THE EFFECT OF GROUT INJECTION ON MINE SPOIL GROUNDWATER HYDROLOGY[1]

by
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Abstract. A 3.2-hectare (8 acre) parcel of a reclaimed surface mine in Upshur County, West Virginia has been monitored to evaluate the effect of grout injection on the spoil groundwater hydrologic characteristics and geochemistry. In February and early March, 1990, the site was injected with a pozzolan grout in an attempt to ameliorate acid mine drainage production by encapsulating targeted zones of acid-producing spoil. The spoil aquifer was monitored for water-quality changes and tested to determine the effect of the grouting on the groundwater flow regime, water table and other aquifer properties. The grouting project has the potential to reduce porosity, eliminate large void space, or close connection between voids and consequently to reroute groundwater flow paths and produce changes in the water table configuration. Monitoring was initiated 14 months prior to grouting and continues to the present. Aquifer tests were performed 3 months before and 4 months after grouting to ascertain changes in hydraulic properties caused by the grouting efforts. Slug tests and constant-discharge aquifer (pumping) tests were performed to determine transmissivity, hydraulic conductivity, and other hydrologic parameters of the spoil directly adjacent to and between monitoring wells. The slug tests indicate that characteristics of the spoil aquifer directly adjacent to the monitoring wells were unaffected by the grout injection. The pumping tests indicate that hydraulic conductivity and transmissivity of the spoil between some wells were generally unaffected. Maps of the water table, under similar flow conditions, indicate no significant change in water level or flow direction has occurred due to the grouting. A high amount of sodium in the fly ash portion of the grout permitted the tracking of groundwater movement after grout

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introduction. Minor groundwater quality changes in two wells was attributed to elements added by the grout and possible groundwater flow path rerouting. Analysis of the sodium plume movement indicates a bimodal (porous media and pseudokarst) flow regime within the spoil, although in general the spoil behaves as a porous medium under steady state conditions.

Additional Key Words: pozzolan grout, porous media, pseudokarst, slug test, constant-discharge test, plume.

Introduction

Acid mine drainage (AMD) formation in surface coal mines occurs when iron disulfides contained in the spoil material are oxidized and subsequently hydrolyzed. AMD production and transport can be controlled by restricting the contact of oxygen and groundwater with the high sulfur spoil zones. An attempt was made to inject a pozzolanic grout, a mixture of fly ash, portland cement, and water, into selected zones in a surface mine backfill to reduce the effective permeability and restrict the contact of groundwater with potentially acid-producing spoil. Approximately 500 cubic yards of the grout was injected into 62 wells into the backfill. Well location was determined by electromagnetic terrain conductivity and magnetometry surveys. The focus of this study was to determine the effect of the grouting operation on the hydrologic characteristics. Because the work presented here is ancillary to the original intent of the project, detailed descriptions on the physical grouting will not be discussed here. Grouting of the spoil has the potential to fill up void space and cause changes in groundwater flow paths. To ascertain changes to hydraulic parameters before and after grout injection, aquifer testing (slug and pumping tests) was performed, water table maps were compared under average conditions and for synoptic records under similar flow conditions, and water quality at monitoring wells and the main discharge were analyzed. The effect of grouting on site hydrologic characteristics and water geochemistry will provide insight into the potential for hydrologic control of groundwater in mine spoil in the future.

Studies have shown that groundwater movement through surface mine spoil does not occur as it would in a pure porous medium. Large voids or conduits in spoil exist, permitting pseudokarst groundwater flow (Caruccio and Others, 1984; Hawkins and Aljoe, 1990). Piping of the fine grained material and differential compaction create or accentuate voids within the backfill (Groenewold and Bailey, 1979). These conduits influence the movement and storage of groundwater in spoil. When the aquifer is stressed during transient periods or from aquifer testing, the pseudokarst characteristics become even more prominent. Pseudokarst flow occurs within conduits, while porous media flow occurs between these conduits. Under steady state conditions, the aquifer generally exhibits porous media flow characteristics overall (Hawkins and Aljoe, 1991, In Press).

Site Background

A 3.2-hectare (8 acre) parcel of a reclaimed surface mine was monitored and tested to determine potential changes to the hydrologic characteristics, the groundwater flow regime, and water quality caused by the grouting operation. The site was mined in 1976 and reclamation was completed by the end of 1977. The mine was terrace backfilled creating a steep outslope. Figure 1 depicts the post mining site configuration.

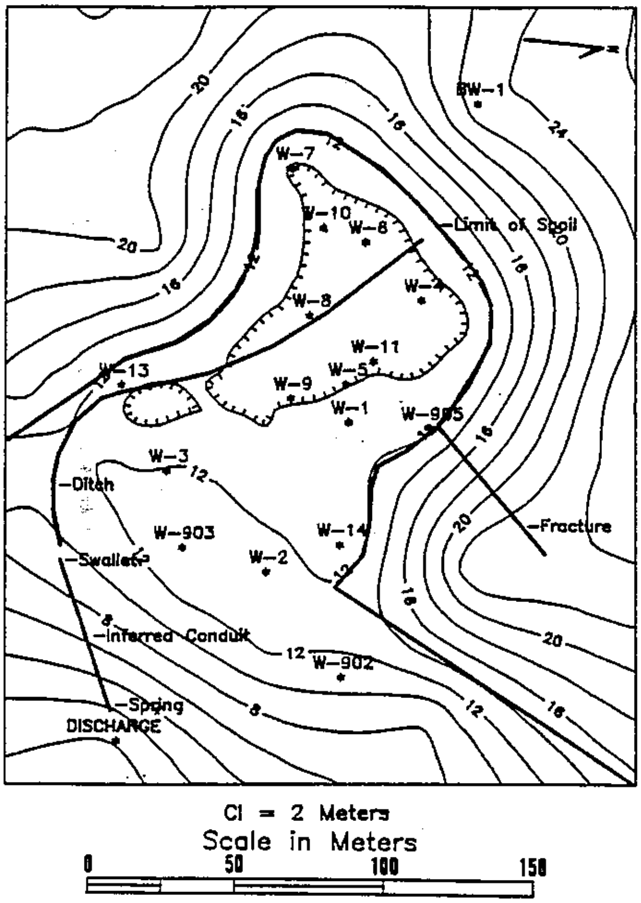

Figure 1. Map of study site exhibiting surface contours, monitoring wells, and other surface and subsurface features. The main discharge is datum.

The middle and lower Kittanning coal seams were mined on the site. 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 overlies the middle Kittanning (Figure 2). The sandstone becomes brown and highly friable upon weathering. The interburden between the two seams is primarily a dark gray to black carbonaceous shale. Acid base accounting (ABA) of the overburden indicates the black shale is a potentially acidic zone. ABA is a type of overburden analysis that determines the potential of rock units to produce alkaline or acidic mine drainage from total sulfur and calcium carbonate equivalent content. Total sulfur concentration in the shale ranges from 0.16 to 0.87 percent. In evaluating the ABA, total sulfur concentrations exceeding 0.5 percent are considered potentially acidic. The shale likewise contains the only significant neutralization potential (31.25 tons of calcium carbonate equivalent per 1000 tons of material). A neutralization potential value of over 30 is considered potentially alkaline. Although, the sulfur content of the sandstone is low (0.005 percent), the presence of effervescent salts (most likely sulfate salts) on subaerially exposed rock surfaces indicate it may also contribute significantly to AMD production.

The lithologic units of the premining overburden are such that the spoil consists of both large blocky fragments and fine grained material. This facilitates the formation of conduits and voids, which result in strong hydraulic conductivity heterogeneities in the spoil.

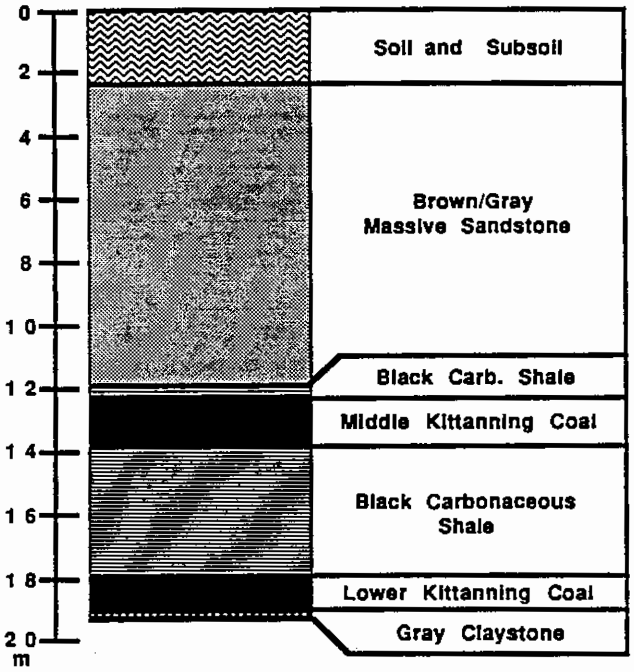

Figure 2. Stratigraphic section of the site overburden before mining.

Fifteen monitoring wells were constructed on the site. All but one of these wells (BW-1) are screened in spoil material. The wells were used to monitor groundwater level fluctuations, sample water quality, and conduct aquifer tests. The wells were constructed with 5.1 cm. (2 inch) PVC casing with the bottom 3 meters (10 ft) of slotted (0.01 inch) well screen. All holes were drilled to the pit floor, except well 12. The annulus between the casing and well bore was filled with drill cuttings and spoil material for all cased wells.

Slug Tests

Prior to grouting, slug withdrawal tests were performed on the spoil wells to determine aquifer characteristics. These tests along with post grouting slug injection tests were performed in an attempt to determine the effect of grouting spoil hydraulic conductivity and degree of grout propagation. For the slug withdrawal tests, a slug of water was removed with a bailer. The slug volume depended on the amount of water in the well. The recovery rate was recorded for each well with a pressure transducer placed into the well. The transducer had to be placed in the well after the removal of the bailer, because the bailer was too large to fit past the transducer cable. The testing revealed that some wells responded with a gradual recovery as in porous media groundwater flow. Other wells exhibited a dual recovery response (DRR), where a large part of the recovery was very rapid (almost instantaneous) and the remainder was more gradual. The first 20 seconds was usually lost with the slug withdrawal tests, because of the lag time required to set the pressure transducer. The early portion (first 20 seconds) of the recovery was too rapid (turbulent flow) to be testable by conventional means and is therefore not subject to Darcy's Law (Hawkins and Aljoe, 1991, In Press). The latter portion of the recovery did yield aquifer parameters, although these values may be somewhat questionable, because of the lack of the early test data. The testing suggests than the late data may be indicative of diffuse flow in the high recovery wells. Table 1 lists the hydraulic conductivity values obtained from the slug withdrawal tests. Hydraulic conductivity (K) values ranged from 2.1 x 10^{-7} to 5.7 x 10^{-5} meters per second prior to grouting. The Bouwer and Rice

	HYDRAULIC CONDUCTIVITY		TRANSMISSIVITY	
WELL	PREGROUTING	POST GROUTING	PREGROUTING	POST GROUTING
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-07	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

Table 1. Hydraulic conductivity (K) and transmissivity (T) values obtained from the pregrouting slug withdrawal and postgrouting slug injection tests.

method was used to calculate these values from the data (Bouwer and Rice, 1976).

Four months after grouting was completed, the wells were retested using slug injection. In the slug injection tests a fixed amount of water was rapidly dumped down the casing. Slug injection permitted a larger amount water to be introduced to the aquifer than was withdrawn during the earlier slug withdrawal tests. The amount of water each well casing could accommodate without overflowing was selected as the slug volume. The pressure transducer remained in the well throughout the entire test, which permitted collection of water level data throughout the test. Hydraulic conductivity values for all slug tests are listed on Table 1. As with the slug withdrawal tests the Bouwer and Rice method was used to analyze the data (Bouwer and Rice, 1976). The same wells that strongly exhibited the DRR during the slug withdrawal tests likewise did so during the slug injection test; therefore, the later data points were used to determine hydraulic conductivity for the comparison.

No definite trends were observed that could be attributed to the grouting project. The majority of the wells exhibited a change of less than one order of magnitude from before to after grouting. Three wells (3, 7, and 8) showed a hydraulic conductivity increase of approximately one order of magnitude. The differences noted appear to be directly related to the rapid recovery of these wells and/or to the modification of the slug test procedure. The DRR effect was strongly exhibited in wells 3 and 8 and moderately exhibited in well 7. The non-Darcian type of recovery indicates that the applicability of this test to these wells may be questionable. Assuming the latter portion of the tests are valid and represent diffuse flow, the larger slug volume and earlier data acquisition in the second set of tests (slug injection) increased the accuracy, which may account for the observed increase in hydraulic conductivity values.

Slug tests yield aquifer hydrologic data for the area in proximity of the well tested. However, no definite relationship was seen between proximity of grouting wells and hydraulic conductivity changes observed in the monitoring wells. Of the five monitoring wells located within 10 meters of grout wells (1, 3, 4, 10, and 14), three showed a decrease and two showed an increase in hydraulic conductivity (Figure 3 and Table 1). Well 14 was the only well within 5 meters of a grout well. This well exhibited virtually the same hydraulic conductivity (4.9261×10^{-6} to 3.3362×10^{-6}), this was within the expected variation of retesting based on experience.

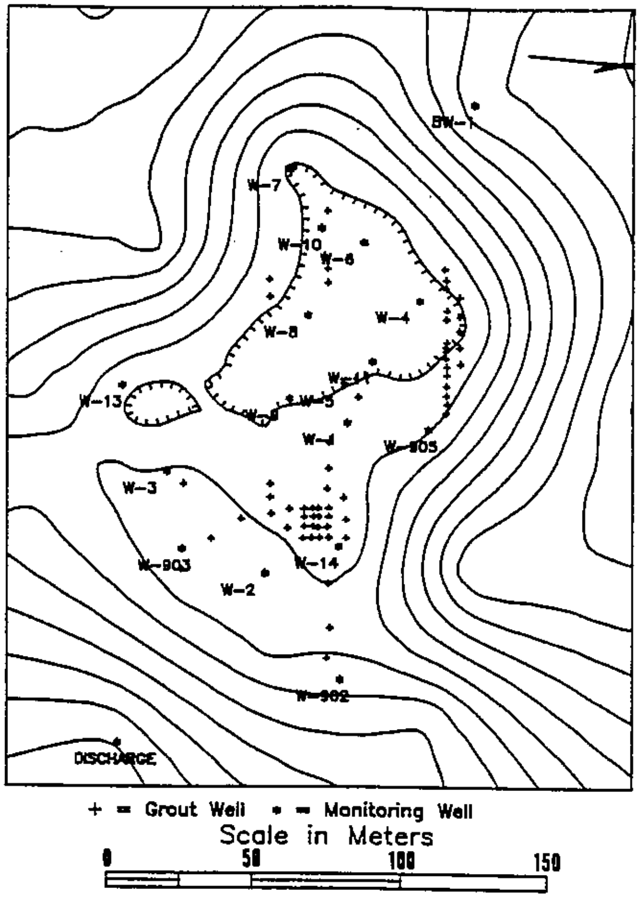

Figure 3. Map showing the location of the grout injection and monitoring wells.

Effect of grouting on the hydraulic conductivity of the monitoring wells will depend on the distance, direction, and/or degree of grout propagation. If grout propagation was under 5 to 10 meters no changes in response to the slugging would be expected in the monitoring wells beyond this distance from the grout wells. Grout propagation of at least 10 meters was observed by grout "break through" at the surface. This indicates that the degree of grouting may have been insufficient to significantly affect the hydraulic characteristics of these wells; however, it was more likely that the direction of grout propagation was anisotropic, and unlikely that it would flow directly toward the monitoring wells. The grout would tend to follow the path of least resistance, therefore the direction of grout movement would be greatly influenced by the location and orientation of the conduits. Unless a conduit connected a grouting well and a monitoring well, little or no change would be expected.

Comparison of the hydraulic conductivity values determined from the slug tests before and after grouting indicates that, in general, no discernable change in hydraulic conductivity within 5 to 10 meters of the grout injection wells, thus attributed to grouting. The differences observed are easily attributable to minor testing errors and/or natural variation.

Constant-Discharge Tests

Two constant-discharge aquifer (pumping) tests were performed prior to grouting and were repeated afterward, utilizing the same wells and approximately the same pumping rate and duration. The pumping tests yield information over a larger area than the slug tests. The low transmissivity values yielded by the slug testing indicated the need for low pumping rates, therefore a bailer or a small hand pump was used to withdraw water during these tests. The first test consisted of pumping well 9 for 2 hours at a rate of 5 liters per minute, while wells 1 and 5 were monitored using pressure transducers linked to a data logger. During this test, air-rotary drilling was actively occurring approximately 50 meters to the east near well 14. When air was blown into the drill hole it would cause the water level in monitoring well 5 to rise above static water level, while the level in wells 1 and 9 declined. This suggested the presence of a conduit connection between wells 5 and 14. Because of the drilling interference, data collected from well 5 were not useable. The water level in well 1 was unaffected by the drilling however, and thus these data are useable. In the second pre-grouting pumping test, well 6 was pumped for two hours at a rate of 6 liters per minute, while the water levels wells 8 and 10 were monitored. The Theis method was used to calculate transmissivity, storativity, and other aquifer parameters on the time-drawdown curves of the three monitoring wells (Theis, 1935).

Table 2 lists the hydraulic conductivity and transmissivity calculated from the pre- and post grouting pumping tests. As with the slug tests, no appreciable changes in pumping test transmissivity values can be directly attributed to the grouting project. Transmissivity differences before and after grouting were slight. The differences in transmissivity determined from the pumping tests were less than one order of magnitude. These differences are all within the anticipated variation of retesting of a well and/or created by the subjectivity of curve matching using the Theis method (Theis, 1935). However, the transmissivities determined by pumping tests are over four orders of magnitude higher than those determined from the slug tests. These transmissivity differences may be caused by greater transmissivities in the spoil over greater distances than can be measured by slug testing or by the lack of early data during testing the DRR wells, which may not permit true determination of transmissivity.

There is a possibility that grouting did slightly effect the hydraulic characteristics of the spoil. Although the differences are small, the greatest net decrease/increase in transmissivity occurred in wells 8 and 10 by comparison to well 1. A substantial amount of grouting occurred in the near wells 8, 10, and the pumping well, while no grouting was performed between wells 9 and 1. The changes may be due to the physical action of the grouting breaching and/or connecting previously unconnected conduits. The possibility of this breaching action was indicated by the build up of back pressure during grouting, followed by a complete pressure

HYDRAULIC CONDUCTIVITY			TRANSMISSIVITY	
WELL	PREGROUTING	POST GROUTING	PREGROUTING	POST GROUTING
1	8.6542E-03	1.4026E-02	3.2280E-02	4.7690E-02
8	1.3329E-02	5.0769E-03	4.8650E-02	1.6500E-02
10	9.3194E-03	2.7630E-02	2.6840E-02	6.5760E-02
	m/sec	m/sec	m^2/sec	m^2/sec

Table 2. Hydraulic conductivity (K) and transmissivity values (T) obtained from the constant-discharge tests conducted before and after grouting.

release during the injection of several wells. Additional data are needed to support that this action has occurred.

The lack of differences in the pre- and post grouting transmissivities may be caused by the small amount of grout in comparison to the spoil porosity. The spoil porosity may have been higher than originally anticipated (initial estimates were 20 to 30 percent). The total volume of grout injected during this project was 388 cubic meters. Depending on the size of the estimated area of grout influence (45,000 to 79,000 cubic meters), only 1.6 to 4.3 percent of the spoil pore volume was filled by the grout using the original porosity estimates. The porosity range for material similar to spoil (unconsolidated sand and gravel) is 25 to 70 percent (Freeze and Cherry, 1979). If this range were applied to the spoil, the grout would have filled 0.7 to 3.4 percent of the spoil pore volume. Even if the porosity of small discrete spoil areas around the injection wells were completely grouted, the overall site porosity was only very slightly affected. The consistency of the grout could also be a contributing factor to the lack of changes. The grout was approximately 47 percent water by volume. This high water content would permit greater propagation of the fluid and gravitational settling of the solid fraction of the grout than originally anticipated, thus causing only partial filling of the voids prior to, and especially after, solidification.

Water Table Variation

Grouting of the spoil has the potential to eliminate void space, open or close connection between voids, and consequently to reroute groundwater flow paths and produce changes in the water table configuration. Grouting-induced groundwater regime variations may be permanent or may be only seasonal or temporary. Flow path rerouting may be indicated by spatial variations in water quality and/or by directional or level changes in the groundwater hydraulic gradient.

Comparison of average static water table conditions before and after grouting indicates that no major changes occurred in groundwater flow directions or gradients (Figures 4 and 5), although the maps exhibit some variations. These maps were created by averaging static water levels for the pre- and post grouting period, respectively.

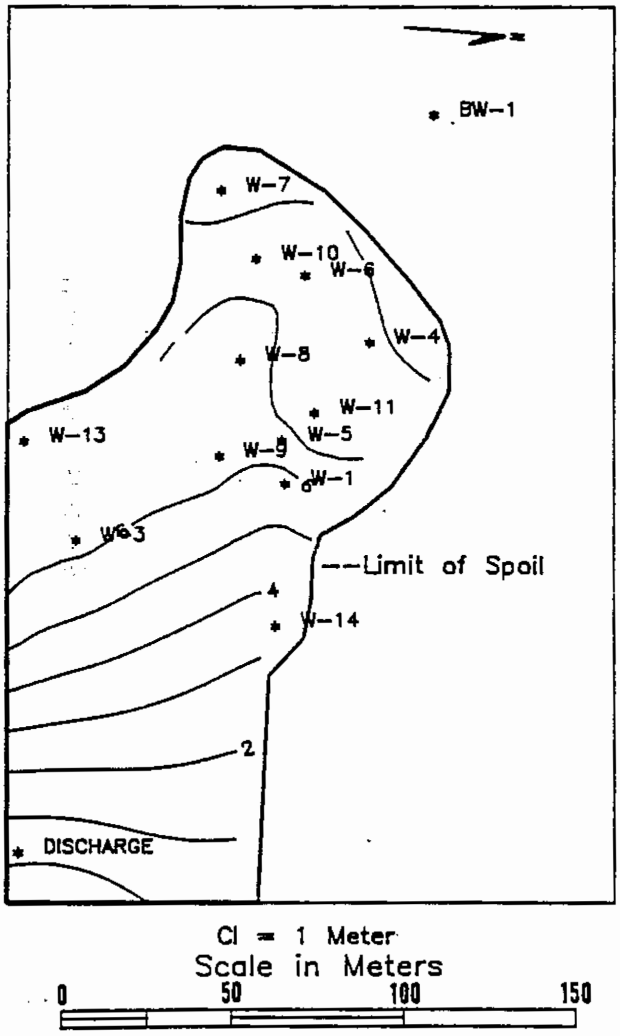

Figure 4. Average water table contour map prior to the grouting project. The main discharge is datum.

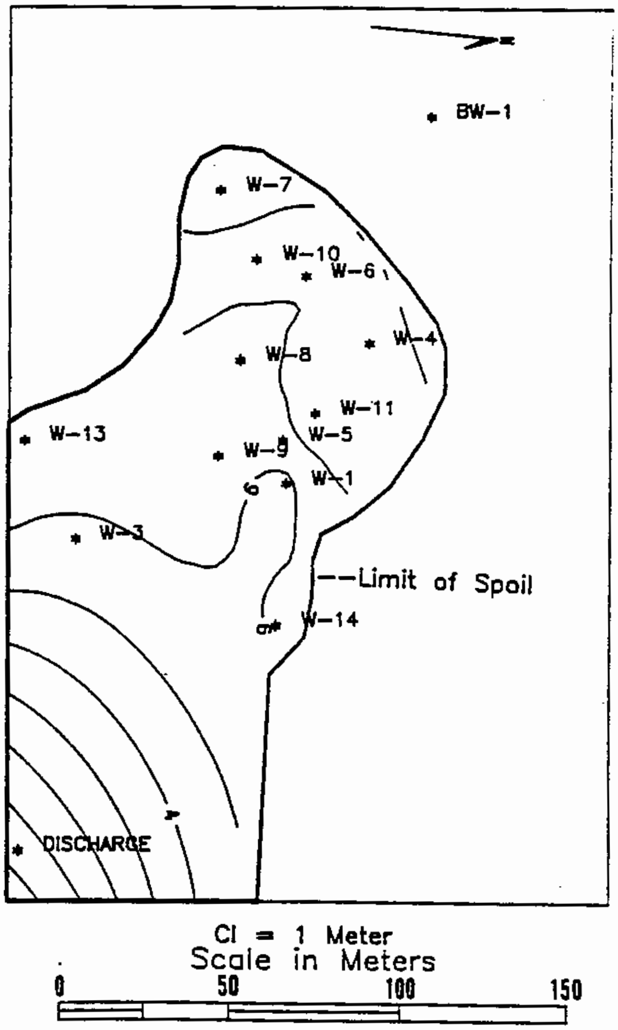

Figure 5. Average water table contour map after grouting was completed. The main discharge is datum.

The differences are likely due to temporal variations caused by differing precipitation amounts and subsequent recharge to the aquifer. The contour differences occurring between the wells and discharge point are caused by the contouring program extrapolating into an area with little control data, and does not reflect true changes there. Overall configuration and absolute water table levels are not significantly different as a consequence of the grout injection, except for a small flexure in the contours in the area between wells 1 and 9 and well 14. This flexure appears to be directly related to the numerous grout wells (27) in that area. Additional data collection is needed to more accurately substantiate this change. The lack of major configuration changes is not surprising, because this was not the intent of the original project, which was to encapsulate selected isolated acidic spoil zones. The small amount of grout used compared to the potential void space is a possible explanation.

Two pregrouting monitoring periods were compared to two post grouting periods to determine if under similar flow conditions, changes to the water table configuration or levels are discernable. Comparison periods were chosen where precipitation type and amounts for the preceeding 30 days were approximately the same. Recharge rates were assumed to be approximately the same, because of similar seasonal conditions, no direct measurements were made. Groundwater recharge rate was assumed unchanged. Two pregrout periods were selected to compare to two post grout periods, March 30, 1989 to April 5, 1990 and September 28, 1989 to April 12, 1990. Figures 6 and 7 (March 30, 1989 and April 5, 1990 respectively) exhibit no major differences that can be attributed to the grouting operation. A comparison of the site on September 28, 1989 to April 12, 1990 likewise indicates no definite changes caused by grouting (Figures 8 and 9). Hawkins and Aljoe (1991, In Press) indicated that groundwater flow through the site generally follows porous media principles (except under transient conditions or periods of stress), therefore if the grout mainly filled conduits, it is not unexpected that no change was seen in the water levels. The contour line flexure noted for the average water table was not observed during this time. It is possible that the contour anomaly observed for the average conditions becomes evident under different flow conditions than those seen during the two comparison periods.

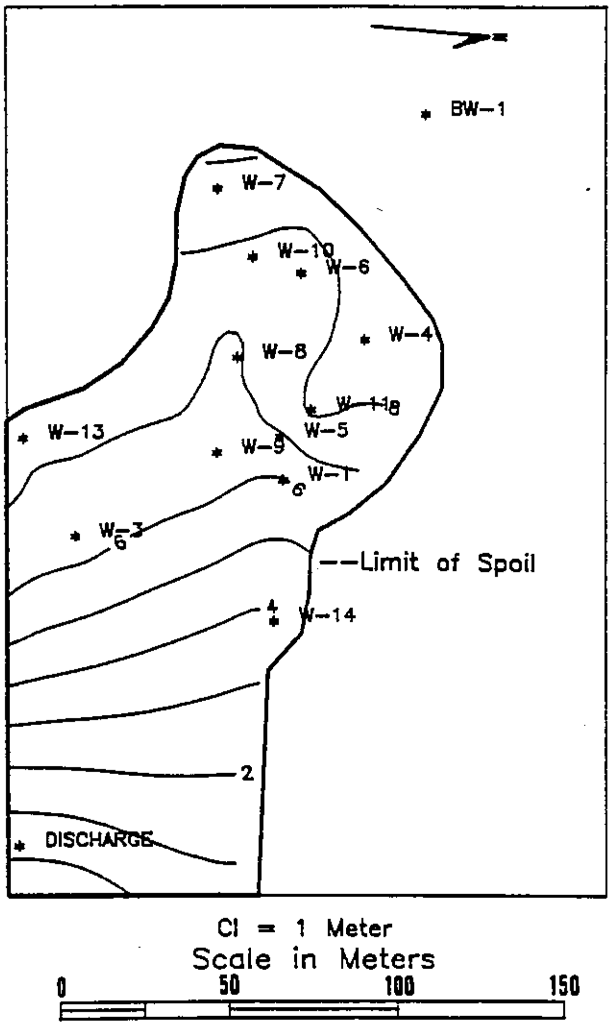

Figure 6. Water table contour map from March 30, 1989. The main discharge is datum.

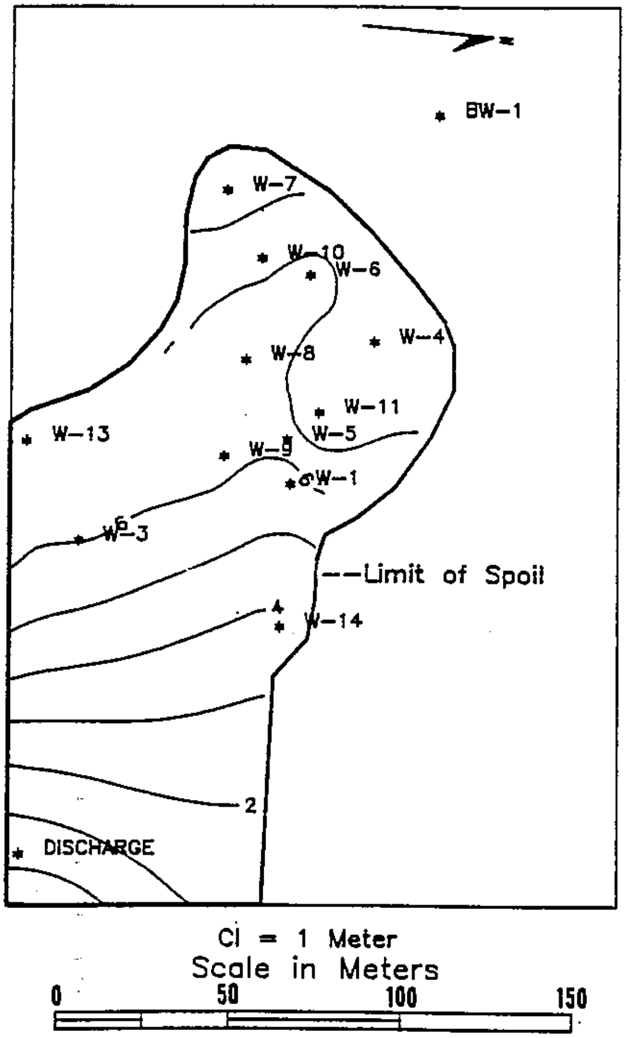

Figure 7. Water table contour map from April 5, 1991. The main discharge is datum.

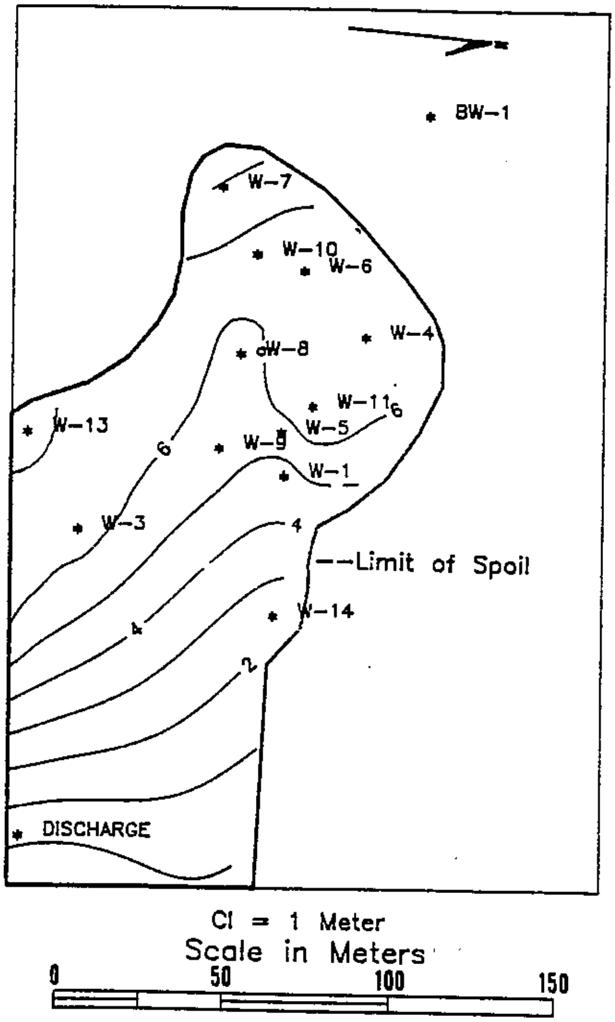

Figure 8. Water table contour map from September 28, 1989. The main discharge is datum.

Water Quality

Grouting is likely to induce water quality changes within the site in several ways. The grout material contained significant concentrations of both calcium and sodium. The fly ash was 2.4 percent calcium and 0.29 percent sodium, which means that nearly 6000 kg of calcium and 700 kg of sodium were injected. The main source of calcium was probably the portland cement portion of the grout. Calcium in the form of hydraulic calcium silicates, calcium oxides, and hydrated calcium sulfate are primary components of portland cement (ESSROC Materials). Chemical changes may be caused by the components of the grouting material reacting with groundwater. Chemical changes also may be caused by amelioration of the AMD production by the coating of potentially acidic spoil, thereby limiting physical contact of oxygen and/or groundwater with this spoil. Another possible consequence is the rerouting of vadose and phreatic groundwater flow paths within the spoil, thus possibly changing the spoil it comes in contact with, affecting

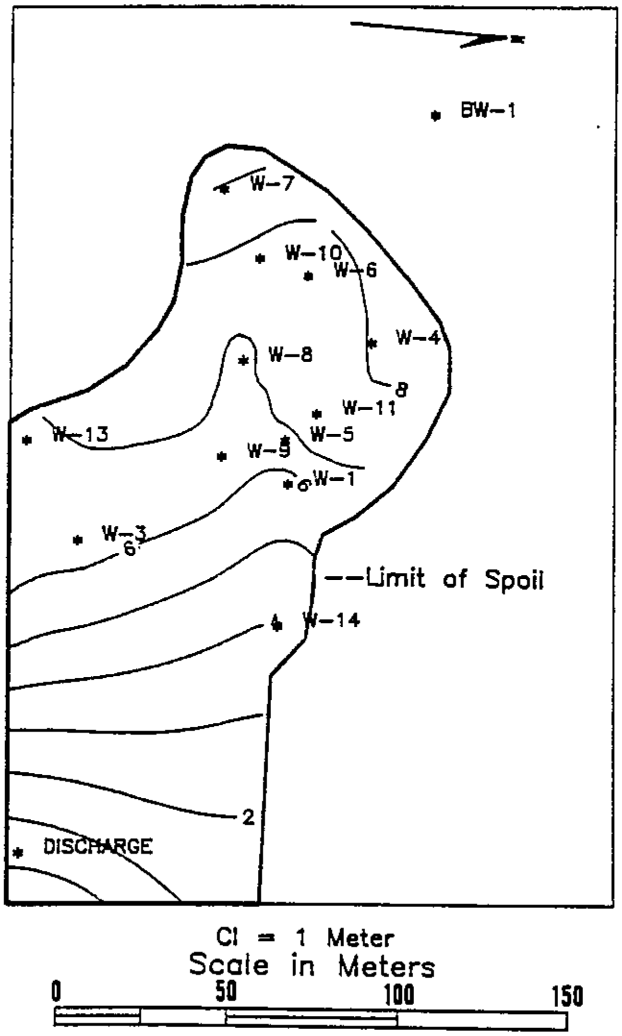

Figure 9. Water table contour map from April 12, 1990. The main discharge is datum.

the commingling of groundwaters of differing chemical quality, or changing lateral and vertical recharge rates.

In 1951, Stiff suggested a system where the cation and anion concentrations in milliequivalents per liter (meq/l) were plotted on opposite sides of a vertical axis. The points are connected by lines giving each plot a distinctive polygonal shape. This system was originally developed for analysis of natural waters, therefore care must be exercised that the high iron and sulfate levels usually associated with AMD do not mask trends of other cations and anions.

Stiff diagrams were created from the average spoil water quality data before and after grouting. These diagrams are a means of graphically displaying similarities in water sample analyses and showing differences caused by chemical reactions or mixing. Relative concentrations of cations and anions are converted to percent meq/l rather than milligrams per liter (mg/l).

The Stiff diagrams revealed that the main discharge and the majority of the wells showed no discernable change after grouting. Wells 2, 8, 11, and 13 exhibited minor changes from before to after the grouting project (Figures 10, 11, 12, and 13, respectively). As expected all sample points exhibited a strong sulfate type anion characteristic. The high sulfate concentrations associated with AMD strongly influence the data on the anion side of the diagram. Well 2 (Figure 10) exhibits an increase in calcium and sodium relative to the iron and magnesium. Changes in well 8 (Figure 11) are related to an increase in the sulfate and iron dominance after grouting. An increase in the relative concentrations of iron after grouting of wells 11 and 13 (Figures 12 and 13, respectively) is related to an increase in total iron concentration.

Well 2 exhibited a significant change in water quality in the period following grouting (Figure 10). The cation type changed from a mildly magnesium dominant type to a stronger calcium type with increasing sodium. This change

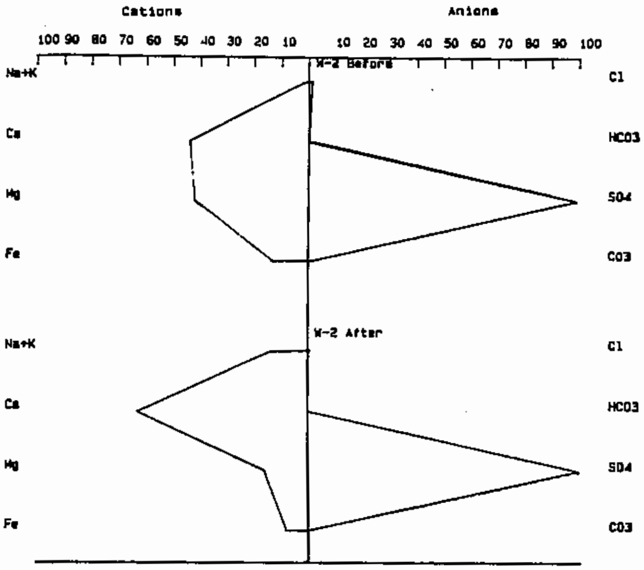

Figure 10. Stiff diagrams graphically illustrating cation changes in well 2. Cation and anion values are in percent milliequivalents per liter.

appears to be directly related to the grouting near the well. Numerous grout wells (26) are hydrologically directly up gradient of well 2.

Well 2 is located in a perched-water table zone within the spoil aquifer, which is underlain by a lower permeability material than the surrounding spoil (Hawkins and Aljoe, 1990). Groundwater accessed by this well is removed (above) from the water table reflected by the other spoil wells. Given lower permeability and being limited to direct recharge, flow through spoil in the vicinity of well 2 is slower than other portions of the site. Groundwater flushing through this area will take longer than through other parts of the site. Therefore, the water quality changes noted in well 2 are may only be temporary.

Well 8 became more strongly sulfate dominant after grouting (Figure 11). This trend is not due to an increase in sulfate, but is caused by a substantial decrease in the bicarbonate (HCO_3) concentration. It is possible that a rerouting of groundwater caused this change. The water quality has become more like that of wells 4, 6, and 7, which are hydrologically up gradient. Because of the limited amount of data, the apparent change must be verified by the collection of data over a longer time period. It is also possible that increased calcium content from the grout caused calcium carbonate ($CaCO_3$) to form and precipitate, thereby reducing the bicarbonate concentration.

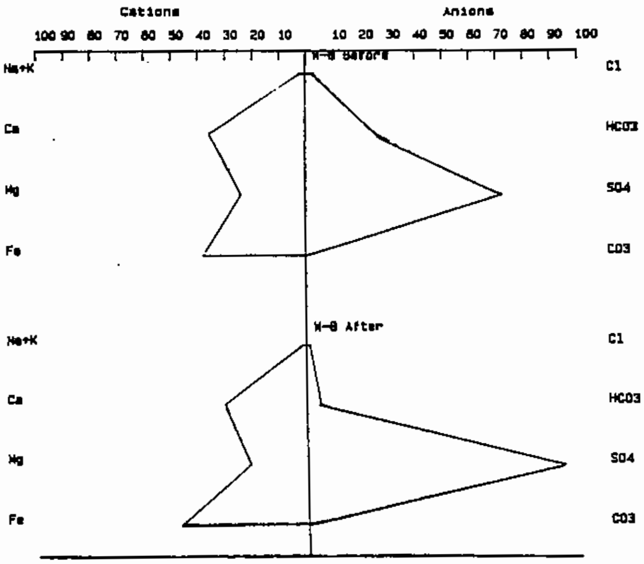

Figure 11. Stiff diagrams graphically illustrating anion changes in well 8 caused by grouting. Cation and anion values are in percent milliequivalents per liter.

The changes at well 11 are caused mainly by an increase in magnesium and iron (Figure 12). The differences found in well 13 resulted from an increase in iron, while calcium and magnesium decreased somewhat (Figure 13).

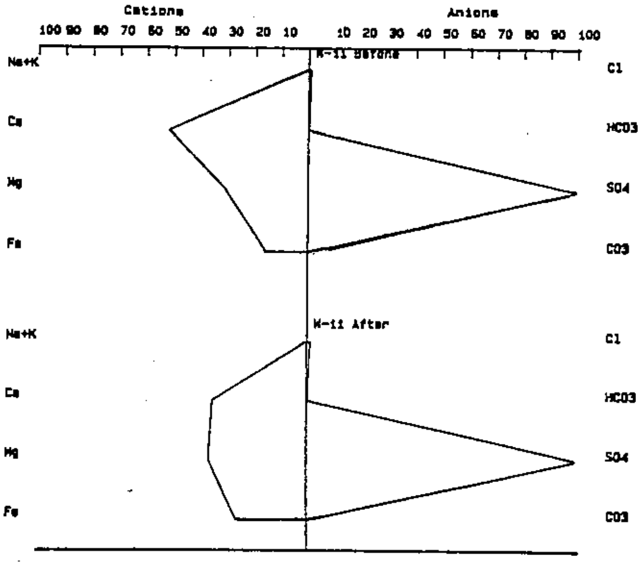

Figure 12. Stiff diagrams graphically illustrating cation changes in well 11 caused by grouting. Cation and anion values are in percenter milliequivalents per liter.

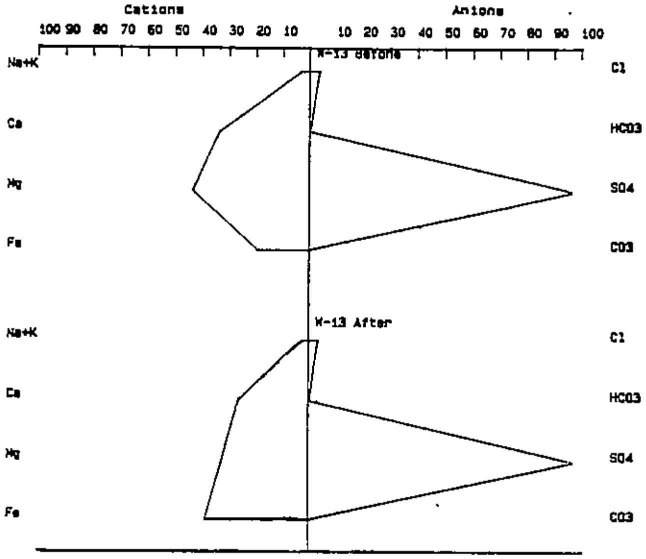

Figure 13. Stiff diagrams graphically illustrating cation changes in well 13 caused by grouting. Cation and anion values are in percent milliequivalents per liter.

There is no indication that these changes are related to the grouting. Only one grout well was within 25 meters of well 11 and none were hydrologically up gradient of this well. No grout wells were within 40 meters or hydrologically up gradient of well 13. The changes appear to be related to temporal differences which may be attributed to the small data set and the use of percent milliequivalents instead of actual concentration values.

Grout Plume Tracking

Background sodium concentrations in the groundwater were low prior to grouting, generally averaging below 2 mg/l. The substantial amount of sodium contained in the fly ash (700 kg) permitted its use as a groundwater tracer of the grout injection. The main discharge and wells 1, 2, 8, 10, and 11 all exhibited a significant sodium concentration spike following the grout injection. The remaining wells showed no definite sodium peak, although most exhibited apparent increases of sodium levels.

The main discharge, approximately 80 meters from the nearest grout injection well, exhibited a jump in sodium concentration (from about 1 to 5 mg/l) within about 20 days after the initiation, but before completion of grouting (see Figure 14). At this rate, average linear velocity is 4.6 x 10^{-5} meters per second. The average linear velocity is similar to values obtained from a earlier tracer test and is comparable to glacial sediments (Hawkins and Aljoe, 1991, In Press). The concentration began to decline exponentially after

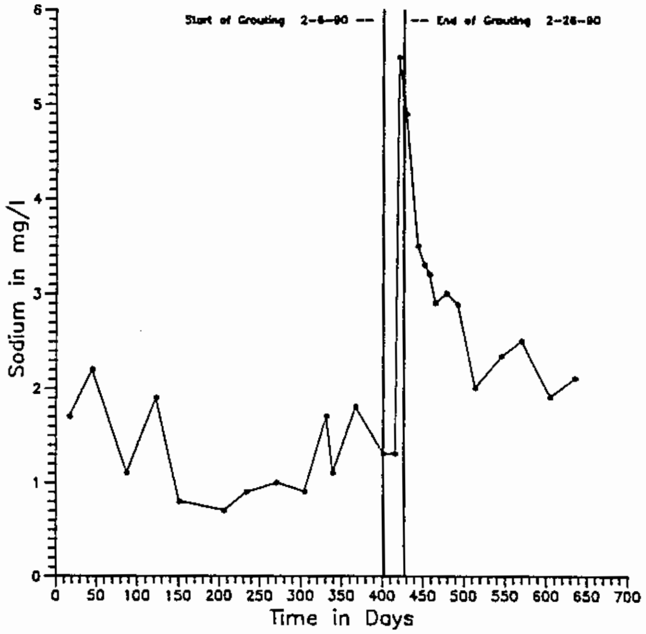

Figure 14. Sodium concentration at the main discharge.

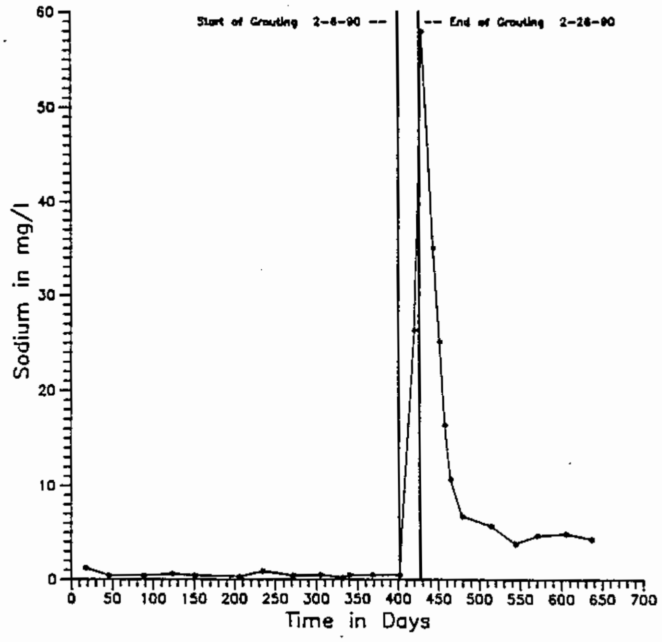

Figure 15. Sodium concentration at well 2.

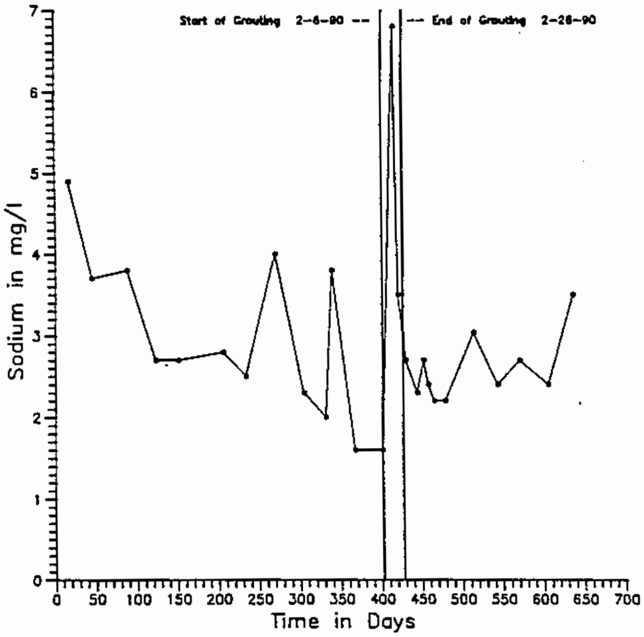

Figure 16. Sodium concentration at well 8.

completion of grouting. Given this rate of decline, the sodium concentration should return to the level of the pregrouting average approximately 280 days after completion of grouting. This indicates that groundwater flushing of the grouted portion of spoil should be virtually complete in under 10 months.

Wells 2, 8, and 10 also exhibited a very rapid sodium spike followed by a nearly as rapid decline (see Figures 15, 16, and 17). The sodium concentration of well 2 rose to almost 60 mg/l from a pregrouting background average of 0.5 mg/l. Sodium levels quickly dropped to about 5 mg/l and then more slowly decreased, although they have not yet returned to pregrouting background levels. The rapid rise in sodium levels appears to be caused by large amounts of sodium-rich grout forced into spoil by the numerous grout wells near well 2. The slow return to background levels can be explained by the limited recharge to, and the low transmissivity of, the perched spoil zone intersected by well 2. The sodium concentrations in wells 8 and 10 returned to background levels nearly as fast as they rose. This indicates rapid

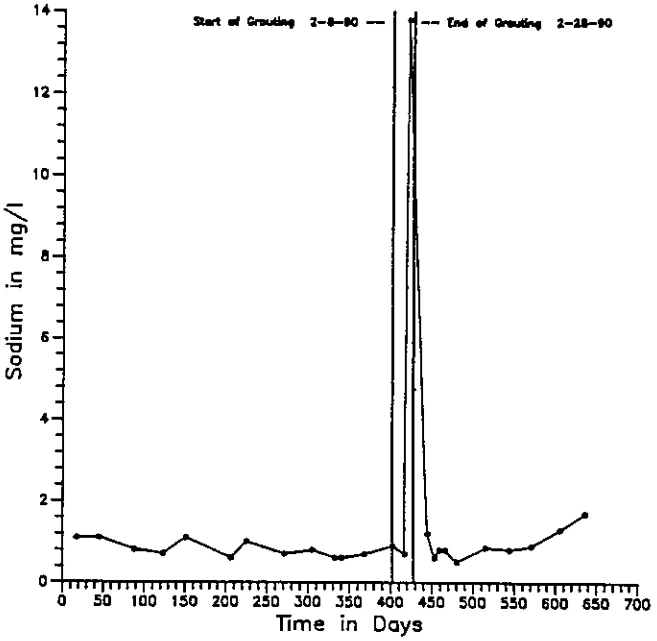

Figure 17. Sodium concentration at well 10.

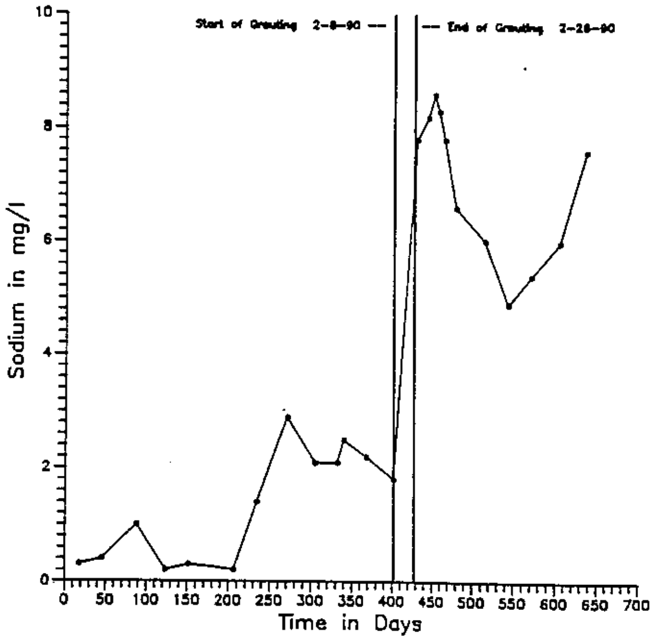

Figure 18. Sodium concentration at well 1.

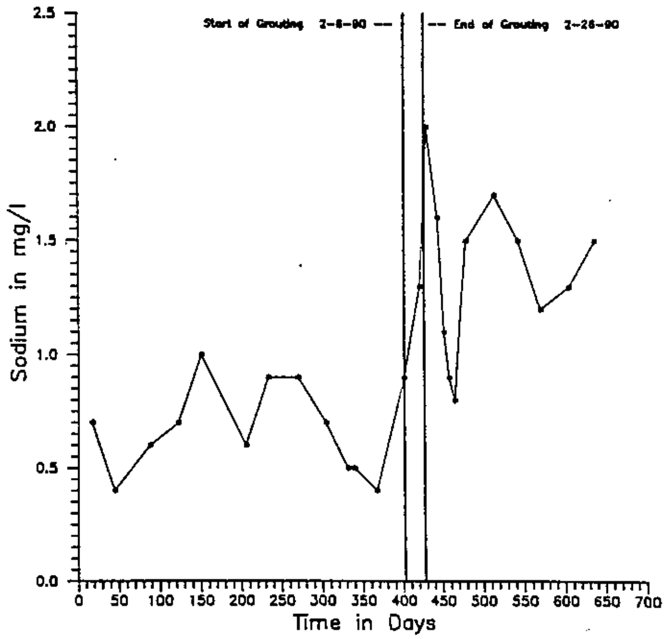

Figure 19. Sodium concentration at well 11.

groundwater movement quickly flushed much of the sodium out of the portion of the spoil around these wells. Previous work has indicated well 8 intersects a conduit or void in the spoil (Hawkins and Aljoe, 1991, In Press). The presence of a conduit will permit more rapid groundwater flow near and around well 8 and perhaps well 10 (data indicate that interconnected voids also exist in that area) than in portions of the spoil where primarily porous media flow occurs.

Wells 1 and 11 also exhibited a sodium spike that began a fluctuating decline after the effects of the grouting passed (Figures 18 and 19). Both wells show sodium concentration fluctuations after grouting that are below the peak, but well above background levels. These fluctuations appear to be directly related to recharge events. Both show a marked increase in the fall and early winter months when recharge rates are lower. This indicates the concentration at these wells is strongly controlled by the amount of dilution available from the recharging waters. The aquifer testing of these wells indicates groundwater flow in this area is porous media type, which will allow much slower movement than conduit flow. Sodium concentrations should continue to fluctuate with recharge and eventually return to background levels. Rate of return will depend mainly on the spoil recharge rate.

The differences in the sodium concentrations at various wells following grout injection indicate the spoil is highly heterogeneous and anisotropic. Zones of rapid groundwater movement appear to be related to conduits within the spoil. Areas of slower groundwater movement exist where porous media flow dominates. Sodium has proven to be an adequate groundwater tracer to determine the average linear velocity and direction of groundwater movement. Approximately 280 days are required for sodium at the main discharge to return to background levels. As stated earlier, overall the spoil aquifer behaves primarily as a porous medium under steady state conditions.

Conclusions

Slug tests and pumping tests give widely different results, possibly attributable to the subjectivity of the data reduction techniques employed. Nevertheless, aquifer tests before and after grout injection of the monitoring wells indicate the grouting caused no discernable widespread changes in the hydraulic properties of the spoil, although hydraulic conductivity in parts of the spoil may have changed. No major changes in groundwater flow direction or water table level were observed, although a localized flexure of the post-grouting water table appears to be caused by grouting. The original intent of the grouting project, to grout small isolated potentially acidic spoil zones to restrict contact with oxygen and groundwater, along with the small amount of grout injected relative to the total spoil pore volume and the watery consistency of the grout are the main reasons for the lack of significant hydrologic changes.

Two wells less than 20 meters hydrologically down gradient from grout injection wells exhibited slight water quality changes that could be attributed to the grouting operation. The changes were caused by compounds introduced by the grout and by groundwater flow rerouting. The remainder of the wells exhibited no water quality changes that can be attributed to grouting.

Sodium in the grout can be used to track the movement of groundwater through the spoil. Tracking of the plume and monitoring of the sodium concentrations will give insight into the groundwater flow regime and flushing rates. The movement of the plume as it passes monitoring wells indicates a bimodal flow regime of groundwater, as have previous studies. The sodium concentration at the site discharge indicates a porous media groundwater flow regime for the site as a whole.

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