HYDRUS-1D Modeling Applications to Waste Disposal Problems in Brazil

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Abstract

This paper summarizes three studies in which HYDRUS-1D was used to investigate the performance of different types of waste disposal sites in Brazil: a conventional mining installation containing naturally occurring radioactive materials (NORMs), a municipal landfill, and a radioactive waste repository. In the first application we used HYDRUS-1D to predict long-term (tens of thousands of years) radionuclide transport vertically through both the landfill and the underlying unsaturated zone, and then laterally in groundwater. The second study concerned water fluxes into and through a municipal solid waste (MSW) landfill in the city of Rio de Janeiro. We considered two cover systems that could minimize percolation through the landfill. One used a capillary barrier made from MSW compost, and the other one a vegetation cover using either grass or native vegetation. The third application involved a near-surface repository containing ^{137}Cs wastes resulting from decontamination of Goiania city in Brazil after the 1987 accident with a CsCl teletherapy source. Long-term simulations were carried out of ^{137}Cs transport from the repository through the concrete liner below the waste and the underlying vadose into groundwater. The examples show the flexibility of HYDRUS-1D to address different types of problems.

1. Introduction

Numerical models such as the HYDRUS codes (Šimůnek et al., 2008a) are increasingly used for predicting or analyzing water flow and contaminant transport processes in the subsurface, including the vadose zone. In this paper we summarize three recent applications of HYDRUS-1D to waste disposal problems in Brazil. One application involves the disposal of NORM mining wastes (i.e., wastes containing naturally occurring radioactive materials) in an industrial landfill. HYDRUS-1D (Šimůnek et al., 2008b) was used to predict long-term radionuclide transport vertically through both the landfill and the underlying unsaturated zone, and then laterally in groundwater. Calculations were carried out for both a best-case scenario assuming equilibrium transport in a fine-textured subsurface, and a worst-case scenario involving preferential flow.

The second study concerned water fluxes into and through a municipal solid waste (MSW) landfill in the city of Rio de Janeiro. Two different cover systems were considered that would minimize infiltration of rain water into the landfill. One used a capillary barrier made from MSW compost, and the other one a vegetation (evapotranspiration) cover using either grass or native vegetation from the area.

The third application considered a near-surface repository containing ^{137}Cs wastes resulting from decontamination of Goiania city in Brazil after the 1987 accident with a CsCl teletherapy source.

The study provided estimates of water fluxes through the soil cover into and through the repository and concrete liners of the repository towards underlying groundwater. Performance of the cover system and engineered barriers was followed for 400-years, which included accounting for the effects of concrete degradation. Simulations were further carried out of ^{137}Cs transport from the repository through the concrete liner below the waste and the underlying vadose towards groundwater below the site.

2. NORM Waste Disposal Site

The first application concerned the subsurface transport of radionuclide decay chains (notably the ^{238}U and ^{232}Th series) leached from a conventional mining installation in Amazonia processing ore containing natural occurring radioactive materials (NORMs). The disposal site contained slags having radionuclide concentrations many times higher as compared to the original ore. Dimensions of the disposal unit were 70 m wide by 100 m long and 6.0 m deep. Initial radionuclide concentrations were 71 Bq/g for ^{238}U and ^{234}U, 67 Bq/g for ^{230}Th, 63 Bq/g for ^{226}Ra and 4.8 Bq/g for ^{210}Pb. The slag waste layer had a measured bulk density (ρ_b) of 1.89 g/cm^3. Hydraulic properties of the waste were estimated from drainage experiments on large lysimeters containing slags from the site. Batch measurements produced radionuclide distribution coefficients (K_d) very close to those of a clay soil (ISAM, 1998), except for Ra, whose K_d value was closer to that of sand. For these reasons we used K_d values typical of clay for U, Th, and Pb (1.6, 5.8, and 0.54 m^3/kg, respectively), and the measured value (0.88 m^3/kg) for Ra. An impermeable liner under the waste layer (a requirement of the Brazilian regulatory agency) was not considered in our analysis.

The unsaturated zone below the waste layer consisted of reddish Belterra clay as described by Dennen and Norton (1977) and Truckenbrodt and Kotschoubey (1981). Soil texture, bulk density (1.3 g/cm^3) and the saturated hydraulic conductivity (K_s = 21 m/y) were locally measured. Other parameters of Belterra clay were taken from Belk et al. (2007), except for the soil hydraulic parameter α (we used a value of 4.5 m^{-1}). The saturated zone contained red saprolite interspersed with lighter-colored lenses derived from feldspars. The phreatic aquifer had an average thickness of 4.5 m, with a natural hydraulic gradient of 0.0562. Geotechnical essays produced K_s values between 4.2 x10^{-5} and 7.9x10^{-4} cm/s. For our calculations we used a value of 1.7 x 10^{-4} cm/s.

Average annual precipitation measured in the area was 2,430 mm, and the average evapotranspiration rate (as calculated with the Penman-Monteith equation) was 1,610 mm. Adjusted for runoff, the long-term average recharge rate at the site was estimated to be 657 mm/y. This recharge rate was used as a surface flux boundary condition for the steady-state simulations of water flow through the site and into groundwater.

We used HYDRUS-1D to first predict radionuclide transport vertically through both the landfill and the underlying unsaturated zone, and then one-dimensional laterally in groundwater. Calculations were carried out for both a best-case scenario assuming equilibrium transport, and a worst-case scenario with preferential flow as modeled using the physical nonequilibrium (dual-porosity) formulation of van Genuchten and Wierenga (1976). The performance assessment was carried out using a leaching and off-site small farm scenario (Pontedeiro et al., 2010).

Radionuclides transported in groundwater were assumed to be intercepted by a well 100 m down gradient of the landfill. For the safety analysis we used concentrations of the aquifer at the well.

Figure 1 shows the effect of preferential flow separately through the waste later, the vadose zone and the aquifer. For preferential flow we assumed a value of 0.5 for the fraction immobile water, and different values of the mass transfer coefficient (denoted here by the parameter β in year^{-1}). Results indicate that the highest U concentrations in the leachate leaving the waste were obtained for equilibrium transport. This shows that preferential flow (smaller value of β) of rain water through the waste leads to less pollution of the subsurface. This situation is reversed when preferential flow occurs in the unsaturated zone below the waste, or in the phreatic aquifer. Preferential flow then leads to more rapid transport and higher concentrations.

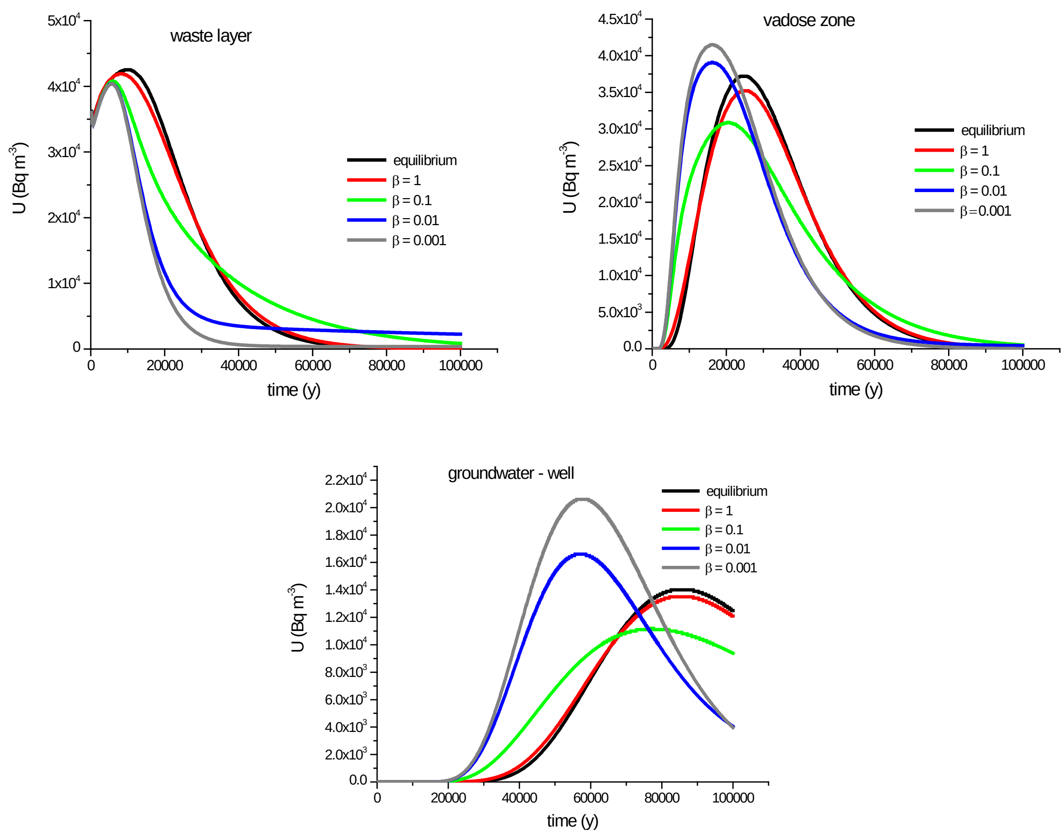

Figure 1. Calculated uranium concentrations versus time in the waste layer (upper right), the bottom of the vadose zone (upper right) and the downgradient well (bottom). Results are for different values of the mass transfer coefficient β (year^{-1}).

Figure 2 shows results of the safety assessment for both equilibrium transport and the situation where preferential flow would occur in all three regions simultaneously (waste, vadose zone, groundwater). A safety assessment is often used to provide evidence that human health and the environment are protected as much as possible in the future. The scenario used here assumes that the downgradient well was the only available source of water for direct consumption by residents, and for irrigation and animal use. We refer to Pontedeiro et al. (2010) for details. The results in Figure 2 show that preferential flow causes the risks to shift to much earlier times, but that the maximum or annual risk is not much affected by preferential flow. Most of the risk in Figure 2 was caused by uranium followed by thorium.

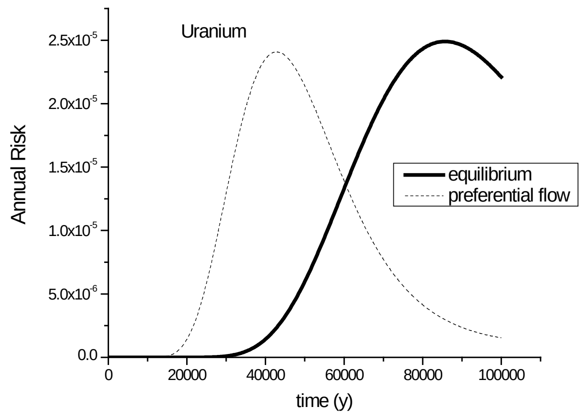

Figure 2. Calculated annual risk assuming equilibrium transport and preferential flow.

3. Municipal Solid Waste Landfill

The second case study concerned water flow into and through a municipal solid waste (MSW) landfill in the Nova Iguaçu suburb of Rio de Janeiro (Fig. 3). The landfill occupies an area of 1.2 million m^2 and contains mostly non-hazardous wastes (classified as Class IIA and IIB according to Brazilian standards). The location includes, among other things, a central treatment plant for the collected leachate and a biogas collection facility to generate electricity. Two studies were carried out to investigate the performance of a final cover that would minimize infiltration into the waste. One was a capillary barrier made from MSW compost, while a second scenario considered a vegetative cover using grasses or native species.

Figure 3. Aerial view of the Nova Iguaçu landfill showing four sub-landfills.

Table 1. Physical and soil hydraulic parameters of the waste.

ρ_b (g/cm^3)	K_s (cm/day)	θ_s cm^3/cm^3)	θ_r (cm^3/cm^3)	α (cm^{-1})	n (-)	l (-)
0.632	233	0.53	0.25	0.20	1.98	0.50

Local data were used as much as possible. The average saturated hydraulic conductivity (K_s) of the cover soil was measured to be 2.3 cm/day. Hydraulic parameters were estimated from measured soil texture data of the fines (on average 32% clay, 19% silt, and 49% sand) using the Rosetta pedotransfer functions in HYDRUS-1D, and adjusted for gravel (4%). Hydraulic parameters for the waste were taken from Breitmeyer (2011) and are listed in Table 1.

For all simulations we considered the intermediate (during operation) and final cover layers to have a thickness of 60 cm, and the waste layer to be 500 cm thick. In order to calibrate the model, we initially modeled each vertical landfill cell separately. For this we considered the influence of rainfall and evaporation on each cell independently, with the premise that the amount of liquid generated by each cell was fully captured by the drainage network of the landfill, and that the overall recharge rate was simply the sum of the deep drainage rates of all cells combined. It was estimated to be 0.257 m/y (0.0703 cm/day) using local weather data and potential evapotranspiration rates calculated with the equation of Hargreaves (1975). The simulations were performed for profiles varying from 1 to 10 meters, after which the individual cells were superimposed to cover the entire landfill. The total amount of leachate simulated for Sub-Landfill1 during 2010 was found to be 27,020 m^3, which compared well with the measured drainage volume of 33,100 m^3.

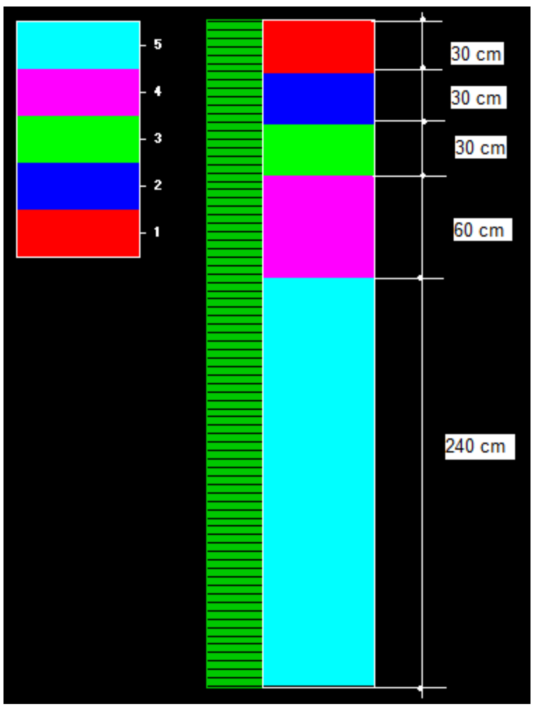

Figure 4. Composition of the capillary barrier system and underlying waste.

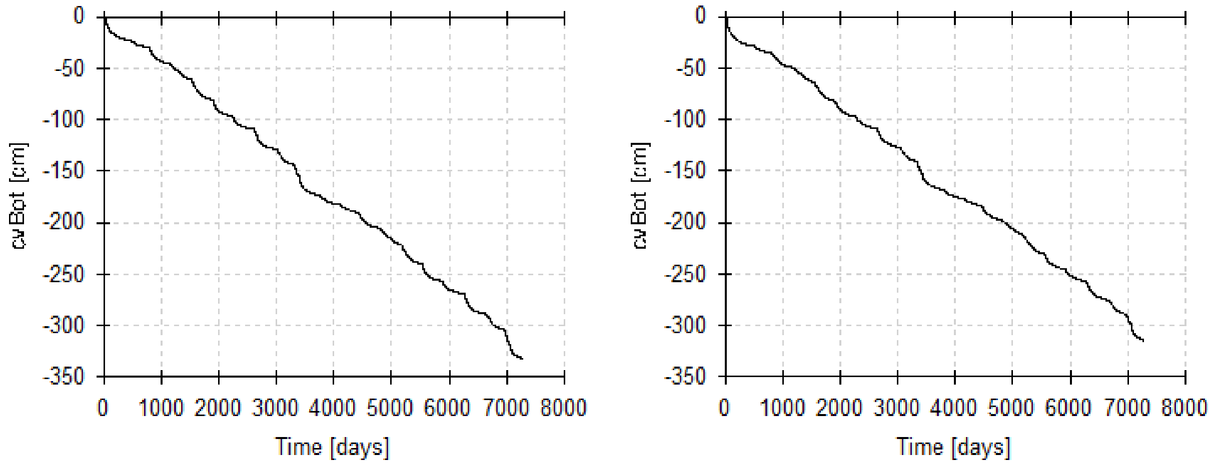

Figure 5. Cumulative drainage fluxes at a depth of 3 m assuming the capillary barrier to have a thickness of 30 cm (left) and 50 cm (right).

Another option we analyzed was the use of vegetation on the cover: either grass with roots uniformly distributed in the top 20 cm, or native vegetation (*brachiaria humidicola)* with roots having a distribution as reported by Costa (2002). The recharge rate with grass was estimated to be 0.0467 cm/day, as compared to 0.0367 cm/day for the native vegetation.

Figure 6 summarizes the drainage calculations. The use of a capillary barrier or vegetation on top of the landfill resulted in a water flux reduction of about 38% for a capillary barrier layer of 30 cm, 42% for a capillary barrier of 50 cm, 34% for grass and 48% for *brachiaria*. Our results confirm literature findings that vegetative covers (also referred to often as evapotranspiration covers) can significantly reduce water flow rates through a landfill by promoting root water uptake and hence evapotranspiration (e.g., EPA, 2003; McGuire et al., 2009), not only in arid and semi-arid regions but also in more humid areas. Additional details of this study are given by Ottoni (2010).

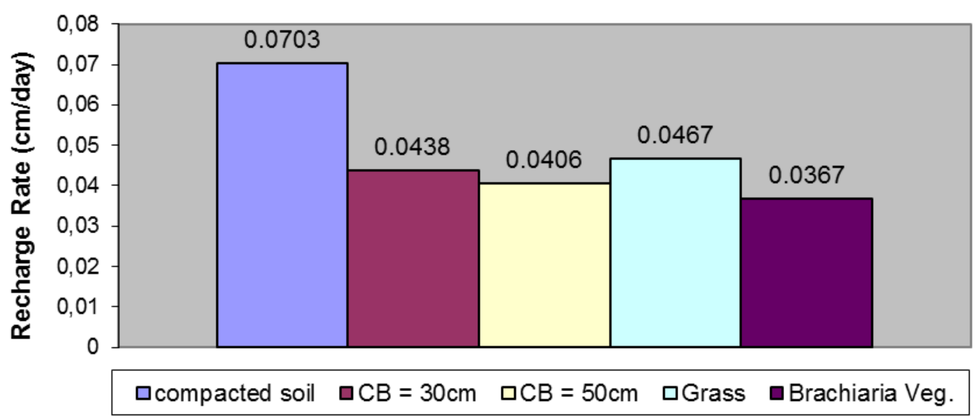

Figure 6. Comparison of calculated drainage rates from a landfill containing a compacted surface soil, capillary barriers (CBs) of 30 and 50 cm, and vegetative covers using grass and vegetation native to Rio de Janeiro, Brazil

4. The Goiania Repository

In September 1987 a major accident occurred with a ^{137}Cs teletherapy source in Goiania, Brazil (Paschoa et al., 1993; Heilbron et al., 2002). The accident caused widespread contamination of radioactive material (1375 Ci of ^{137}Cs) in the town of Goiania. Subsequent cleanup generated about 3,500 m^3 of solid radioactive wastes (about 6,000 tons of material). The wastes were disposed in a near-surface repository built in concrete. The purpose of this study was to perform a safety assessment of the low level radioactive waste deposit containing 137Cs over a time period of about 400 years.

The study was designed to provide estimates of water infiltrating through the soil cover above the repository into and through the repository and its concrete liners towards underlying groundwater. This was done by applying first a detailed water balance to the soil cover accounting for local precipitation and evapotranspiration rates, including root water uptake by grass on the cover. All calculations were carried out using HYDRUS-1D. Estimates were obtained of the infiltration of water from the cover through the concrete surface of the repository into and through the radioactive waste and underlying concrete liner. These flow rates were used next to simulate long-term ^{137}Cs transport from the repository through the bottom concrete liner into the underlying vadose zone until reaching the groundwater aquifer below the repository. Radionuclide transport calculations accounted for the effects of ^{137}Cs sorption and radioactive decay. Simulations provided estimates of possible future radionuclide fluxes into groundwater, thus permitting an evaluation of potential consequences to the environment and possible exposure to the public.

The subsurface repository was built in concrete, having dimensions of 19.6 m length, 60 m width and 6.20 m high, and with 20 cm thick concrete walls. A 50-cm thick uniform soil cover was placed on top of the repository and vegetated with grass. The waste inside the repository consisted mostly of compacted soil contaminated with ^{137}Cs (4.38 m). Figure 7 gives an above-ground view of the repository. A schematic cross-section of the facility and underlying vadose zone is shown in Figure 8. The repository is located at 16° 45′ 32″ S, 49° 26′ 16″ W, about 770 m above sea level.

Figure 7. View of the Goiania repository.

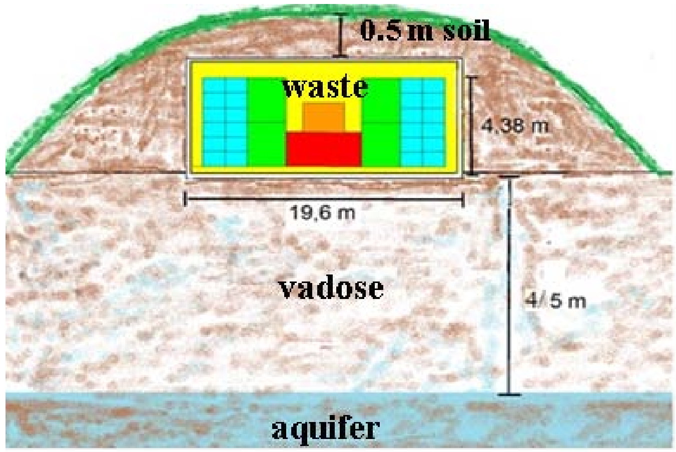

Figure 8. Schematic of the Goiania repository and underlying vadose zone.

CNEN, the Brazilian Nuclear Regulatory Agency, defined a maximum annual dose for the public of 0.25 mSv/y for a low-level radioactive waste repository. Two safety assessments were performed in the past (Heilbron et al., 2002). The present study was carried out 10 years later as part of the enforcement of national regulations. Modeling of the repository was done in two steps. First the behavior of the cover was studied assuming some degradation of the concrete liners with time (400 years). Fluxes through the upper liner into the repository obtained in this manner were used next to estimate ^{137}Cs transport rates from the waste vertically down towards the water table.

For the soil cover we used soil hydraulic parameters from a typical Cerrado soil (Batalha, 2010) containing 53% of sand, 10% of silt and 37% clay. The initial hydraulic properties for the concrete were taken from Schneider (2012). The soil cover above the upper concrete wall was modeled as a 50 cm layer covered by grass (30 cm rooting depth). Potential evapotranspiration rates (Fig. 9) needed for the simulations were obtained with the equation of Hargreaves (1975) using 10 years of temperature and precipitation data from a local weather station. These data were repeated 40 times to cover the 400 year total simulation period. For the root water uptake calculations we used the model of Feddes et al. (1978).

The saturated hydraulic conductivity (K_s) of the upper and lower concrete walls (liners) were assumed to decrease slowly due to natural degradation. We approximated this degradation process with a discrete function, using K_s=0.00315 m/year for the first 100 years, 0.0315 m/year for the next 100 years, and 0.315 m/year between 200 and 400 year. The porosity was simultaneously doubled after 100 and 400 years, while keeping the same values for the other hydraulic parameters of the concrete.

The contaminated waste layer in the repository was taken to be 4.38 m thick, situated over a 20-cm thick concrete liner and a 4 to 5 m thick vadose zone (Fig. 8) depending on fluctuations of the water table. Hydraulic properties of the waste layer were measured (Pereira, 1996), including the bulk density (1.7 g/cm^3) and for the calculations it was measured a value of 463 cm^3/g for the K_d in that layer. The relatively bulk density of the waste reflected compaction of the ^{137}Cs contaminated soils. The concrete liner below the waste was assumed to have the same unsaturated hydraulic properties as the degraded upper concrete cover. A partitioning coefficient (K_d) of 10 cm^3/g was used for the concrete (Aguiar, 2006). Hydraulic properties and K_d of the vadose zone were measured (Pereira, 1996), with a bulk density of 1.3 g/cm^3 and mean value of 430 cm^3/g for the K_d.

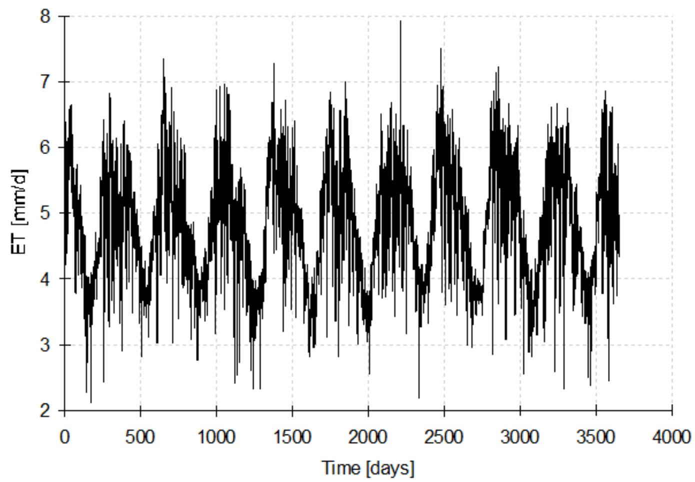

Figure 9. Calculated potential evapotranspiration rates.

Simulations for the infiltration of water from the cover through the upper concrete liner into the repository gave the following results: 0.00280 m/year for the initial period (0 to 100 years), 0.0290 m/year from 100 to 200 years, and 0.238 m/year for the period from 200 to 400 years. These infiltration rates were subsequently used for the ^{137}Cs transport equations. Figure 10 shows calculated ^{137}Cs concentrations of fluid leaving the waste layer and moving into the lower concrete liner. The three local concentration maxima in the curve are a consequence of the three conductivities used to approximate the concrete degradation process, leading to three flow rates and causing a different maximum during each for the three stages of concrete degradation. ^{137}Cs concentrations eventually approach zero because of radioactive decay.

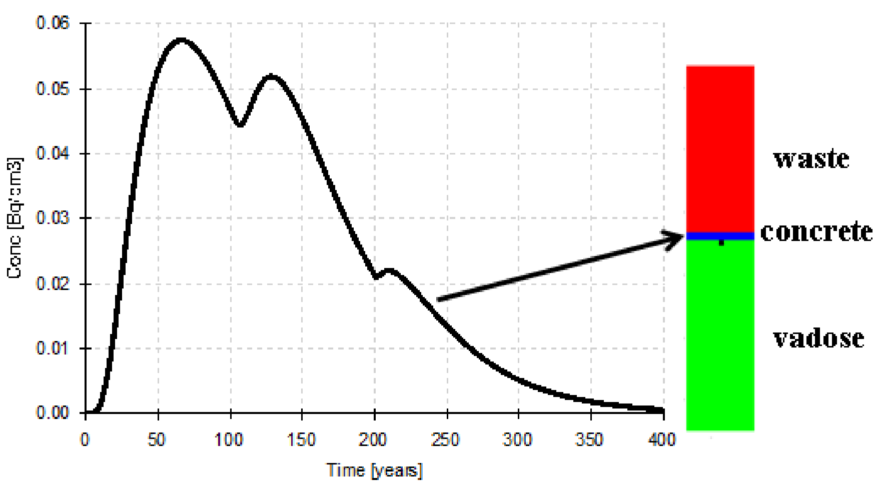

Figure 10. Calculated ^{137}Cs concentrations at the bottom of the waste layer.

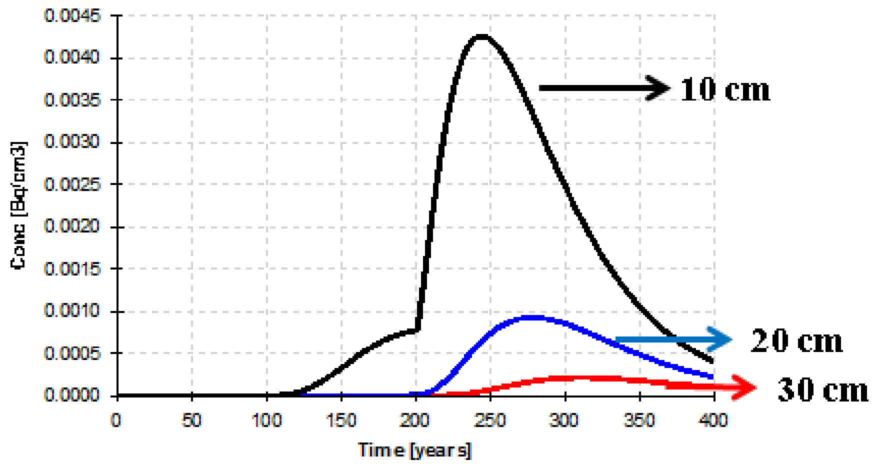

Figure 11. Calculated ^{137}Cs concentration at three locations in the vadose zone below the lower concrete liner.

5. Conclusions

In this paper we summarized three studies in which the HYDRUS-1D software package was used to investigate the performance of different types of waste disposal sites in Brazil: a conventional mining installation containing naturally occurring radioactive materials (NORMs), a municipal solid waste landfill, and a low-level radioactive waste repository. The three examples show the flexibility of HYDRUS-1D in being able to address different types of problems at involving different time and spatial scales. All calculations were based on the standard equilibrium formulation for variably-saturated flow (the Richards equation). Solute transport in the first example considered both equilibrium transport and some preferential flow as modeled with a dual-porosity type physical nonequilibrium transport formulation. The HYDRUS-1D code was found to be very appropriate and extremely easy to use for the required calculations.

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