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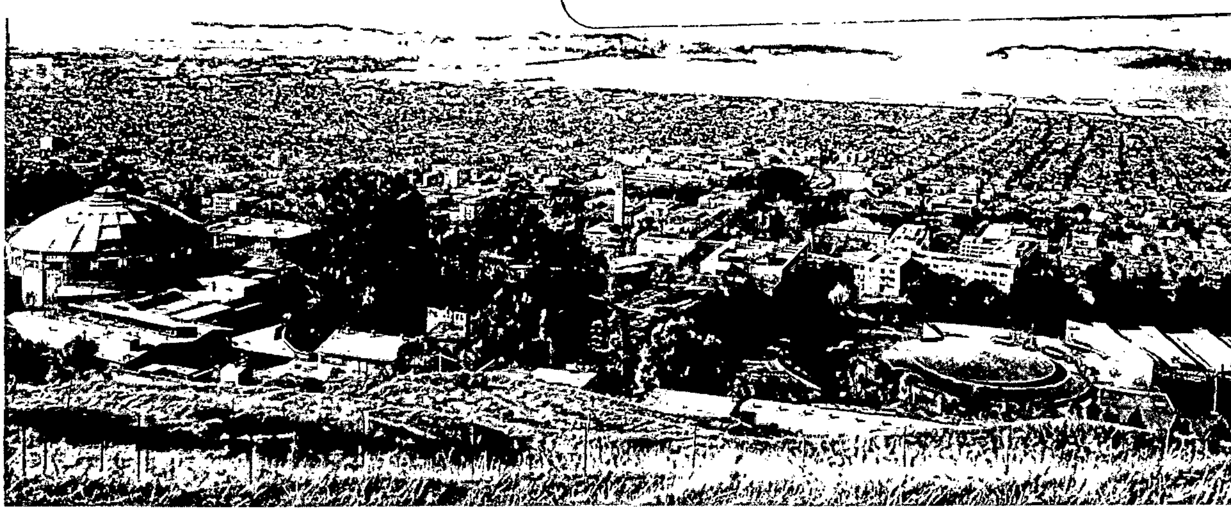

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DISCLAIMER

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by
T. Tokunaga and T.N. Narasimhan*

ABSTRACT

Field and laboratory hydrologic studies of two inactive uranium mill tailings piles are presented. The Riverton, Wyoming site is in close proximity to the water table, while the Maybell, Colorado site represents the contrasting case of the local water table being far below the tailings pile. Field studies included monitoring of hydraulic head profiles of the piles with tensiometers and piezometers, and infiltration tests. Laboratory tests on core samples from the tailings and soil cover included saturated and unsaturated hydraulic conductivity measurements, saturation versus matric head measurements, particle-size analysis, as well as determination of bulk densities and porosities.

The tensiometer data indicate that the major portion of the tailings water at both piles exists under near steady-state unsaturated conditions with flow downward towards the water table. The zero-flux surface in these regions is within a meter of the upper surface of the tailings. A case of upward flow from the aquifer through the tailings was also observed in the thinnest, eastern portion of the Riverton tailings.

Combined field data and laboratory results lead to an estimated steady-state downward flow of tailings water in a typical region of the Riverton tailings in the range of 10^{-10} m$\cdot$s^{-1} to 10^{-9} m$\cdot$s^{-1}. This is equivalent to about 3 x 10^{-3}m$\cdot$yr^{-1} to 3 x 10^{-2}m$\cdot$yr^{-1}, a small fraction of the local mean annual precipitation (2.5 x 10^{-1} m$\cdot$yr^{-1}). This suggests that the bulk of the precipitation input at the Riverton tailings is lost by evapotranspiration within the upper meter of soil cover and tailings.

INTRODUCTION

Evaluation of contaminant transport problems associated with inactive uranium mill tailings piles requires information on a number of their hydrologic features. Knowledge of hydraulic head profiles, hydraulic conductivities, saturation vs. matric head relations, and porosities of the tailings and soil cover is essential in characterizing the water flow patterns within the tailings.

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This study is directed towards measuring the aforementioned parameters of two characteristic inactive uranium mill tailings piles under the Uranium Mill Tailings Remedial Action Program (UMTRA) Program. The Riverton, Wyoming tailings pile represents the shallow aquifer case while the Maybell, Colorado tailings pile represents the deep water table condition. These two sites are described in detail in a previous report (Narasimhan, et al., 1982). Both field measurements and laboratory experiments are used to obtain the required hydrologic information.

This paper presents only a portion of the test results. Most of the work is still in progress and will appear in future reports.

Results of this study are to be used in two general ways. First, simple estimates of flux densities of tailings water can be made directly from measured hydraulic head gradients and the associated hydraulic conductivities. An example of such a calculation will be provided. A second, more sophisticated use involves applying the measured hydraulic parameters to computer flow simulation programs. A wide variety of flow conditions can then be efficiently modelled and further analyzed in the context of chemical transport. The ultimate goal of this study is to evaluate the nature of the contaminant potential of the piles with sufficient detail so that appropriate remedial measures can be designed and implemented under the UMTRA Program.

FIELD METHODS

The Riverton tailings pile is primarily monitored at three sites, referred to as RA, RB, and RC (Figure 1). Site RA is located in the thickest portion of the pile with over 7m of tailings. Tensiometers at site RA are placed at depths ranging from 0.15m to 6.1m below the upper tailings surface. The centrally located site RB is equipped with tensiometers over depths ranging from 0.15m to 4.55m below the 0.30m thick soil cover. The 4.50m depth at site RB corresponds to the original soil surface. The shallow tailings at site RC are monitored with tensiometers at depths ranging from 0.15m to 1.7m below the soil cover surface. The original soil surface at RC is found at a depth of 1.0m. Tensiometer depth intervals at Riverton are 0.15m in the upper tailings, 0.30m at intermediate depths, and 0.60m at depths greater than 2m. All tensiometers at a given site are encircled by a ring for infiltration tests. Depths to the water table at sites RA and RB are continuously recorded through observation wells. An observation well at site RC and a number of piezometers on and around the tailings piles provide other monitoring locations.

Infiltration tests at sites RA, RB, and RC were conducted during the first year of this study. Single 0.91m diameter rings were embedded into the upper tailings surface (sites RA and RB) or into the soil cover (site RC). A column of water maintained within the rings helped maintain constant potential boundary conditions. Water was ponded at the surfaces of sites RA and RB to a head of 0.10m, while at RC the surface head was kept at 0.03m. Both cumulative infiltration and tensiometer responses were recorded at all three sites.

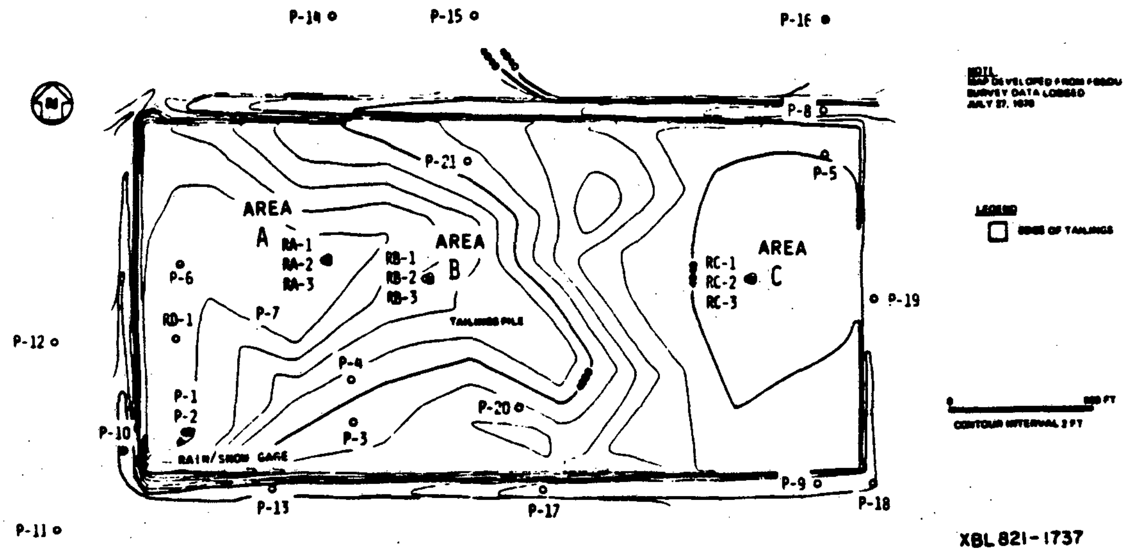


Figure 1. Map of the tailings pile at Riverton, Wyoming showing the location of the three instrumentation sites, RA, RB, and RC. Number P-1 through P-19 denote piezometers.

Tensiometer measurements at the Maybell tailings pile were begun during the second year of this study (summer 1982). A single site designated MA is now equipped with tensiometers over depths from 0.61m down to 5.87m into the tailings (Figure 2).

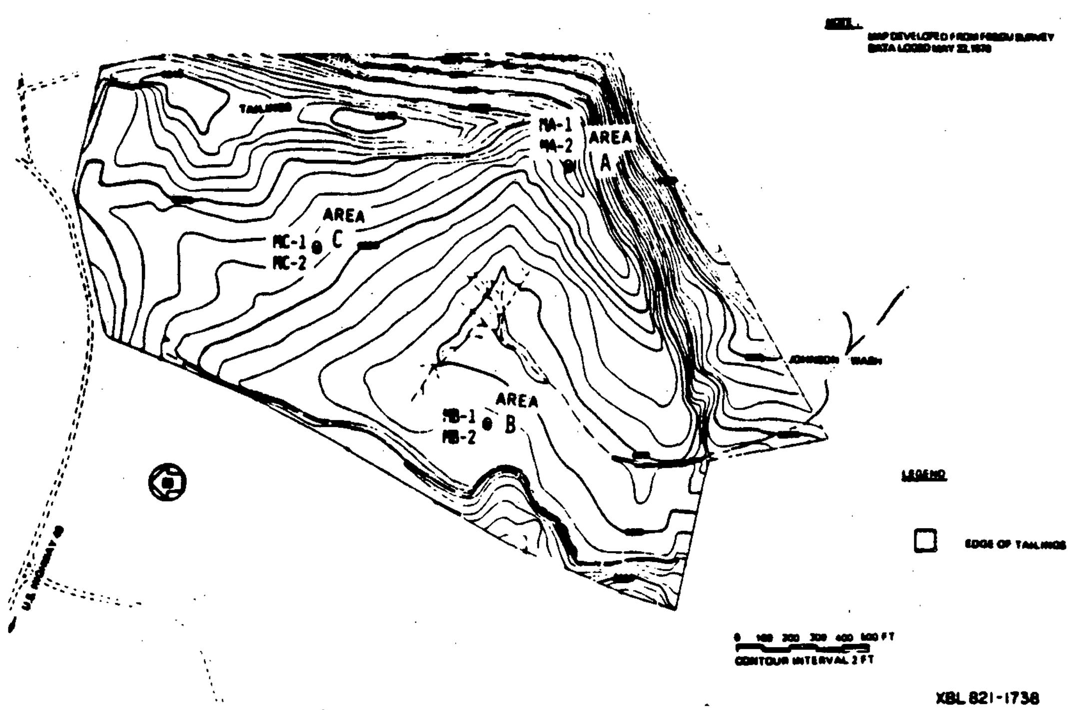


Figure 2. Map of the tailings pile at Maybell, Colorado, showing the location of the boreholes at sites MA, MB, and MC.

FIELD RESULTS

Typical profiles of hydraulic head, ϕ, versus depth at the Riverton sites are presented in Figure 3 (datum at RA is at the upper tailings surface, while the RB and RC depths are referenced to the surface of the soil cover). The gravitational head, z, is plotted on these profiles as the dashed diagonal lines of unit slope. The matric head, $\psi_M = \phi - z$, corresponds to the horizontal distance between the ϕ and z lines at a given depth. The matric head throughout most of the tailings is within the range of -0.5m H_2O to -2.0m H_2O. The hydraulic head profiles at sites RA and RB reveal near steady-state downward flow of tailings water under an approximately unit gradient at depths greater than one meter. The zero flux surfaces at both sites are within the upper meter of tailings. Evapotranspirative water losses from the upper meter of soil cover and tailings are indicated by the hydraulic head gradients in these surface regions of sites RA and RB.

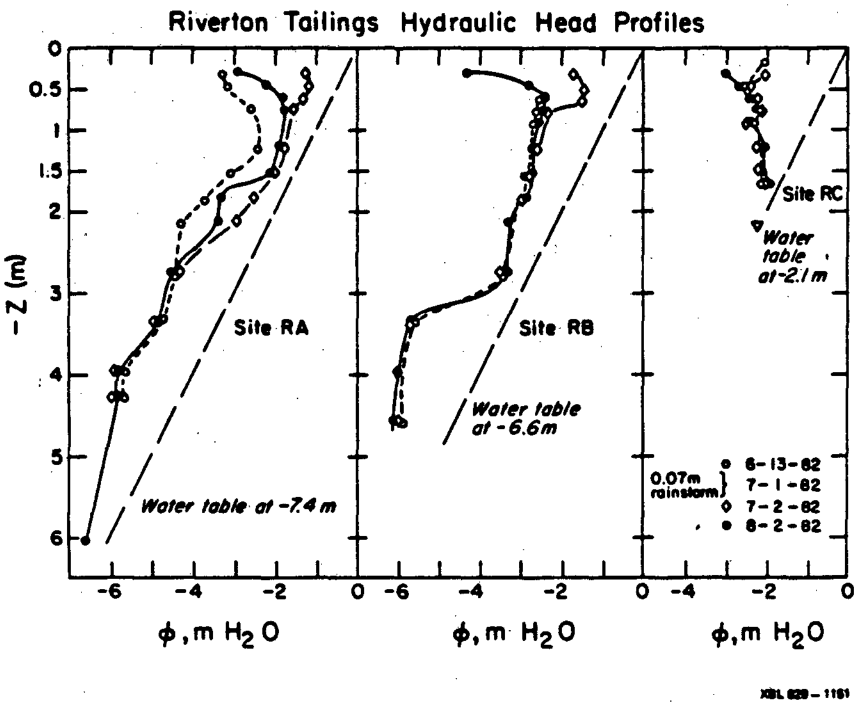
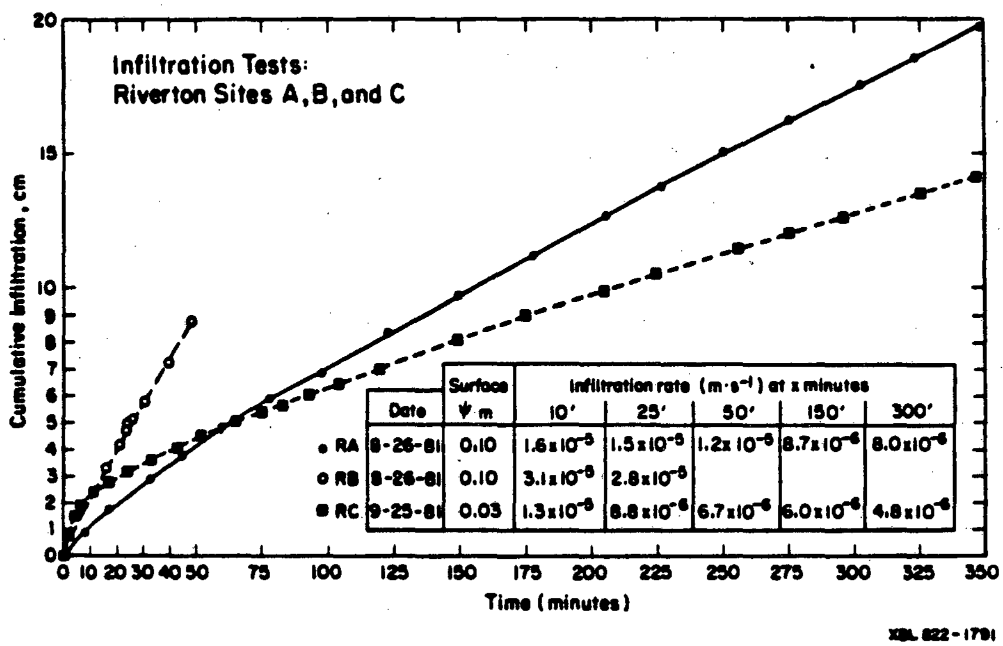


Figure 3. Profiles of hydraulic head potentials observed at sites RA, RB, and RC, Riverton, Wyoming, between June and August, 1982.

A distinctly different hydraulic head pattern characterizes the thin layer of tailings overlying the very shallow water table at site RC located at the eastern extremity of the Riverton pile. During the late spring and early summer a nearly hydrostatic condition dominated the profile. A hydraulic head of about -2.2 M H_2O extended over the full range of tensiometer monitored depths. An extremely steep hydraulic head gradient within the upper 0.15M of soil cover at site RC is inferrable. During the later summer months the hydraulic head gradient develops in the direction indicative of upward evaporative water loss through the full range of monitored depths at site RC.

Infiltration test results at the Riverton tailings pile from the summer of 1981 are summarized in Figure 4. The final infiltration rates in the range of 8 x 10^{-6} $m \cdot s^{-1}$ for site RA and 3 x 10^{-5} $m \cdot s^{-1}$ for site RB provided estimates of the saturated hydraulic conductivities of the upper 0.6m of tailings at each of these sites. The final infiltration rate at site RC of 5 x 10^{-6} $m \cdot s^{-1}$ estimates the saturated hydraulic conductivity of that sites upper 0.6m of soil cover and tailings. A detailed account of the infiltration tests can be found in Narasimhan, et al., (1982).



	Date	Surface ψ m	Infiltration rate ($m \cdot s^{-1}$) at x minutes 10'	25'	50'	150'	300'
• RA	8-26-81	0.10	1.6×10^{-5}	1.5×10^{-5}	1.2×10^{-5}	8.7×10^{-6}	8.0×10^{-6}
o RB	8-26-81	0.10	3.1×10^{-5}	2.8×10^{-5}			
■ RC	9-25-81	0.03	1.3×10^{-5}	8.8×10^{-6}	6.7×10^{-6}	6.0×10^{-6}	4.8×10^{-6}

Figure 4. Summary of infiltration test data, Riverton, Wyoming.

The hydraulic head profiles measured at the Maybell tailings pile reveal a near steady-state unit gradient over most of the monitored depths (Figure 5). The matric head at most of the measured depths is of very low magnitude, appearing to give way to positive pressure heads at depths greater than 4.5m. The occurrence of positive pressure heads at these depths is contrary to water level records as well as observations during augering of the tensiometer access holes. Drift in tensiometer gage zeroes or drift due to non-isothermal effects may account for the anomalous positive pressure heads within the Maybell tailings.

LABORATORY METHODS

Laboratory tests on the tailings samples include saturated and unsaturated hydraulic conductivity measurements, saturation versus matric head measurements, particle size analysis, and determination of bulk densities and porosities. Intact 5.5 cm diameter, 3 cm thick cores are removed from the 3-inch O.D. Shelby tube samples of the piles. The 5.5 cm diameter cores are cut and retained in stainless steel rings.

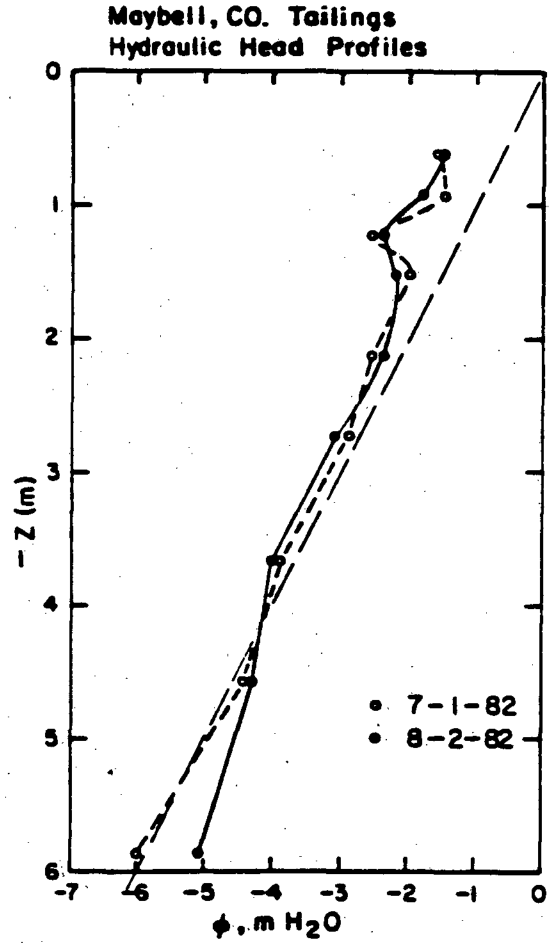


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Figure 5. Profiles of hydraulic head potentials observed at site MA, Maybell, Colorado.

Cores are then water saturated and measured for saturated hydraulic conductivity by the falling head method (Klute, 1965). The saturated cores are then placed in pressure plate cells for determination of saturation versus matric head relations (Reginato and Van Bavel, 1962). The samples are measured over a range of 0.00m H_2O to -9.50m H_2O of matric head. Intermediate equilibration at matric head values of -0.25, -0.75, -1.50, -1.70, -3.00, and -6.00m H_2O during draining, and -3.00, -1.00, and -0.30m H_2O during rewetting allowed for measuring hysteresis in the moisture characteristic curves.

Unsaturated hydraulic conductivities are calculated from the draining branches of the moisture characteristic curves using the modified Millington-Quirk Method (Kunze, et al., 1968), matched to measured saturated hydraulic conductivities. Independent estimates of the unsaturated hydraulic conductivity at a matric head of -1.6m H_2O are obtained with the transient pressure plate outflow method (Gardner, 1956). The assumptions used in this latter method lead to some uncertainties in the calculations (Jackson, et al., 1963) although the small pressure step used in an usually smooth region of the moisture characteristic curves (1.50m H_2O to 1.70m H_2O) help to minimize errors.

Bulk densities are calculated from weighing the oven-dry core samples upon completion of the saturation studies. Bulk densities of the annular samples (between the core samples and Shelby tube walls) are measured when calculations on the cores are questionable. Porosities are estimated from the measured bulk densities and assumed particle densities of 2.65 $g \cdot cm^{-3}$.

Particle-size analyses are the last tests performed on the cores. The combination of sieving and sedimentation-hydrometer methods (Day, 1965), are applied to determine the sand, silt, and clay size fractions at specified depths. The separated size fractions are retained for later radiological studies.

LABORATORY RESULTS

The initial laboratory studies have focused primarily on the Riverton site RA Shelby tube samples. Some results have also been obtained for site RB tailings as well as for the soil cover at site RC. Due to space limitations, only representative examples of saturation relations ($S(\psi_M)$), and unsaturated hydraulic conductivities ($K(\psi_M)$) will be presented. The complete set of results will be presented in future reports.

Portions of the depth profiles of saturated hydraulic conductivities, K_{sat}, have been completed for the Riverton sites RA and RB (Figure 6). The significant variation of K_{sat} with depth is clear at both sites. Changes in K_{sat} by three orders of magnitude within several centimeters of depth are not unusual.

Saturation curves for several samples at RA near the 3.9m depth are presented in Figure 7. The initially rapid decrease in saturation is typical of most of the tailings tested, and is expected due to the high sand contents of these tailings. Residual saturations of 0.2 to 0.3 are also typical of our results.

The corresponding $K(\psi_m)$ curves (Figure 8) for these depths exhibit the rapid decreases of $K(\psi_m)$ expected for sandy materials. The relatively close agreements between the modified Millington-Quirk and pressure plate outflow methods at -1.6m H_2O is also demonstrated in these plots.

Particle-size analyses are included in the summary table (Table I). The high proportion of sand, and low clay contents of nearly all of the tailings is evident.

The moisture characteristic curve of soil cover from RC is included in Figure 7 for comparison with typical tailings saturation curves. The greater water retention at a given potential for the soil cover is expected due to its higher clay and silt contents (Table I).

DISCUSSION

Both the field and laboratory results from the Riverton tailings reveal a great deal of spatial variability in hydraulic properties. The differences in both infiltration rates and hydraulic head profiles

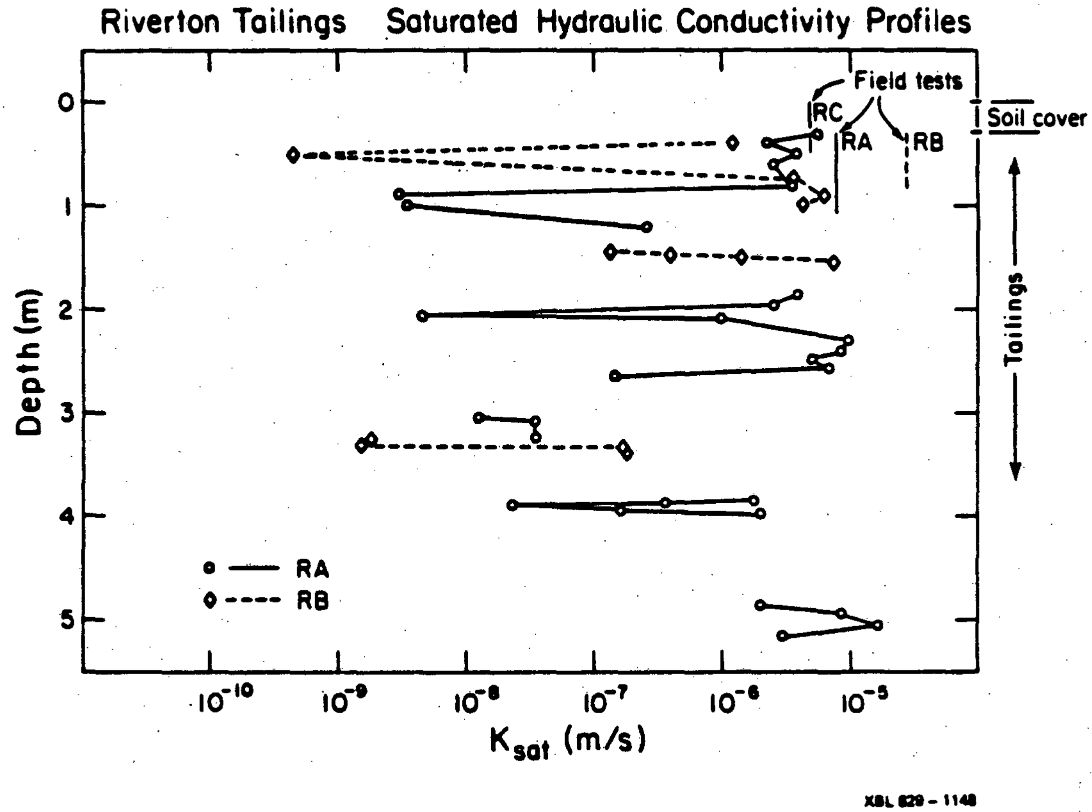

Figure 6. Variation of saturated hydraulic conductivity with depth at sites RA and RB, Riverton, Wyoming.

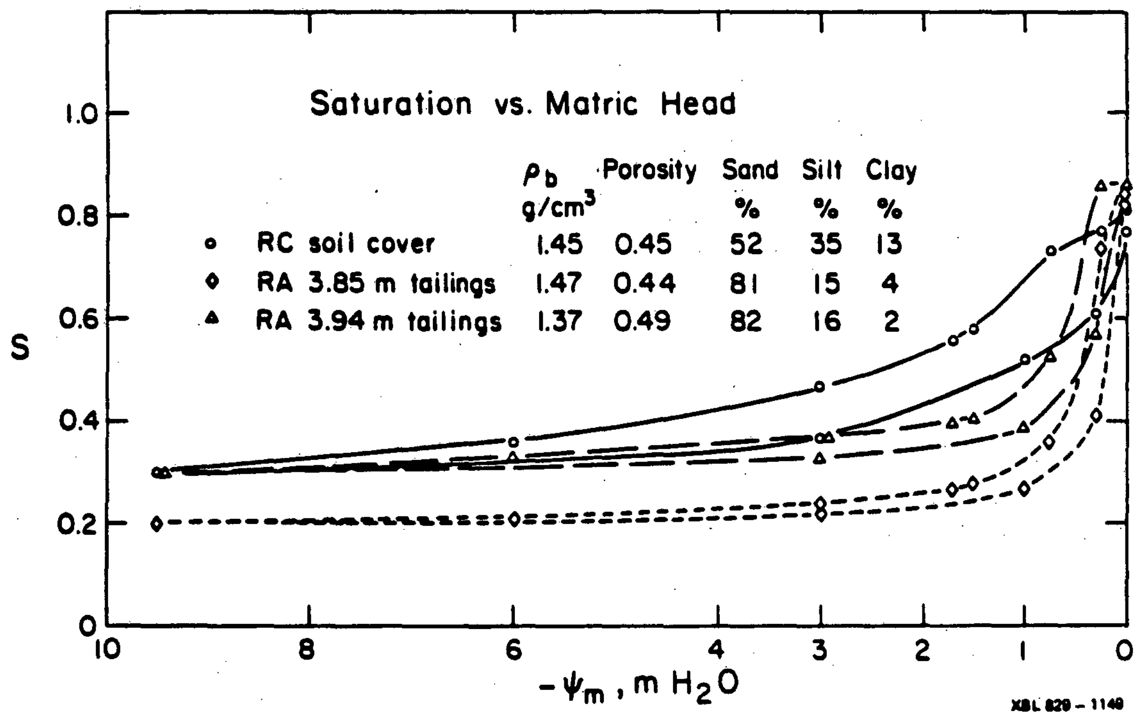

Figure 7. Saturation as a function matric head for two samples from site RA and the soil cover from site RC. Note the hysteresis displayed by the curves.

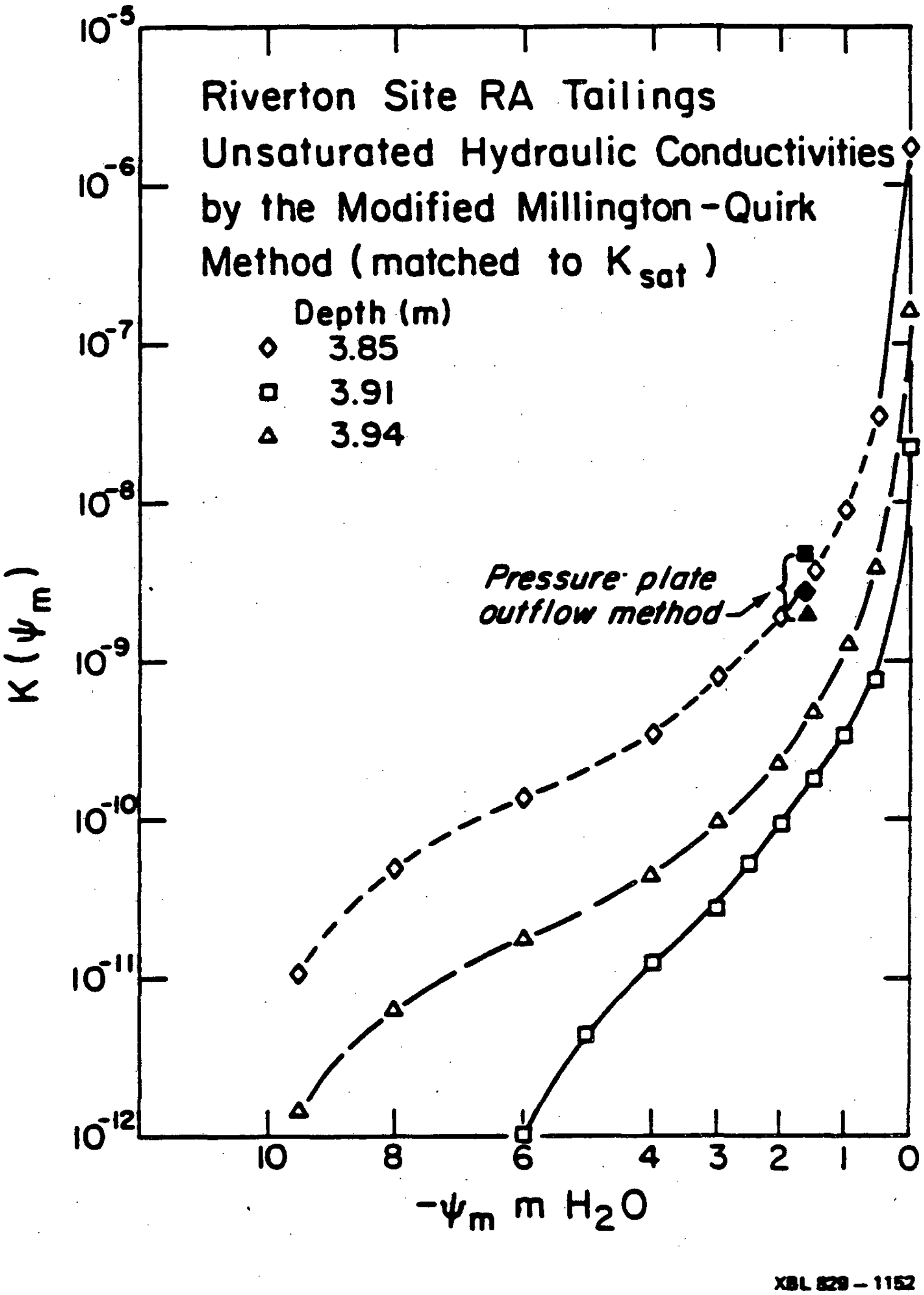

Figure 8. Variation of hydraulic conductivity as a function of matric head for three samples from site RA, Riverton, Wyoming.

at the three sites demonstrate lateral variations in tailings properties. The laboratory analyses of saturated hydraulic conductivity profiles reveal vertical inhomogeneities.

Despite these complications the relatively stable hydraulic head profile at site RA and fairly similar hydraulic conductivities at the relevant matric potentials of these tailings can be combined to obtain an estimate of flux denisities. The field results demonstrate that the major portions of site RA have near unit hydraulic gradients, with

TABLE I

Soil Physics Data on Riverton Tailings

	Depth m	Depth inches	K_{sat} $m \cdot s^{-1}$	ρ_b $g\ cm^{-3}$	Porosity	Clay <2μm %	Silt 2⇌50μm %	Sand 50μm⇌2mm %	S_r*
RB	0.39	15	1.2×10^{-6}						
RB	0.51	20	4.4×10^{-10}						
RB	0.76	30	3.5×10^{-6}						
RB	0.89	35	6.5×10^{-6}						
RB	1.02	40	4.2×10^{-5}						
RB	1.44	56	1.3×10^{-7}						
RB	1.47	58	4.0×10^{-7}						
RB	1.50	59	1.4×10^{-6}						
RB	1.53	60	7.7×10^{-6}						
RB	3.27	129	1.8×10^{-9}						
RB	3.30	130	1.5×10^{-9}						
RB	3.33	131	1.7×10^{-7}						
RB	3.36	132	1.7×10^{-7}						
	RA soil cover			1.39	0.47	9	25	66	.40
	RC soil cover			1.45	0.45	13	35	52	.30
RA	0.30	12	5.6×10^{-6}						
RA	0.40	16	2.2×10^{-6}						
RA	0.50	20	3.9×10^{-6}						
RA	0.60	24	2.5×10^{-6}						
RA	0.80	32	3.4×10^{-6}						
RA	0.90	35	3.0×10^{-9}						
RA	1.00	39	3.5×10^{-7}			4	65	31	
RA	1.20	47	2.5×10^{-7}						
RA	1.85	73	4.0×10^{-6}	1.40	0.47	4	12	84	.15
RA	1.96	77	2.6×10^{-6}	1.42	0.46	3	23	74	
RA	2.06	81	4.3×10^{-9}	1.44	0.46	4	38	58	.68
RA	2.18	86	1.0×10^{-6}	1.48	0.44	5	16	79	.23
RA	2.30	91	9.9×10^{-6}	1.46	0.45	0	8	92	
RA	2.40	94	8.4×10^{-6}	1.46	0.45	0	10	89	
RA	2.48	98	5.2×10^{-6}	1.45	0.45	0	10	90	
RA	2.57	101	6.9×10^{-6}	1.44	0.46	0	9	91	
RA	2.66	105	1.4×10^{-7}	1.47	0.45	2	17	81	
RA	2.75	108		1.26	0.52	7	11	82	.37
RA	2.85	112		1.25	0.53	10	13	77	.17
RA	3.02	119		1.42	0.46				.11
RA	3.05	120	1.2×10^{-8}						.30
RA	3.07	121							
RA	3.25	128	3.5×10^{-8}						
RA	3.85	152	1.8×10^{-6}	1.47	0.44	4	15	81	.20
RA	3.88	153	3.5×10^{-7}	1.29	0.51	4	27	69	.30
RA	3.91	154	2.2×10^{-8}	1.43	0.46	1	11	88	
RA	3.94	155	1.6×10^{-7}	1.40	0.47	2	16	82	.30
RA	3.97	156	2.0×10^{-6}	1.37	0.49	3	15	82	
RA	4.84	190	2.0×10^{-6}						
RA	4.93	194	8.7×10^{-6}						
RA	5.04	198	1.6×10^{-5}						
RA	5.17	203	3.0×10^{-6}						

*S_r = Residual Saturation

matric heads near -1.5m H_2O. Laboratory conductivities for these tailings at this matric head are largely in the range of 10^{-10} $m \cdot s^{-1}$ to 10^{-9} $m \cdot s^{-1}$. Applying Darcy's law with a unit gradient in hydraulic head provides an estimated steady-state downward flux density in this same range. This is equivalent to an annual recharge of about 3×10^{-3} to 3×10^{-2} m H_2O through the tailings at site RA. The hydraulic gradients in the upper meter of site RA indicate that the bulk of the mean annual precipitation (2.5×10^{-1} $m \cdot yr^{-1}$) is evapotranspired back to the atmosphere.

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