Experimental Injection of Alkaline Lime Slurry for *In-Situ* Remediation of an Acidic Surface-Mine Aquifer

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ABSTRACT

Injection of alkaline waste-lime slurry was performed at a West Virginia surface coal mine site, to attempt neutralization of acid springs. Deep trenching (>15 feet) using an excavator yielded the most effective injection into the aquifer. Water from two springs, 300 feet from the deep trench, showed 70%-80% reduction in acidity in response to injection. Neutralization persisted >170 days after treatment, with pH between 5.1-5.7 and metal acidity from 25-60 mg/L. A minor fraction of lime introduced was consumed. The sustained neutralization is attributed to reaction of acid water with subsurface lime, entrained below the water table by macropore infiltration. Characteristics of groundwater transport are critical in determining recharge structure location.

Introduction

Following surface mining near-surface of pyritic coal, overlying rock are backfilled on site, creating piles of unconsolidated acidic spoil, of sandstone, shale, and coal residue. Recharge to the spoil induces a permanently saturated zone up to 10's of meters above the underlying pit floor (Hawkins and Aljoe, 1992). Ground-water flow is generally controlled by the dip of the pit floor. Discharge occurs from springs, generally at or above where pit floor outcrops (Avery et al, 1999).

Ground-water geochemistry in acidic spoil aquifers is controlled by the balance between acid-producing and acid-neutralizing reactions. Basic minerals such as calcite, dolomite, and portlandite [lime; $Ca(OH)_2$], are used to remove metals, either in conventional or passive point-of-dicharge water treatment structures. More recently, techniques have been developed to effect metal removal using in situ techniques of alkaline recharge (Caruccio *et al.*, 1984; Nawrot et al., 1994; Donovan *et al*., 1997).

Reported difficulties with the *in situ* technique relate to (a) introducing adequate alkalinity, and (b) the flow and transport characteristics of the aquifer. Such groundwater flow has been described as "pseudokarstic" due to inferred interconnected macroporous conduits (Hawkins and Aljoe, 1992), analogous to "preferred-flow pathways" by Ritzi *et al*. (1994) (PFP's). The structure, orientation, and interconnection of PFP's within minespoil aquifers is difficult to identify, except where experimental evidence exists, such as response to recharge, pond leakage, etc. (Donovan and Frysinger, 1997). The nature and distribution of these flow paths is nonetheless important if alkaline recharge structures are to be located rationally.

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This paper describes results of attempts to implement and test strategies for in situ alkaline injection using lime slurry. The goals of the technique are: (1) to preciptate metals in solution *in situ* in the spoil , and (2) to bring the spring discharge as close to net alkaline as possible, making it amenable to passive treatment (limestone drains, wetlands, etc.) for polishing. The workplan had three phases: (I) baseline characterization of groundwater flow, spring discharge, and chemistry, (II) slurry injection trials, and (III) monitoring of well and spring chemical response.

The aquifer selected for evaluation is typical of surface-mine spoil aquifers producing acid-mine drainage (AMD). The Y aquifer (Figure 2) underlies a reclaimed surface mine operated from 1976-83, located 20 km southeast of Buckhannon, WV (Figure 1, 2). The spoil is 14-22 m thick, the bottom 4-6 of which is saturated and overlies an underclay/shale aquitard, the former pit floor. Aquifer properties are extremely heterogeneous, with a bimodal distribution of hydraulic conductivity, or K (Maher and Donovan, 1997). It has only a few perimeter springs: P00, P01, P02, and P03 at the head of Plant Creek, MA1 along Panther Creek, and MA2 along Woody Creek. Their flows vary both seasonally and between springs and show increased flows immediately following recharge, receding exponentially with aquifer water level (Avery et al., 1999). P00 and P02 tend to be ephemeral.

Low-K boundaries surround the aquifer on three sides. The east end of the site, the updip extent of mining, has a colluvium-covered rock highwall (Figure 2). On the north is a spoil-covered lowwall, left unmined to restrict seepage from Panther Fork. It is successful except for spring MA1. This rock barrier is exposed where it crosses a mine road on the west boundary. The rest of the west and the entire south perimeter is spoil-covered coal outcrop along the down-dip side of the aquifer. The most down-dip (lowest) cropline is the west boundary, where the four P springs are found. These account for >50% of the aquifer discharge. Along the south boundary, only spring MA2 discharges from coarse rubble. The location of spring P03 may have been engineered during mining, as it discharges from a large-diameter steel culvert within a rock drain, reported to extend ca. 60 m upgradient to intercept west-flowing groundwater from flowing into Woody Creek.

Collected spring discharge is treated at several locations and flows downstream into lower ponds where it is treated using either caustic soda (20% by weight NaOH). Treated water is discharged downstream, but alkaline (pH>8) water-rich sludge of metal oxides accumulating in ponds – such as Pond 13, Fig. 2 -- is periodically pumped onto the Y aquifer for disposal in the T1 pond. The pond is unlined and leaks rapidly into the underlying Y aquifer. As Pond 13 also drains runoff from the head of Woody Creek, the chemistry of its sludge is more dilute than treated MA2 water. Dissolved Na is relatively concentrated (90-280 mg/L) in treated Pond 13 water, in contrast to its <10 mg/L concentration in local acid groundwater (Donovan *et al*., 1997). Therefore, Na is a useful tracer for treated sludge transferred from Pond 13 into the leaky T1 pond.

Methods

Sampling for Groundwater Chemistry

Sampling of wells and springs was done to determine baseline chemistry and sample response to *in situ* treatment. Samples were collected between January 1997 and June 1999 for springs P00, P01, P02, and P03 and between May 1997 and June 1999 for springs MA1 and MA2. Spring samples were collected at a monthly interval during baseline and at a weekly frequency starting 5/27/98, after injection trials had begun. Following some recharge trials, spring sample frequency was increased to daily to capture arrival times of alkalinity at springs. Spring samples were collected as close as possible to the source to minimize sample aeration. Flow measurements were taken using a calibrated bucket and stopwatch. Wells were sampled approximately monthly from 11/97 to 2/98 during the baseline period. Monthly sampling was continued during the early portion of trials until 7/98, after which the frequency was reduced to quarterly. At least one casing volume was purged prior to sample collection. Groundwater was sampled using either a bailer or a submersible pump. The

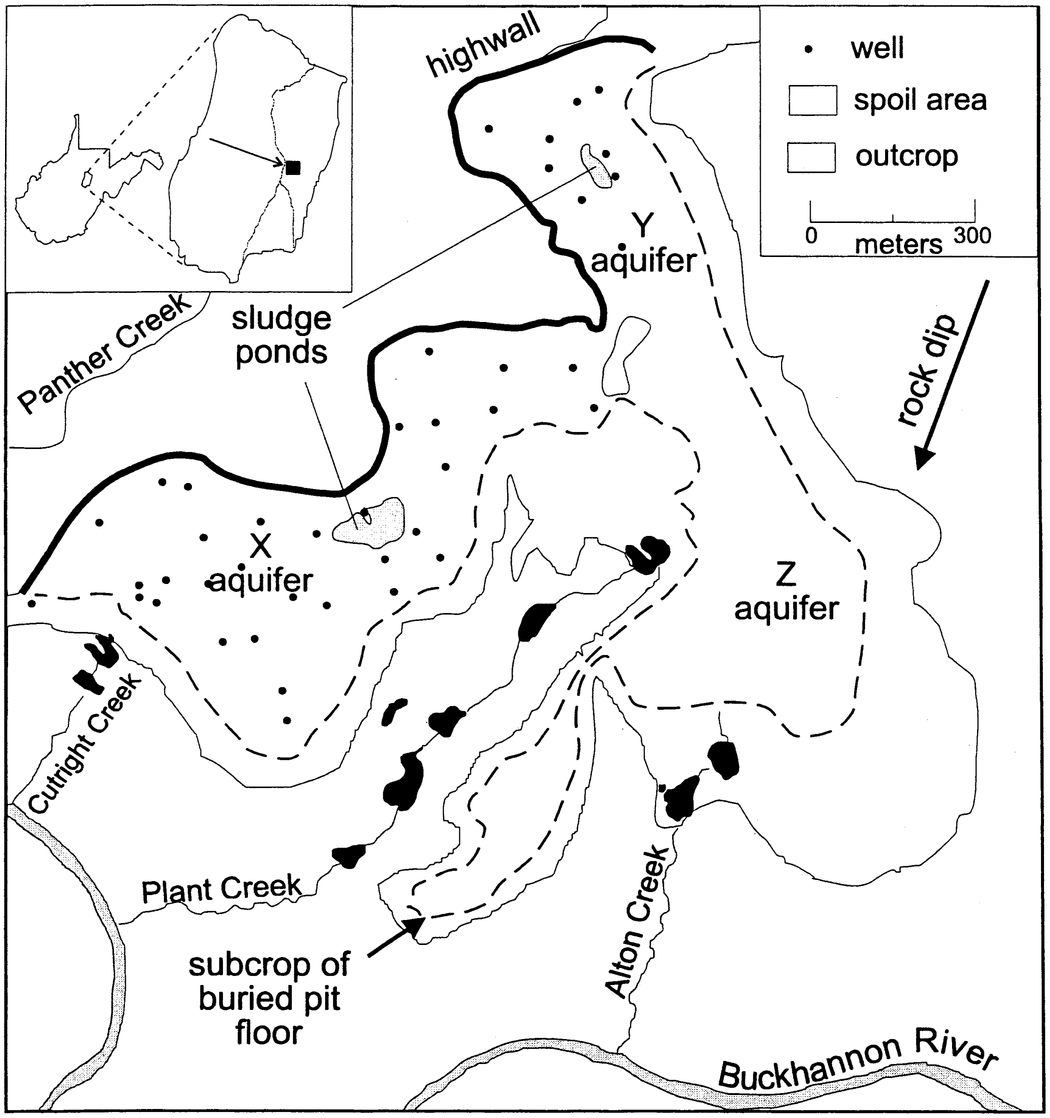


Figure 1. Location of the Y aquifer.

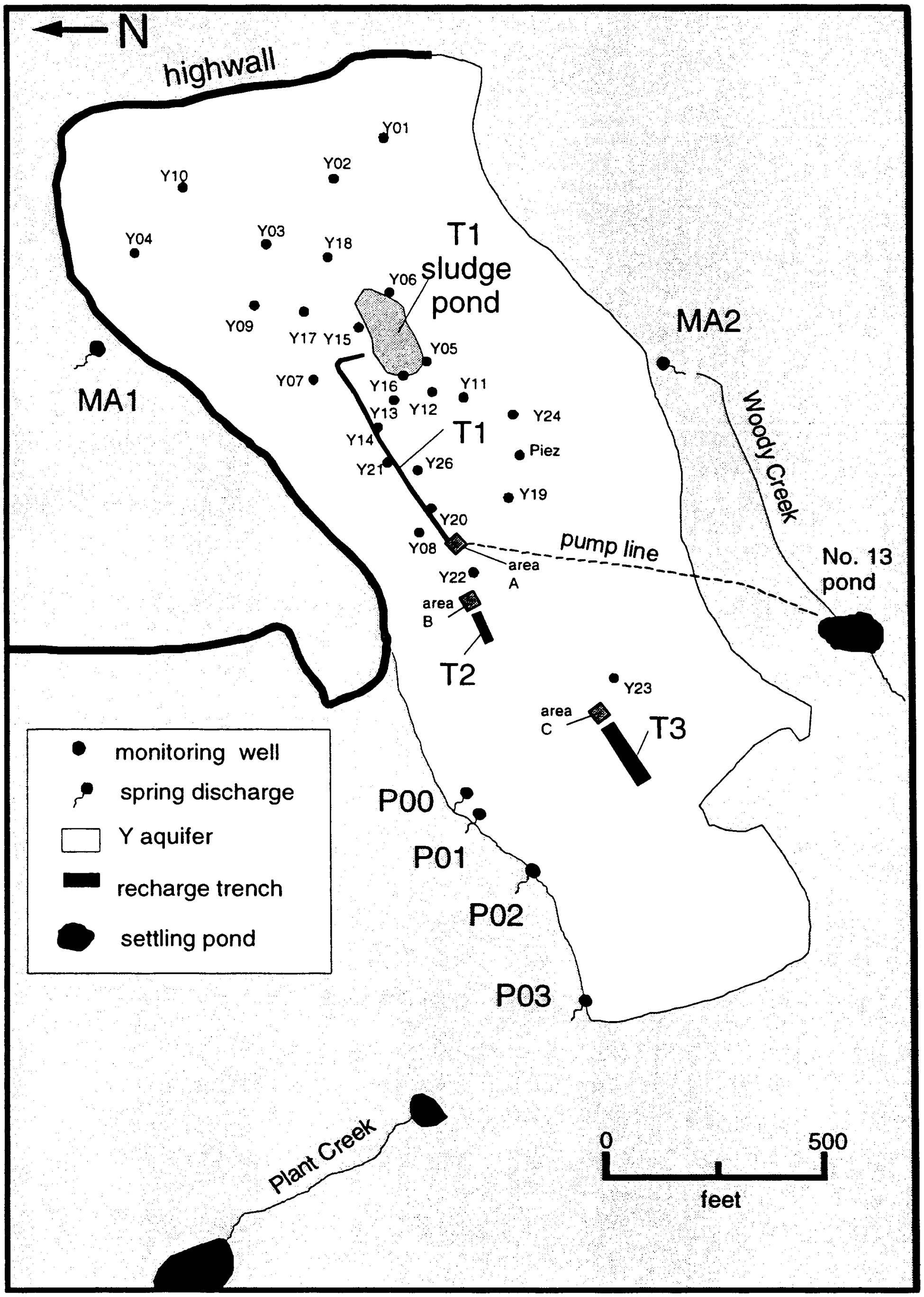


Figure 2. Recharge structures (T1, T2, and T3), springs, and wells on the Y aquifer.

pump allowed water to be directed into a sealed flow-through cell, to determine pH, specific conductance, temperature, and dissolved oxygen without exposure to the atmosphere. Sampling was preformed only after all the parameters had stabilized and one well volume was purged.

The sampling protocol differed slightly between well and spring samples. At each well, two pumped samples were collected. One sample collected was immediately filtered (0.45 µm nitrocellulose) and acidified to pH <2 within 24 hours for dissolved metals (Fe_{tot}, Al^{3+}, and Mn_{tot}) and major cation species (Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}). The second sample was chilled without treatment and used for alkalinity titration, by H_2SO_4 addition to pH 4.5. In some wells, close to sources of alkaline recharge, it was necessary to filter samples for titration to remove particulate carbonates.

For both well and spring samples, total acidities were calculated using the analytical results for principal metals (Fe, Mn, and Al), under the reasonable assumption that the large majority of both Fe and Mn are present in reduced form. Calculated acidities were used in preference to titrated acidities, which are subject to operator error and must be done immediately in the field. With square brackets indicating millimolar concentrations, acidity (in hydrogen-ion milliequivalents/L) is calculated as:

1)

under the assumption that both iron and manganese in spring discharge occur dominantly in reduced form. The value of (1) may be converted from hydrogen-ion equivalents to mg/L as $CaCO_3$ by multiplying by 50. The calculated value neglects acidities from Zn, Pb, and other trace metals, which were thought to be of minor concentration.

Installation of Recharge Structures

Four trenches (T1, T2, T3, and T4) were installed over the Y aquifer to allow induced recharge of alkaline fluids. The trenches employed different designs, construction technique, and locations.

Trench T1 was installed in January 1998 using a D6 dozer. It is 10 feet wide, less than 2 feet deep, and about 800 feet long. It is gently inclined east from Lime Handling Area A (near well Y20) to the T1 pond. The recharge approach was to slake lime in treated water from Pond 13 at Handling Area A, then allow this slurry to gradually infiltrate while flowing at moderate velocity along T1. A flow rate of about 1200 L/min was employed. About 14 tons of lime were slurried at a time. Slurry that did not infiltrate into the trench was allowed to overflow to the T1 pond at the end of the trench. Both trench and pond lie in the central portion of the pond, and so it was hypothesized that target springs might include any of those on the site.

Trench T2 was installed in April 1998, also with a D6-dozer. It was about 6 foot deep and 100 feet long by 20 feet wide and lies on level ground near well Y22. The injection approach was to fill the trench with lime slurry mixed at Handling Area B using treated water from Pond 13. Target springs were P00, P01, P02, and P03. A flow rate of about 1200 L/min was used, but with much less lime (4 tons at a time) because the rate of leakage from T2 was slow. After an early series of slurries (Figure 3), a large mass of uninfiltrated lime, perhaps half or more of that applied, had started to occlude the bottom of the trench. Therefore, T2 applications were suspended and the trench re-excavated using a long-reach excavator to about 8 feet depth. Thereafter, the trench was used again with 4 ton dosages with higher leakage rate and better success.

Trench T3 was installed in November 1998. It is about 16 feet deep by 270 feet long by 40 feet wide and, unlike T2, was initially dug with a long-reach excavator. Its location is about 300 feet upgradient of target

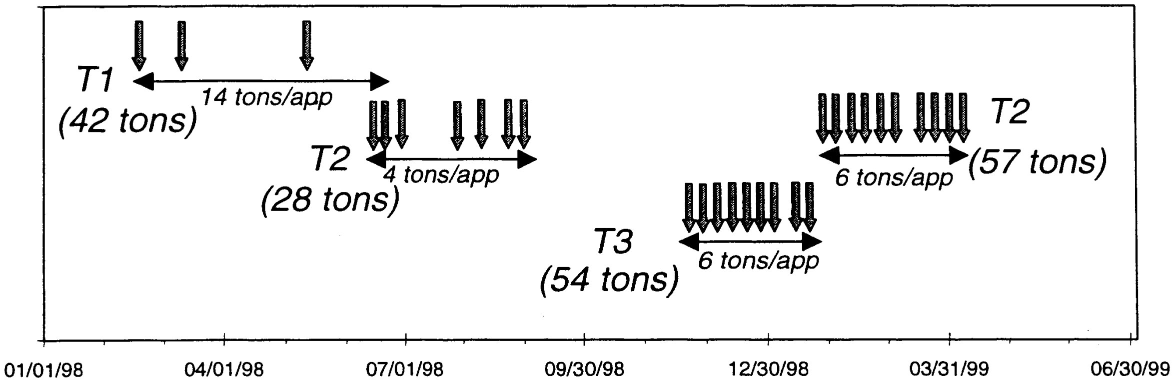


Figure 3. Experimental matrix for alkaline recharge application in Y aquifer trenches.

springs P01, P02, P03, and P00. Its orientation is parallel to the spring line and follows the slope contour. It was filled with alkaline slurry mixed at Handling Area C using treated water from Pond 13.

The alkaline material employed for recharge was fine-grained "waste lime", mainly lime hydrate ($CaOH_2$, the mineral portlandite) and calcium oxide (CaO) with minor calcite ($CaCO_3$) and insoluble matter. The product was obtained from a lime plant in Germany Valley, WV, where it is collected as discards from conveyor and kiln cleanings. Dominantly white and very fine-grained, it slakes easily when mixed with water. During outdoor storage, it remains loose and powdery within piles covered by an outer crust <10 cm thick of hardened lime and calcite, formed by exposure to air and moisture.

Figure 3 shows the matrix of lime applications at the three trenches. A total mass of about 177 tons of lime was applied in three sets of experiments: one at the shallow T1 trench and pond (42 tons); one at the intermediate-depth T2 trench (73 tons, in two stages); and one at the deep T3 trench closest to the springs (54 tons). The lime was slurried at intervals of from 1 to 6 weeks. Volumes of lime applied were estimated by counting backhoe bucket loads and are likely accurate to _15%. There were considerable inefficiencies in lime infiltration at T1 and the initial T2 trench, with surface lime accumulation rather than infiltration. Here, as much as 50% of the lime applied did not reach the subsurface. However, both T3 and the re-excavated T2 accepted lime readily and completely through coarse macropores, with essentially 100% of the lime applied infiltrating to the subsurface.

Results

Groundwater Flow

Groundwater flow within the Y aquifer was described using numerical modeling techniques. The purpose was to determine steady-state flow directions and fluxes for the Y aquifer. Although a brief review is given here, full description of model methodology and calibration is given in Daly (1998).

To estimate the steady-state water balance, flows from springs were averaged over the 12 months of 1997 to give annual average recharge rate to the water table. These are as follows:

P00	0.1	L/min (considered ephemeral)
P01	99.2	
P02	7.5	
P03	80.9	
MA1	53.9	
MA2	24.5	

The recharge was distributed in three zones (Figure 4): (1) steep perimeter slopes (zero); (2) the upper surface of the aquifer (a “normal” rate of 85.8 cm/year) and (3) the T1 pond (14.6 times the “normal” rate). The pond recharge rate accounts for 1997 sludge-disposal loadings. The aquitard beneath the aquifer, interpolated from drilling data (Figure 5), slopes from east (the highwall) to west (springs P00, P01, P02, and P03). Spring fluxes were simulated using constant-head cells set to 1.5 meters above the pit floor outcrop elevation. Hydraulic conductivity (K) values were varied in zones to yield calibration with known surveyed hydraulic heads at wells, as well as agreement with average springflows (within ±5%). The heterogeneous distribution of K zones was implemented to reflect a series of preferred flow paths (PFP’s), connecting springs to the main body of the aquifer and focusing discharge in these areas. The deterministic pattern of zones (Figure 6) is neither unique nor precisely known, but is consistent with both calibration fluxes and heads as well as with observations of solute transport around the T1 sludge disposal pond (Daly, 1998).

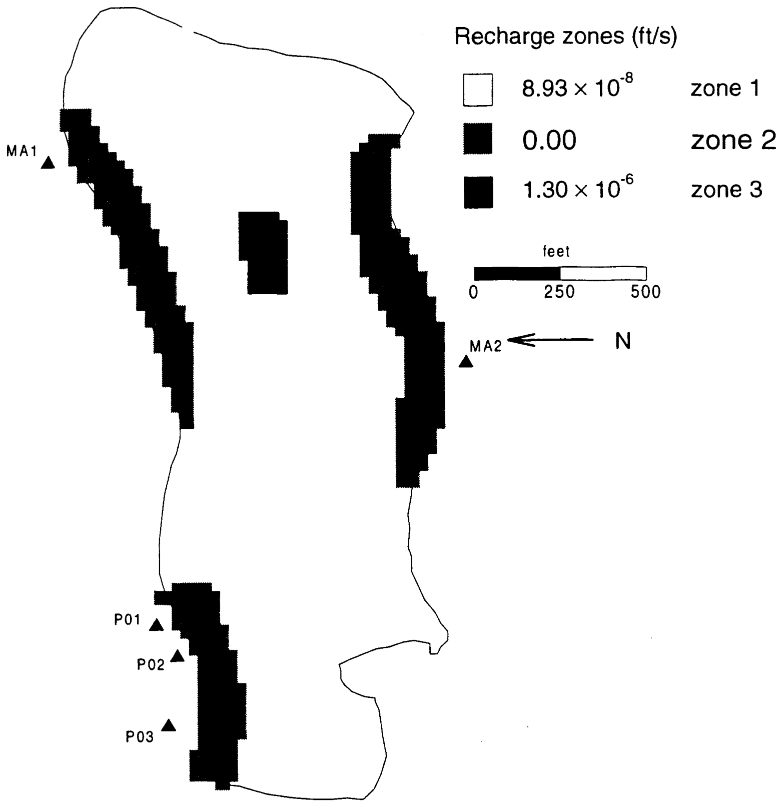


Figure 4. Recharge zones (values in ft/day) used for steady-state flow model of the Y aquifer.

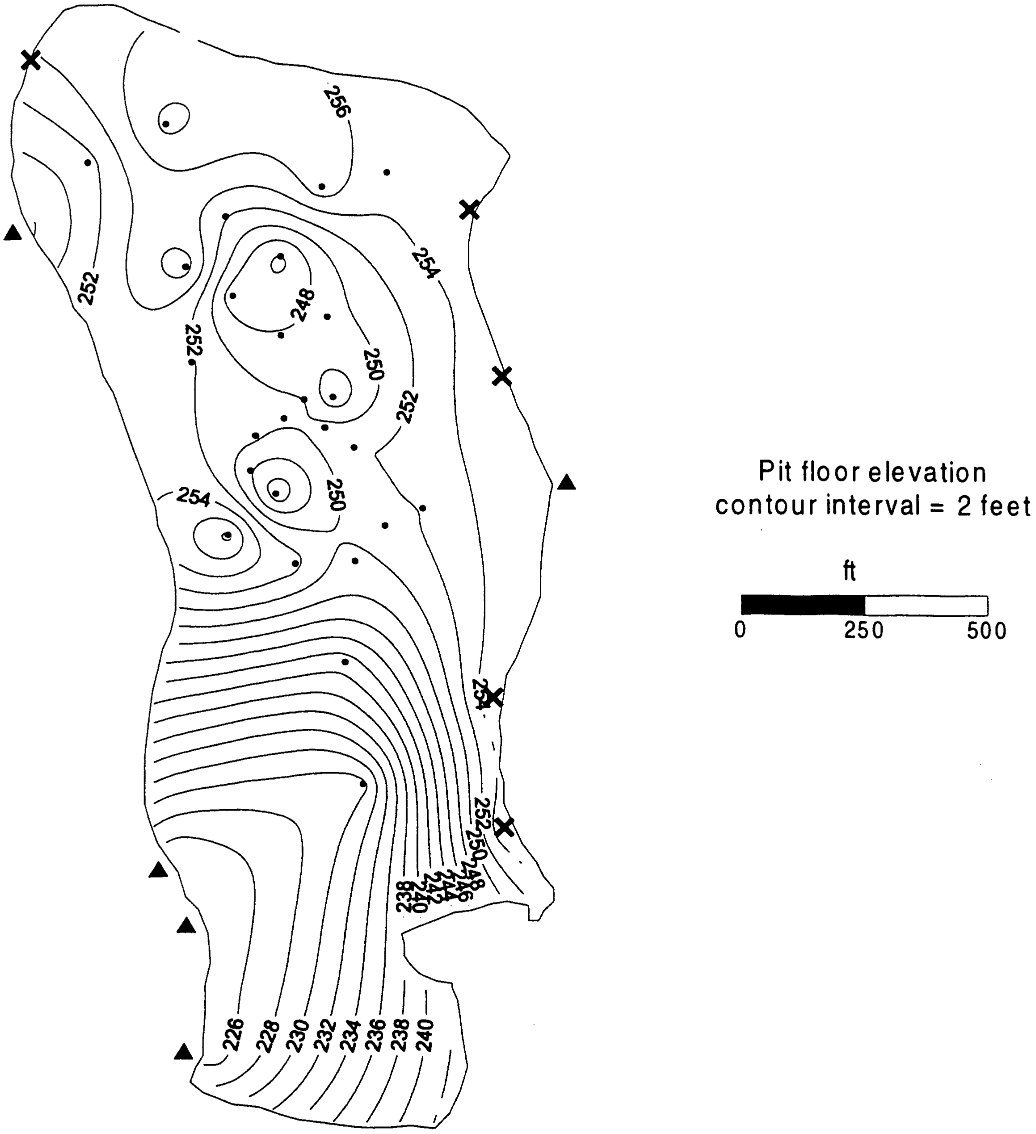


Figure 5. Structure contours, in feet, of the pit floor beneath the Y aquifer

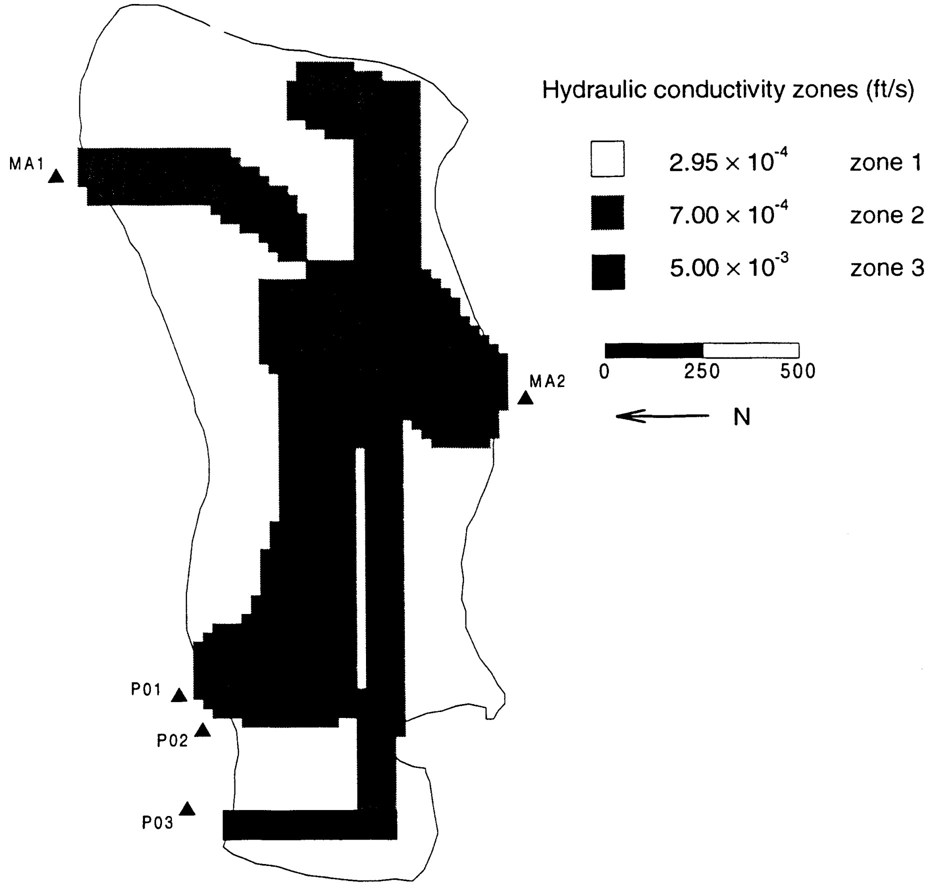


Figure 6. Hydraulic conductivity zones (values in feet/day) used for steady-state flow model of the Y aquifer.

Simulation results are shown for hydraulic head (Figure 7) and advective pathlines (Figure 8). Pathlines were calculated from the steady-state heads using backward particle tracking from each spring, assigning particles in proportion to spring discharge. Each pathline pair brackets an equal flux of 110 L/min.

The modeled potentiometric surface (Figure 7) suggests that the recharge pond forms a central mound within the west-dipping flow field, induced by the pit floor slope. Although closer in space to the T1 pond than the P springs, the catchments of both MA1 and MA2 are located primarily upgradient of the pond, with most flowlines originating at or near the highwall (Figure 8). Most pathlines originating at the pond are turned by the bedrock slope downdip to the P springs and do not reach MA1 or MA2.

The model results suggest that, despite the proximity of MA1 and MA2 to the T1 pond, most flow from the pond is likely to be directed west to the P springs, in the direction of rock dip. The model infers that P00, P01, P02, and P03 receive their recharge principally from between the T1 pond and the T3 trench.

These results should be qualified, as they represent the results of a simplified steady-state simulation employing average recharge conditions. In reality, recharge is episodic and not uniform in time; therefore, the hydraulic head and flow patterns may at times differ substantially from that shown in Figures 7 and 8. During wet periods, flow gradients may steepen and cause increased flow. During periods of filling of the T1 pond or of lime trenches T2 and T3, increases and/or reversals in flow are likely to occur. Nonetheless, the steady-state flow model is useful for understanding the general hydrogeology of the spoil and, in particular, its spring catchments.

Chemistry Response of Springs to Lime Slurry

Chemistry analyses for springs MA1 and MA2 are presented for Fe, Al, and Na (Figure 9) and for acidity and pH (Figure 10). Similar plots for springs P00, P01, P02, and P03 are shown in Figures 11 and 12, respectively. The period prior to February 8, 1998 is baseline for MA1 and MA2, prior to T1 operation. The period prior to 8/98 is baseline for P00, P01, P02, and P03, prior to T2 and T3 operation.

The T1 experiment.

The T1 experiment, applied from 2/99 to 5/99, injected lime into the central portion of the aquifer, closest to MA1 and MA2, which could have only been influenced by T1 slurry. Prior to lime infiltration, spring MA1 displayed anarrow baseline pH range of 3.3 to 3.6 and acidity of 160-170 mg/L. The most abundant metal (in equivalent units) was Al (17-23 mg/L), followed by Fe (9-22 mg/L). Na concentrations were low, from 6 to 8 mg/L. The chemistry of MA1 was the most uniform of all the springs, both before and after alkaline injection. Spring MA2 had a baseline pH of 3.0 to 3.5 and acidity of 180-416 mg/L. The most abundant metal was also Al (25-57 mg/L), with low baseline Fe (2-13 mg/L) and Na (1-5 mg/L) concentrations as at MA1, but MA2 showed more seasonable variability than at MA1, particularly in Fe concentrations.

Response after initial T1 infiltration (2/9/98) gave little evidence that either lime slurry or Na-rich water arrived at either MA1 or MA2 (Figures 9, 10). At MA1, both pH (2.9 to 3.2) and acidity (145 to 190 mg/L) remained relatively constant, with periods of only minor increases in Na concentration, to as high as 13 mg/L. At T2, while metal acidity levels ranged in the first half of 1999 from 120-280 mg/L and were somewhat lower than in 1998 (180-350), this difference is not easily be attributed to T1 leakage given the low Na concentrations. It is impossible to rule out that pond leakage influenced MA2, but any effects were minor and spread over a considerable period of time.

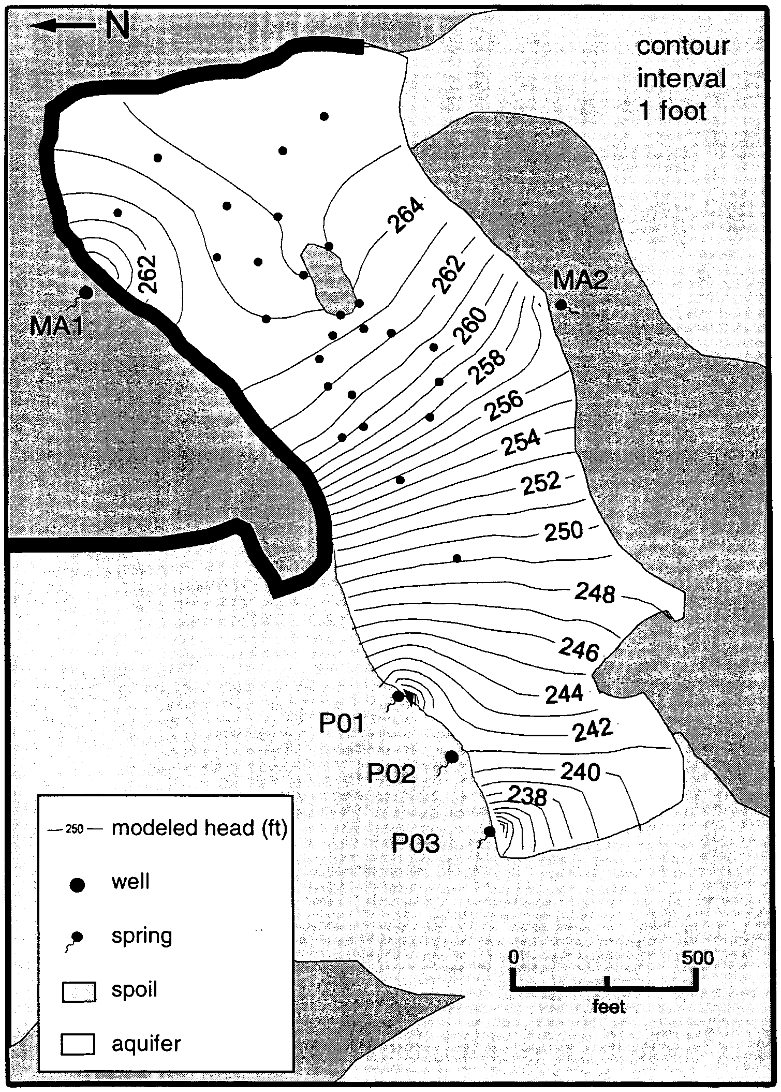


Figure 7. Potentiometric contours, in feet, of groundwater in the Y aquifer, based on simulated average steady-state flow conditions from 12/96 to 12/97.

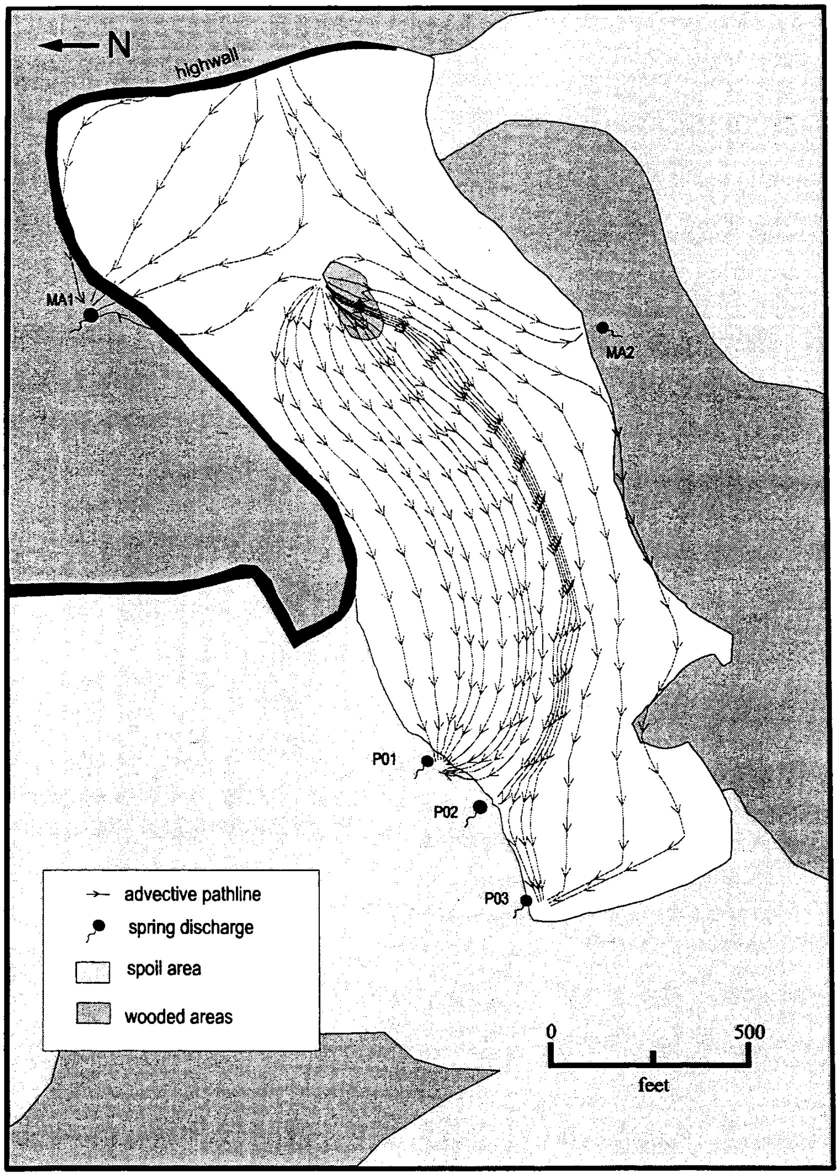


Figure 8. Advective pathlines based on the flow model of Figure 5. Flux between pathlines is 110 liters/minute.

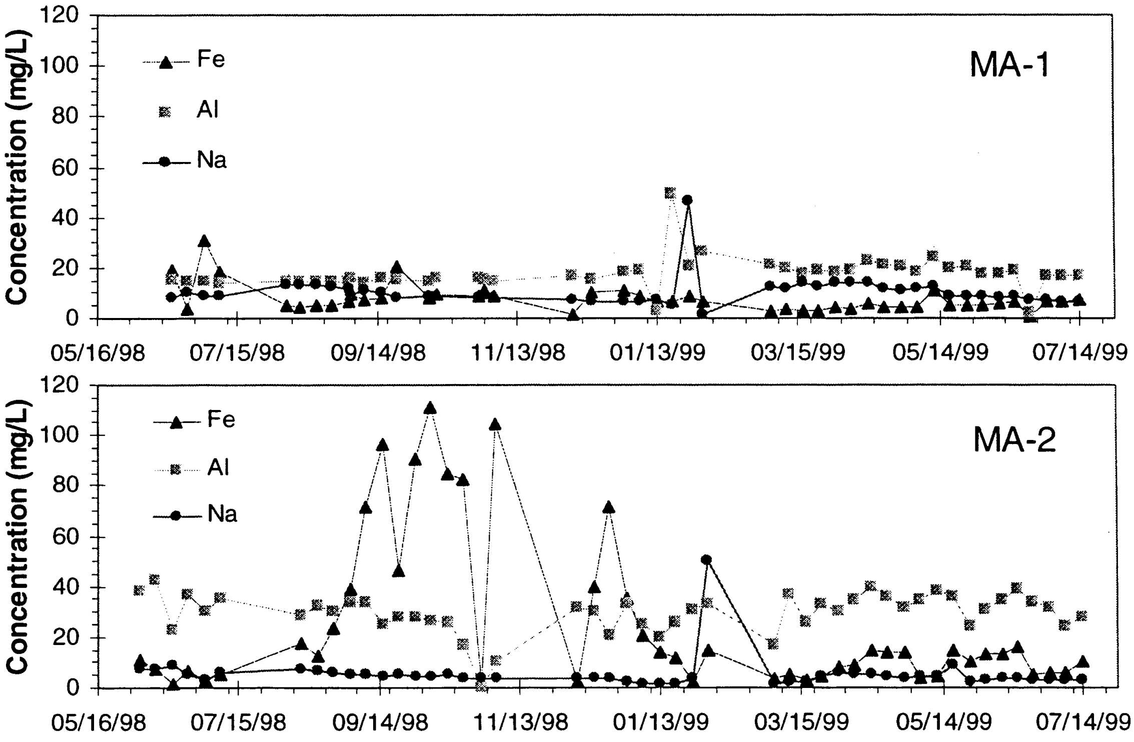


Figure 9. Concentrations of total Fe, Al, and Na for springs MA1 and MA2..

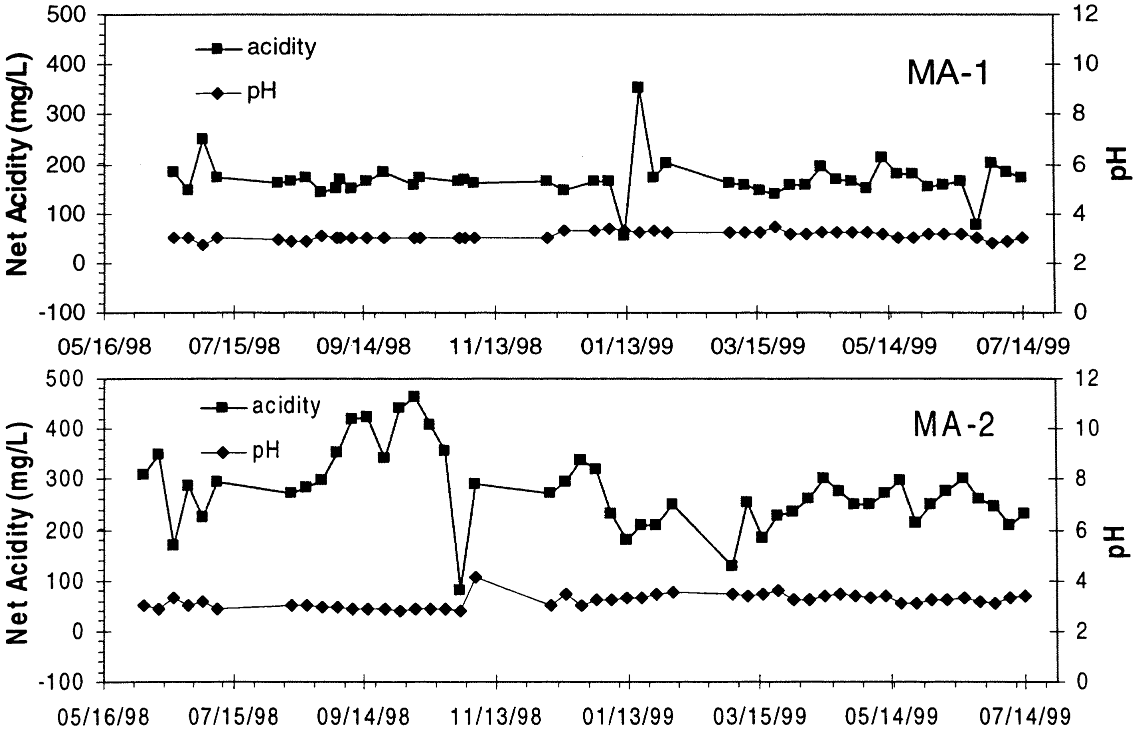


Figure 10. Concentrations of pH and acidity for springs MA1 and MA2..

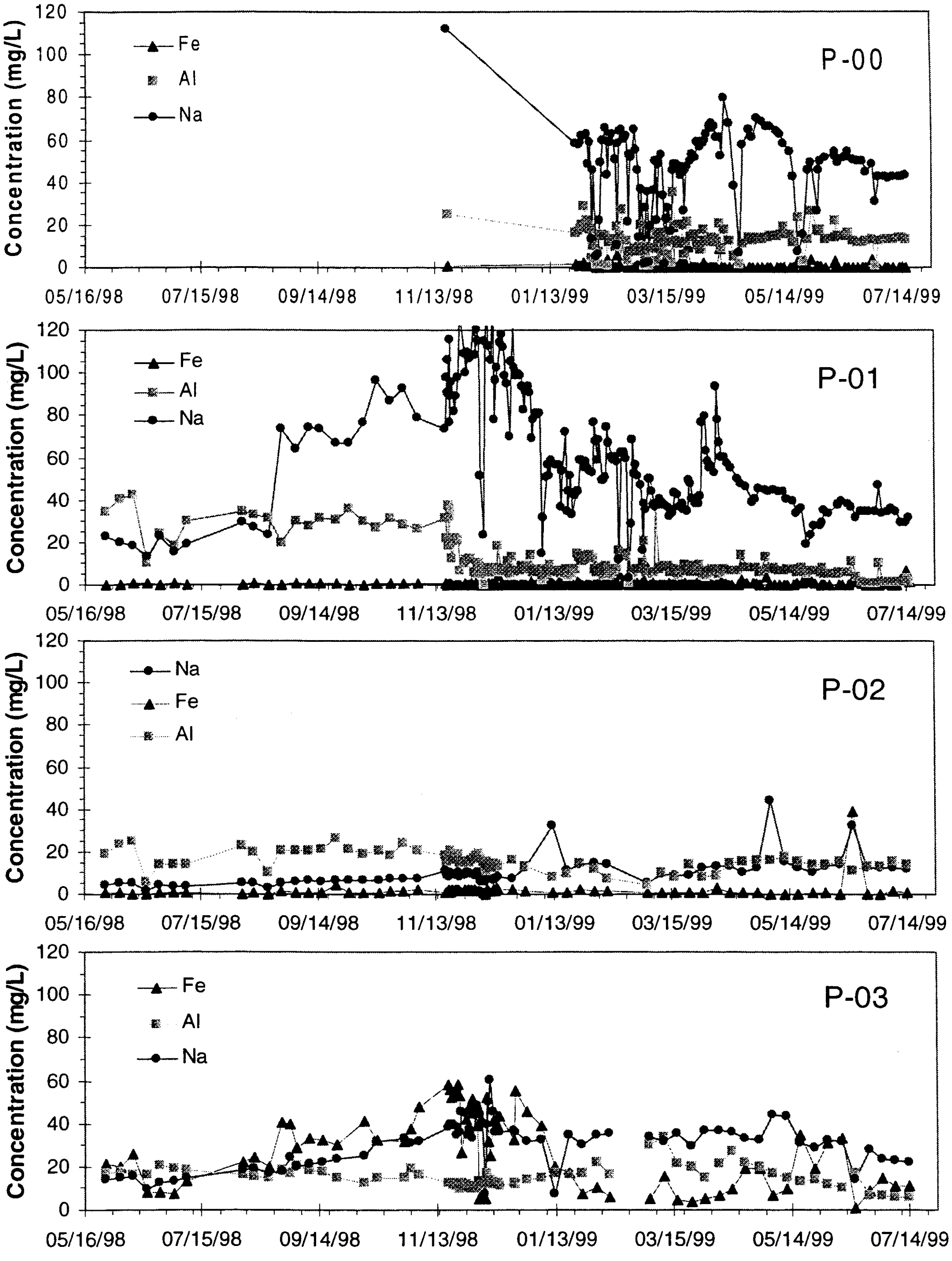


Figure 11. Concentrations of total Fe, Al, and Na for springs P00, P01, P02, and P03..

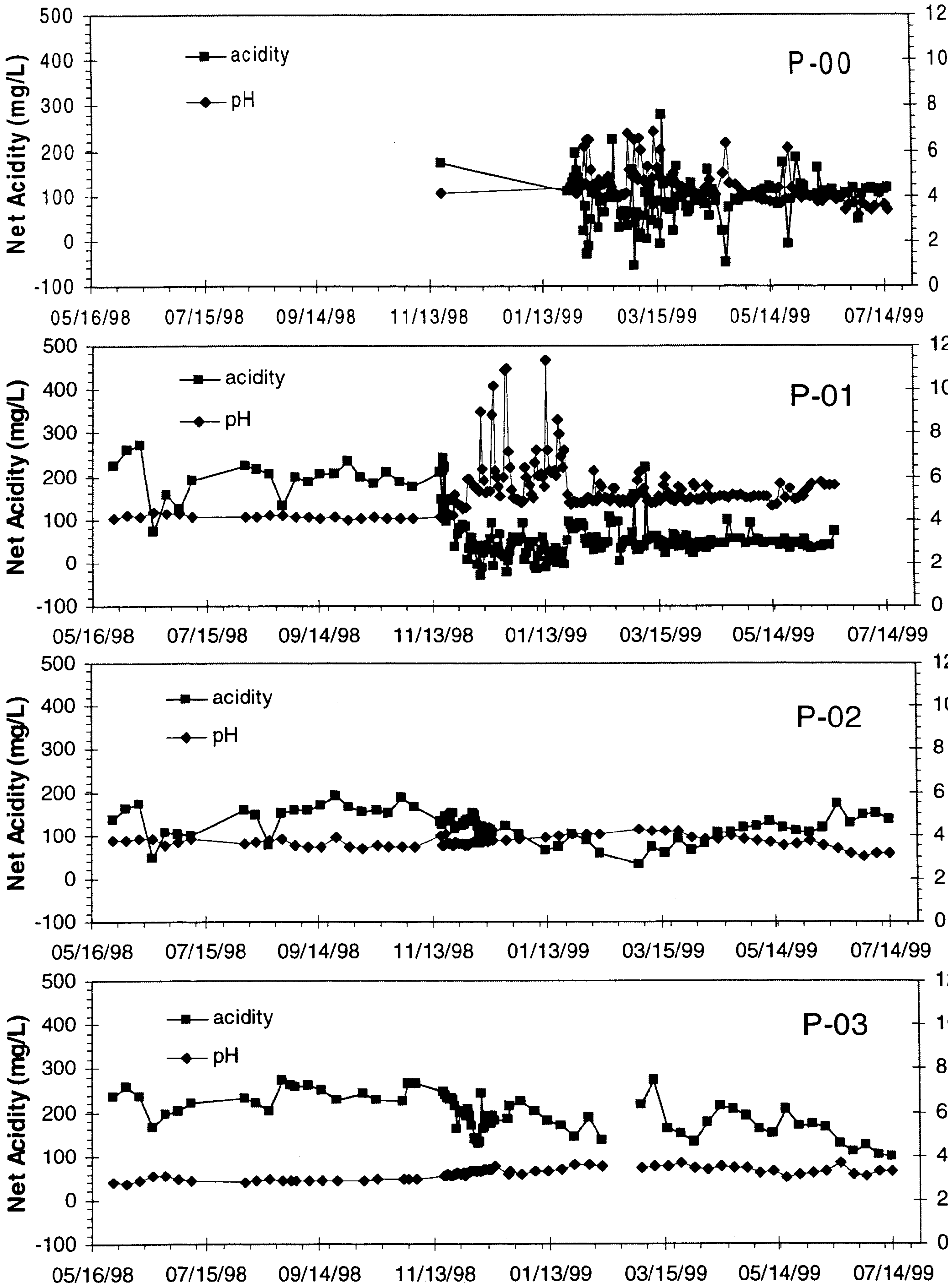


Figure 12. Concentrations of pH and acidity for springs P00, P01, P02, and P03.

This leaves the question of the fate of the infiltrated lime. Figure 13 shows a plot of pH during and after T1 was initiated. These two are about 3 months apart (11/97 and 2/98). Evident is a strong pattern of neutralization, focused on the T1 pond but with an elongate and irregular pattern parallel to rock dip. A similar pattern was displayed for Na. The influence of T1 operation on the extent of the neutralized zone was minor. pH rose slightly in wells immediately surrounding the T1 pond from 2/98 to 9/98, to as high as 8.9 in a few cases, but the spatial extent of this neutralization pattern did not appreciably vary. It may be inferred that much of the neutralized groundwater surrounding the pond resulted from disposal of alkaline sludge into the pond prior to the T1 experiment, and that the focus of this discharge was not MA1 or MA2, due to prevailing groundwater transport conditions. The neutralization zone was made slightly more alkaline, but only moderately increased in pH, by lime slurry injection into what was effectively a non-acidic portion of the aquifer.

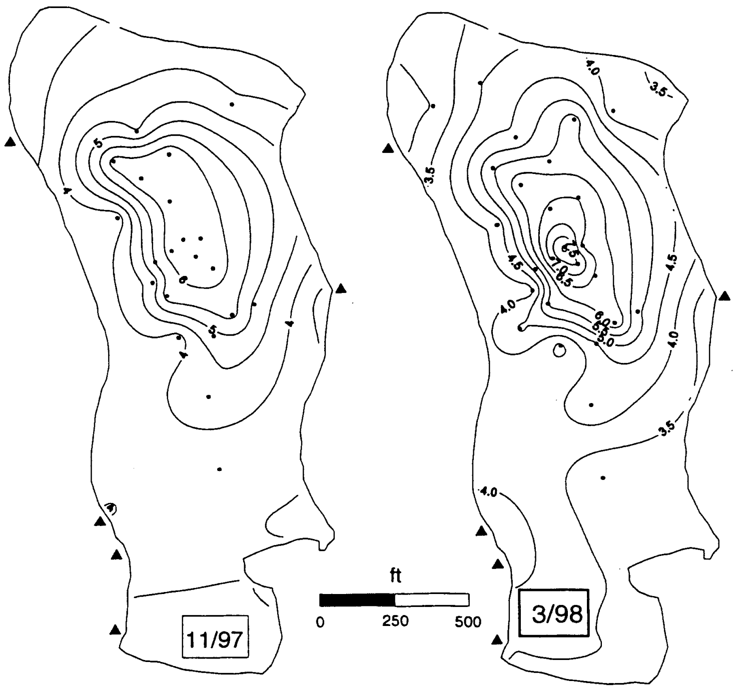
The T2 and T3 experiments.

The T2 and T3 trenches were, based on the results of the numerical model, well down-gradient from the MA1 and MA2 catchments and could have only influenced the other springs. Springs P01, P02, and P03 grossly resembled each other in baseline pH and acidity. P2 (pH 3.7 to 4.4), P03 (3.25 to 3.9), and P01 (3.86 to 4.39) all lacked alkalinity in baseline and were similar in acidity (190 to 300 mg/L; 45 to 160 mg/L; and 150 to 230 mg/L, respectively). P01 and P02 both showed low Fe (< 1.5 mg/L in both springs) and much higher Al. For P-03, on the other hand, the two metals are more equal in concentration during baseline, suggesting more reduced aquifer conditions and/or higher iron loadings. Baseline Na concentrations were 10 to 20 mg/L for P01 and P03 and <10 mg/L for P02. The highest baseline values were 23 mg/L for all springs. Few data were available for P00 in baseline due to its very low flow.

Both T2 and T3, as well as T1, are upgradient of these springs and should have influenced their chemistry. Na concentrations indicating pond or trench leakage reached all 4 springs (Figure 11), most pronounced at P00 (up to 70 mg/L Na) and P01 (up to 170 mg/L Na). Values were also above baseline for P02 (up to 40 mg/L) and P03 (up to 50 mg/L). The pronounced increase in Na was first noted on 8/6/98 and was largest in magnitude for P01.

At P01, acidity dropped to between 120 and 200 mg/L in early June, attributed to the operation of T2. It dropped again to between –40 (negative values indicate alkalinity) and +60 about 8 days following 11/18/98, the beginning of T3 injections. Chemical response to T3, especially, is pronounced. Fe remained <0.4 mg/L, but Al dropped to between 5 and 10 mg/L, and Mn concentrations to <6 mg/L. After the initial front of neutralization arrived, an abrupt increase in pH and alkalinity occurred within about 1 day after each weekly injection; this lag time was the delay in the arrival of increased pressure and flow at the spring. Spring P01 seems to continue to respond to the first few loadings of T2 from 2/99 to 4/99, especially in terms of flow (Figure 14). However, both pH (4.8-5.3, rising to 5.7 at the end) and acidity (20-70) remain rather uniform between the final T3 injection (1/20/99) and the end of observation (7/14/99). It is clear that most of the discharge from T2 focused on P01, but the level of neutralization of P01 discharge was not substantially increased by T2.

The flow at the P01 spring was very sensitive to both T3 and the second series of T2 injections, with flow increasing up to a factor of 5 from the antecedent level. Although no springflow increases of note were observed at P02 and P03, they also appeared to have received some influence from the T3 test. Na concentrations observed at P02 increase at the same time (but much less in magnitude) in comparison to P01. Both P02 and P03 declined in acidity compared to baseline values (Figure 12), but much less than at P-01. These covariations in time indicate that there may be some lateral (i.e., perpendicular to pit-floor dip) hydraulic connection within the aquifer immediately upgradient of springs.



pH
contour interval = 0.5 units

Figure 13. Spatial distribution of pH around the T1 pond before and after T1 injection.

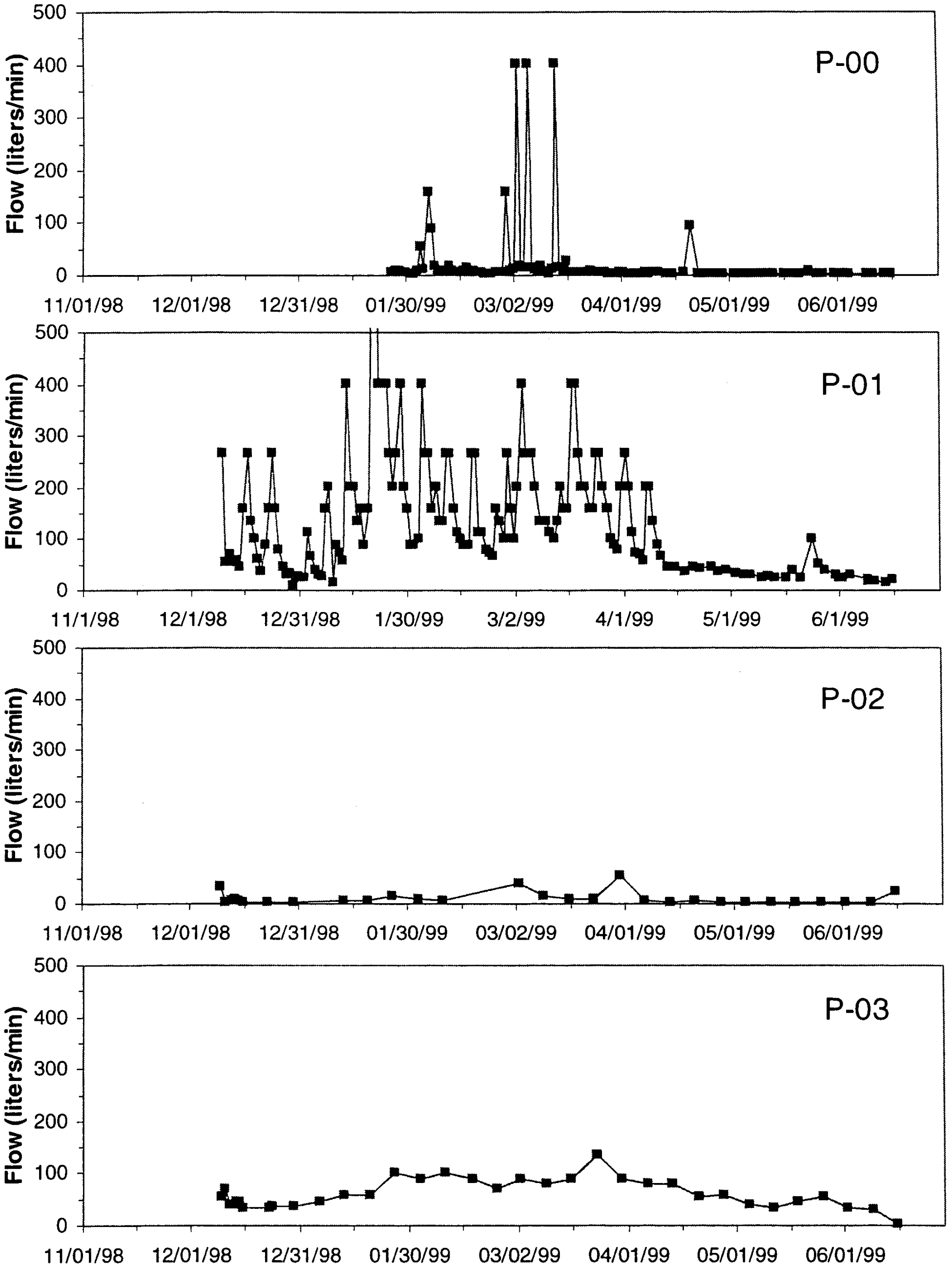


Figure 14. Comparisons of flows for springs P00, P01, P02, and P03.

Hydraulic Observations at the P Springs

Springflows for the P springs are shown in Figure 14, taken during the weekly injection of slurry into T3 and T2 from 11/98 to 6/99. These flow hydrographs suggest that

- springs P03 and P01 had much higher flows at this time compared to P00 and P02 (consistent with the groundwater flow model)
- springs P00 and P01 responded to lime injection at both T3 and T2 with “flashy” flow behavior, while P02 and P03 did not

The response pattern of P01 and P00 are subtly different. P01 clearly responded in flow sensitively to all T3 and T2 injections, and in fact P01 flow is similarly sensitive to injection of both trenches. P01 also displays a characteristic 5-day “lag time” for flows to recede to antecedent levels. At P00, similar “flashy” behavior is observed, but with a much shorter decay time (<1 day) and inconsistently (some injections are missed). It appears that the increased P00 flows return to “normal” levels, within a 24-hour period. In addition, the “base flow” of P01 is increased by the induced recharge from trenches, while at P00 it is unaffected. These observations suggest that flow is directed predominantly towards P01 – the spring with much higher flow – from either trench at all times. On the other hand, T2 injection appears to influence P00 at some times, but not others. This indicates that flow hydraulics leading to the two springs are different and that P01 is a “dominant spring” within this PFP network.

In addition, neither P02 nor P03 are sensitive in flow to T3 or T2. Most of the flow is intercepted by P01, from both trenches, and not allowed by go further downgradient. However, there is some indication of chemical effects related to T3 operation at P03 and P02.

Comparison of Pre-neutralization and Post-neutralization Chemistry at P-01

The chemistry of spring P-01 water between "pre-neutralization" chemistry (8/14/97), that during T3 trench filling (12/25/98), and that on 6/14/99, 160 days after T3 operation ceased, may be compared (Table 1). The 12/98 sample was taken 1 day following a slurry injection and is thought to represent the highest level of neutralization attained. The 6/99 sample is characteristic of stable post-injection chemistry observed over the 5 month Phase III monitoring.

The most significant reductions were in Al, Mn, and acidity, with increases in Na and Ca. There were 90% reductions in Mn and Al, the major sources of acidity, during T3 operation, decreasing to 80% reduction by the end of monitoring. The Al concentrations over most of the post-neutralization period ranged from 2 to 18 mg/L and averaged 7.9; in baseline they averaged 41 mg/L. Similarly, average net acidity was 43.3 mg/L, down from 258.8 in baseline.

Not all of the residual Al represents acidity; calculated values were uncorrected for aluminum complexes, which are quantitatively important above a pH of 5.2 or so. At a pH of 6, aluminum is substantially complexed by hydroxide and only about 20% of the total Al represents aluminum ion. Within the limit of uncertainty in the analytical data, the water from P01 was largely net alkaline much of the period from 11/26/98 till the trench became inactive on 1/20/99. Thereafter, the net acidity increased to a reasonably stable level between 10 and 70 mg/L, and, although there were several “spikes”, is approximately net alkaline.

Spring P01 is inferred to have received substantial alkalinity from T3, as well as from T2 leakage. The Na peaks in response to T2 use are interpreted to be related to trench operation on 6/12 to 7/13, then again from 8/21 to 10/9. These are inferred to have caused increases in Na concentrations beginning on 8/26/98, a lag of about 74 days from 6/12/98 and another on 10/7/98, a lag of 49 days.

Table 1 **Comparison of spring P-01 chemistry between baseline, treatment, and post-treatment.**

	field		net acidity	Na	K	Si	Fe	Mn	Al	Ca	Mg	alkalinity
spring	**date**	**pH**	**mg/l ***	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/L**	**mg/L ***
P-01	08/14/97	3.86	390	13.4	5.3	9.4	0.9	25.4	60.3	305	169	0
P-01	12/22/98	7.13	2	102	8.3	1.2	0.1	1.9	6.2	419	41	36
P-01	6/16/99	5.59	73	36.8	5.3	5.3	1.7	7.4	11.0	373	163	5.0

* indicates calculated as $CaCO_3$

Acidity Reduction and Lime Utilization Efficiency

Using time-integrated fluxes, calculations may be made regarding neutralization at each spring. Fluxes were calculated for all springs of both “observed acidity” and “neutralized acidity” (baseline minus observed acidity) using measured springflow rates. Fluxes associated with individual samples were integrated over time for each spring using the measured concentration-springflow product between time midpoints separating successive samples. Acidity reduction (AR) attributed to lime recharge was estimated as the ratio of “neutralized acidity” to “total acidity” (neutralized plus observed). Similarly, lime utilization efficiency (LUE) was estimated as neutralized acidity (converted from equivalents to tons of lime, under the simplified assumption that the injected lime was 100% pure portlandite, $Ca(OH)_2$) divided by the amount of lime applied. LUE is the approximate proportion of injected lime that had been consumed. Lime from trench T2 was assigned to P00, under the assumption that only T2 lime was encountered by groundwater flowing to P00. Similarly, lime from T3 was assigned to P01. MA1, MA2, and P03 were influenced only by diffuse alkalinity and showed no pronounced response, and so were not considered.

Table 3 summarizes these results. Substantial acidity reduction was observed for both P00 (74%) and P01 (80%), in response to trenches T3 and T2. Spring P01 is calculated to have consumed approximately 8.1% of the lime injected, much greater than that for P00 (0.5%). While these lime consumption calculations are only crude, they do support that much unreacted lime remains in the aquifer.

DISCUSSION

Method of Recharge Structure Construction

Of the three alkaline injection methods tested, the deep-trench technique (T3, deepened T2) was clearly the most effective. Both T1 (shallow) and T2 (intermediate) trenches left substantial volumes of lime accumulated at the surface or in trench bottoms. A co-factor may be the method of construction. Excavation with a dozer appeared to slightly compacft the bottom of trenches T1 and T2 and cover or restrict large pores.

In contrast, the “re-excavated” T2 accepted water and lime readily, in contract to its performance after dozer excavation. Excavation with a bucket appeared to leave a less compact trench bed, with large open macropores. These appear focal to success of the technique.

Table 2 Calculated acidity reduction and lime-utilization efficiency for springs P00 and P01.

Spring	Primary trench	baseline acidity (pre-11/98) mg/L	actual acidity flux (11-98 to 7-99)	calc. acidity neutralized	acidity reduction (AR)	tons applied (primary trench)	lime use efficiency (LUE)
			---------[tons Ca(OH)2]---------				
P-00	T2	240	0.42	0.15	74%	85	0.5%
P-01	T3	125	4.38	1.11	80%	54	8.1%

Effectiveness at Neutralizing Spring Discharge

While all of the springs except MA-1 showed some degree by influence from Na and/or alkaline fluids, all but P01 and P00 showed minor levels of neutralization. In these cases, lack of effectiveness is ascribed to the groundwater transport characteristics of the flow field and the specific location of trenches.

Substantial neutralization was obtained for P00 and P01. Neutralization of P01 discharge was noteworthy, as its discharge and metal fluxes are about an order of magnitude higher than P00. Both manganese and aluminum were reduced by 80-90% over baseline levels. The effluent water during trench operation was commonly at pH >6.0, approximately net neutral with respect to acidity, and near equilibrium with an aluminum hydroxide phase. This water would be suitable for discharge with only minor polishing employing passive treatment.

In addition, P01 neutralization was persistent long after actual injection to T3 ceased. From 1/20/99 to 6/30/99, Fe averaged 0.5, Mn 5.2, Al 7.9 mg/L, pH 5.21, and net acidity 46 mg/L. For baseline, these were Fe 0.5, Mn 14.8, Al 34 mg/L, pH 4.16, and net acidity 220 mg/L. The spring displayed a few minor “breakouts” of acidic water but in general fluctuated little about this mean value of acidity. The longer-term buffering of water chemistry at P01 is ascribed to contacting of acidic water with lime within the saturated PFP connecting T3 to P01. These results suggest that, long after the active treatment has been suspended, macropore-injected lime may continue to be active in neutralizing metals and removing them prior to spring discharge.

At spring P01, there was some indication of precipitates of calcite forming around the spring mouth, observed after trench loading periods. However, no indication of metal precipitates was observed. That is, no sludge formed within the aquifer discharged to the surface via springflow.

Conclusions

Alkaline recharge experiments involving lime were performed at a West Virginia surface-mine spoil. Three recharge trenches, of different depths (shallow intermediate, and deep) and construction method were installed and injected with slurries of waste lime (portlandite) admixed with treated (pH>8) acid mine drainage. The slurries were pumped into the recharge trenches at intervals of 1-4 weeks in an attempt to induce alkaline spring discharge.

At the end of the project, water from the only neutralized spring (P01) contained very low iron (<0.5 mg/L) and low Mn and Al (<10 mg/L). The water was pH 5.2-6.1, had up to 15 mg/L dissolved alkalinity, and had 40-70 mg/L net acidity, decreased from a baseline value of 280 mg/L. This water chemistry was persistent for at least 5 months after the trench was operated, suggesting a residual effect of injected lime. This water would be suitable for discharge after minor passive treatment to polish metals.

The following conclusions regarding alkaline recharge may be drawn.

_ Deep-trenching (>15 feet) using an excavator yielded most efficient delivery of lime slurries to the water-table aquifer. The interpreted mechanism is macropore recharge, allowing transport of entrained lime solids to below the water table.

_ alkaline recharge was least successful in the setting far from the target springs, due to lower flow velocities in this area and to the tendency to overapply lime and force calcite to precipitate. While groundwater was neutralized locally, no springs were neutralized.

_ short-term neutralization in these experiments was caused by water used to slurry the lime, yielding net-alkaline water in spring P01 when injection was in progress.

_ long-term neutralization was also accomplished in this spring, by a mechanism involving reaction of acidic aquifer water within a PFP leading to the spring. Spring discharge averaged pH 5.6 and 46 mg/L net acidity, a 80% reduction from baseline levels. Persistence was still continuing 170 days after T3 injection ceased.

_ alkaline recharge was successful only where substantial macropore infiltration could be accomplished, by excavation into coarse rubbly spoil. Introduction of suspended lime at high velocity into macropores is critical, as long-term alkalinity is derived from particulate lime below the water table. Macropore recharge also prevents lime sediment from sealing recharge structures.

All three trenches, both near and far from the springs, allowed some leakage but only the deep trench closest to the springs was able to fully neutralize any spring to an alkaline condition. All trenches were not able to direct recharge to all springs, due to location within the groundwater flow system. Future remediation of springs using this method may be feasible only if the location of the trench is appropriate to direct recharge to specific springs. The characteristics of the groundwater flow system, not convenience, should be the dominant factor in determining recharge structure location.

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