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Deep row trenching of waste water treatment works sludge: modelling water flow and nutrient transport in soil profile with HYDRUS-2D

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ABSTRACT: HYDRUS-2D was used in simulating water flow and nutrient (nitrate and phosphorus) transport through soil profile from entrenched waste water treatment works sludge under four different application treatments. The objective was to simulate nutrient migration processes with conceptual simplifications of the inputs to the model based on field evidence, soil survey data and applicable literature. Hydrological modelling of the system require the relationship between the soil moisture content (θ), soil water potential (h) and saturated hydraulic conductivity (Ks). Model application indicated that, the simulated water flow in soil profiles over the monitoring period compared favorably to measured observed soil water contents. However, simulated nutrients transport indicated generally poor direct correlations with measurements but responses of the simulation and observations are similar and the similarities are true for the range of depths simulated in each profile.

Keywords: HYDRUS-2D; Modelling; Nutrients; sludge; Water

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I. INTRODUCTION

The contamination of ground water from the deep trench application of WWTW sludge is of great concern. The HYDRUS-2D (Simuneket al., 1999) modelling software have been used to simulate water and nutrient dynamics in wastewater applications to land and its impact on the surrounding subsurface environment. Studies have been carried out on wastewater application methods to land, such as landfilling, drains and septic tanks.

Two forms of HYDRUS-2D are available. The first kind is the HYDRUS-2D which has to do with executable code and a graphics-based interface. A mesh generator is available for relatively simple rectangle domain geometry in this instance. Users can either create the input files which describes the domain geometry and the associated finite element mesh by itself or use of the internal mesh generator to make a simple rectangular structured transport. The second kind comprises the first version and a CAD program MESHGEN2D use in designing more of the general domain and its discretization into an unstructured finite element mesh for a variety of problems involving variably-saturated subsurface flow and transport. The finite element model is a numerical technique derived from variational method for finding approximate solutions to boundary value problems. It is numerically stable, meaning that errors in the input and intermediate calculations do notaccumulate and can cause the resulting output to be waste (McCray et al. 2005).

Kirkleyet al., (2007) used HYDRUS-2D to model potential vadose-zone transport of nitrogen from onsite wastewater systems (OWS) at a development scale. HYDRUS-2D is obtained from flow codes SWMS-2D of Simuneket al. (1992) andCHAIN-2D of Simunek and van Genuchten (1994). A standard HYDRUS-2D package consistsof seven main modules including: HYDRUS2D, PROJECT MANAGER, MESHGEN2D, H2D_BERC(boundary), H2D_CALC (HYDRUS2), H2D_CLCI (HYDRUS2) and H2D_GRAF (Graphics). However, HYDRUS-2D is the main program that controls execution of the program and also help evaluate the kind of modules need to run for a particular simulation. HYDRUS2D contains manager of a project as well as the pre-processing and post–processing units. Results of the modelling simulations show that best-estimate model input parameter values lead to complete removal of nitrogen from the soil.

MESHGEN2D happens to be a meshgenerator for unstructured finite element. The program, is however, based on Delaunay triangulation andis seamlessly integrated in the HYDRUS-2D environment. MESHGEN2D is used to defineany two-dimensional geometric transport domain and subsequently to design a finiteelement discretization for that domain. BOUNDARY module helps the user to specify boundary andinitial conditions for both water flow and solute transport, and define the spatial distribution ofother parameters characterizing the flow domain (e.g., spatial distribution of soil materials,hydraulic scaling factors, root-water uptake parameters, and possible hydraulic anisotropy)and/or observation nodes (Sinton 1982; Closeet et al., 1989). Kostyanovskyet al., (2011) studied leaching potential and forms of phosphorus in deep row applied biosolids underlying hybrid poplar.

The capacity of HYDRUS-2D to converge to a stable solution depends on the discretization andtemporal iteration schemes (Pang et al., 2000; Ventrella et al., 2000; Hassan et al., 2004). The finite mesh was recommended by Simuneket al. (1996)to be constructed with close nodal spacing where the hydraulic gradient is expected to be largeas the soil surface for atmospheric BCs, and near internal source/sinks such as tile drains. Aspaced mesh is especially needed for coarse-textured soil with high n-values and somealpha values Their result was that the HYDRUS model was adequate to simulate effluent flow and NO_3 transport through soil domains under different environmental and application conditions. In addition, Mailholet al. (2001) studied the impact of fertilization practices on N leaching under irrigation through field experiments and numerical modelling (HYDRUS-2D). According to them, despite the sufficient application depth of water, the amount of leaching N is not that much high, thus 22% N/ha which is about 11% the amount of N application which was realized through measurement at the field and simulation by modelling approach suitable for 2D water and transfer of solute in HYDRUS-2D.

The objective of this paper was to use HYDRUS-2D as a tool, to develop our understanding of (a) the dynamics of soil water contents with respect to trenching of WWTW sludge under different application rates (b) the effect of preferential flow on water flow and nutrients transport. The study provided recommendations for effective management strategies to minimize the risk of nutrients leaching through soils into groundwater.

II. MATERIAL AND METHODS

The experiment was conducted at ShaftonKarkloof Falls, about 10 km from Howick, in the Kwazulu-Natal province (29°24’ S and 30°12’ E). The entrenchment plot within a catchment area of a stream on the southern edge is shown in Figure 1. The site lies in gently undulating terrain at 1260m above sea level. The site is well-suited to E. dunnii and highly representative of commercial eucalypt stands in the KwaZulu-Natal Midlands, in terms of site index, climate, soil properties and historical land use. The mean annual rainfall is around 950mm, the long-term mean monthly minima for the coldest month (June) and the warmest month (January) are 3.7°C and 14.8°C respectively, while corresponding maxima are 19°C and 25°C. The sites suitable for forestry in the Midlands of KZN are dominated by highly-weathered soils derived from sedimentary rocks (shale, sandstone and mudstones), with igneous (dolerite) intrusions. The soil at the trial site is derived from a mixture of dolerite and shale. It has a humus-rich, clayey A horizon (0 to 0.3m depth) overlying a yellow-brown clayey B2 horizon, which grades into weathered shale at a depth of about 1.2 m.

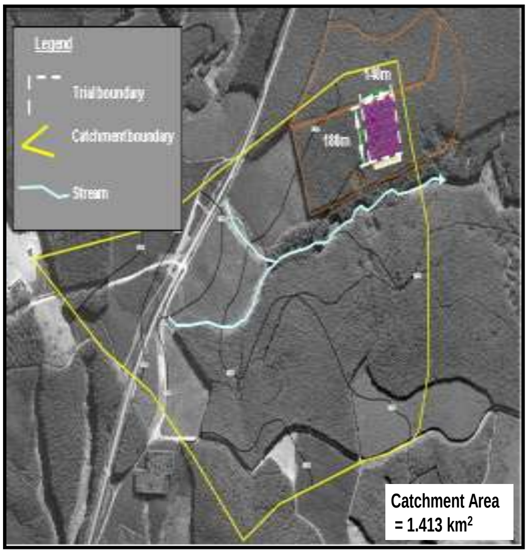


Figure 1. Map of WWTW trenching site and catchment area.

The trench layout at the WWTW sludge burial site is shown in Figure 2. The trial consists of four treatments of WWTW sludge, assuming 1% N in wet sludge:

i. Treatment 1 (T1): 250mm (Sludge thickness) in trench, 5400kg N/ha
ii. Treatment 2 (T2): 500mm (Sludge thickness) in trench, 10800 kg N/ha
iii. Treatment 3 (T3): 750mm (Sludge thickness) in trench, 16200kg N/ha

iv. Treatment 4 (T4): control, no sludge application, and
v. T5-Undisturbed locations.

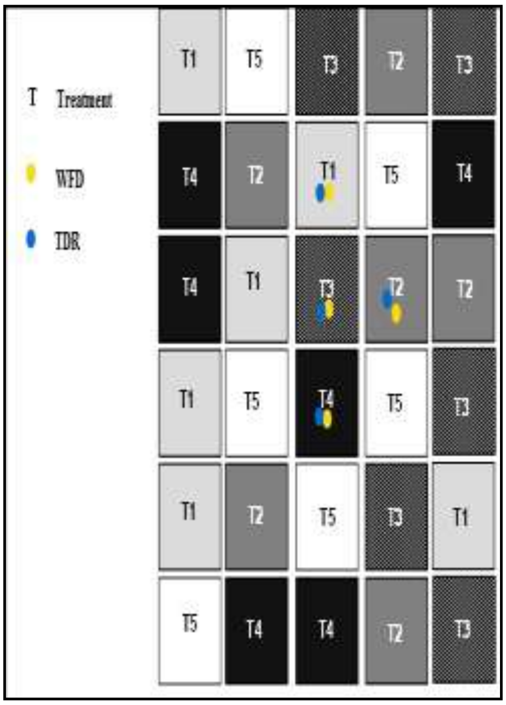


Figure 2. Schematic layout of Experimental plot and measurement locations.

Each of these were replicated to cover an area 20m x 20m, which will allow for 6 rows of 20m within each replicate, tree spacing of 3m between and 2m within the rows. The trenches were dug using a backhoe to a depth of 1.3m and a width of 1.0m. The trenches were backfilled to allow for the required amount of sludge to be filled to 30cm below the surface. It was then covered and all the soils replaced, creating a heaped overburden, which was anticipated to sink as dewatering of the sludge occurs. The trees were then planted into the overburden.

Campbell Scientific TDR100 system was used to measure the water contents in the materials which may become saline. The system measures volumetric water contents and electrical conductivity of the material simultaneously. TDR probe were installed in the trenches of one selected trench in each of the four treatments at depths 0.15 m, 0.5 m and 1.2 m as shown in Figure 3. The TDR read volumetric water contents and electrical conductivity at these predetermined depths. TDR soil water content measurements are based on the travel time measurements of electromagnetic (EM) waves in the TDR probes installed in the soil (Toppet al., 1980). The readings were taken manually by means of the PCTDR software installed on a laptop at least twice a month.

FullStop WFDs were installed in pairs at each treatment at the depths of 0.5m and 1.2m to from which water samples were extracted periodically for analysis. When water gets focused inside the funnel and the soil at the base becomes so wet that water seeps out of it, passes through a filter, and is collected in a reservoir (Stirzaker 2003). The DR/2000 Spectrophotometer instrument was used to measure nitrate of nitrogen and orthophosphate which was then calibrated to read nitrate and phosphorus.

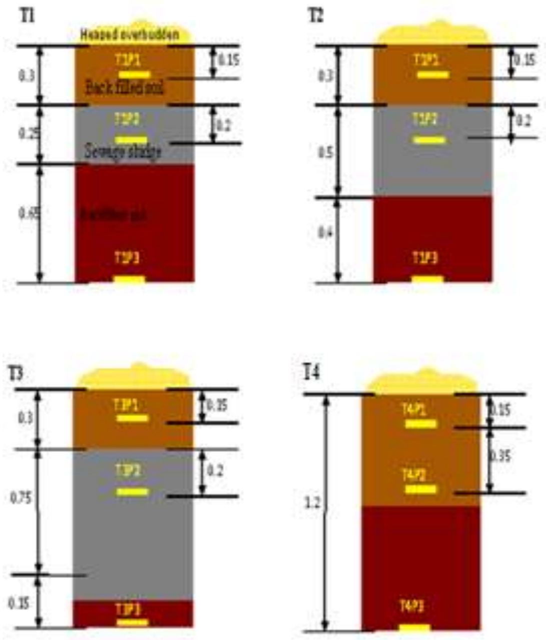


Figure 3. Schematic layout of TDR probes in Treatments T1, T2, T3 and T4.

HYDRUS-2D solves the Richards equation numerically (Equation 1) for variably saturated flow of water through soil (Richards, 1931). The van Genuchten equations (Equations 2 and 5) define the hydraulic characteristics of the soils. The resulting equations are solved iteratively. The governing flow equation considers two-dimensional isothermal Darcy flow of water in variably saturated porous medium. These conditions are given by a modified Richard's equation:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_i}+K_{iz}^{a}\right)\right]-S$$

1

where θ = volumetric water content [m^3/m^3]
h = soil water pressure head [m]
S = sink term for root water uptake [1/d]
x_i(i=1, 2) = special coordinates [m]
t = time [d]

K_{ij}^A= components of a dimensionless anisotropy tensor K^A [-]

K = unsaturated hydraulic conductivity function [m/d]

Where $K(h, x, z) = K_s(x, z)\, K_r(h, x, z)$

K_r = relative hydraulic conductivity [m/d]

K_s = saturated hydraulic conductivity [m/d]

The properties of the unsaturated soil, θ (h) and K (h) in equation 2.1 are generally non-linear but not always functions of the pressure head. This knowledge of the soil hydraulic characteristic is essential to model water movement in the vadose zone. Therefore, HYDRUS-2D permits the use of three different analytical forms of the hydraulic relationship. These are:

- Brooks & Corey, 1964;
- Van Genuchten, 1980 and
- Vogel &Cislerova, 1988.

During the simulations in this study, the van Genuchten characteristic equations were applied. The van Genuchten model uses a statistical pore size distribution model of Mualem (1976) to obtain the equation for the unsaturated hydraulic conductivity function in terms of soil retention parameters. The equations of the van Genuchten characteristics are given by:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \quad h < 0 \qquad 2$$

$$\theta(h) = \theta_s \quad h \geq 0 \qquad 3$$

$$K(h) = K_s S_e^I \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad 4$$

$$m = 1 - 1/n \quad n > 1 \qquad 5$$

θ_r = residual water content [m^3/m³]

θ_s = saturated water content [m^3/m³]

α = inverse of the air-entry value [1/m]

n = pore size distribution index [-]

K_s = saturated hydraulic conductivity [m³/m³]

l = pore connectivity parameter [-]

S_e = effective water content $(\theta-\theta_r/\theta_s-\theta_r)$

These seven independent parameters describe the soil hydraulic properties. Where K_s, $\theta_r$and $\theta_s$can be determined by field measurements, the parameters α, n and I are merely empirical coefficients based on air entry pressure (α), pore size distribution (l) and Poiseuille's law defining the shape of the hydraulic functions.

The material characteristics, the soil water and solute dynamics time series were analysed to develop parameters for simulation and calibration of the soil water and solutes. The soil hydraulic characteristics measurements were used to predict the van Genuchten parameters (α, n, L), using the Rosetta program (Schaapet al., 2001), which is used for estimating the hydraulic properties of soil. These predictions were modified during the modelling to accurately predict the variability of observed water content and nitrate and phosphorus concentrations in the soil. From these simulations the soil water fluxes of evaporation, transpiration, drainage and the solute migration fluxes were quantified for each site. A historic time series of meteorological data could be used to simulate beyond the monitoring period in order to assess the impact of wet and dry periods as well as extreme events.

The depths of soil layers in the trenches of each treatment were 0-30, 30-60, 60-90, 90-150 cm; but with variation inside the trenches of each treatment with the introduction of WWTW sludge of different depths. The standard Hydrometer method (Gee and Baunder, 1986) was used to determine the particle size distribution. The four undisturbed soil samples from each treatment (T1, T2, T3 and T4) at depth intervals of 0-30, 30-60, 60-90, and 90-150cm, were used to determine the soil water retention curve at 2, 5, 10, 20, 50, 100, 200, 500, 1000, 1500 kPa, using the controlled outflow cell and pressure plate extractor. The most sensitive parameter to model water flow is the saturated hydraulic conductivity (K_s). To determine this parameter, two commonly-used methods were used, the soil infiltration rates (cm/h) were determined under saturated conditions at depths of 0-30 cm, 30-60 cm, 60-90 cm and 90-150 cm, using the double ring method (in situ) (Bouwer, 1986) for T3 and T4 and the Guelph permeameter test for T1 and T2 (Reynolds and Elrick, 1986).

The boundary conditions used for each cross-section were atmospheric boundary condition at the surface, free drainage boundary condition at the bottom and no-flux boundary condition at the right and left sides (Figure 4). HYDRUS-2D version 1x was use to run the simulations. To run the simulation, observation points were placed at points 0.15 m, 0.5 m and 1.2 m within the trench in order to compare the simulation and the observation at that point. These were the same positions where TDR probes have been placed for volumetric water content reading in a trench in each treatment. Wetting front detectors located at 0.5 m and 1.2 m also collected samples for nitrate and phosphorus analysis. The initial condition of nitrate and phosphorus transport at the beginning of the simulation (1 January 2010) for each cross-section were assigned using measured nitrate (357 mg/l) and phosphorus (23 mg/l) concentrations from samples collected from wetting front detectors installed in the sludge. The constructed finite element mesh with the selected boundary and initial conditions were used to simulate water flow, nitrate and phosphorus transport. In addition to precipitation, the potential evaporation and the potential transpiration were required for model application. Daily potential evapotranspiration rates were calculated with the ACRU model (Smithers et al., 2002), to derive the time variable boundary condition, using data from the nearby weather station near the site. A crop factor was applied by choosing the vegetation “Forested e.g. wattle trees” in the ACRU model to account for crop factor.

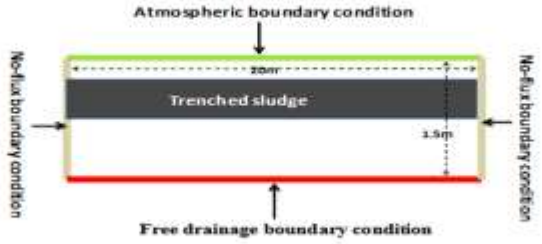


Figure 4. Conceptual model and boundary conditions for the trenches.

III. RESULTS AND DISCUSSIONS

The Hydraulic parameters optimised from the RETC input data from particle size distribution measurements of the WWTW sludge was used as input for the modelling as presented in Table 1. For the soil profiles, the hydraulic parameters were also optimised from RETC with particle size distribution coupled with water retention characteristics as shown in Table 2. However, the measured saturated hydraulic conductivity values were used in modelling.

Table 1. Hydraulic parameters for sewage sludge.

Profile	**θ_r mm^3.mm^{-3}**	**θ_s mm^3.mm^{-3}**	**α mm^{-1}**	**n (-)**	**K_S mm.day^{-1}**	**l (-)**
WWTW sludge	0.099	0.497	0.0017	1.269	229.0	0.5

Table 2. Van Genuchten parameters for hydraulic characteristics in Treatments 1-4.

Profile	**Depth (mm)**	**$\theta_r$mm^3.mm^{-3}**	**$\theta_s$mm^3.mm^{-3}**	**α mm^{-1}**	**n(-)**	**K_S mm.day^{-1} (predicted)**	**K_S mm.day^{-1} (measured)**	**l (-)**
T1	0-300	0.001	0.615	0.004	1.366	243.90	2.69	0.5
	Sludge:300-550	0.001	0.615	0.004	1.366	229.00		0.5
	550-600	0.000	0.644	0.000	1.314	93.70	4.21	0.5
	600-900	0.000	0.600	0.000	1.837	360.60	7.38	0.5
	900-1500	0.000	0.592	0.000	1.399	346.40	1.09	0.5
T2	0-300	0.000	0.501	0.002	1.427	168.10	5.02	0.5
	Sludge: 300-800	0.099	0.497	0.002	1.268	229.00		0.5
	800-900	0.000	0.459	0.000	1.602	360.60	7.09	0.5
	900-1500	0.000	0.421	0.000	1.369	100.70	1.31	0.5
T3	0-300	0.000	0.589	0.000	1.388	119.00	2400.3	0.5
	Sludge: 300-1050	0.099	0.497	0.002	1.269	229.00		0.5
	1050-1500	0.000	0.479	0.001	1.345	115.30	5111.8	0.5
T4	0-300	0.000	0.557	0.002	1.631	1201.10	2978.3	0.5
	300-600	0.000	0.582	0.000	1.430	146.00	1943.4	0.5
	600-900	0.000	0.464	0.000	1.462	323.30	4415.4	0.5
	900-1500	0.000	0.562	0.006	1.436	294.80	3002.4	0.5

The parameters were used by Hassan et al., 2010 to study solute transport dynamics in which treated effluent was applied to soil at different rates and frequencies of dosing. In thisstudy, series of soil columns were used to simulate a subsurface drip irrigation system and dosed with recirculating media filter effluent at different rates of application (518, 1,036, and 2,071 cm^3/d)and dosing frequencies (6, 12, and 24 doses/d). The two-dimensional code used in HYDRUS-3D wasused to simulate solute transport (ie Cl, NO3 and PO4^{-3}) in the system. Results show that most ofthe Cl were lost from the system through seepage (91 % to 98 %), meanwhile seepage (65 %) anddenitrification

(31 %) were the main mechanisms for reducing NO3 concentrations in the soil.Much of the $PO4^{-3}$ remained in the soil (thus between 94 % and 98 %), with loss of seepage accountingfor a small percentage of the $PO4^{-3}$ that was added (from 90.01 % to 4 % at the 518 and 2,071cm^3/d application rates, respectively). The agreement between the determined and simulated Cl, NO3,and $PO4^{-3}$ concentrations indicated that HYDRUS adequately simulated transport of the solutes by the soil under a range of environmental and effluent application conditions. The$PO4^{-3}$ simulated concentrations in the soil leachate was slightly higher than the measuredconcentrations and might be underestimated by P immobilization based on the sorption of Pisotherms. The most important chemical processes in soils that was affecting $PO4^{-3}$ transport and contamination in ground and surface water ecosystems was adsorption and desorption (Johnsonand Cole, 1980). Langmuir $PO4^{-3}$ adsorption isotherm coefficient for soil textural class wasadapted from Hassan et al. (2010) work and used for transport of Phosphorus.

Specific physical and chemical parameters are needed when simulating the transport of nitrates and phosphorus through soils. These parameters were adapted from a study by Hassan et al., 2010 in modelling effluent distribution and nitrate transport through an On-Site wastewater system using the two-dimensional code in HYDRUS-3D. The solute transport parameters adapted for simulations in this study are shown in Table 3.

Table 3. Solute transport and reaction parameters for Treatments T1-T4 at SAPPI.

Profile	**Depth (mm)**	**Soil texture class**	**NO_3**				**P**
			SinkL1' (day^{-1})	**LongD (mm)**	**TrsnsD (mm)**	**D (mm^2d^{-1})**	**K_d ($mg^{-1}mL^3$)**
T1	0-300	Sandy loam	0.005364	200	40	84	30
	Sludge:300-550	Silty clay loam	0.005364	150	30	84	34
	550-600	Sandy clay loam	0.005364	50	10	84	30
	550-900	Loamy sand	0.005364	100	20	84	34
	900-1500	Sandy loam	0.005364	200	40	84	30
T2	0-300	Sandy clay loam	0.005364	50	10	84	30
	Sludge:300-800	Silty clay loam	0.005364	150	30	84	34
	800-900	Sandy loam	0.005364	200	40	84	30
	900-1500	Sandy clay loam	0.005364	50	10	84	30
T3	0-300	Sandy clay loam	0.005364	50	10	84	30
	Sludge:300-1050	Silty clay loam	0.005364	150	30	84	34
	1050-1500	Sandy clay loam	0.005364	50	10	84	30
T4	0-300	Loamy sand	0.005364	100	20	84	34
	300-600	Sandy clay loam	0.005364	50	10	84	30
	600-900	Sandy loam	0.005364	200	40	84	30
	900-1500	Sandy loam	0.005364	200	40	84	30

SinkL1': first-order degradation rate constant for dissolved phase in the decay chain reaction (1/day); LongD: longitudinal dispersivity (mm); TransD: transverse dispersivity (mm); D: molecular diffusion coefficient in free water (mm2/day); Kd: Langmuir PO4-3 - P adsorption isotherm coefficient (/mg mL3).

Observation points were positioned to correspond to measurement locations so that comparisons of simulations with measured values can be used to assess model performance and thereby have confidence on model predictions. Volumetric water content readings from TDR were used as observed data. The different patterns of water content distributions between the treatments are thought to be mainly due to the amount of sewage sludge in the trench (Figure 5). Soil physical properties in the four treatments did not show significant variation. The results as seen in Figures 5 indicated that simulated and observed water contents follow a similar trend. The correlation coefficient between observed and simulated water contents in all treatments (T) at the 3 depths (P1=0.15m, P2=0.5m and P3=1.2m) varies from 0.0642 to 0.785 with the exception of T3P2 with a value of -0.793. Root mean square error (RMSE) between simulated and observed values was also estimated to examine the predictability of the model. RMSE values varied from 0.019 to 0.059. While the direct correlations are generally poor the responses of the simulation and observations are similar and the absolute magnitudes of the simulated and observed water contents are mostly close with certain periods showing differences (maximum difference is 0.20). Moreover, the similarities are true for the range of depths simulated in each profile. Hence simulated fluxes can be accepted.

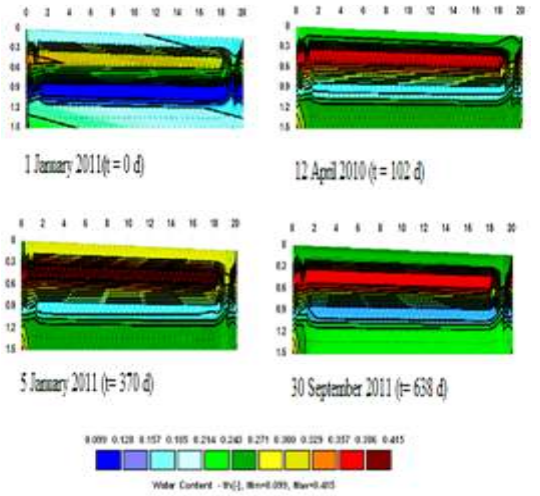
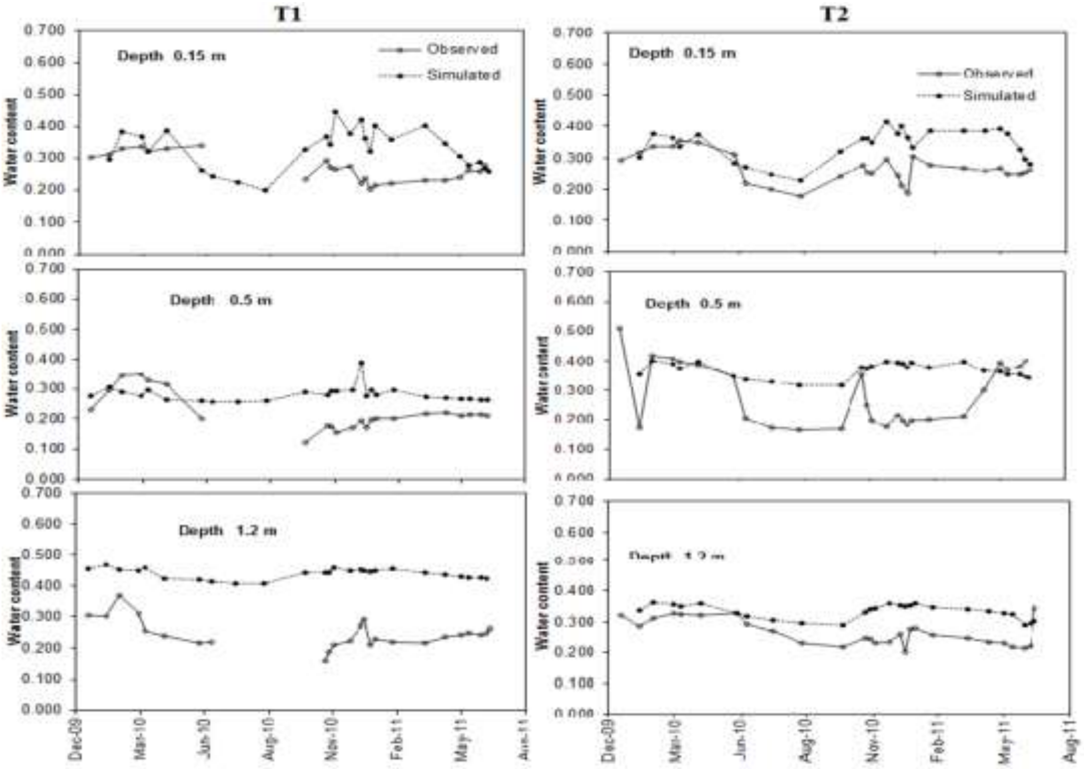


Figure 5. Simulated water content in Treatment 1 for 4 characteristic times during the periodfrom 1 January 2010 to 30 September 2011 in the trench (dimensions in m).

Water contents simulated by HYDRUS-2D compared to the water content from field data collected from each treatment at the study site (by TDR) for the top 120 cm of the soil profile over the season (Figure 6) indicated that the model moderately over-estimated the measured water contents over most of the season at all treatments, potentially due to under-estimation in the amount of free drainage occurring at the sites and an over-estimation of the soil porosity. From December January 2010 to September 2011, the model under-estimated the measured water contents at some sites at certain periods; potentially the result of an over-estimation in the amount of free drainage (default free drainage parameter in HYDRUS was used) or ET. The difference in the observed and simulation may be due to the undisturbed samples taken, while the profile was highly disturbed during trenching of sludge.



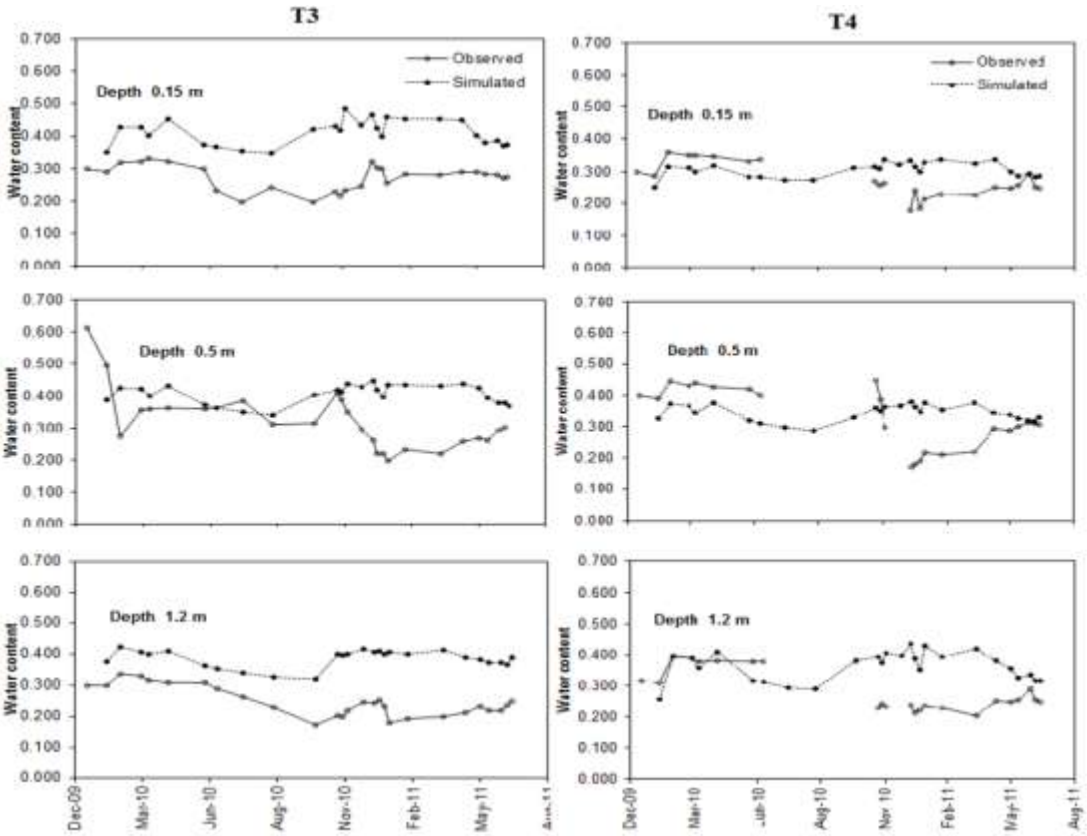


Figure 6. Observed and simulated water contents in treatments T1, T2, T3 and T4.

Using dispersivity values adapted from Hassan et al. (2010), observed and simulated nitrate concentrations were compared for treatments T1, T2 and T3. However, WFD installed at T4 could not capture water for nutrient analysis because of rapid drainage due to profile disturbance coupled with lack of sludge material. To examine the predictability of the model, the simulation was carried out to predict the nitrate distribution, using a simulation period of 638 days (number of days from the start of experiment to the last day of data collection). Simulated nitrate transport in Treatments 3 (T3) for six characteristic times at the site is shown in Figure 7. Simulated and observed values of nitrate indicated some differences in treatments at certain depths (Figure 8). The correlation coefficient between simulated and observed nitrate concentration varied from -0.602 to 0.959. The RMSE between simulated and observed varied from 3.84 to 74.19. These differences might have occurred through biological or chemical changes following collection, which affected the observed data. The collected samples were kept in cold storage until analysis, but further precautions may have been necessary. For example, the samples could have been treated with mercuric chloride ($HgCl_2$) to inhibit bacteria, which are applicable for nitrogen and phosphorus forms. In addition, the parameter selection such as dispersivity values and hydraulic properties may require accurate measurements.

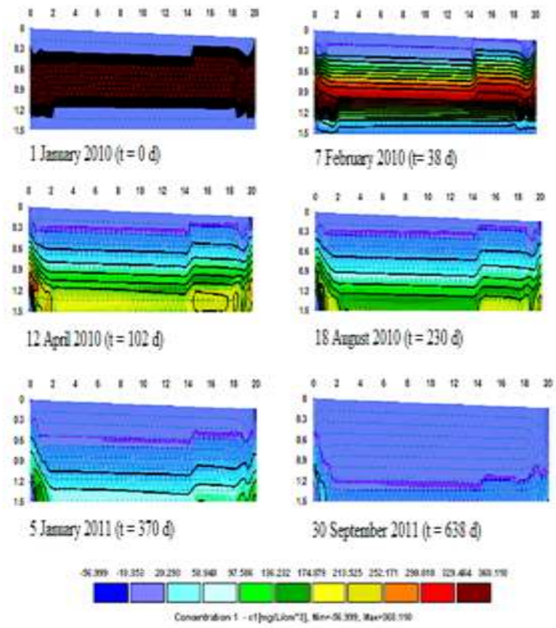


Figure 7. Simulated nitrate transport in Treatments 3 (T3) for six characteristic times at the trench (Dimensions in m).

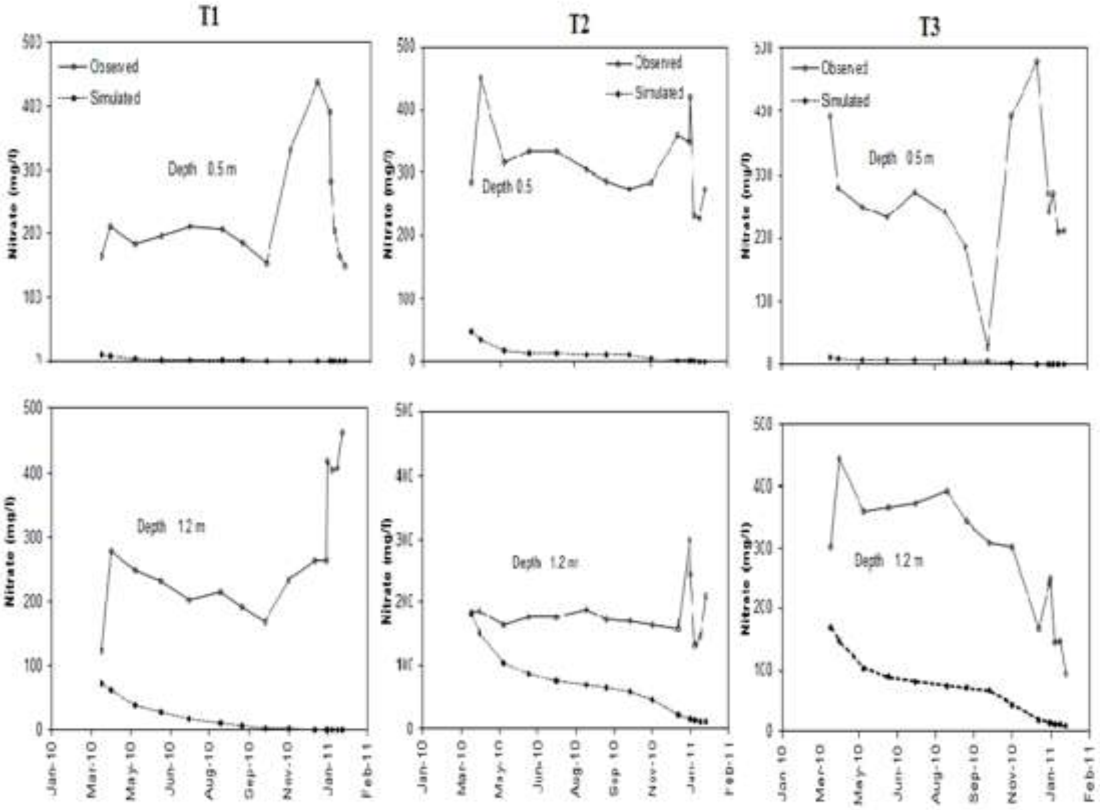


Figure 8. Observed and simulated nitrate in treatment T1, T2 and T3

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HYDRUS 2-D simulations, compared to the field data from wetting front detectors indicated an under-estimation of nitrate concentrations in the profile in most of the treatments. Clearly, the degradation rates used in the model should be reduced.

Phosphorus (P) in solutions is attached soil particles and is strongly absorbed by the soil, forming stable bonds with the soil. The soil absorbs P molecules in the soil solution. Phosphorus then interacts with soil particles in its exchangeable form. Although phosphate is strongly absorbed by soil particles, many recent studies have shown that phosphate can easily be found in subsurface fresh water (Enright and Madramootoo, 2003; Simard, 2005). As the concentration of phosphate increases in the soil solution, the phosphate is adsorbed to the soil, while the concentration of phosphate in the solution is depleted, the phosphate adsorbed in the soil dissolves back into solution. The prediction of phosphorus transport in soil can be improved with the correct application of computer modelling for simulating P distribution under laboratory and field conditions. Ben-Gal and Dudley (2003) concluded in their experiment that the Langmuir isotherm, provided with the HYDRUS-2D model, is inadequate for describing P sorption. It assumes instantaneous equilibrium between the solid and solution interfaces. The comparison of simulated and observed P (Figures 9) in all treatments, shows that there was no significant variation in concentration over the monitoring period, except in a few cases, where the model over-estimated the P concentrations at certain depths. This could be due to an inappropriate adsorption coefficient (too low) used in the model for these soils.

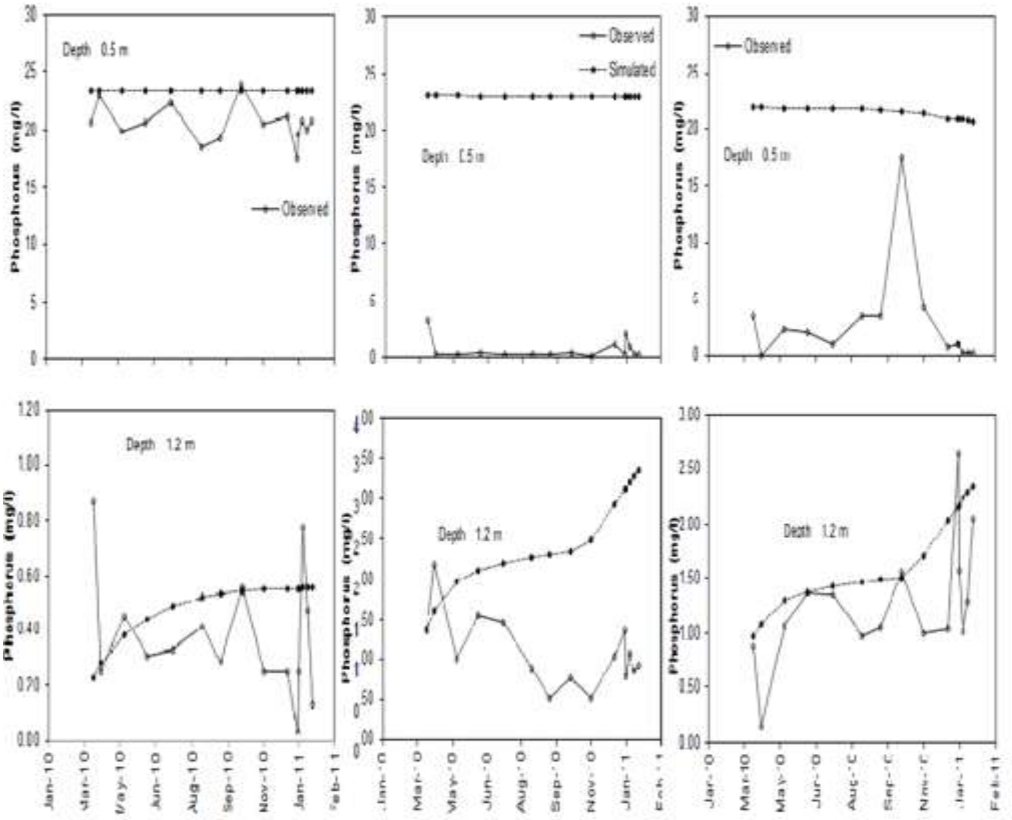

Figure 9. Observed and simulated phosphorus in Treatment T1, T2 and T3.

The results indicated that there was good correlation between observed and simulated NO_3 and P concentrations in some of the treatments and depths, while some show significant differences. Treatment 3 (T3) at the depth of 1.2 m showed the highest R^2 value of 0.5746 between observed and simulated nitrate concentrations, and R^2 value 0.3405 for phosphorus concentration, and also in T2 at the depth of 1.2 m with R^2 value of 0.3405 for phosphorus concentrations. T1 at the depth of 0.5 m also indicated moderately less R^2 value of 0.1057 and R^2 value of 0.2015 and 0.1545 for nitrate and phosphorus concentrations respectively at T1 at the depths of 0.5 m and 1.2 m. The rest of the treatments and depths indicated very low R^2 values from 0.0023 to 0.0953 for nitrate and phosphorus concentrations. The higher R^2 values indicated a good correlation and the smaller R^2 values an indication of significant differences between observed and simulated concentrations (Table 4). While the direct correlations are generally poor the responses of the simulation and observations are similar. Moreover, these similarities are true for the range of depths simulated in each profile. Hence simulated nutrient fluxes can be accepted. The differences between model and experiments may be as a result of the application of default free drainage boundary condition in HYDRUS, without sufficient time for the reaction between the soil and solute. Overall, the simulated P concentration in the treatments tended to be slightly higher than observed concentrations. These differences may also occur as a result of the increase in error with depth, due to preferential flow paths and/or the choice of incorrect adsorption isotherms.

Table 4. Correlation between observed and simulated NO_3 and P concentrations at SAPPI.

Treatment	Depth(m)	R^2	
		NO_3	P
T1	0.50	0.1057	0.0953
	1.20	0.2015	0.1545
T2	0.50	0.0501	0.0967
	1.20	0.0210	0.3405
T3	0.50	0.0023	0.0847
	1.20	0.5746	0.3405

IV. CONCLUSIONS AND RECOMMENDATIONS

The potential for the use of the HYDRUS-2D to model soil-water, phosphorus and nitrate movement for the trial, was investigated. It was determined that it is a valid approach to determining water flow and nutrient fluxes. The modelling results suggest that the model is sufficient and adequate for simulating water movement and nutrient transport through soil profile under natural climatic conditions. The model over-estimated the P concentrations at certain depths. This could be due to an inappropriate adsorption coefficient (too low) used in the model for these soils. NO_3 concentrations were under-estimated the all treatments at all depths. The direct correlations are generally poor but responses of the simulation and observations are similar. Moreover, these similarities are true for the range of depths simulated in each profile.

The simulations provide evidence that nitrate degradation values derived from a study on the use of effluent in irrigation (Hassan et al.,) cannot be transferred to this case where the soil water nitrate was derived from seepage from the waste sludge. The study also suggests that the disturbance of the soil during trenching may change the hydraulic properties of the soil profiles. Management practices to reduce nutrient leaching from deep trench application of WWTW sludge must be aim to minimize the effect of preferential flow by adopting appropriate application methods coupled with thorough investigation of soil and geology of the site.

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Conflicts of Interest:
The authors declare that there are no conflict of interest.

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