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SOME PHYSICAL PROPERTIES OF WATER TRANSPORT IN WASTE ROCK MATERIAL

Michael M. Noël and A. Ian M. Ritchie

Managing Mine Wastes Project, Australian Nuclear Science and Technology Organization
Private Mail Bag 1,
Menai NSW 2234, Australia
Phone +61 2 9717 3948, Fax +61 2 9717 9129
e-mail: Michael.noel@anto.gov.au

ABSTRACT

A series of water transport simulations of typical waste rock material was carried out to assess flux and moisture content changes over time. Typical seasonal cycles of precipitation were used for the simulations. The results indicated that the moisture content varies little over the seasonal cycles. Also, the time for the flux at the base of a 20 m high dump to react (response time) to a flux change at the top is short (few weeks) while the water residence time is much longer (few years). These observations are critical for the proper selection of methods and devices to monitor water and contaminant transport in unsaturated waste rock material.

INTRODUCTION

Water is the dominant transport mechanism in the transport of pollutants in sulfidic waste rock material. Understanding water transport is also an important aspect in the management of the environmental impact caused by these dumps. The modelling of water transport in waste rock material can provide essential information for selecting the appropriate methods and devices to monitor water and contaminant transport in waste rock dumps.

Waste rock by its nature is highly heterogeneous with particle size varying from boulders of several metres to clay size particles. The bulk and intrinsic physical properties of waste rock are relatively well documented in the literature. However, the literature contains little information on soil-water relationships and the unsaturated hydraulic conductivity for waste rock. Also, these parameters are often considered to have large uncertainties. This can be explained in large part by the difficulties and the costs associated with measuring these parameters in waste rock.

The time scale of water and contaminant transport in waste rock material is another area where there appears to be uncertainties and some confusion. Mine operators have some understanding and quantification of these time scales when they develop their plans for managing pollutant drainage coming from waste rock dumps. Such polluted drainage is often called acid rock drainage. For example, mine operators may want to estimate the time it will take for the water quality in drainage to improve after a soil cover is placed on top of a waste rock dump. In an effort to clarify this issue of time scales, we investigate two basic parameters: the response and residence times. For the purposes of this paper, the **response time** is the time required for the water flux at a given depth in the dump to start to change following a change in the infiltration flux condition at the surface. If the change at the surface is a step change then the response time at depth corresponds to the time halfway between when the flux change was first detected and when the flux reached its maximum value. The **residence time** corresponds to the time it takes for a conservative pollutant dissolved in water to travel from the surface to a given point along a vertical profile in the dump. Its quantification is similar to that for the response time.

The literature contains numerous studies on unsaturated water transport. These studies are often applied to "conventional" soils (clay to sand size particles) and the water table is often relatively near the surface. Waste rock dumps are generally unsaturated with the bulk of the material situated far above the water table. Also, the water infiltration rate in waste rock dumps is usually much lower than the rate required to saturate the material. Such conditions usually lead to moisture contents in the dump at or near the minimum water content achievable for the type of waste rock present in the dump. To the casual observer, such waste rock appears to be quite dry.

Water flow under low infiltration conditions tends to be the opposite to that observed in saturated media. Under saturated or unsaturated conditions close to saturation, water flows mostly in the coarse portion of the medium where the larger voids are present. However, under "dry" unsaturated conditions, the only water left in the medium is in the fine portion where the small pore size can hold the water by surface tension. Newman and al. (1997) presented a case where the water "preferred" to travel in the fines when the porous material was dry and in the coarse fraction where it was near saturation. Birkholzer and Tsang (1997) carried out a detailed modelling exercise and arrived at a similar conclusion. El Boushi (1969) studied the infiltration of water in coarse rock particles and suggested that the fine portion present in coarse particles will likely act as a wick to attract the water infiltrating coarse material.

Considering that waste rock is highly heterogeneous, is often under dry conditions and that the soil-water relationships are difficult to measure, we have carried out a series of water transport simulations to tentatively address the following questions:

- What is the variation in water content in waste rock material for a range of infiltration rates typical of those expected from rainfall?
- How quickly will the water flux inside a waste rock dump react to a change of infiltration flux at the surface (response time)?
- How long will it take for a conservative pollutant dissolved in water to travel through from the top of the waste rock dump to various depths within the dump (residence time)?
- What measuring devices are appropriate or inappropriate to monitor the movement of water in waste rock dumps?
- How sensitive are the response and residence times to the hydraulic properties used to describe water transport in the dump under typical infiltration rates?

MODEL DESCRIPTION

The simulations were carried out using SWIM v.2.1 (Verburg et al., 1996). SWIM is a one-dimensional model based on a numerical solution of Richards' equation. SWIM has the capability of modelling runoff, infiltration, redistribution of water and solute, solute transport, plant uptake and transpiration, soil evaporation, deep drainage and leaching. SWIM accepts time dependent boundary conditions and uses the finite difference method. SWIM was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia.

Water retention curves and hydraulic conductivity functions are normally measured in laboratory and are then fitted by a mathematical expression. Several expressions are available in the literature. SWIM has the capability of using 7 different expressions for the water retention relationship and 3 different hydraulic conductivity functions. Instead of using θ, these relationships use a normalised parameter defined as the effective degree of saturation S_e.

$$S_e(\psi) = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} \qquad (1)$$

where θ = volumetric water content

ψ = matric potential (m)

θ_r = residual volumetric water content

θ_s = saturated volumetric water content

The residual volumetric water content corresponds to the minimum volumetric water content value obtained by free drainage. The saturated volumetric water content is the maximum value that can be reached for a given soil. The saturated water content should not be equated to the porosity of the soil (usually 5 to 10% smaller) because of entrapped or dissolved air (van Genuchten 1991). However, the saturated volumetric water content is often considered equal to the porosity of the soil for modelling purposes.

The simulations presented herein used the van Genuchten formulation (van Genuchten 1980, 1991) for the water retention relationship. The expression is:

$$S_e(\psi) = [1 + (\alpha|\psi|)^n]^{-m} \qquad (2)$$

where: α = empirical constant (m^{-1})

n, m = empirical constants

Two hydraulic conductivity functions were used for the simulations depending on the soil type: van Genuchten (van Genuchten, 1980, 1991) and Brooks-Corey (Brooks and Corey, 1964, 1966). The van Genuchten function is defined as:

$$K(\psi) = K_{sat} S_e^p \, [1 - (1 - S_e^{1/m})^m]^2 \quad \text{with } m = 1 - 1/n,\ n > 0 \qquad (3)$$

where: K = hydraulic conductivity ($m\ s^{-1}$)

K_{sat} = saturated hydraulic conductivity ($m\ s^{-1}$)

p = pore interaction index

The Brooks-Corey hydraulic conductivity function is as follows:

$$K(\psi) = K_{sat} S_e^{p+2+2b} \qquad (4)$$

where: b = empirical constant

The van Genuchten formulation has the disadvantage of having an infinite slope at saturation ($\psi = 0$) which can sometimes cause numerical convergence problems. The Brooks-Corey expression does not have this property.

THE SIMULATIONS

Three different dump heights, 10 m, 20 m and 40 m, were used in the simulations. The node spacing was 0.1 m for the 10 m and 20 m profiles while a node spacing of 0.16 m was used for the 40 m profile. The node spacing was increased for the 40 m profile because of the maximum number of nodes allowed by SWIM.

The bottom boundary was set to a matric potential of 0 m. It corresponds to a situation where there is a groundwater table right at the base of the dump from which water can drain freely. This is similar to the situation in a soil column experiment in laboratory where the bottom of the column is open to air and is free to drain.

The boundary condition at the surface was specified by a time dependent infiltration flux. No infiltration flux was applied for the initial 50 years of simulation. The 50 years drainage period with no infiltration was selected long enough to allow each soil type to reach drained steady state condition before the cyclic infiltration rate was applied. A cyclic infiltration flux was then applied from 50 years to 72 years. The 22 year period of cyclic infiltration was selected to assure that a pseudo-steady-state condition with the flux would be reached within that time and that it was long enough to measure the residence time through the profile of the dump. The initial 20 years of infiltration had an output interval of 146 hours and the interval was reduced to 4 hours for the last 2 years (70 to 72 years). The shorter interval was used to measure the relatively short response time. Although the simulation time may seem long, SWIM solved these simulations within a few minutes.

The initial condition was set to a matric potential equal to -0.5 m for the entire profile except for the bottom 0.5 m where the it decreased linearly from –5 to 0 m (bottom boundary). The low initial matric potential was intended to have a moisture content high enough to allow for some water to be drained during the initial 50 years.

The cyclic infiltration rates used in the simulations were based on rates typical of those expected from rainfall in many places around the world. The cycles were used to simulate the seasonal variation that is generally associated with rainfall. For the purpose of simulation, we used 1500, 750 and 375 mm of infiltration per year applied over a period of 5 months. These precipitation quantities correspond to fluxes of 1.14×10^{-7} m s^{-1}, 5.70×10^{-8} m s^{-1}, 1.14×10^{-8} m s^{-1} maintained over the 5 month period. The remaining 7 months of the year had no rain. For simplicity, we assumed that there is no evaporation and that all the water infiltrated the waste rock material. The flux at the surface was too low to have runoff because it is well below the saturated hydraulic conductivity of the material ($K_{sat} = 10^{-3}$ m s^{-1}).

Solute transport was used to measure the residence time in the profile. A solute with the properties of water was applied at the surface boundary at 55 years. It was applied continuously at a constant concentration for the remaining 17 years of the simulation. The solute was applied after the flux condition had already reached pseudo-state conditions in the profile.

Eight material types were used for the simulations, ranging from coarse waste rock to clay soils. Properties from four different waste rock materials were selected from the literature: Mine Doyon (Lefebvre, 1994), Kennicott Mines (Gardner, 1992), Gas Hills (Troncoso and Shackelford, 1999), Kidston Gold Mine (Bews et al., 1997). Four basic soil types were selected from Rawls et al. (1982) to complement the waste rock data.

To compare the parameters defining the unsaturated properties, we normalised the soils to the Kennicott waste rock for the saturated hydraulic conductivity, the residual and saturated volumetric water content. The saturated hydraulic conductivity (K_{sat}) was set to 10^{-3} m s^{-1}, the residual volumetric water content (θ_r) to 0.18 and the saturated volumetric water content (θ_{sat}) to 0.38. Table 1 presents the parameters associated with the eight different soil types.

Material type	Method to calculate K_{unsat}	α (m^{-1})	n	p
Clay	bc	2.7	1.131	7.000
Clay loam	bc	3.9	1.194	3.500
Gas Hills	vg	2.0	1.160	0.500
Kennicott	bc	15.0	2.500	0.500
Kidston	bc	4.9	1.300	1.500
Mine Doyon	vg	4944.0	1.299	0.504
Sand	bc	13.8	1.592	1.100
Sandy loam	bc	6.8	1.322	2.500
Note: bc = Brooks-Corey method; vg = van Genuchtten				

Table 1. Parameters defining the unsaturated properties.

The extremely high value of α reported for the Mine Doyon material should be noted.

RESULTS

The modified material properties were plotted as a function of the volumetric water content and the hydraulic conductivity (Figure 1). It shows the wide range of properties used for the simulations. This figure also demonstrates that typical water infiltration rates are several orders of magnitude smaller than the rate required to saturate the materials.

Figure 1 also shows that the Kennicott material exhibits the lowest volumetric water content for a given infiltration rate while the clay and the Gas Hills materials have the highest values.

The response time is illustrated in Figure 2 where the water flux and the volumetric water are plotted as a function of time over 2 years for the Kennicott material (20 m profile). This typical case shows that it takes about 45 days before the water flux at the bottom to change after the infiltration had started at the surface. The response time at the end of the infiltration

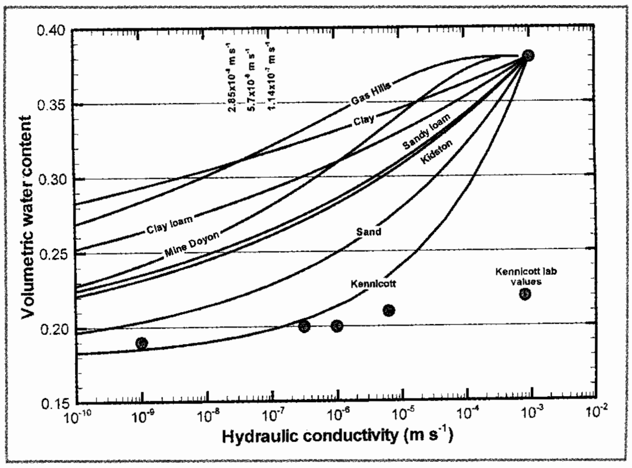

Figure 1. Volumetric water content versus hydraulic conductivity.

cycle ("dry" front) was shorter. This behaviour was observed for all the simulations. The volumetric water content for the 20 m depth is not shown in Figure 2 because it corresponds to the boundary condition where we imposed saturated conditions.

The response time varies depending on infiltration rate and material type. Table 2 lists the response times for a 20 m high dump, for all the material types and for the three infiltration rates. The response time is as short as three weeks and is as long as 6 months but with the exception Mine Doyon, it varies only by about a factor of two for a given infiltration rate over the range of material types.

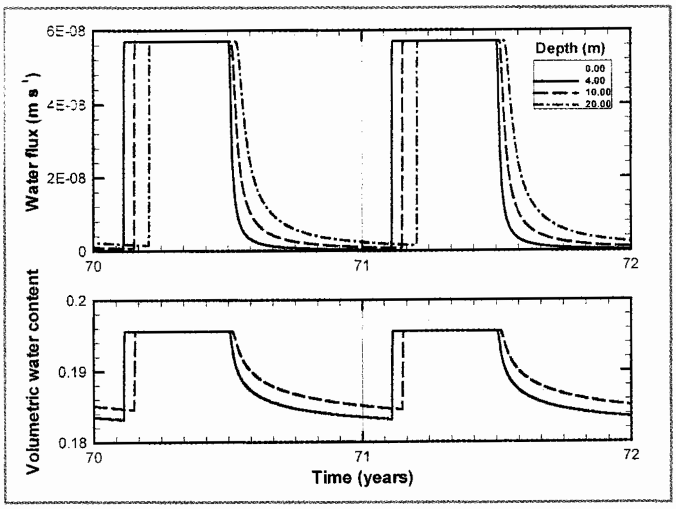

Figure 2. Water flux (top) and volumetric water content (bottom) versus time, Kennicott material, 20 m profile, infiltration flux of 5.70 x 10^{-8} m s^{-1}.

	Response time (**days**)		
Infiltration rate (m s^{-1}):	1.14 x 10^{-7}	5.70 x 10^{-8}	2.85 x 10^{-8}
Clay	22	34	50
Clay loam	32	50	69
Gas Hills	41	55	82
Kennicott	29	45	72
Kidston	37	58	83
Mine Doyon	71	116	191
Sand	47	75	119
Sandy loam	46	76	118

Table 2. Response time at the bottom of the 20 m profile.

Figure 3 shows the water flux and the volumetric water plotted as a function of time for the Kennicott material (20 m profile) over the initial 20 years of cyclic infiltration. The water flux curves indicate that the pseudo-steady state condition was achieved within the first two years. A pseudo-steady state condition was obtained in less than 3 years for all the cases.

The bottom graph of Figure 3 shows the residence time obtained for the Kennicott material for the 20 m profile under an infiltration rate of 5.70 x 10^{-8} m s^{-1}. This typical case shows that it will take about 5 years for a conservative pollutant dissolved in water to travel from the surface down to the base of a 20 m dump. Since the pseudo-state condition was achieved within the initial 2 years of infiltration, the solute could have been applied at 52 years to obtain the same residence time.

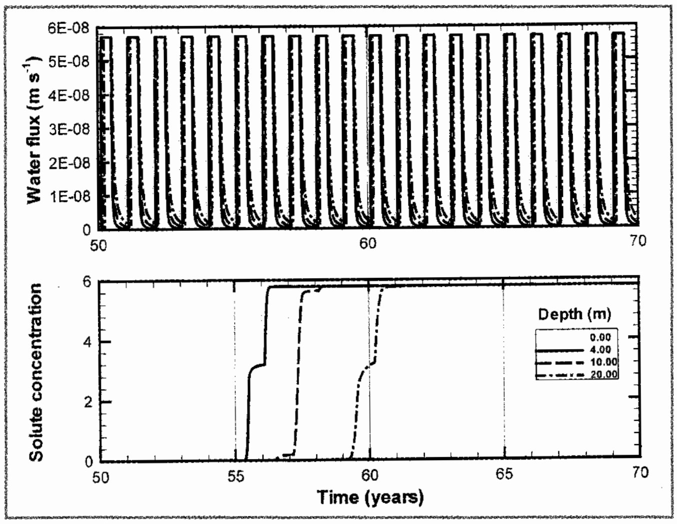

Figure 3. Water flux (top) and solute concentration (bottom) versus time, Kennicott material, 20 m profile, infiltration flux of 5.70 x 10^{-3} m s^{-1}.

Table 3 below summarises the residence times for all the material types obtained with the 20 m profile. As for the response time, the residence time varied considerably between the simulations.

Figure 4 shows the variability of the response time and the residence time as a function of the water flux for the 20 m profile with the Kennicott material. It indicates that the response and residence times both increase when the infiltration flux is reduced. This was also the case with the other material types.

	Response time (**years**)		
Infiltration rate (m s^{-1}):	1.14 x 10^{-7}	5.70 x 10^{-8}	2.85 x 10^{-8}
Clay	4.3	8.4	16.3
Clay loam	3.8	7.8	14.5
Gas Hills	4.2	8.3	16.3
Kennicott	2.4	5.0	10.3
Kidston	3.3	6.9	13.1
Mine Doyon	3.5	7.0	13.4
Sand	2.8	5.6	11.3
Sandy loam	3.4	6.8	13.1

Table 3: Residence time at the bottom of the 20 m profile

The volumetric water content was plotted as a function of depth for the 20 m profile using the Kennicott and Gas Hills materials. These two materials reflect the range in the capacity of the material used in the simulations to hold water (se Figure 1). The "dry" condition is the lowest water content obtained during the annual cycle and the "wet" condition is the highest water content obtained for the maximum flux used in the simulations (1.14 x 10^{-7} m s^{-1}). This figure shows that the maximum variability in volumetric water content will be in the range of 2% to 3%.

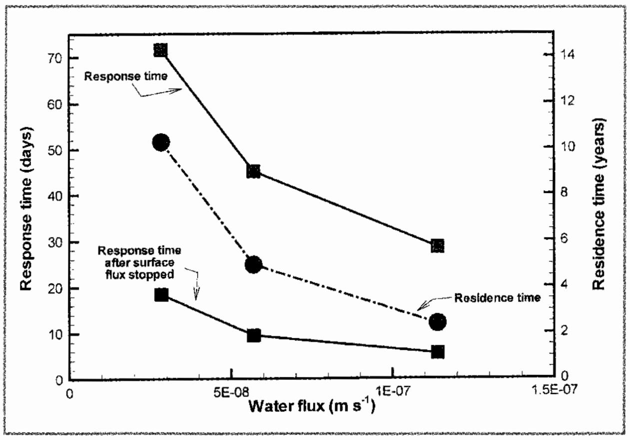

Figure 4. Response and residence time versus water flux, Kennicott material, 20 m profile.

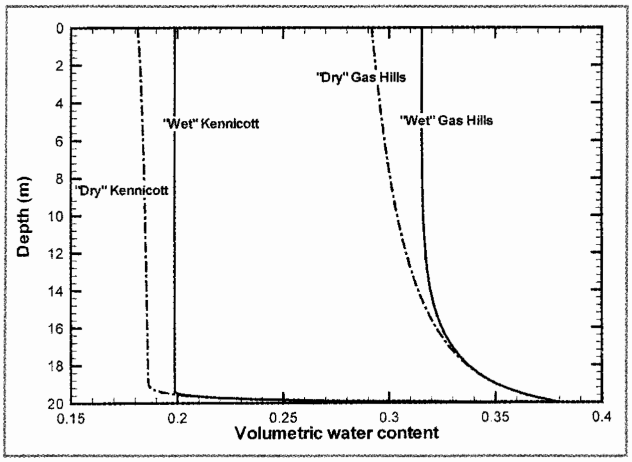

Figure 5. Volumetric water content versus depth, Kennicott and Gas Hills materials, 20 m profile.

DISCUSSION

The approximation used to define the material-water relationship for the Kennicott material (Figure 1) may appear to be inadequate near saturation but is well defined in the range of fluxes used in the simulations. As indicated in Figure 5, the region with near saturation conditions is negligible and occurs only at the bottom boundary. This emphasises the importance of having adequate unsaturated properties that correspond to the conditions for the range of infiltration fluxes occurring in the system.

The normalisation of the material properties resulted in some material types that are probably unrealistic, such as the clay and the Gas Hills material where their water retention curves would normally correspond to a much smaller hydraulic conductivity value. Again, our interest is to assess the importance of the parameters used to describe the unsaturated properties of waste rock material.

The simulations indicated that the response and residence times depend on the water flux applied to the system (see Table 3). The longest residence time was obtained with the clay and Gas Hills materials and they both have the highest water content values. The shortest residence time was obtained with the Kennicott material which maintains the lowest water content.

The different time scales obtained for the response time and the residence time have important implications for understanding water and contaminant transport in waste rock dumps. An example is the response of the drainage from a waste rock dump following the placement of a soil cover on its top. The soil cover will likely decrease the infiltration flux by about an order of magnitude or more. From Figure 4, a reduction in the infiltration flux will increase considerably the response and residence times. Although the placement of a cover over waste rock will reduce the discharge quantities within weeks, the benefits of the cover on the pollutants could take tens of years before it can be measured.

The variation in water content as shown in Figure 5 indicates that the volumetric water content hardly varies over time when typical infiltration rates of those expected from rainfall are applied to waste rock dumps. The variation in water content ranged from only 2% to 3% between the "dry" and "wet" season. The low range was obtained for all material types. This is consistent with the measurements reported by Daniel et al. (1979), and Goodman et al. (1981). They measured water content profiles during the wet and dry season at Rum Jungle and did not see any significant difference between the dry and wet season. Goodman et al. (1981) also observed that the water content did not vary much with depth over the top 5 m.

The low range in variation of the water content with changing infiltration rate has another important consequence. The detection limits of the devices (ie. TDRs) for measuring water content is about 1 to 2%. It follows that water content monitoring is not a practical way to measure infiltration rates in waste rock dumps.

CONCLUSION

Provided that Richards' equation describes water transport in waste rock and provided it is reasonable to normalise the hydraulic properties of different material types such that the saturated hydraulic conductivity is the same, the simulations indicated that:

- The range of variation of the water content in waste rock is only about 2 to 3% over the range of infiltration rates typical of those expected from rainfall.
- The response time is short, in the order of a few weeks for a 20 m high dump.
- The residence time is long, in the order of a few years for a 20 m high dump.
- The range in variation of the water content with changing infiltration rate is of similar magnitude to the detection limits (about 1 to 2%) of current devices for measuring water content. It follows that water content monitoring is not a practical way to measure infiltration rates in waste rock dumps.

For a given infiltration rate, the response and residence times vary only by about a factor of 2 over the range of hydraulic properties used in the simulations.

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