1 Ranges of Hydraulic Conductivity and Transmissivity in Surface Mine Spoil

Geographic Area	Hydraulic Conductivity in m/s	Transmissivity in m^2/s
Western Pennsylvania (Hawkins, unpublished data)	4.2×10^{-9} to 7.6×10^{-2}	1.2×10^{-9} to 2.0×10^{-1}
Northern West Virginia (Hawkins, unpublished data)	9.5×10^{-8} to 2.7×10^{-4}	1.4×10^{-7} to 2.9×10^{-4}
Eastern Ohio (Weiss and Razem, 1984; Bonta et al., 1992)	5.4×10^{-8} to 1.9×10^{-5}	No Information
Western Kentucky and Southern Illinois (Herring, 1977; Lindorff, 1980)	2.4×10^{-5} to 4.1×10^{-5}	2.2×10^{-4}
Western North Dakota (Groenewold and Bailey, 1979)	2.9×10^{-5} to 4.6×10^{-5}	No Information
Northern Great Plains (Rehm et al., 1980)	8.0×10^{-7}	No Information
Wyoming Moran et al., 1979)	1.9×10^{-6} to 2.1×10^{-4}	No Information
Edmonton, Alberta, Canada (Moran et al., 1979)	1.5×10^{-6}	No Information

(Table 3.1). The hydraulic conductivity of surface mine spoil in three watersheds in eastern Ohio ranged from 5.4×10^{-8} to 6.7×10^{-6} m/s (Bonta and others, 1992).

Published information on spoil aquifer testing in the Midwest is somewhat limited. Herring (1977) measured a hydraulic conductivity of 2.358×10^{-5} m/s and transmissivity 2.2×10^{-4} m^2/s based on a constant-discharge test conducted on a surface mine in western Kentucky (Table 3.1). An average hydraulic conductivity of 4.1×10^{-5} m/s was recorded for three surface mines in Illinois (Lindorff, 1980).

Extensive testing of saturated surface mine spoil for the western coal fields have yielded a wide variability for hydraulic conductivity. Groenewold and Bailey (1979) observed hydraulic conductivity values ranging from 2.9×10^{-9} to 4.6×10^{-5} m/s for surface mine spoils in western North Dakota (Table 3.1). Rehm and others (1980) reported a hydraulic conductivity range of 6 orders of magnitude with a geometric mean of 8×10^{-7} m/s for the northern Great Plains region (North Dakota, Montana, Wyoming, and Alberta, Canada). Similar hydraulic conductivity values were observed by Moran and others (1979) in the northern Great Plains. They recorded hydraulic conductivities of 1.9×10^{-6} and 2.1×10^{-4} m/s from aquifer testing on a Wyoming surface mine. Spoil aquifer testing near Edmonton, Alberta, Canada yielded a mean hydraulic conductivity of 1.5×10^{-6} m/s.

The hydraulic conductivity of mine spoil in the Appalachian coal fields is considerably greater than that of the undisturbed rock. Hawkins (1995) analyzed data from five Northern Appalachian surface mines and observed that the hydraulic conductivity of mine spoil (1.2×10^{-5} to 1.4×10^{-4} m/s) ranged from nearly 1 to over 2.5 orders of magnitude greater than adjacent bedrock (3.8×10^{-8} to 4.1×10^{-6} m/s) with a geometric mean 2 orders of magnitude greater. In other words, mine spoil tends to be approximately 100 times more conductive than undisturbed bedrock. The differences in hydraulic conductivity cause differences in water levels between mined and unmined areas. In some cases, perched aquifers on the unmined rock can also account for these water level differences. Water levels in spoil wells were 50% lower than those measured in wells of similar elevation in adjacent unmined aquifers. This illustrates that premining water level measurements may not be indicative of postmining levels.

Herring (1977) noted that in the Illinois Basin, spoil is more transmissive than aquifers in unmined overburden. This was based on the observation that more water was entering the active pits from adjacent spoils than was coming from adjacent unmined overburden. Weiss and Razem (1984) likewise observed greater conductivities in spoil compared to premining values at a mined watershed in eastern Ohio.

Porosity

As with testing for hydraulic conductivity, porosity determination in mine spoil is difficult. Therefore, the amount of published data concerning porosity is limited and many of the empirically derived values were determined in the laboratory. Spoil porosity is important to mine drainage quality prediction in terms of determining groundwater storage volumes and predicting water level changes stemming from recharge or discharge. These characteristics impact the nature and scope of groundwater contact with different spoil zones.

Wells et al. (1982) reported laboratory porosities of 25 to 36 percent for surface mine spoils from Eastern and Western Kentucky. The spoils tested were composed mainly of shale and sandstone. Laboratory-measured values on eastern Ohio spoil samples ranged from 41 to 48 percent with a mean of 44 percent (Mezga, 1973). Field tests indicate that the laboratory-generated values are significantly greater than actual field conditions.

Cederstrom (1971) estimated that the porosity values of cast spoil ranges between 15 and 25 percent. He stated that this range was 7 to 25 times greater than the porosity of undisturbed strata. The magnitude of increases in porosity depends greatly on the premining aquifer porosity, which is determined mainly by lithology and fracture density. Based on pumping tests, storage coefficients of 17 and 23 percent were determined for spoil in Wyoming (Rahn, 1976, reported in Moran et al., 1979). For unconfined conditions, storage coefficient is roughly equivalent to the effective porosity. Effective porosity calculations for a reclaimed surface mine in Upshur County, West Virginia, determined by the author, ranged from 14 to 16 percent. These values were determined using slug and tracer test results, conducted more than 13 years after the site was reclaimed.

The field-determined porosity values approximate the percentage of backfill volume increase (swell) created when overburden is spoiled during mining. Herring (1977) stated that the swell for the Illinois Basin is about 20 percent. Van Voast (1974) estimated that the

swell is roughly 25 percent. He stated that the backfill volume increase was accompanied by an increase in porosity and vertical permeability.

Given the relatively high porosity values of mine spoil, reclaimed surface mines are capable of storing large volumes of groundwater. For example, a 10 ac (4.05 ha) reclaimed surface mine with a 10 ft (3.05 m) saturated zone and 18% porosity will have nearly 6 million gallons (.023 million m^3) of groundwater in storage. When making this type of calculation, a range of effective porosity values is better than a single value. Effective porosity values for reclaimed surface mine spoil should be based on field testing or measured swell as opposed to laboratory determinations.

The porosity values for Appalachian surface mine spoil tend to be significantly greater than for the undisturbed overburden. Effective porosity values for fractured-rock aquifers have been estimated to range from 0.001 to 0.1% (MacKay and Cherry, 1989). Brown and Parizek (1971) determined porosity for coal-bearing strata in the laboratory. They observed a primary porosity range of 0.8 to 9.4% with a mean of 3.9%. However, secondary porosity can be much higher in the Appalachian Plateau (Chapter 2).

Groundwater Velocity

Aquifer testing indicates that the groundwater velocity in surface mine spoil is substantially greater than that of the undisturbed overburden. Average groundwater velocities are affected by recharge rate, effective porosity, hydraulic conductivity, and head differential, and can vary widely depending on site-specific conditions. Determination of groundwater velocity is important in mine drainage prediction because it relates directly to groundwater contact with the spoil and groundwater storage turnover rates.

Hawkins and Aljoe (1991) measured a groundwater velocity range in the backfill of a reclaimed surface mine in central West Virginia of 1.2×10^{-5} to 4.9×10^{-5} m/s. Caruccio et al. (1984) observed similar velocities, ranging from 1.4×10^{-5} to 1.8×10^{-5} m/s, for another reclaimed mine in central West Virginia. A groundwater velocity of 2.0×10^{-5} m/s was determined for a surface mine in eastern Ohio (Mezga, 1973). Ladwig and Campion (1985) observed a groundwater velocity of 6.1×10^{-4} m/s at a surface mine in Pennsylvania. A groundwater velocity range of 2.7×10^{-3} to 4.3×10^{-3} m/s was measured in surface mine spoil in eastern Kentucky (Wunsch and others, 1992). Most of these velocities are below the groundwater velocities commonly measured for true karst aquifers, underground mines, and accentuated fractured rock aquifers. However, the measured groundwater velocities were similar to velocities in unconsolidated glacial sands and gravels (Hawkins and Aljoe, 1992).

Groundwater velocity measurements from the literature should be considered as a range of values and should be applied as such. Determination of the actual groundwater velocity for a site requires on-site testing, which is not possible for premining prediction.

Groundwater Recharge

Initially, after reclamation, diffuse recharge from the surface is generally well below premining levels because of the destruction of soil structure, soil compaction by mining equipment, and low vegetative growth, which tend to promote surface water runoff rather than infiltration (Razem, 1983; Rogowski and Pionke, 1984). Wunsch and others (1992) noted that, during re-excavation, spoil within a few inches of the surface was dry indicating little infiltration was occurring. Decreases in recharge may also be facilitated by increases in porosity in the unsaturated zone (Razem,

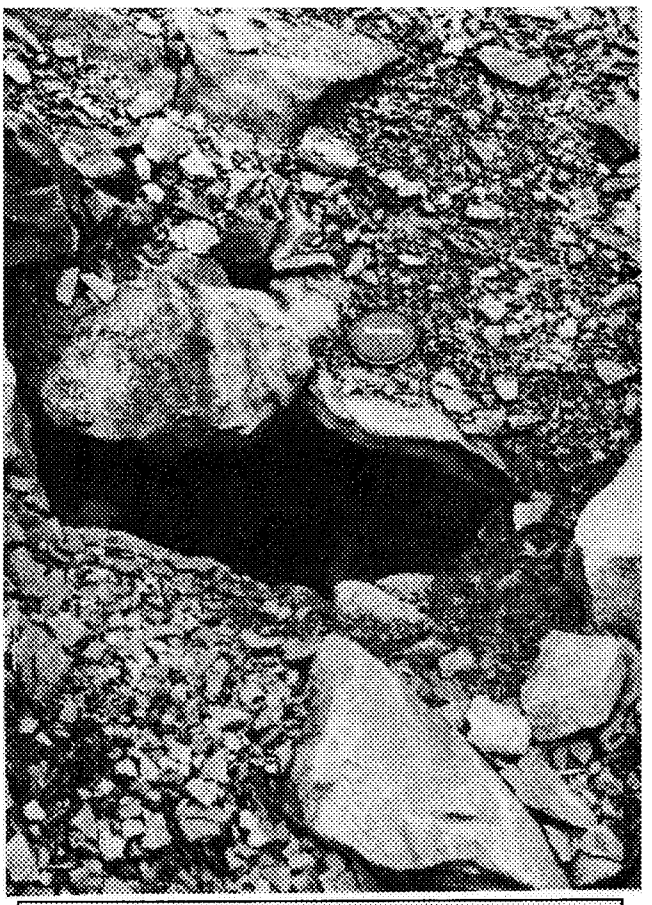

Figure 3.6 Exposed void (swallet) at the surface of a backfilled surface mine.

1984). Flow-duration curves show that receiving streams after mining have reduced base flows, which indicate that recharge is decreased (29% less than pre-mining levels) and surface runoff is increased (Weiss and Razem, 1984). After this initial period, as soil structure and vegetation re-establishes, diffuse recharge from the surface begins to increase. This may coincide with the observed increases in hydraulic conductivity after 30 months, as previously mentioned. The slow recovery of the water table during this period may be linked to the decreased recharge shortly after reclamation and the increased effective porosity and permeability of the spoil.

Some of the recharge from the surface during this early period occurs through discrete openings or voids exposed at the surface (Hawkins and Aljoe, 1991; Wunsch et al., 1992). Figure 3.6 illustrates a surface-exposed void that facilitates groundwater recharge at a surface mine in central Pennsylvania that has been reclaimed for over 15 years. Surface runoff flowing across the mine surface enters the spoil through these exposed voids and flows rapidly downward via conduits to the saturated zone. The recharging water has a limited contact period within the unsaturated spoil zone. In some instances, this infiltrating water will reappear a short distance away (e.g., 100 m) as a high-flowing ephemeral spring, but in most cases the water recharges the spoil aquifer and is more slowly released at perennial discharge points. Experience indicates that these exposed voids continue to receive significant amounts of recharge long after final reclamation, re-establishment of the soil structure, and successful revegetation. Groenewold and Bailey (1979) observed that surface water running into these swallets may enlarge them and cause considerable subsidence from piping of the finer grained materials. However, this has not been observed to be a significant problem in the Appalachian coal fields.

Others contend that mining may improve the recharge potential from undisturbed areas (Cederstrom, 1971). Herring (1977) observed than the overall recharge and surface water runoff to reclaimed surface mines in the Illinois Basin were greatly increased. He attributes the increased recharge to the dramatic increase in permeability of the cast overburden. He observed a four fold increase in recharge from mining one half of a watershed in Indiana. Those two studies did not factor in the impact of mining on the soil horizon as discussed by Razem (1983, 1984). Once the infiltrating water has passed through the soil horizon, it appears that the recharge potential is dramatically increased.

In the Appalachian basin, surface mine spoil aquifers receive a substantial amount of lateral in-flow from adjacent areas (Wunsch and Dinger, 1994). Adjacent unmined areas (low walls and highwalls) as well as previously reclaimed areas will contribute groundwater to the newly reclaimed site. Groundwater modeling by Hawkins and Aljoe (1990) and Hawkins (1994) indicates that groundwater flowing from adjacent areas may be the main source of recharge to the spoil aquifer and that this type of recharge occurs on a more continuous basis at a more consistent but lower rate than the recharge through the exposed surface voids. The surface voids will only recharge the spoil when runoff is occurring. In contrast, lateral recharge is controlled primarily by the hydraulic properties of the adjacent aquifer and the hydraulic gradient.

Under certain conditions, spoil can be recharged from groundwater flow from the underlying strata. If artesian conditions exist beneath the stratum underlying the coal (seat rock), groundwater can flow under pressure via fractures in the intervening strata or through boreholes drilled through the pit floor and recharge the spoil. Artesian-induced recharge has been observed in a reclaimed surface mine in southern Tennessee (Robert S. Evans, personal communication).

Summary

The information and data in this chapter can be used to predict the groundwater hydrologic regime in reclaimed surface mine spoils prior to mining. The data presented here should be viewed as a potential range of values. Given this information, the groundwater velocity, water table elevation, discharge rate, and volume of water that will be stored in the spoil can be predicted. The potential groundwater flow direction and flow paths can also be estimated.

This hydrologic information used in conjunction with the overburden geochemical data can be used to improve mine drainage predictive models and methods. Hydrologic data will give individuals involved with mine drainage prediction a better understanding of the spoil material that is contacted by the groundwater and the physical, spatial, and temporal nature of this contact. This information is directly applicable to the use of special handling of acid-forming materials and placement of alkaline materials to prevent acid mine drainage.

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