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PSEUDOKARST GROUNDWATER HYDROLOGIC CHARACTERISTICS OF A MINE SPOIL AQUIFER

by

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ABSTRACT

Aquifer tests of surface coal mine spoil indicate two distinctly erent groundwater hydrologic characteristics exist. Slug tests rically indicate the presence of discrete conduits within the spoil. ndwater flow within conduits is pseudokarst and flow between conduits is us media. Under transient or stress conditions, pseudokarst groundwater in the spoil becomes prominent, while under steady state conditions us media flow dominates. Tracer testing indicates the average linear city of groundwater through spoil is close to pure porous media and ificantly lower than true karst flow. Physical observations substantiate existence of conduits.

INTRODUCTION

One of the keys to the control, remediation, or abatement of acid mine nage (AMD) is a quantitative knowledge of groundwater flow in spoil rial. If the movement and occurrence of groundwater in mine spoil can be icted, it may be controlled in such a manor to prevent, halt, or diminish formation and transport of AMD. Extensive aquifer testing and monitoring urface mine spoil yield data that are necessary for the formulation of a ical model and the calibration of computer models.

The hydrologic differences between pseudokarst and porous media ındwater flow are strong and readily distinguishable. Pseudokarst 'acteristics are essentially the same as true karst although the mechanism :onduit or cavity development differs (Hawkins and Aljoe, 1990). In true ;t, dissolution of carbonate rock (e.g. limestone and dolostone) will ıte the conduits within the aquifer. In pseudokarst situations, conduits usually formed by the piping of fine grained unconsolidated sediment ›ugh the aquifer. Aquifers exhibiting pseudokarst characteristics are usually associated with glacial or pyroclastic sediments (Jennings, 1971). Karst/pseudokarst groundwater flow is characterized by multiple flow paths, extreme ranges of hydraulic conductivity, and a high degree of unpredictability. Multiple water tables (piezometric surfaces), changes in groundwater flow direction, rapid or "flashy" response to recharge, and large fluctuations in water levels are common characteristics of these groundwater flow regimes. Because of the extremely high Reynolds numbers (R) yielded by conduit flow, Darcy's Law does not apply. Therefore, hydrologic variables and conditions in these type of aquifers may not be quantified by conventional means (Thrailkill, 1968).

Conventional porous media flow is characterized by slower-moving diffuse flow through the intergranular pore spaces and/or fractures in the rock. The behavior is generally predictable and subject to the provisions of Darcy's Law. For a particular aquifer, a single water table or piezometric surface will exist. The groundwater gradients are gradual and continuous. Hydraulic conductivity values are more consistent spatially than those seen in karst aquifers. Rapid response to recharge, speed of groundwater movement, and large head fluctuations are greatly attenuated over those seen in karst aquifers. The water table will usually reflect the overlying topography, which is often not the case in karst terrains.

In 1984, Caruccio and Geidel suggested groundwater flow through mine spoil may be pseudokarstic. They observed that groundwater mostly occurs in and flows through large void spaces or conduits within the spoil. Void and conduit formation is facilitated by differences in spoil particle size and is caused by piping of the finer spoil material or differential settling (Groenewold and Bailey, 1979). Location and magnitude of conduits is controlled to a large extent by the overburden lithology, equipment used during surface mining, surface mining method, configuration of mining, and recontouring methods. Spoil ridges and valleys vary greatly in particle size. The larger well indurated blocks tend to roll into the spoil valleys, segregating them from the smaller material that remains on the ridges. This situation facilitates post reclamation piping and conduit formation (Rehm et al., 1980).

BACKGROUND

In this study, a 3.2 hectare (8 acre) parcel of a surface coal mine in Upshur County, West Virginia, U.S.A., was monitored and tested to determine the hydrologic characteristics and the groundwater flow regime in mine spoil. The site was mined in 1976 and reclamation was completed by the end of 1977. The mine was terrace backfilled with a steep outslope. The interior spoil zone is flat and slopes gently toward the final highwall (Fig. 1). Reclamation caused the formation of closed contour depressions, which permits surface water impoundment. A drainage ditch had been installed in an attempt to dewater the impoundments, but this was only partially successful.

Two coal seams existed on the site, the middle and lower Kittanning coals. The middle Kittanning was mined across the entire site. The lower seam, due to poor coal quality, was only mined in selected areas. A massive gray sandstone overlaid the middle Kittanning (Fig. 2). The sandstone became brown and highly friable upon weathering. The interburden between the two seams was primarily a dark gray to black carbonaceous shale. The lithology of the premining overburden was such that the generated spoil consists of both large blocky fragments and smaller material, which permits the formation of conduits.

Initially, 15 monitoring wells were constructed on the site (Fig. 1). All but one of these wells (BW-1) are in spoil material. In 1990, 5 additional wells (901-905) were constructed. One well (904) was later lost

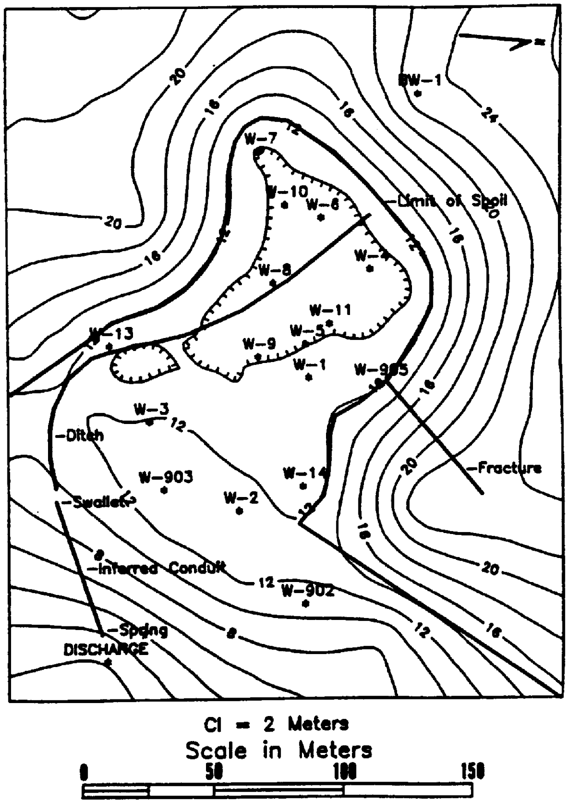

Figure 1. Map of study area showing topography, monitoring wells, surface and subsurface features.

because of casing collapse. Well 901 is dry because of the shallow completion depth. The remaining wells were used to monitor groundwater level fluctuations, to sample for water quality, and to conduct aquifer tests. The initial wells were constructed with 5.1 cm (2 in) PVC casing with the bottom 3 meters (10 feet) of slotted well screen. All holes were drilled to the pit

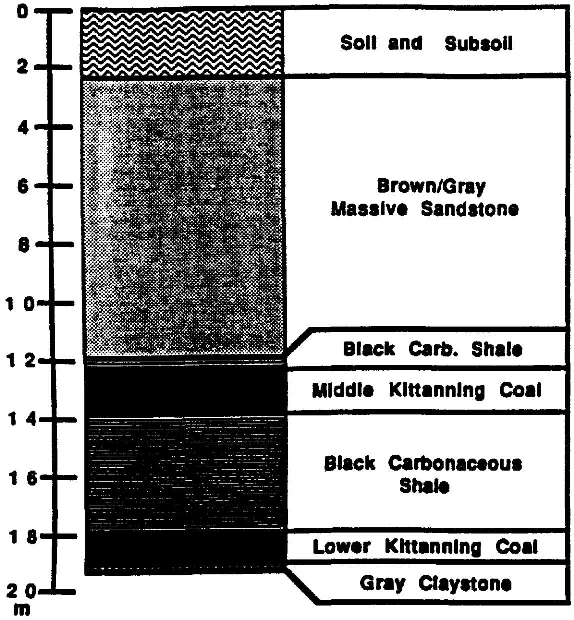

Figure 2. Generalized stratigraphic section of the study site overburden prior to mining based on drill hole information.

floor, except well 12 which was completed to a depth of 12 ft. The annulus between the casing and well bore was filled with drill cuttings and spoil material. The wells drilled in February, 1990 were also drilled to the pit floor, when possible and completed with 5.1 cm PVC casing. The lower 3 meters were slotted PVC well screen. A sand pack was placed between the bore hole and the casing. The upper 0.61 meters (2 ft) was sealed with bentonite clay to prevent surface water infiltration. Many voids were encountered during the drilling of the additional wells in 1990.

SLUG TESTS

In November 1989, slug withdrawal tests were performed on the original 15 wells. A bailer was used for the removal of the slug of water. Once the bailer was withdrawn from the well, a pressure transducer was inserted and interfaced with an automatic data logger. Each test was run until the water returned to or very near the original level. All wells were tested at least once and several were retested to confirm the results. The Bouwer and Rice Slug Test method was used to analyze the test data (Bouwer and Rice., 1976; Bouwer, 1989).

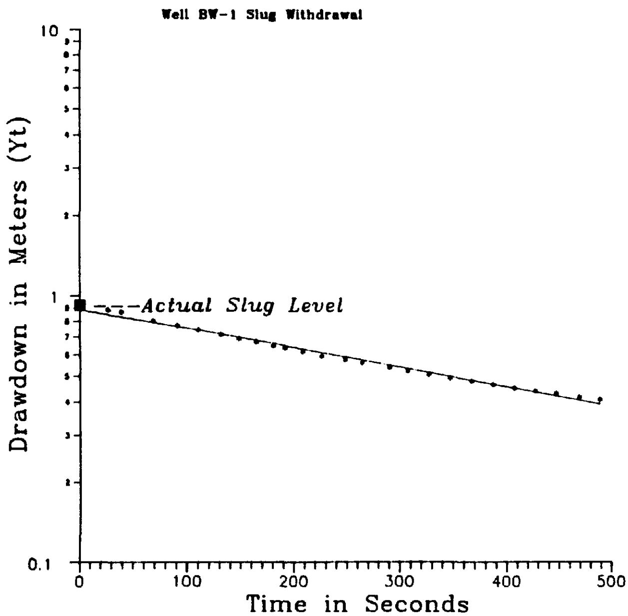

Figure 3. Slug withdrawl test from well BW-1 exhibiting porous media type recovery of the undisturbed strata.

Well BW-1 is in undisturbed strata and illustrates that the slugging techniques will yield a straight-line in a known porous medium (Fig. 3). Several of the spoil wells showed straight line recovery as is expected for a test performed within a porous medium. Well 1 shows a straight-line recovery (Fig. 4), indicating flow through the spoil aquifer to well 1 is diffuse porous media. The drawdown from the slug withdrawal and the Y axis intercept of the best-fit line to the data closely coincide. This indicates that the recovery is gradual and continues throughout the entire test. Wells 9, 10, 11, and 14 also exhibited a porous media type of recovery.

Conversely, some of the wells exhibited a drastically different recovery scenario. Figure 5 illustrates this type of recovery in well 8. The "calculated drawdown" level is much greater than the Y axis intercept of the best-fit line to the data. The calculated drawdown was determined from the volume of water removed from the well. Most of the water level recovery occurred prior to the first data point, which was followed by a gradual porous media inflow. The rapid recovery occurred again when the test of well 8 was

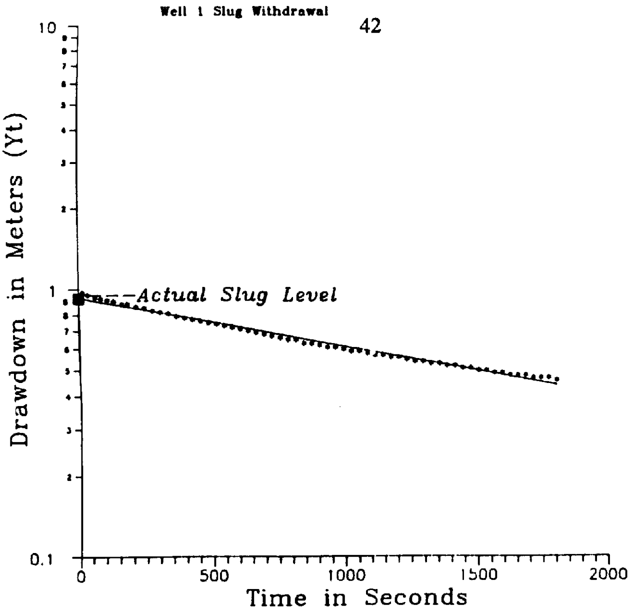

Figure 4. Slug withdrawl test of well 1 exhibiting porous media recovery of the spoil aquifer.

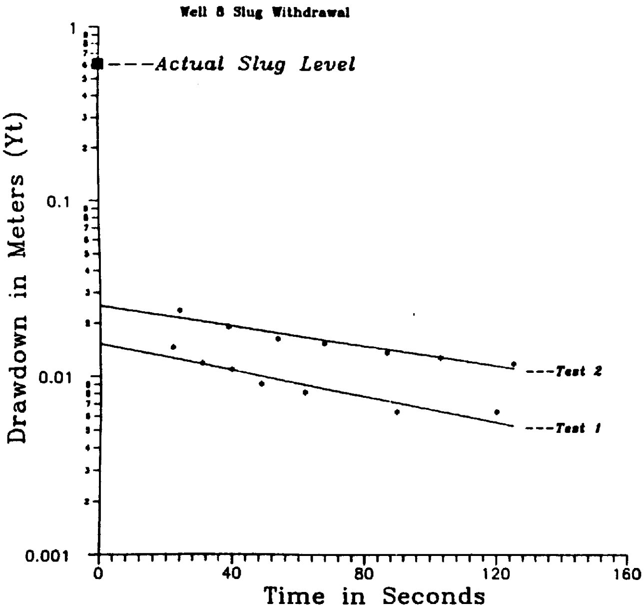

Figure 5. Slug withdrawl test of well 8 exhibits dual recovery response (DRR). A very rapid partial recovery of the slug is followed by a secondary slower recovery of the remainder.

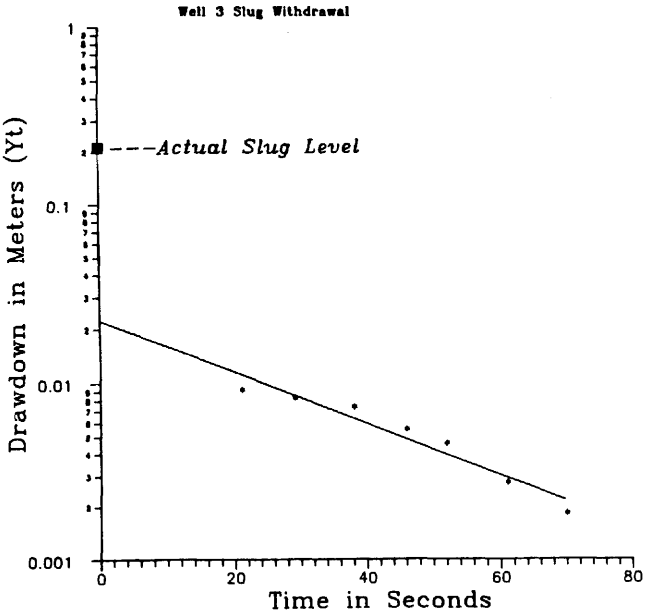

Figure 6. Well 3 exhibits DRR in response to the slug withdrawal.

repeated. This rapid influx "jump" was also observed in well 3 (Fig. 6) and to a somewhat lesser extent in wells 5 and 13. The response to slugging of these wells has been termed dual recovery response (DRR). This situation indicates these wells intersect large voids or conduits in the spoil aquifer that permit very rapid unrestricted inflow into the well as soon as the slug is removed. Because the volume of the void is finite, the rapid recovery does not completely return the water to the preslug level. The remainder of the recovery is through diffuse flow ascribed to porous media inflow from the surrounding spoil into the void, which acts as if the aquifer is infinite laterally given the limited slug volume (up to 2.0 liters). Therefore the water level slowly returns to steady state conditions.

The possibility existed that the time lag between the slug removal and the insertion of the pressure transducer (approximately 20 seconds) may have allowed a double straight line effect to be missed. This effect is commonly seen in wells with a sand or gravel pack (developed zone) and is caused by greatly differing permeabilities of the developed zone and the aquifer (Bouwer, 1989). These wells do not have a developed zone.

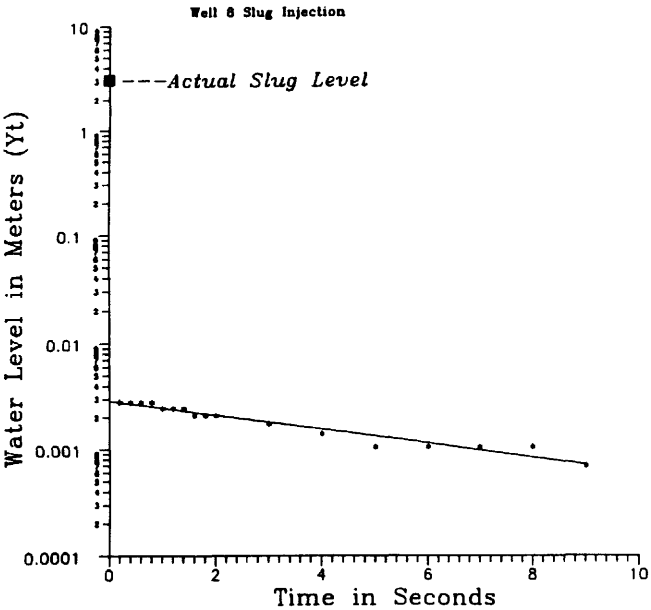

Figure 7. Slug injection of well 8 exhibits strong DRR effect. The recovery at this well is almost instantaneous.

In order to test the possibility of an earlier straight line, the wells were retested using slug injection. With slug injection, more water could be introduced to the well than was removed with slug withdrawal, and the pressure transducer could be in the well throughout the entire test. The data logger used permitted the first data point to be collected within the initial 0.2 seconds. In the first log cycle, data points were collected at 0.2 second intervals up to 2 seconds. At 2 seconds, the second log cycle starts; the collection interval ranges from 1 second up to 20 seconds, which permits the collection of a total of 28 data points.

The slug injection tests consisted of placing the pressure transducer at the bottom of the well. As much water as each well casing could accommodate without overflowing was selected as the slug volume. A specifically designed and constructed bucket was used as the slugging device. The slug of water was metered into a graduated bucket and poured as fast a possible, with minimal spilling, into the slugging bucket. This system permitted very rapid almost instantaneous water inflow into the relatively small diameter wells (e.g. 5.1 cm). The data logger was started prior to the injection of the water into the well.

The slug injection of well 8 again exhibited the DRR effect as seen in the earlier slug withdrawal test (Fig. 7). Over 99 percent of the injected water had dissipated into the spoil aquifer prior to the logging of the first data point at 0.2 seconds. This shows that the water enters the aquifer from this well as quickly as physically possible. Only large voids or conduits are able to accept water this fast. Because the outflow of water is so rapid in the early portion of the test, Darcy's Law does not apply and the aquifer

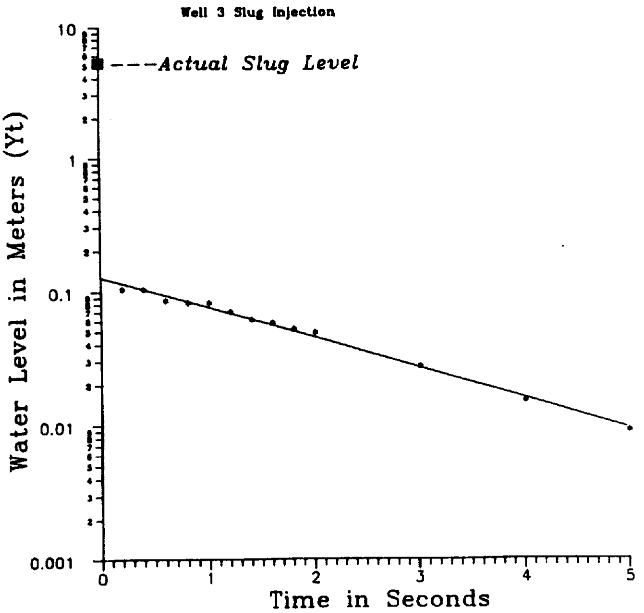

Figure 8. As with the slug withdrawl test (figure 6), the slug injection of well 3 strongly exhibits DRR effect.

hydraulic characteristics can not be quantified by conventional analytical procedures. As with the earlier test, the remaining water level shows a more gradual decline, which is characteristic of conventional porous media flow and can be analyzed by standard procedures. Well 3 also strongly showed the DRR effect with 98 percent of the water dissipating into the spoil within the first 0.2 seconds (Fig. 8). Wells 4, 5, 6, 7, and 10 exhibited the DRR effect to a lesser extent (32 to 85 percent water loss prior to the collection of the first data point). Some of the water loss could be caused by minor spillage or by other means during the slugging procedure.

Well 1 behaved during the slug injection as it had during the slug withdrawal test (Fig. 9). Wells 2, 10, 11, 13, and 14 likewise exhibited a straight line without the early rapid recovery. A straight line indicates porous media flow in the spoil surrounding the well.

The slug tests indicate that some wells directly intersect conduits, other wells are very close to conduits or intersect smaller conduits, and the remaining wells are removed from conduits. The wells that directly intersect the conduits exhibit the DRR effect strongly. Wells that are close to conduits may show some of the DRR effect, while wells that are a significant distance from conduits will behave as porous media flow. This scenario is what would be expected in true karst as well as pseudokarst aquifers. Some wells will intersect conduits and others will not. The presence of the conduits becomes apparent when the system is stressed by the slug test. High permeability contrasts exist within the site as expected. Hydraulic conductivity and transmissivity values derived from the slug withdrawal and injection tests are listed on table 1. For the DRR wells, these aquifer parameters were calculated from the later data points and do not reflect the higher values indicated by the early rapid recovery.

Table 1. Hydraulic conductivity and transmissivity values derived from the slug tests.

	Hydraulic Conductivity		Transmissivity	
Well	Withdrawal	Injection	Withdrawal	Injection
1	2.0686E-07	9.3679E-07	9.9086E-07	4.5434E-06
2	6.2580E-07	3.0357E-06	1.0513E-06	6.1625E-06
3	8.9360E-06	1.3427E-04	5.0935E-06	7.3580E-05
4	6.8995E-06	6.7560E.06	3.1669E-05	2.9186E-05
5	1.9254E-05	1.2434E-05	5.9302E-05	3.8545E-05
6	1.2974E-05	3.1400E-05	4.1776E-05	9.5456E-05
7	5.0955E-06	5.3352E-05	1.4369E-05	1.6112E-04
8	4.6605E-06	8.2299E-05	1.5519E-05	2.8475E-04
9	5.6940E-05	2.3191E.05	1.3609E-04	5.4963E-05
10	1.2617E-06	1.0066E-06	2.2837E-06	1.7314E-06
11	9.1445E-07	3.8857E-06	1.8929E-06	7.2663E-06
13	9.6128E-07	8.5636E-97	2.2109E-06	1.9439E-06
14	4.9261E-06	3.3362E-07	1.6897E-05	1.2077E-06
	m/sec	m/sec	m^2/sec	m^2/sec

TRACER TEST

A tracer test was performed to determine the average linear velocity of groundwater through the site. On November 17, 1989, 72.6 kilograms (160 pounds) of granular sodium chloride were applied at a known spoil recharge source along a bedrock fracture adjacent to the spoil (Fig. 1). In the Appalachian region, groundwater is mainly stored in and flows through fractures in the rock (secondary permeability). Primary permeability (intergranular pore spaces) typically plays a very minor role in groundwater movement (Wyrick and Borchers, 1981). The fracture shown on Fig. 1 recharges the site throughout the year as well being a major source of rapid recharge during rain and snow melt events. Water table maps created from average conditions, transient (high) flow, and steady state (low) flow indicate fracture flow of groundwater from undisturbed bedrock mainly recharge the spoil (Hawkins and Aljoe, 1990). Snow melt and light rain in the days immediately following the tracer application caused the introduction of all tracer material into the groundwater in the bedrock fracture system within one week.

To avoid making calculations on two unknowns (velocity through the fracture in the bedrock and the spoil), known hydrologic values were used to determine the velocity through the fracture. Hydraulic conductivity, change

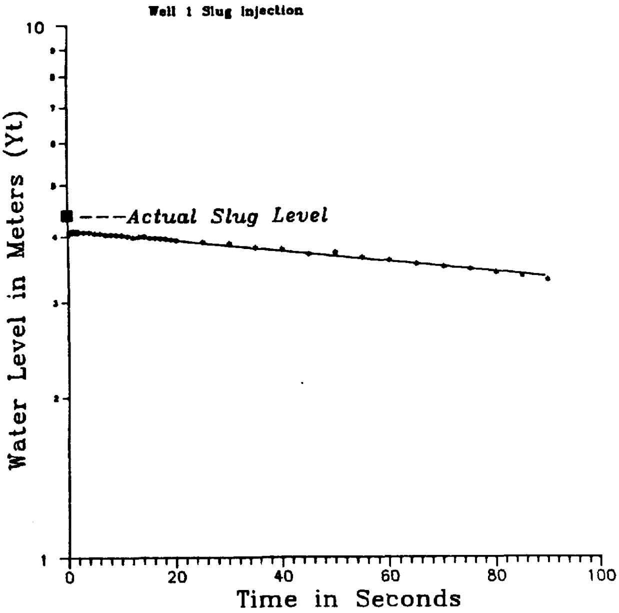

Figure 9. Well 1 exhibits porous media recovery from the slug injection as it had during the slug withdrawal test.

in head, and flow distance were empirically determined. Porosity was set on previously determined range of values for fractured-rock aquifers. Fractured rock ranges from 0.001 to 0.1 percent porosity (Mackay and Cherry, 1989). Using these values, travel time through the fracture was determined to range from 23.2 to 2318 days. The tracer was observed in monitoring wells in less than 60 days, therefore the lower value (23 days) was considered to be more representative.

Determination of groundwater average linear velocity through the spoil was difficult. Only wells down gradient of the fracture and the discharge itself were expected to show the tracer. Of the down gradient wells, well 2 was eliminated because it is hydrologically isolated from the rest of the spoil saturated zone. A grouting project initiated in the middle of February 1990 introduced large amounts of the tracer element (sodium) and ended the test.

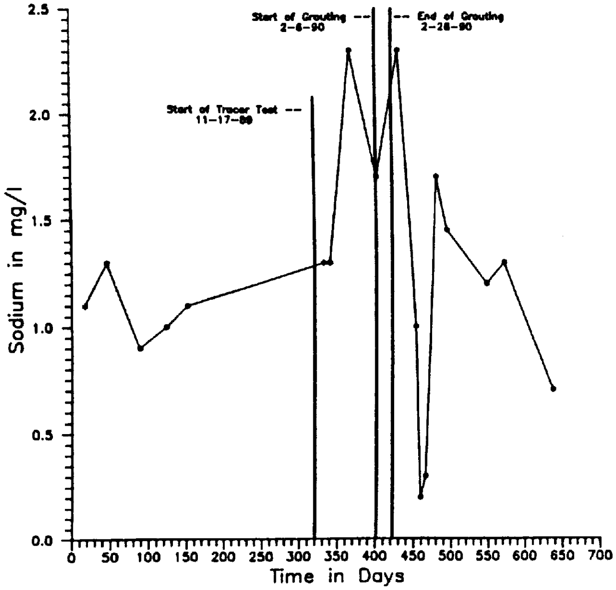

Figure 10. The first sodium concentration peak is caused by the sodium chloride tracer and the second peak is caused by the sodium from the grout.

Prior to the grout injection, wells 3, 11, and 14 exhibited a tracer "spike", allowing groundwater velocity to be calculated. Fig. 10 illustrates a spike from the tracer and a secondary spike from the grout at well 3. Velocity of groundwater to the wells through the spoil ranged from 1.2E-05 to 4.9E-05 meters per second (3.9E-05 to 1.6E-04 ft/second). These average linear velocity measurements were later corroborated by the rate that the grouting effects were observed at the main discharge (4.6E-05 meters per second), indicating the assumptions made to determine groundwater velocity through the fracture were valid (Hawkins and Aljoe, 1991). Fig. 11 compares the range of velocity values to those of other hydrologic situations. This graph must be viewed in the context that recharge rate, porosity, and head differential, all of which effect groundwater velocity, will vary widely from site to site. However, the range of given values allow a relative comparison. The velocity of groundwater in the spoil is well below the ranges for true karst, an underground mine, and accentuated fracture flow aquifers. The velocity of groundwater through a true porous media aquifer (glacial sediments) is close to the spoil although slightly lower. These data indicate that while conduits do exist throughout the site, they are discontinuous and porous-media-type flow occurs between them. Flow through these conduits only becomes prominent when the system is stressed under transient conditions or during an aquifer tests (Hawkins and Aljoe, 1990). The degree of conduit interconnection and hydraulic properties of the interstitial spoil material will dictate the velocity of groundwater and overall flow regime.

RELATED OBSERVATIONS

Field investigation of the site revealed the presence of a swallet (stream sink) and corresponding resurgence spring within the spoil. Fig. 1 shows the location of the these features. Runoff water leaving the site via the drainage ditch enters a highly permeable spoil zone. In this area, the water rapidly infiltrates into the spoil over a short distance (approximately 3 meters). Concurrent with water infiltration, spring resurgence occurs. The resurgence spring only flows when water from the ditch is entering the sink area, stressing the system. The distance from the sink to the resurgence spring is about 61 meters (200 ft) indicating the existence of a more significant conduit than observed in other parts of the spoil. Water quality data also indicate the presence of this link between the swallet and spring. This conduit exists in the outslope portion of the spoil where drilling and

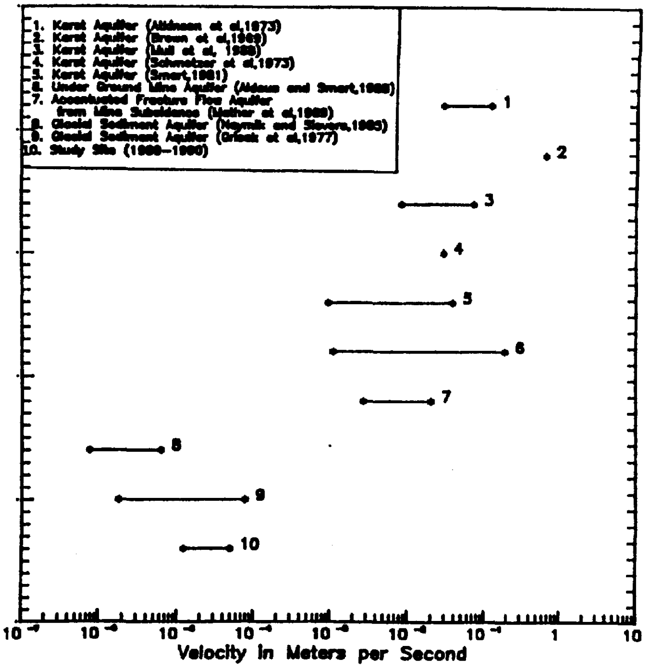

Figure 11. A comparison of groundwater movement through the spoil to true karst, fracture flow, and porous media aquifers shows the average linear velocity is closest to pure porous media.

modeling have indicated that void density, size, and interconnection are greater than in the interior spoil area (Hawkins and Aljoe, 1990).

SUMMARY AND CONCLUSIONS

Aquifer tests empirically indicate the presence of conduits within the spoil aquifer. Wells that intersect or nearly intersect conduits exhibit a dual recovery response effect during slug tests. Wells that do not intersect the conduits exhibit porous media flow characteristics. These tests indicate that pseudokarstic flow becomes prominent when a stress is applied to the aquifer. Under steady state conditions, porous media flow remains dominant, which indicates the conduits are relatively isolated and poorly interconnected.

The tracer test indicates that the average linear velocity of groundwater through the spoil is much slower than that for true karst or accentuated fracture aquifers. Velocity is close to that of unconsolidated glacial sediments (true porous media). This infers the conduits are discrete and flow between them is porous media through the interstitial spoil material.

Physical observations and comparisons indicate the presence of conduits within the spoil. As with the aquifer and tracer tests, the pseudokarstic flow of the conduits only becomes prominent when the aquifer is stressed during periods of high recharge. Under steady state conditions, porous media flow characteristics are observed.

Additional sites of varying age, lithology, topography, and mining styles need to be examined in order to determine the applicability of the porous media/pseudokarst flow systems to other surface mine spoils. Our experience with other surface mines and data from other investigators indicate that these characteristics are widespread.

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