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Chapter 9

# Simulation of Phosphorus Transport in Soil Under Municipal Wastewater Application Using Hydrus-1D

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Additional information is available at the end of the chapter

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## Abstract

Today, wastewater irrigation is one of the best options to reduce the stress on limited availability of fresh water and to meet the nutrient requirements of crops. In the present study, the simulation accuracy and performance of the HYDRUS-1D model to predict phosphorus leaching have been evaluated and compared to lysimeter data. More specifically, the effects of irrigation using four types of water (wastewater, effluent, mixture of freshwater and effluent, and freshwater) on three types of soil (sandy loam, loam, and clay loam) have been investigated both experimentally and numerically. Barley was planted as a common agricultural crop. The leachates from lysimeters have been collected and sampled at the beginning, middle, and end of the growing season. These samples have then been analyzed for phosphorous. The results show that the trend of change in nutrient concentration (P) was a function of plant requirement. Maximum process of leaching occurred concurrent with minimum plant requirement. The average phosphorus leaching into the root depths turns out to be insignificant, as it amounts to only 0.65–1.65%. This reassuring result means that wastewater with high concentrations of phosphorus compounds (up to 5–10.3 $PO_4$-P $mgl^{-1}$) can just be treated through an intermittent application to the land surface. Overall, a good agreement between experimental- and numerical-model results is obtained, wherefore the model overestimates the mean phosphate leaching during the growing season of the crop slightly. On the basis of these results, soil with loamy texture was considered to be the most suitable type for irrigation with wastewater and effluent. The results of this research indicate that with a proper management program in regard to the types of soil to be used, crops to be cultivated, water quality, and timing maneuver, the negative impacts of low quality water on soil/plant/groundwater systems can be minimized.

**Keywords:** irrigation, wastewater, phosphorous, barley, HYDRUS-1D

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## 1. Introduction

Besides wastewater usage and their environmental impact, water shortages are a severe problem in several parts of the world. Many parts of the world are threatened by water scarcity. In the Middle East, the threat of water scarcity is particularly important as it is an arid region with limited fresh water sources. Therefore, seeking for unconventional sources of water is inevitable in this area. The use of treated sewage water for irrigation ensures the reuse of water resources. Municipal wastewater not only offers an alternative water irrigation source, but also the opportunity to consider as low price fertilizer because of its high nitrogen (N), phosphorus (P), and potassium (K) content [1].

Phosphorus is a valuable nutrient contained in wastewater [2]. There is potential for these nutrients present in recycled water to be used as a fertilizer source when the water is recycled as an irrigation source for agriculture [3]. Phosphorus (P) is commonly found in municipal and agricultural waste and wastewater, originating from the digestion of phosphorus-containing food sources. Municipal wastewaters may contain 5–20 $mgl^{-1}$ of total phosphorus, of which 1–5 $mgl^{-1}$ is organic and the rest is inorganic. Phosphorus in natural waters is usually found in the form of phosphates ($PO_4^{3-}$). During irrigation with wastewater, phosphorus may be leached from or retained in the soil or taken up by plants. Too much phosphorus in the water causes algae to grow faster than the ecosystems can handle.

Phosphorus can move into surface water bodies by runoff or erosion and cause water quality problems such as eutrophication. Phosphates are not toxic to people or animals unless they are present in very high levels. The phosphate in wastewater is initially quite soluble and available [4]. Movement of phosphate is slow but may be increased by rainfall or irrigation water flowing through the soil. Due to erosion of soil and when the sediment reaches a body of water it may act as a sink or a source of P in solution. Therefore, to develop effective management practices, there is a need to improve the understanding of P transport in the soil profile through percolation or matrix flow. In the case of blue-green algae, toxic by-products can be produced, which create health issues if a lake or reservoir would be used as a source of drinking water. For this reason, phosphorus removal is an essential role of wastewater treatment plants and testing for phosphorus in the plant effluent is critical. Controlling phosphorus discharged from municipal and industrial wastewater treatment plants is a key factor in preventing eutrophication of surface water bodies. The objectives of this study were, using HYDRUS-1D model [5], as a tool, to develop an understanding of vertical distribution and transport processes $PO_4$ leaching in soil lysimeter condition. Calibration and validation of HYDRUS-1D model was based on the experimental results.

## 2. Material and methods

### 2.1. Experimental site

The experiment was carried out in the field of lysimeters at the Mashhad research station site, (36°13′ latitude, 59°38′ longitude) in northern east Iran during growing season (2004–2005).

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This research was done to investigate the soil capacity to remove impurities when it is irrigated with wastewater and effluent and to study the potential impacts on groundwater quality. For this purpose, the effects of irrigation with four types of water (wastewater, effluent, mixture of freshwater and effluent, and freshwater) on three types of soil (sandy loam, loam, and clay loam) were investigated. A randomized completely blocked design was performed with three replications. The experiment was carried out, using 36 lysimeter (2 × 1.5 m) as experimental units. The number of lysimeters was equal to the number of experimental treatments × replicates (i.e., 4 × 3 × 3 = 36). Barley was planted as a common agricultural crop. A layer of gravel was placed at the bottom of each lysimeter to facilitate drainage. The leachates from lysimeters were collected and sampled at the beginning, middle, and end of the growing season. The samples were analyzed for chemical oxygen demand (COD) [6], phosphate, and nitrate [7]. Physicochemical characteristics of irrigation water, wastewater, and soil used in this study are summarized in **Tables 1** and **2**, respectively.

| Parameter | Unit | Irrigation water | | | Standard value | |
|---|---|---|---|---|---|---|
| | | Wastewater | Effluent | Well water | FAO[a] | IDE[b] |
| PH | – | 8.3 | 7.9 | 8.2 | 6.5–8.4 | 6–8.5 |
| EC | $dSm^{-1}$ | 1.7 | 1.4 | 0.6 | <3 | – |
| SAR | $(meql^{-1})^{1/2}$ | 3.8 | 4.7 | 0.24 | <3 | – |
| TSS | $mgl^{-1}$ | 254* | 101* | 3 | – | 100 |
| $Na^+$ | $meql^{-1}$ | 8.07 | 8.35 | 0.4 | – | – |
| $K^+$ | $meql^{-1}$ | 0.1 | – | – | – | – |
| $Ca^{2+}$ | $meql^{-1}$ | 3.7 | 2.6 | 1.8 | – | – |
| $Mg^{2+}$ | $meql^{-1}$ | 5.3 | 3.7 | 3.8 | – | 8.2 |
| $Cl^-$ | $meql^{-1}$ | 6.6* | 5.3 | 1.5 | <4 | 6 |
| $Hco_3^-$ | $meql^{-1}$ | 6.7 | 5.6 | 3.9 | <8.5 | – |
| $So_4^-$ | $meql^{-1}$ | 2.9 | 3.5 | 0.5 | – | 5.2 |
| $NO_3$-N | $mgl^{-1}$ | 3.1 | 23.4 | 108 | 5–30 | 10 |
| $NH_4$-N | $mgl^{-1}$ | 29 | 3.4 | 0.2 | – | – |
| Total-N | $meql^{-1}$ | 53.6 | 29 | 3.4 | 2.5–43 | – |
| $PO_4$-P | $mgl^{-1}$ | 5.9** | 3.4 | 0.13 | 4.1 | – |
| COD | $mgl^{-1}$ | 384.6 | 27 | 20 | – | 100 |
| BOD | $mgl^{-1}$ | 252 | 13.3 | 0 | – | 200 |

[a]Food and Agriculture Organization of the United Nations.
[b]Iranian Department of Environment.
*The standard is higher than the range of Iranian Department of Environment.
**The standard is higher than the range of FAO.

**Table 1.** Physicochemical characteristics of water and treated wastewater.

| Soil sample* | Parameters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Anions solution saturation extract ($meql^{-1}$) | | | | Total anions | Cations solution saturation extract ($meql^{-1}$) | | | | Total cations | EC ($dsm^{-1}$) | pH (–) | SAR $(meql^{-1})^{1/2}$ |
| | $CO_3^{2-}$ | $HCO_3^-$ | $SO_4^{2-}$ | $Cl^-$ | | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | | | | |
| **C** | – | 1.8 | 35 | 9 | 45.7 | 14 | 20 | 12 | 0.1 | 45.9 | 4.2 | 7.4 | 0.87 |
| **L** | – | 2.5 | 4.5 | 6.3 | 13.2 | 4.1 | 7.2 | 2.1 | – | 13.1 | 1.2 | 7.7 | 0.9 |
| **S** | – | 2.2 | 5.3 | 6.1 | 13.6 | 4.2 | 7.3 | 2.1 | – | 13.5 | 1.4 | 7.8 | 2.9 |

*C: clay loam, L: loam, and S: sandy loam.

**Table 2.** Some chemical properties of soil layers at the experimental field site at initial condition.

## 2.2. Data collection

In this model, some physical and soil hydraulic properties, concerning soil moisture retention characteristics, $\theta$ ($h$), and saturated hydraulic conductivity, $K_{sat}$, were measured in the field. The parameters of van Genuchten's [8] model were evaluated by fitting on $\theta$ ($h$) data using the curve RETC code. The average values of van Genuchten parameters for lysimeter study at different soil types are given in **Table 3**.

| Soil sample* | Particle fraction (%) | | | Texture (–) | Bulk density ($kgcm^{-3}$) | $\theta_r$ ($cm^3$ $cm^{-3}$) | $\theta_s$ ($cm^3$ $cm^{-3}$) | $a$ ($cm^{-1}$) | $n$ (–) | $l$ (–) | $K_{sat}$ (cm $day^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Clay | Silt | Sand | | | | | | | | |
| **S** | 22.09 | 19.19 | 58.72 | Sandy loam | 1.51 | 0.065 | 0.41 | 0.075 | 1.89 | 0.5 | 106.1 |
| **L** | 20.30 | 39.68 | 40.02 | Loam | 1.43 | 0.078 | 0.43 | 0.036 | 1.56 | 0.5 | 24.96 |
| **C** | 48.65 | 28.75 | 22.6 | Clay loam | 1.3 | 0.095 | 0.41 | 0.019 | 1.31 | 0.5 | 6.24 |

*C: clay loam, L: loam, and S: sandy loam.

**Table 3.** Physical properties and van Genuchten parameters for soil sample with $\theta_r$, residual water content ($cm^3cm^{-3}$); $\theta_s$, saturated water content ($cm^3cm^{-3}$); $a$ ($cm^{-1}$) and $n$(–), empirical parameters; l(–), pore-connectivity and tortuosity factor and $K_{sat}$, saturated hydraulic conductivity (cm $h^{-1}$).

## 2.3. The HYDRUS-1D-flow and transport model

In this study, HYDRUS-1D software, version 4.14, was used to conduct numerical simulations of one-dimensional water flow and phosphorous transport in vertical profiles of unsaturated soil to simulate the phosphorous transport in the different soil types under municipal wastewater application. The total depth of each soil profile was 200 cm with one soil type in each profile. Raw sewage then passes through the filter mesh, effluents-treated municipal wastewater, obtained daily from the Parkanabad wastewater treatment plants, mixture of 50% effluents and 50% well water, and well water was used as the influent. Irrigation water was applied to the lysimeters at a flow of 0.78–0.21 $m^3$ $m^{-2}$ $day^{-1}$ in 2004 and 2005, respectively. Each soil profile was oriented vertically, so that the irrigation water flowed in a vertical direction.

| Plant | $h_o$ | $h_{opt}$ | $h_{2H}$ | $h_{2L}$ | $h_3$ |
|---|---|---|---|---|---|
| | | | cm | | |
| Barley | −15 | −30 | −325 | −600 | −8000 |

*Water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary "anaerobiosis point" $h_o$). Root water uptake is also zero for pressure heads less than the wilting point ($h_3$). Water uptake is considered optimal between pressure heads $h_{opt}$ and $h_2$, whereas for pressure heads between $h_2$ and $h_3$ (or $h_o$ and $h_{opt}$), water uptake decreases (or increases) linearly with pressure head.

**Table 4.** Effective root depth, root water uptake parameters, and root distribution*.

The initial condition for volumetric soil water content was between 0.1 and 0.2 for different soil types in all simulations. In case of water flow, the upper water flow boundary condition was atmospheric boundary condition with surface layer, given by the following equation:

$$-K\left(\frac{\partial h}{\partial x}+\cos(\alpha)\right)=q_0(t)-\frac{dh}{dt} \qquad at\ x=L(Soil\ surface) \tag{1}$$

where $q_0$ is the net infiltration rate (precipitation minus evaporation).

| Irrigation treatments | Data of sampling | | | | | | |
|---|---|---|---|---|---|---|---|
| | 22.6.2004 | 29.6.2004 | 8.7.2004 | 18.7.2004 | 29.7.2004 | 6.8.2004 | Mean |
| Total nitrogen (mg $l^{-1}$) | | | | | | | |
| Wastewater | 43 | 46.5 | 45.9 | 47.6 | 60.8 | 77.6 | 53.6 |
| Effluent | 36.8 | 22.6 | 20 | 30 | 29.1 | 35.2 | 29 |
| Well water | 3.41 | 3.41 | 3.41 | 3.41 | 3.41 | 3.41 | 3.41 |
| Ammonia (mg $l^{-1}$) | | | | | | | |
| Wastewater | 24.5 | 27.6 | 24.3 | 27.3 | 33.3 | 36.9 | 29 |
| Effluent | 1.37 | 2.2 | 2.4 | 5.5 | 3.1 | 5.9 | 3.41 |
| Well water | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 |
| Nitrate (mg $l^{-1}$) | | | | | | | |
| Wastewater | 11.5 | 8.3 | 11.9 | 10 | 9.4 | 13.4 | 10.8 |
| Effluent | 34.1 | 19.3 | 16.2 | 22 | 23 | 26 | 23.4 |
| Well water | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| Phosphate (mg $l^{-1}$) | | | | | | | |
| Wastewater | 3.6 | 5.4 | 3.2 | 5.8 | 7.5 | 10.3 | 6 |
| Effluent | 2.7 | 5 | 2.6 | 2.4 | 1.9 | 6 | 3.4 |
| Well water | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |

**Table 5.** The amount of nitrogen and phosphate in different irrigation water (mg $l^{-1}$).

In this study, the lower water flow boundary condition was free drainage. The minimum allowed pressure head at soil surface is the wilting value and was set at the value of 100,000 cm provided by HYDRUS-1D. The root water uptake by plants is described by the macroscopic approach of Feddes et al.'s [9] model. Information on root water uptake with compensation is available in Ref. [5]. The coefficients of Feddes et al.'s [9] model are presented in **Table 4** [5]. The maximum root depth, seeding depths, and the root growth ratio of barley were 100, 5, and 5 cm, respectively.

To investigate the concentration of nitrogen and phosphate in wastewater, effluent, and well water, at any time of sampling from the Parkanabad wastewater treatment plants, quality of the water/wastewater in terms of total nitrogen, ammonia, nitrate, total phosphate, and chemical oxygen demand (COD) were tested based on standard methods [6]. Mean concentration of nitrogen and phosphate in different irrigation water are presented in **Table 5**.

| Irrigation water** | Soil sample*** | Data of sampling | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 22.6.2004 | | 29.6.2004 | | 8.7.2004 | | 18.7.2004 | | 29.7.2004 | | 6.8.2004 | |
| | | Chemical oxygen demand (*COD*) ($mgl^{-1}$) | | | | | | | | | | | |
| | | 1* | 2* | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| $W_1$ | S | 20 | 13 | 20 | 30 | 20 | 30 | 20 | 20 | 20 | 27 | 20 | 24 |
| $W_1$ | L | 20 | 12 | 20 | 20 | 20 | 28 | 20 | 18 | 20 | 21 | 20 | 19 |
| $W_1$ | C | 20 | 10 | 20 | 28 | 20 | 30 | 20 | 20 | 20 | 28 | 20 | 21 |
| $W_2$ | S | 26 | 18 | 27 | 24 | 29 | 33 | 25 | 29 | 27 | 37 | 24 | 34 |
| $W_2$ | L | 26 | 17 | 27 | 26 | 29 | 35 | 25 | 28 | 27 | 31 | 24 | 39 |
| $W_2$ | C | 26 | 13 | 27 | 27 | 29 | 37 | 25 | 27 | 27 | 38 | 24 | 31 |
| $W_3$ | S | 35 | 17 | 45 | 35 | 25 | 42 | 30 | 28 | 29 | 35 | 27 | 40 |
| $W_3$ | L | 35 | 20 | 45 | 38 | 25 | 35 | 30 | 25 | 29 | 28 | 27 | 33 |
| $W_3$ | C | 35 | 35 | 45 | 37 | 25 | 40 | 30 | 25 | 29 | 27 | 27 | 34 |
| $W_4$ | S | 400 | 25 | 430 | 47 | 380 | 53 | 385 | 38 | 392 | 51 | 381 | 45 |
| $W_4$ | L | 400 | 27 | 430 | 48 | 380 | 57 | 385 | 40 | 392 | 50 | 381 | 41 |
| $W_4$ | C | 400 | 25 | 430 | 50 | 380 | 52 | 385 | 37 | 392 | 48 | 381 | 42 |

1*Input *COD* in terms of milligrams per liter, the pollution load of wastewater, and water used in irrigation.
2*Drainage *COD* in terms of milligrams per liter, contamination of water is drained from the lysimeters.
**$W_1$: freshwater, $W_2$: mixture of and effluent, $W_3$: effluent, $W_4$: wastewater.
***S: sandy loam, L: loam, C: clay loam.

**Table 6.** The amount of chemical oxygen demand (COD) in different irrigation water ($mgl^{-1}$).

As shown in **Table 5**, about 42% of phosphate in raw wastewater is removed during the treatment process. According to Mojid et al. [10], the maximum permissible level of phosphate in wastewater for irrigation should not be more than 4.1 mg $l^{-1}$. In our study, the amount of phosphate in raw wastewater was more than FAO's standard. About effluent, however, the average of phosphate was less than 4.1 mg $l^{-1}$ [11], but in some samples, its concentration was higher than the standard amount. Results of the analysis of chemical oxygen demand (COD)

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and irrigation water are presented in **Table 6**. This table includes the average results from three similar lysimeters in each irrigation (irrigation water and the type of soil) and through this we can observe the relative change transfer of contamination by COD index into the deep soil during the irrigation season.

The HYDRUS-1D model was also used to simulate $PO_4$ transport under different irrigation treatments and soil types in one-dimensional vertical lysimetrs. The HYDRUS-1D was run for the main processes of water flow and general solute transport. No hysteresis was considered in the simulations. A total of three simulations (one for each soil types) were performed. Each simulation modeled one-dimensional unsaturated water flow, root water uptake, and phosphate transport. In each simulation, the precipitation and irrigation water were applied to the soil surface of lysimeter. The soil surface in each simulation was covered with barley crop. The initial values for the longitudinal dispersivity ($\boldsymbol{\lambda}$) were derived from HYDRUS-1D dataset and from a study done by [12, 13]. HYDRUS-1D model was then calibrated manually by using these initial values for the $\boldsymbol{\lambda}$ parameter. The $\boldsymbol{\lambda}$ parameter was calibrated against the concentration of $PO_4$-P in drainage water from lysimeters throughout the experiment. The final value of $\boldsymbol{\lambda}$ was determined by using several iterations when the mass balance errors were minimized to <1%. We assumed the molecular diffusion coefficient in free water (DW) was set to zero, therefore the transport of solute through diffusion was considered negligible. The initial water conditions were specified in terms of water content between 0.1 and 0.2 for different soil types in all simulations. The upper water flow boundary condition at the surface ($x = L$) was specified as the atmospheric boundary condition with a surface layer. This boundary condition imposed time-dependent conditions to specify the atmospheric conditions at the top of the lysimeter. Initial concentration of $PO_4$ on the top node of the lysimeter was specified equivalent to the amount of $PO_4$ wastewater added on top of the lysimeter before running the experiment. The lower water flow boundary conditions were prescribed using gravitational free draining. As for solute ($PO_4$) transport, concentration flux boundary conditions were implemented at the upper boundary, and a zero gradient boundary condition was set at the lower solute boundary condition. The reaction parameters required by the HYDRUS-1D model were derived from the adsorption experiment reported by Abou Nohra et al. [14]. The reaction parameters ($\boldsymbol{k_d}$ and $\boldsymbol{\beta}$) required by the HYDRUS-1D model were derived based on Eq. (2):

$$s = K_d \log c^{\beta} \tag{2}$$

where $s$ is the concentration of $PO_4$ adsorbed to the soil (M $M^{-1}$), $c$ is the concentration of $PO_4$ in solution (M $L^{-3}$), $k_d$ is the equilibrium constant ($L^3$ $M^{-1}$), and $\beta$ is a shape-fitting parameter [15]. The solute transport and reaction parameters considered in the simulations for different soil samples are listed in **Table 7**. The HYDRUS-1D models were run for phosphorous transfer into two stages: calibration and validation. Results obtained from 2004 were used to calibrate the parameters to improve the fit between the simulated and measured data. Similarly, the results obtained from 2005 were used to validate the output from the model.

| Model parameter | Soil sample* | | |
|---|---|---|---|
| | S | L | C |
| Soil bulk density, g $cm^{-3}$ | 1.51 | 1.43 | 1.35 |
| Longitudinal dispersivity, cm | 1 | 1.15 | 1.23 |
| Equilibrium constant-adsorption isotherm coefficient, $cm^3\ mg^{-1}$ | 1 | 1.25 | 1.35 |
| Shape fitting parameter-adsorption isotherm coefficient, – | 1.35 | 1.45 | 1.6 |

*S: sandy loam, L: loam, C: clay loam.

**Table 7.** Transport and reaction parameters for different soil samples.

## 3. Results and discussion

### 3.1. Model calibration and validation

Predicted and measured values of cumulative deep percolation (DP) for different soil types are presented in **Figure 1**. Comparing linear relationship between the predicted and measured values of DP with the 1:1 line, the measured values of DP matched well with the predicted values. This indicated that the HYDRUS-1D model is capable to predict DP at different irrigation treatments. The slopes of the linear relationship are statistically equal to 1.0 and the values of NRMSE and "d" are 0.12–0.15, 0.21–0.991, and 0.987–0.976 for sandy loam, loam, and clay loam, respectively. These indicated a high accuracy of the prediction of DP by HYDRUS-1D model for barley crop.

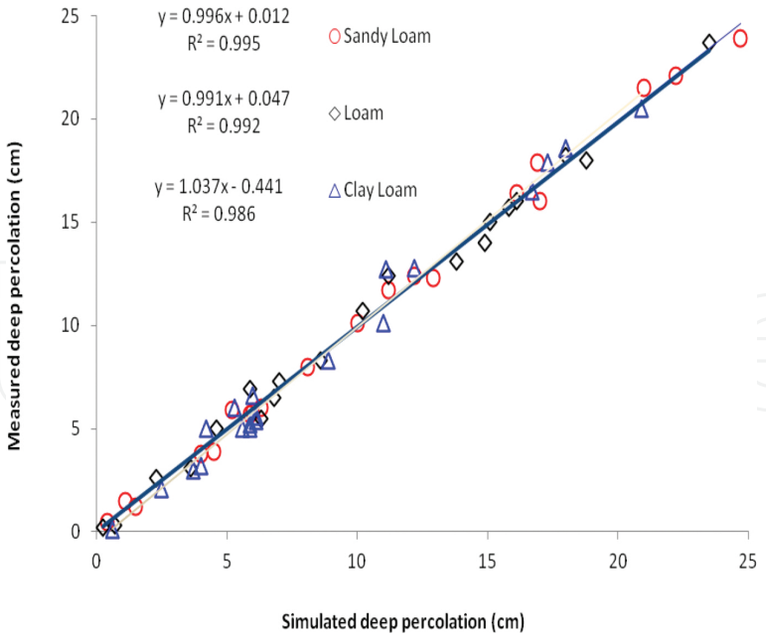



**Figure 1.** Relationship between predicted and measured values of deep percolation for barley.

Values of measured and predicted leached $PO_4$ for barley crop during the growing season at different soil lysimeters and for different irrigation water are shown in **Figure 2**. The linear

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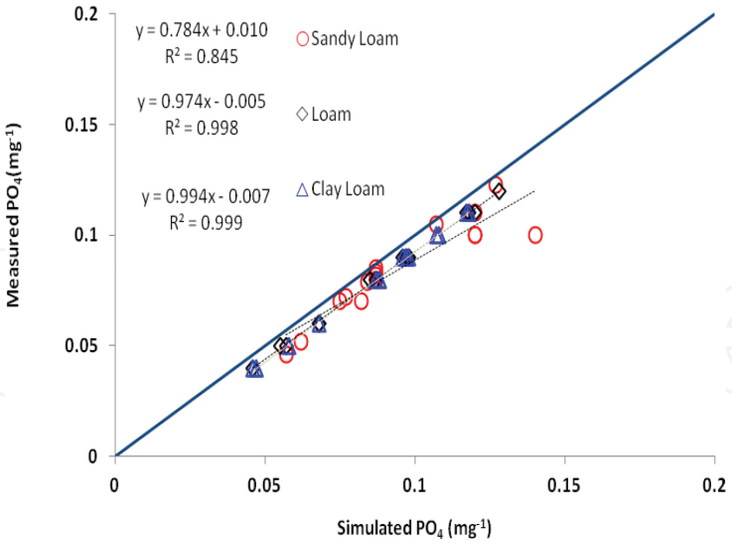



**Figure 2.** Relationship between predicted and measured phosphate leaching for barley.

relationship between the measured and predicted values of leached $PO_4$ were compared with the 1:1 line and the slope and intercept values were calculated. Ideally, the slope and intercept should be one and zero, respectively, indicating a perfect match between predicted and measured values. However, this is a very strict requirement and rarely met in practice. In this study, the slopes of the linear relationship for $PO_4$ is statistically equal to 1.0 and intercept values were 0. 216, 0.870, and 0.036 for sandy loam, loam, and clay loam, respectively. The close similarity between the measured and predicted $PO_4$ content at different soil profile depths over

| Irrigation water* | Soil sample** | $NO_3$ | $PO_4$ | $NO_3$ | $PO_4$ | $NO_3$ | $PO_4$ | $NO_3$ | $PO_4$ |
|---|---|---|---|---|---|---|---|---|---|
| | | AE (–) | | RMSE (mg $l^{-1}$) | | NRMSE (–) | | d (–) | |
| $W_1$ | S | 0.017 | 0.052 | 0.029 | 0.129 | 0.015 | 0.214 | 0.991 | 0.870 |
| $W_1$ | L | 0.077 | 0.081 | 0.133 | 0.173 | 0.073 | 0.223 | 0.990 | 0.881 |
| $W_1$ | C | 0.043 | 0.081 | 0.075 | 0.171 | 0.048 | 0.271 | 0.987 | 0.872 |
| $W_2$ | S | -0.040 | 0.052 | 0.069 | 0.129 | 0.030 | 0.237 | 0.993 | 0.778 |
| $W_2$ | L | 0.003 | 0.038 | 0.006 | 0.091 | 0.003 | 0.271 | 0.994 | 0.891 |
| $W_2$ | C | 0.007 | 0.017 | 0.012 | 0.047 | 0.007 | 0.271 | 0.991 | 0.887 |
| $W_3$ | S | 0.070 | 0.087 | 0.121 | 0.107 | 0.016 | 0.211 | 0.989 | 0.859 |
| $W_3$ | L | 0.127 | 0.210 | 0.219 | 0.189 | 0.040 | 0. 247 | 0.982 | 0.792 |
| $W_3$ | C | 0.180 | 0.290 | 0.312 | 0.202 | 0.053 | 0.258 | 0.987 | 0.897 |
| $W_4$ | S | 0.073 | 0.013 | 0.127 | 0.142 | 0.015 | 0.219 | 0.990 | 0.919 |
| $W_4$ | L | 0.003 | 0.019 | 0.006 | 0.021 | 0.001 | 0.284 | 0.985 | 0.903 |
| $W_4$ | C | 0.030 | 0.020 | 0.052 | 0.087 | 0.012 | 0.253 | 0.984 | 0.898 |

[1]AE, the average error; RMSE, the root mean square error; NRMSE, normalized root mean square error; and d, the index of agreement.
*$W_1$: freshwater, $W_2$: mixture of and effluent, $W_3$: effluent, $W_4$: wastewater.
**S: sandy loam, L: loam, C: clay loam.

**Table 8.** Statistical indexes for calibration and validation of HYDRUS-1D[1].

time resulted in a high correlation coefficient (0.991), high index of agreement (0.984), low average error (0.077), low root mean square error (0.312 mg $l^{-1}$), and low normalized root mean square error (9%), demonstrating a very good calibration of the model (**Table 8**). These indicated a high accuracy of the prediction of leached $PO_4$ by HYDRUS-1D model for barley crop in different soil types. The model overestimated the measured phosphate leaching in all soil types used in the model simulation. Correlation coefficient values were at around 0.914, index of agreement at around 0.907, average error at around 0.305, root mean square error values at around (0.0298 $mg^{-1}$), and normalized root mean square error at around 11% for all lysimeter soil. Overall, the values calculated for phosphate leaching demonstrate a good correlation of the model to field data.

### 3.2. PO4 1 leaching to depth

The findings of phosphor concentration in different kinds of irrigation and drainage water are displayed in **Figure 3**. The percentage of phosphate removal was high in all treatments (between 91 and 99%), which revealed the good potential of crop and soil system in phosphate removal. In **Table 9**, the averages of phosphate in drained water in different treatments during growing season are displayed. The effects of soil and irrigation water on transfer of phosphor to root zone are described below:

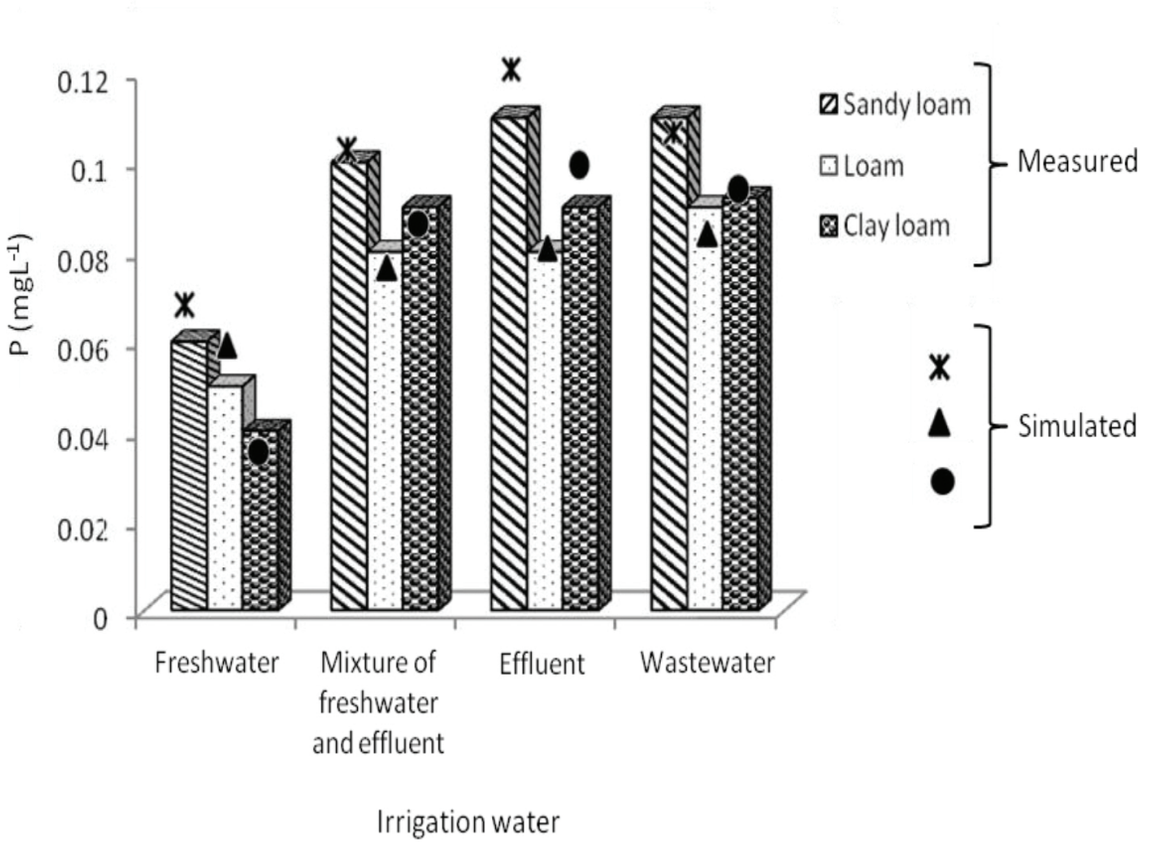



**Figure 3.** Mean phosphate leaching during the growing season.

| Irrigation water* | Soil sample** | 4.7.2004 | | | | 18.7.2004 | | | | 26.7.2004 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) | (1) | (2) | (3) | (4) |
| $W_1$ | S | 0.13 | 0.07 | 0.075 | 50.5 | 0.13 | 0.06 | 0.068 | 43.8 | 0.13 | 0.05 | 0.058 | 37.7 |
| $W_1$ | L | 0.13 | 0.052 | 0.059 | 40.2 | 0.13 | 0.05 | 0.055 | 37.1 | 0.13 | 0.04 | 0.046 | 33.6 |
| $W_1$ | C | 0.13 | 0.046 | 0.057 | 35.5 | 0.13 | 0.04 | 0.046 | 32 | 0.13 | 0.04 | 0.047 | 30.0 |
| $W_2$ | S | 2 | 0.10 | 0.14 | 5 | 1.32 | 0.11 | 0.12 | 8.1 | 1.32 | 0.10 | 0.107 | 5.11 |
| $W_2$ | L | 2 | 0.07 | 0.075 | 3.8 | 1.32 | 0.08 | 0.085 | 6. 2 | 1.32 | 0.08 | 0.088 | 3.9 |
| $W_2$ | C | 2 | 0.08 | 0.087 | 4.1 | 1.32 | 0.09 | 0.098 | 6.7 | 1.32 | 0.09 | 0.096 | 4.2 |
| $W_3$ | S | 3.8 | 0.10 | 0.12 | 2.7 | 2.52 | 0.11 | 0.117 | 4.4 | 2.52 | 0.11 | 0.117 | 2.7 |
| $W_3$ | L | 3.8 | 0.079 | 0.084 | 2 | 2.52 | 0.09 | 0.096 | 3.4 | 2.52 | 0.08 | 0.088 | 2.1 |
| $W_3$ | C | 3.8 | 0.082 | 0.087 | 2.1 | 2.52 | 0.09 | 0.097 | 3.5 | 2.52 | 0.09 | 0.097 | 2.2 |
| $W_4$ | S | 4.5 | 0.11 | 0.12 | 2.3 | 4. 5 | 0.11 | 0.118 | 2. 5 | 4. 5 | 0.11 | 0.118 | 2.2 |
| $W_4$ | L | 4.5 | 0.083 | 0.087 | 1.8 | 4. 5 | 0.09 | 0.098 | 1. 9 | 4. 5 | 0.09 | 0.098 | 1 |
| $W_4$ | C | 4.5 | 0.085 | 0.087 | 1.6 | 4. 5 | 0.09 | 0.097 | 2 | 4. 5 | 0.09 | 0.097 | 1 |

*$W_1$: freshwater, $W_2$: mixture of and effluent, $W_3$: effluent, $W_4$: wastewater.
(1)Total phosphorus inputs in terms of milligrams per liter, from irrigation water.
(2)Total phosphorus output in milligrams per liter, measured in lysimeter drainage water.
(3)Total phosphorus output in milligrams per liter, simulated in lysimeter drainage water.
(4)Percent transfer, represents the amount of total phosphorus observed in drainage water drains compared with the input values of irrigation water at each sampling time.
**S: sandy loam, L: loam, C: clay loam.

**Table 9.** Mean phosphate input, output, and transfers percentage.

**The effect of soil:** Types of soil had significant effect ($p < 0.05$) on phosphate concentration in lysimeters drained water. LSD test showed that the amount of phosphate transferred to root zone in sandy loam lysimeters was significantly higher than in loam lysimeters. Also, the amount of phosphate transferred to root zone in loam lysimeters was lower (except in control treatment) than clay lysimeters. One possible reason for this difference is considerable growth of crop in loam soil and also different permeability of different soil types. Low permeability of clay soil and phosphate absorption by soil particle are the factors influencing less transfer of phosphate to the depth. Of the loam lysimeters irrigated by effluent, wastewater, and mixture of freshwater and effluent, only about 0.97–6.2% of influent phosphor was drained. Also, in clay and sandy loam lysimeters about 1–6.7% and 1.2–8.1% of influent phosphor was drained, respectively. Since in sandy loam soil the amount of phosphor uptake by crop was not high (because of nonconsiderable growth of crop), the removal of more than 90% of phosphor in sandy loam soil suggested the ability of soil in the removal of phosphor available in wastewater and effluent. The findings are consistent with Kardos and Hook [16], who reported in their study that in loam and clay loam, the amount of phosphor leaching in the depth of 120 cm were 1 and 0.1% lower than influent phosphor, respectively. About 97–99% of phosphor removal in crop and soil system was reported by Hasan Oghli et al. [17].

**The effect of irrigation water**: Simulation results showed that the effect of type of irrigation water on phosphate concentration in drainage water of lysimetrs was significant at $p < 0.05$.

There was no significant difference among the amount of phosphate in drained water of lysimeters irrigated with wastewater, effluent, and mixture of freshwater and effluent. However, there were significant differences between the amount of phosphate in drained water of freshwater treatments and the other treatments. According to the findings, we can say that the amount of phosphate output from lysimeters was dependent on the growth of crop and type of soil compared to type of irrigation water.

**The effect of sampling time**: The findings showed that sampling time had no significant effect on the amount of transferred phosphate; however, in the middle of growing season, the amount of transferred phosphate to the depth was at the maximum level.

Once the discharge of drainage water from underground drains to surface water and groundwater is considered, the amount of phosphate phosphor should not be more than the determined standards. In our research, in the worst situations, the amount of phosphate in lysimeters drained water did not exceed 0.11 mg $l^{-1}$, which was lower than the standard level [10].

## 4. Conclusion

Inappropriate management practices in the use of wastewater in phosphorus deteriorate surface and ground water quality, mainly by causing nitrate pollution. The HYDRUS-1D model was calibrated and then validated with different datasets from a lysimeter experiment, and then used to simulate phosphorus leaching through soil under different irrigation treatment (wastewater, effluent, mixture of freshwater and effluent, and freshwater) on three types of soil (sandy loam, loam, and clay loam) to explore and develop better and safer wastewater land application strategies.

Phosphate transferred to the depths was insignificant and it was between 1.6 and 6% of inflow phosphate, which was lower than the maximum standard value of phosphate discharge to surface and groundwater.

Soil and plant systems showed high potential in filtration and removal of nitrate and phosphate, so that the concentration of nitrate and phosphate in drained treatments in all cases was lower than the limit of discharge to surface water and groundwater. It can be confirmed that through proper management and research, in addition to maintaining surface water and groundwater, the effluent, as an available and cheap source, can be used in agricultural irrigation. As there was no significant difference on nitrate leaching between treatments mixture of freshwater and effluent, and freshwater, this demonstrates that it can dilute wastewater as a suitable management strategy for reducing the leaching of impurities in the wastewater and also reduce the effects of probable hazards on soil properties. Simulation study on the process of nitrate leaching to root zone during growing season showed more matches the needs of the plant. Thus, at the time of minimum plant nutrient requirement, we can take suitable management solution such as wastewater dilution to lower leaching of elements to root zone.

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