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Water Resources Research

RESEARCH ARTICLE

10.1029/2023WR034920

On Groundwater Recharge in Variably Saturated Subsurface Flow Models

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Key Points:

- The concept of recharge is not compatible with variably saturated subsurface flow models
- Only potential recharge below an extinction depth can be uniquely extracted in such models
- The issues arise because of the storage dynamics in the capillary fringe above the water table

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Citation:

Gong, C., Cook, P. G., Therrien, R., Wang, W., & Brunner, P. (2023). On groundwater recharge in variably saturated subsurface flow models. *Water Resources Research*, *59*, e2023WR034920. https://doi.org/10.1029/2023WR034920

Received 19 MAR 2023
Accepted 4 AUG 2023

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Abstract

Groundwater models that simulate only saturated flow use groundwater recharge as an input parameter. In contrast, variably saturated subsurface flow models, including integrated surface and subsurface hydrologic models, can jointly simulate the movement of water in the saturated and unsaturated zones. Instead of recharge, they require climate data such as precipitation and potential evapotranspiration. Given that the latter models represent hydrological processes operating throughout the unsaturated zone and at the water table, one might expect that recharge can be readily extracted from them. In this paper, we demonstrate that it is not the case. When the commonly used definitions of groundwater recharge are implemented in variably saturated subsurface flow models, they do not yield meaningful results. Above all, the problems occur because of the storage dynamics in the capillary fringe above the water table. Despite this difficulty, variably saturated subsurface flow models can provide the information required for water resources management directly.

1. Introduction

Groundwater recharge has long been of interest to water resources managers (Hund et al., 2018; Kinzelbach et al., 2010) as quantification of recharge is often considered essential for sustainable aquifer management (Healy, 2010; Healy & Cook, 2002; Scanlon et al., 2002). Numerous methods for estimating recharge exist (Healy, 2010; Scanlon et al., 2002). As recharge is an important component of groundwater in the groundwater budget, hydrogeologists embed the concept of recharge in the way they think about groundwater systems. Understanding recharge dynamics is required to predict the impacts of land use/cover change and climate change on groundwater resources and to determine the risk of groundwater resource contamination by human activities. Groundwater managers often consider recharge rates to evaluate the sustainable level of extraction for a groundwater system.

Groundwater recharge is used in many analytical (Cuthbert, 2010; Haitjema, 1995; Lerner et al., 1990) and numerical solutions of groundwater flow equations (Rubin & Dagan, 1987), including numerical models. However, different types of models handle recharge in different ways. Groundwater models like MODFLOW (Harbaugh, 2005; Harbaugh et al., 2000) simulate groundwater flow and require recharge as an input parameter (Sanford, 2002). They predict groundwater movement in response to recharge and groundwater pumping. In some cases, MODFLOW has been used to determine recharge using data such as hydraulic head, hydraulic conductivity, and/or groundwater age (Baalousha, 2016; Knowling & Werner, 2016; Sanford et al., 2004; Zhu, 2000).

Variably saturated subsurface flow models can simulate vadose zone processes by solving the Richards equation. Hydrus-1D (Šimůnek et al., 2005), a commonly used variably saturated flow model, has been applied to estimate groundwater recharge (e.g., Assefa & Woodbury, 2013; Batalha et al., 2018; Hou et al., 2016; Hu et al., 2019; Tonkul et al., 2019). Typically, such models are set up as one-dimensional (1D), essentially representing a lysimeter. These extracted values represent potential recharge (Healy, 2010; Rushton, 1997), as they focus on the unsaturated zone only and do not consider the position of the water table.

More holistic variably saturated subsurface flow models which solve the three-dimensional (3D) Richards equation in combination with Darcy's law for the saturated zone include HydroGeoSphere (Aquanty, 2018; Brunner & Simmons, 2011; Simmons et al., 2020), Parflow (Maxwell & Miller, 2005), CATHY (Paniconi & Putti, 1994;

Paniconi & Wood, 1993), and Hydrus-3D (Šimůnek et al., 2006). These models simulate infiltration processes through the unsaturated zone of the soil as well as saturated groundwater flow processes and the interactions and feedback mechanisms between the saturated and unsaturated zones. They, therefore, do not require recharge as an input, unlike fully saturated groundwater models such as MODFLOW. In fact, variably saturated subsurface flow models do not explicitly compute recharge internally. Instead, precipitation and evaporative forcing are used as input for simulations. As this type of model incorporates key hydrological processes, one might expect that groundwater recharge can be readily extracted from them. For example, Frei et al. (2009) explored recharge patterns and dynamics along rivers using Parflow. They calculated groundwater recharge as the difference between the infiltrating water flux and the vadose zone storage. Brandhorst et al. (2021) estimated recharge from Parflow based on the water table fluctuation (WTF) method. Waldowski et al. (2023) estimated groundwater recharge by considering the water balance over the vertical extent of the WTFs. Guay et al. (2013) referred to recharge in CATHY as the sum of vertical fluxes that cross a dynamically changing water table.

This paper explores to what extent variably saturated subsurface flow models can be used to extract groundwater recharge. To extract recharge from variably saturated subsurface flow models, a definition of groundwater recharge must be implemented in the postprocessing of the simulations and, to be scientifically sound, the results need to be unique, meaningful, and unambiguous. In this paper, we explore how different definitions of groundwater recharge can be implemented in variably saturated subsurface flow models, and if they yield unique and meaningful results. We first briefly review the available definitions of groundwater recharge, and subsequently implement them in variably saturated subsurface flow models and demonstrate that in fact these models cannot be used to estimate groundwater recharge in a unique way.

2. Definitions of Recharge

Many definitions of groundwater recharge have been proposed. Healy (2010) defined groundwater recharge as "*the downward flow of water reaching the water table, adding to groundwater storage*." Several definitions along similar lines also have been proposed, e.g., by Schmoll et al. (2006), Delleur (2006), Sen (2008), de Vries and Simmers (2002), Sophocleous (1991), Singhal and Gupta (2010), Hillel (1998), Sophocleous and Perry (1985), Shamsudduha et al. (2011), Doble and Crosbie (2016), Carrera-Hernández et al. (2012), and Meixner et al. (2016). Given that the water table is defined as the surface where the pressure head is equal to zero, this type of definition can be implemented in physically based models, as the position of the water table can be tracked throughout the simulations, and the fluxes to and across it can be extracted through postprocessing the simulation results. Because the surface typically is not static, determining the flux across the surface can sometimes be nontrivial, especially if the water table is inclined. For the upcoming implementation of recharge definitions in numerical models, we label this approach *Recharge Definition I* (water crossing the pressure head equal to zero plane).

Others define groundwater recharge as "*the entry of water to the saturated zone*" (Freeze & Cherry, 1979). Note that the boundary between the saturated and unsaturated zones is the top of the capillary fringe, which is above the pressure head equal to zero plane. Definitions similar to that of Freeze and Cherry (1979) have been provided, e.g., by Nimmo et al. (2006), Tóth (2009), Simmers (2013), Fitts (2013), Lerner (1996), Poehls and Smith (2011), Haitjema (1995), Kresic and Stevanovic (2009), Sharp (2003), Xu and Beekman (2018), Gemitzi et al. (2017), and Dingman (2015). The boundary between fully saturated and unsaturated zones can in principle be tracked throughout the simulation and the fluxes to and across this boundary can be monitored. Likewise, fluxes at any other height above the water table can be monitored, no matter if it is a fixed or a dynamic height (such as the height of the capillary fringe). We label these definitions as *Recharge Definition II* (the entry of water to the saturated zone, crossing the boundary defined through the plane separating fully saturated and unsaturated conditions).

The definitions above are based on tracking a flux across a boundary. Other definitions of recharge are implicit in approaches that quantify recharge through the response of the system to infiltration and drainage. For example, the WTF method relates a rise in the water table to groundwater recharge (Healy & Cook, 2002). Note that in some applications of the WTF method, a drainage term is also included to account for the discharge of the aquifer (Cuthbert, 2010). This method therefore implicitly defines recharge using a mass balance approach as the change in an aquifer's saturated volume minus groundwater discharge. We label this approach as *Recharge Definition III* (recharge obtained from joint observations of the water table and groundwater discharge).

Table 1
The Soil Water Retention Characteristic Parameters Based on Carsel and Parrish (1988)

Soil type	θ_s(cm^3/cm^3)	θ_r (cm^3/cm^3)	α (m^{-1})	β (−)	K_s (m/d)
Sand	0.43	0.045	14.5	2.68	7.13
Loam	0.43	0.078	3.6	1.56	0.25
Sandy loam	0.41	0.065	3.7	1.89	1.06
Loamy sand	0.41	0.057	12.4	2.28	3.50

Some authors have defined recharge as net-infiltration. For example, Dassargues (2018) defines recharge as "*The water that penetrates the soil flows deep underground (groundwater recharge) if it is not consumed by plants or humans*." Delleur (2006) refers to recharge as "*Deep soil water percolation, often referred to as groundwater recharge by soil scientists, is the water that has moved past the evaporative and root zones in the vadose zone and is no longer available to plants*." Scanlon et al. (2002) pointed out that net-infiltration, drainage, or percolation below the root zone are often equated to recharge in many vadose zone studies. Similarly, de Vries and Simmers (2002) state that "*all water that passes the root zone is assumed to have escaped evapotranspiration and could recharge the groundwater reservoir*." Cech (2009) defines groundwater recharge as "*Downward movement of water from the land surface into and through upper soil layers*." If recharge is defined as the net-infiltration as proposed by these authors, in principle, one should also be able to extract this potential recharge by keeping track of the fluxes at a depth below the surface at which water can no longer be lost to the atmosphere (below the root extinction depth), provided the water table is below this extinction depth. Note, however, that net-infiltration can significantly differ from recharge defined at or close to the water table, especially in systems with a large unsaturated zone. For the subsequent discussion, we label this approach as *Recharge Definition IV* (net-infiltration below the extinction depth) This is also called *potential recharge*.

The four definitions of recharge are subsequently implemented in the numerical models described in the following sections.

3. Methods

3.1. Numerical Model

Given that the formulation of vadose zone processes is essentially the same in all variably saturated subsurface flow codes, the choice of a numerical code is not critical for this study as long as variably saturated infiltration processes are represented. Therefore, we use HydroGeoSphere (Aquanty, 2018), a variably saturated numerical model that uses the control volume finite-element method to solve 2D overland flow fully coupled with 3D subsurface flow described by Richards' equation. We simulate infiltration and drainage processes through simple 1D vertical columns.

We deliberately use simple models for the following reason: if the estimation of recharge cannot be obtained reliably from these simplest models, it will also be impossible to do so in more complicated models where, e.g., the water table is inclined or complex catchment-scale processes are simulated.

We simulate 1D vertical soil columns of 5 m in height. The surface area of the soil columns is 1 m^2. The soil columns are vertically discretized into 1,000 finite-element layers. The very fine vertical discretization ensures that there is no influence of grid discretization on the simulation results. The soil is assumed to be homogeneous for any given simulation. Different soil types (sand, loam, sandy loam, and loamy sand) are considered for some simulations and their soil water retention characteristics are described by the van Genuchten functions (van Genuchten, 1980). Soil properties are presented in Table 1, where θ_s is the saturated water content, θ_r is the residual water content, K_s is the saturated hydraulic conductivity, and α and β are fitting parameters of the van Genuchten functions.

Initially, all models are in a hydrostatic equilibrium. A constant specified flux q_{inf} equal to 0.02 m/d is then applied to the upper boundary. Evapotranspiration is not simulated and so the specified flux represents a net-infiltration rate. Depending on the simulation, the lower boundary is either a no-flow boundary or a drainage boundary. The water table is within the model domain. All models are run in a transient mode and model results are analyzed after a dynamic steady state is reached, e.g., when the increase or decrease of the elevation of the water table has reached a constant rate. The specified flux at the upper boundary (q_{inf}) is applied from the 5th day and the total simulation time is 45 days. The bottom drainage boundary used for some models is shown by q_d in Figure 1. The initial and maximum time steps are 0.01 days and an adaptive time-stepping scheme is employed. Simulation results are written out daily and are postprocessed with the Tecplot 360 2020 software (Tecplot, Inc, Bellevue, WA, USA).

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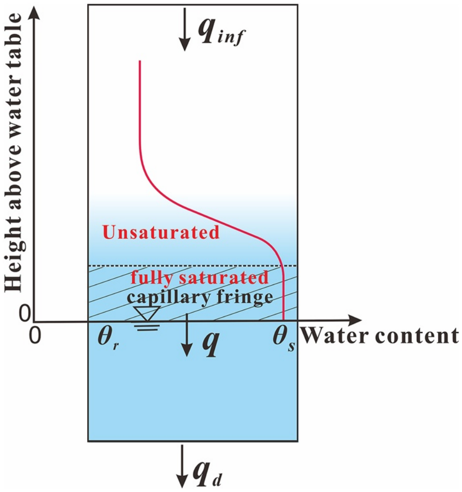

Figure 1. Schematic diagram of the imposed infiltration and drainage rates. The red line corresponds to the soil moisture profile above the water table. q_{inf} is the specified flux infiltrating the soil column, q is the flux across the water table, and q_d is the drainage flux. Several cases are simulated: In Case 1, $q_{inf} = q_d$; in Case 2, $q_d = 0$ while $q_{inf} > 0$; and in Case 3, q_d can either exceed or be smaller than q_{inf}.

Different cases are simulated: (a) a steady water table where the assigned infiltration flux at the top and drainage flux at the bottom are equal, which corresponds to a dynamic steady-state flow, (b) a rising water table due to infiltration but without drainage ($q_d = 0$) and therefore all the infiltrating water contributes to increasing the water table, and (c) constant but differing infiltration and drainage fluxes where, depending on the relative magnitudes of these fluxes, the water table rises or falls. Cases 1 and 2 are special cases of the more general Case 3.

Case 1. Dynamic steady-state system under infiltration conditions
We consider first a special case for steady-state flow where the specified infiltration flux is equal to the drainage flux (Figure 1). The constant drainage flux q_d is assigned as 0.02 m/d. Once the dynamic steady state is reached, the inflow flux is equal to the outflow, the water storage in the column does not change and therefore the water table remains at the same location.

Case 2. All infiltration contributes to the rise of the water table
Here, we focus on a 1D column with a no-flow boundary at the bottom, which is equivalent to a closed lysimeter. Initially, the water table is below the surface, infiltration is zero and the system is at a steady state (Figure 2a). Recharge is then triggered by infiltrating water, which leads to a rise in the water table (Figure 2b). Because the bottom is impermeable, there is no groundwater flow below the water table and all infiltrating water contributes to raising the water table. Four different homogeneous soil columns, with properties described previously (sand, loam, sandy loam, and loamy sand) are employed in this case. The initial heads throughout the columns for the four soil columns are 1 m.

Case 3. Infiltration partially contributes to groundwater fluxes
In Case 2, we examined a column equivalent to a closed lysimeter without any groundwater flow below the water table and toward the lower boundary, and therefore with all infiltrating water contributing to rising the water table. In Case 3, we consider a more general case with drainage at the bottom boundary and where infiltrating water can contribute to raising the water table and also to vertical groundwater flow below the water table. Two soil columns were employed in this case and the material specified corresponds to sand. The initial heads throughout the columns are 2 m for both columns. Constant drainage fluxes q_d are assigned to the lower boundary from the 5th day (Figure 1) with values equal to 0.01 and 0.025 m/d for the two columns, respectively. As before, a constant specified flux of 0.02 m/d is assigned to the top

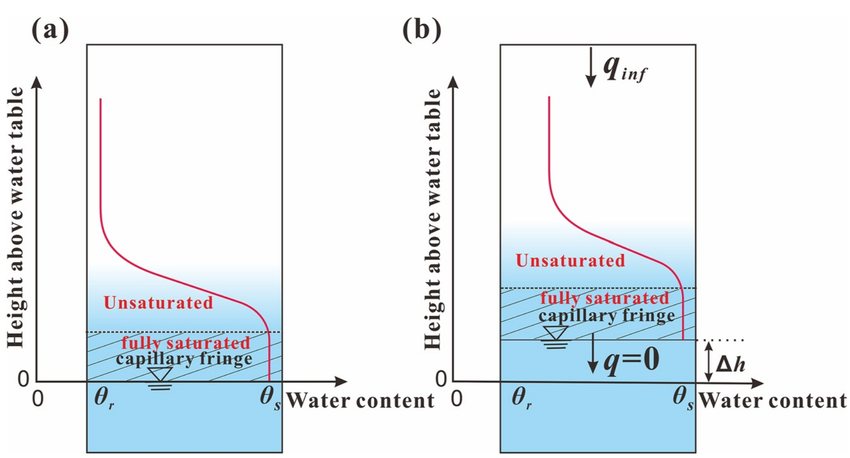

Figure 2. Schematic diagram of groundwater recharge (corresponding to Case 2). (a) Before infiltration and (b) during infiltration. The infiltration causes a rise of the water table equal to Δh. The water content is shown on the x-axis and the height above the water table is on the y-axis. The red lines show the soil moisture profile above the water table. q_{inf} is the specified flux infiltrating the soil column, and q is the flux across the water table.

boundary. The special case where the drainage flux corresponds to the infiltration flux (and the system thus remains in a dynamic steady state) corresponds to Case 1 and has already been discussed previously. Based on the imposed drainage flux, the following situations will develop: (a) for $q_d = 0.01$ m/d, the water table elevation increases in the soil column; (b) for $q_d = 0.025$ m/d, the water table decreases in the soil column.

3.2. Assessing the Implementation of Recharge Definitions and the Extraction of Recharge

For the hydraulic configurations, the different definitions of recharge are implemented in the following way.

1. Implementation of *Definition I* and recharge extraction

In *Definition I*, recharge is defined as the flux that crosses the water table vertically (with the water table defined as the isosurface with pressure head h_p equal to zero). One can extract these fluxes by postprocessing the output from the variably saturated subsurface flow models by keeping track of the position of the $h_p = 0$ plane as a function of time and integrating fluxes across this plane. This definition of recharge is based on Healy (2010).

2. Implementation of *Definition II* and recharge extraction

In *Definition II*, recharge is defined as the flux across the boundary between the saturated and the unsaturated zones (e.g., Freeze & Cherry, 1979). Technically, the extraction plane is defined through the degree of saturation equal to 1 and is tracked throughout the simulation while the fluxes through this plane are extracted. Other boundaries, be it a fixed height above the water table or a fixed saturation, can be dynamically monitored in the same way.

3. Implementation of *Definition III* and recharge extraction

In *Definition III*, recharge is defined through the response of the system to infiltration and drainage. To implement *Definition III*, we focus on the variations of the water table, but in some cases also consider the deep drainage as proposed by Cuthbert (2010). The WTF approach is a widely used field method to estimate groundwater recharge (Gong et al., 2021; Healy & Cook, 2002). Likewise, it can be employed in variably saturated subsurface flow models jointly simulating groundwater levels and variably saturated subsurface flow. A key assumption of this approach is that the rise of the water table is not related to horizontal fluxes, but instead to recharge, which is the case for the soil column with an impermeable bottom. In more complex two-dimensional (2D) or 3D models with horizontal flow components, this contribution could be extracted through appropriate postprocessing.

In its most basic application, only the specific yield and the temporal changes (i.e., the change of the water table for a given time) in the water table are required, and recharge R [L/T] is given by

$$R = S_y \frac{dh}{dt} \tag{1}$$

where S_y [–] is specific yield, h [L] is the height of the water table, and t [T] is time. A commonly used formula to determine specific yield is given by (Freeze & Cherry, 1979)

$$S_y = \theta_s - \theta_r \tag{2}$$

However, this expression for specific yield ignores the initial soil water content profile. As pointed out by multiple authors, e.g., Allison et al. (1990), Healy and Cook (2002), Crosbie et al. (2005), and Zhang et al. (2020), this simplification can result in a significant overestimation of recharge. Conversely, the addition of a small amount of water can cause a significant rise of the water table if the soil above the water table is close to saturation (Gillham, 1984). If the initial soil water content above the water table is considered, a modified specific yield S_y^* can be employed

$$S_y^* = \theta_s - \theta_i \tag{3}$$

where θ_i [cm^3/cm^3] is the initial soil water content, which varies with increasing height above the water table. Note that in the application of the WTF method as proposed by Cuthbert (2010), a drainage term is added to Equation 1.

4. Implementation of *Definition IV* and recharge extraction

Definition IV defined recharge as the net-infiltration, i.e., the precipitation minus evapotranspiration. As opposed to *Definitions I* and *II* which define recharge at or above a certain height of the water table, *Definition IV* is

Table 2
Extracted Values of Recharge for All Simulations and the Different Implementations of Recharge Definitions

		Cases						
		Case 1	Case 2				Case 3	
							Case 3(a)	Case 3(b)
		$q_{inf} = 0.02$; $q_d = 0.02$	$q_{inf} = 0.02$; $q_d = 0$				$q_{inf} = 0.02$; $q_d = 0.01$	$q_{inf} = 0.02$; $q_d = 0.025$
Definitions		Sand	Sand	Loam	Sandy loam	Loamy sand	Sand	Sand
Definition I	$h_p = 0$ plane	0.02	0	0	0	0	0.01	0.025
	Above $h_p = 0$ plane	0.02	0–0.02 (Figure 3)	0–0.02 (Figure 3)	0–0.02 (Figure 3)	0–0.02 (Figure 3)	0.01–0.02 (Figure 5)	0.02–0.025 (Figure 6)
Definition II	Saturation = 1 plane	0.02	0	0	0	0	0.01	0.025
	Saturation < 1 plane	0.02	0–0.02 (Figure 4)	0–0.02 (Figure 4)	0–0.02 (Figure 4)	0–0.02 (Figure 4)	0.01–0.02 (Figure 5)	0.02–0.025 (Figure 6)
Definition III	S_y WTF only	0	0.027	0.127	0.047	0.031	0.013	–
	Discharge	0.02	0	0	0	0	0.01	0.025
	S_y^* WTF only	0	0.003	0.012	0.002	0.004	0.0004	–
	Discharge	0.02	0	0	0	0	0.010	0.025
Definition IV		0.02	0.02	0.02	0.02	0.02	0.02	0.02

Note. WTF means water table fluctuation method, and the unit in the table is m/d. The entries under *Definition I* (values above $h_p = 0$ plane) and *Definition II* (saturation < 1 plane) are additional simulations to illustrate the issues related to these definitions.

evaluated at a depth below the land surface where the infiltrating water is no longer exposed to evapotranspiration. As in the current context evapotranspiration is not simulated, the net-infiltration is equal to the specified infiltration flux imposed.

4. Results

The results of simulations and extraction of recharge are shown and analyzed in the subsequent section. Table 2 provides an overview of all simulations and the corresponding recharge definitions that were implemented to extract recharge.

4.1. Case 1: 1D Dynamic Steady-State System Under Infiltration Conditions

For *Definitions I*, *II*, and *IV*, the extracted recharge is equal to the specified infiltration flux (Table 2). For *Definition III*, the analysis based the WTF method yields a recharge flux of 0 as the water table is not moving. If the drainage term is considered, the extracted recharge is also equal to the specified infiltration flux. For this special case of a steady water table under infiltrating conditions, all definitions of recharge yield the same results, namely that recharge is equal to the net-infiltration. Note, however, that if the WTF approach is employed this value is only obtained if the drainage term is considered.

4.2. Case 2: All Infiltration Contributes to the Rise of the Water Table

1. Extraction recharge based on *Definition I*

For all soils, the flux directly across the water table is shown by the left-most bar for each type of soil in Figure 3 and it is very close to 0, see the histogram in Figure 3 ($h_p = 0$ plane; the left-most bar of each histogram). This result is related to the presence of a fully saturated zone, the so-called capillary fringe above the water table (Figure 2a). The result is also related to the impermeable boundary at the bottom, which causes infiltrating water to "pile up" on top of the water table. The strict application of the definition of recharge as being equal to the flux across the pressure head equal to zero plane thus provides an unrealistic estimate of recharge equal to 0 for this situation.

In principle, one could argue that, instead of extracting recharge across the pressure head equal to zero plane (the water table), recharge could be obtained by extracting vertical infiltration fluxes crossing a horizontal plane located at some height above the water table. This corresponds to the less strict definitions of recharge mentioned in the previous section (definitions of recharge), e.g., Scanlon et al. (2002). Therefore, fluxes crossing planes above the rising water table at heights of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 m were also extracted as indicated in Figure 3. As expected, the extracted values increase from 0 to 0.02 m/d for an increasing height above the water table. With an increasing height, we approximate *Definition IV*, and the extracted fluxes tend toward the net specified flux imposed (q_{inf} = 0.02 m/d). However, there is no clear indication of how this height should be chosen. The extracted results are thus ambiguous.

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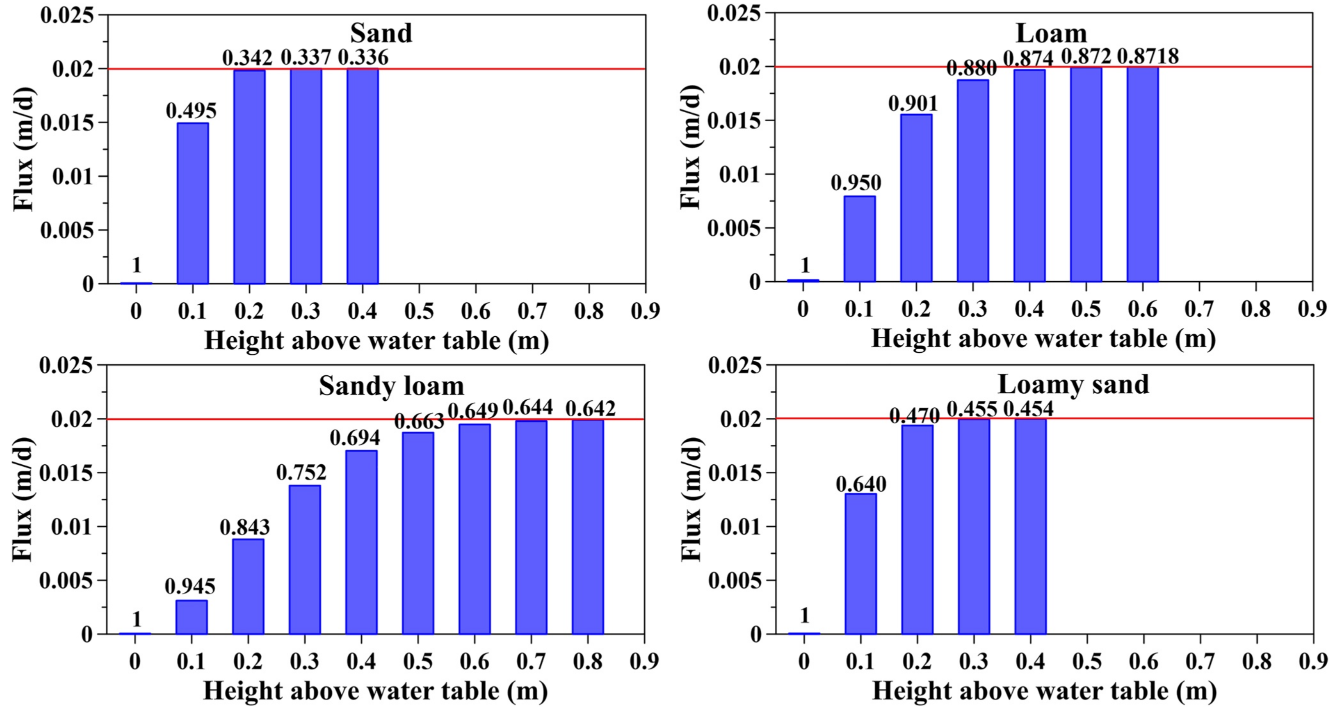

Figure 3. Fluxes across planes above the water table (pressure head equal to zero plane) and at constant heights above the water table for different soil types. The inverse of air-entry value (a proxy for the saturated height above the water table) is 0.069 m for sand, 0.278 m for loam, 0.270 m for sandy loam, and 0.081 m for loamy sand. The specified flux infiltrating all soil columns is equal to 0.02 m/d (red line). The values above each column are the saturations at each height.

2. Extracting recharge based on *Definition II*

One could define recharge as the flux contributing to the saturated zone (*Definition II*; Freeze & Cherry, 1979). The integration plane would thus not be defined as the $h_p = 0$ plane, but rather as the plane above the water table where the saturation drops below 1. If the soil water retention curve is represented with the van Genuchten function, the exact numerical location of this plane corresponds to the pressure equal to zero plane as opposed to, e.g., the Brooks-Corey function (1964) where a specific height above the water table, corresponding to the inverse of the air-entry pressure, marks the boundary between the saturated and the unsaturated zones. However, even with the van Genuchten approach one can define a saturation value smaller than 1 for which the soil can reasonably be considered to be fully saturated (Silliman et al., 2002). Figure 4 shows how the extracted fluxes vary when computed across a plane defined by a saturation value rather than the pressure head equal to zero plane. The planes ($h_p = 0$ or a given saturation) move according to the simulation results. The results clearly indicate that the definition of a cutoff for saturation has a major influence on extracted recharge rates.

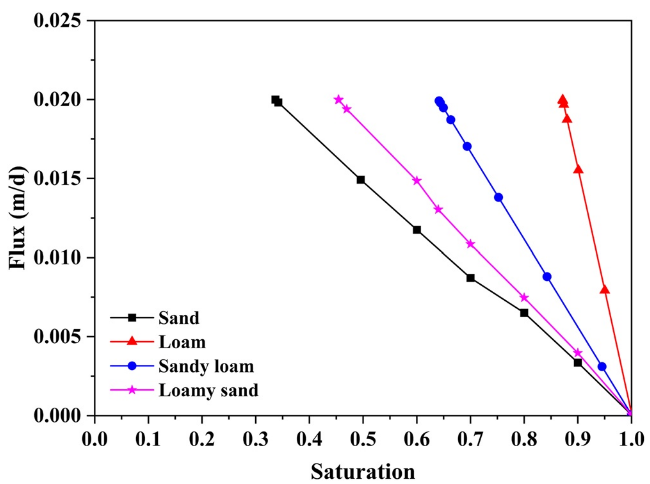

Figure 4. The fluxes across planes defined by the degree of saturation for sand, loam, sandy loam, and loamy sand. The infiltration flux is 0.02 m/d.

3. Extraction of recharge based on *Definition III*

Definition III relates recharge to the changing water level fluctuations (see Equations 2 and 3) for the different notations of the specific yield. Note that, in some applications of the WTF method, a drainage term is considered and added to Equation 1, as suggested by Cuthbert (2010). As in this specific simulation case there is no drainage, this additional term is not considered.

By using Equation 1 (the change of the water table is extracted with a daily timestep) and assuming a static value of the specific yield (Equation 2), the estimated recharge rate for loam (see Table 2 for other soil types) is 0.127 m/d, which is greater than the infiltration rate. This overestimation is easily explained. The water table rises at a rate of 0.359 m/d and the rate

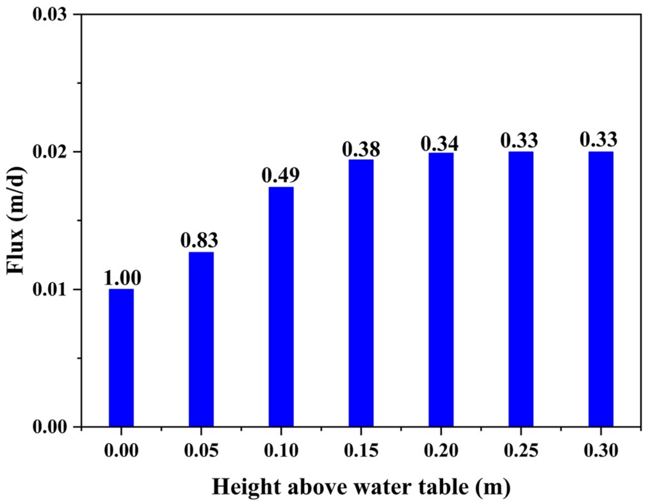

Figure 5. Fluxes across planes across the water table ($h_p = 0$) and at constant heights above the water table for sand for imposed infiltration rates of 0.02 m/d. The values above the columns represent the saturations on the planes. The drainage rate is 0.01 m/d, the water table rises.

is then multiplied by the specific yield S_y, which is the difference between saturated and residual water contents. Using values shown in Table 1 for loam, its specific yield is equal to 0.352. The specific yield in this formulation does not consider the initial water content above the water table, as opposed to the approach where the initial water content above the water table is considered and a modified specific yield S_y^* is defined (see Equation 3 and entry for S_y^* in Table 2). The consideration of the initial water content to estimate recharge with the WTF method is feasible through appropriate postprocessing of the model output. A problem with this approach is that the estimation of recharge rates will heavily depend on the temporal discretization used for the simulations. If the change in the height of the water table (dh) in one time step is less than the height of the capillary fringe, then the initial soil water content (θ_i) will be equal to or very close to the saturated water content. The modified specific yield according to Equation 3 is therefore equal to zero, which leads to a recharge equal to zero. Therefore, applying the WTF method to estimate recharge yields ambiguous results that depend on the time step size.

4. Extraction of recharge based on *Definition IV*

As in this context evapotranspiration is not simulated explicitly, the imposed infiltration flux corresponds to net-infiltration and thus *Definition IV*. The graphs in Figure 3 show that for an increasing evaluation height above the water table, the corresponding extracted recharge approximates the net-infiltration and thus *Definition IV*. The factors influencing at what height above the water table the extracted recharge corresponds to the net-infiltration is influenced by the infiltration rate, the hydraulic conductivity, and the air-entry pressure.

4.3. Case 3: Infiltration Partially Contributes to Groundwater Fluxes

4.3.1. Case 3(a) $q_d = 0.01$ m/d, $q_{inf} = 0.02$ m/d: The Drainage Flux is Smaller Than the Infiltration Flux and the Water Table Rises in the Soil Column

In this case, the infiltrating water will both contribute to rising the water table and to groundwater flow below the water table. The extracted flux across the water table plane (*Definition I*) is equal to q_d (0.01 m/d). Likewise, the extracted flux across the saturation equal to 1 plane (*Definition II*) is also equal to q_d (0.01 m/d). In analogy to the previous section recharge values extracted from planes above the water table and above the full saturation plane were also extracted, see Figure 5.

In employing *Definition III*, the rise of the water table is related to groundwater recharge. One can also consider the drainage rate (0.01 m/d), in addition to the recharge estimated based on the increase of the water table. As before, the calculation of the specific yield has a significant influence on the results. The result is 0.013 m/d if the specific yield is based on Equation 2, and 0.0004 m/d Equation 3 is used.

The results of recharge using *Definition IV* (net-infiltration) can also be found in Figure 5. With the increasing height above the water table, the extracted recharge rate approximates the infiltration rate ($q_{inf} = 0.02$ m/d).

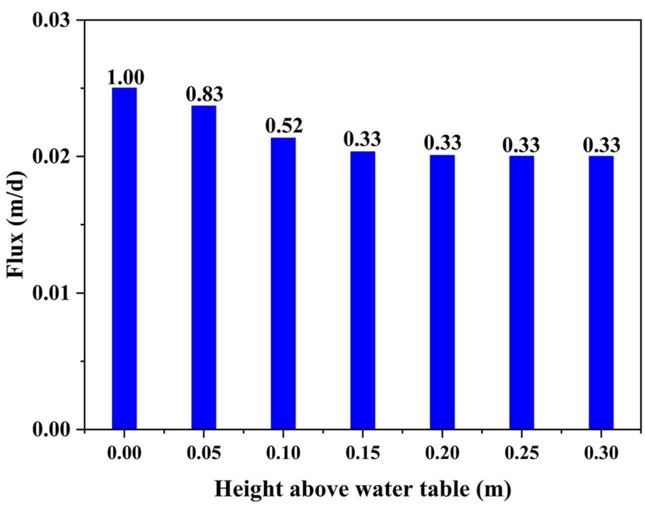

Figure 6. Fluxes across planes across the water table ($h_p = 0$) and at constant heights above the water table for sand for imposed infiltration rates of 0.02 m/d. The values above the columns represent the saturations on the planes. The drainage rate is 0.025 m/d, water level decreases.

4.3.2. Case 3(b) $q_d = 0.025$ m/d, $q_{inf} = 0.02$ m/d: The Drainage Flux is Greater Than the Infiltration Flux, and the Water Table Elevation Decreases in the Soil Column

If recharge is extracted based on *Definition I*, the flux across the pressure head equal to zero plane is equal to q_d (0.025 m/d), see Figure 6. As before, results from different heights above the water table are also plotted. The infiltrating water arrives above the capillary fringe and thus the flux across the water table is equal to the drainage flux.

Employing *Definition II*, the flux across the saturation equal to 1 plane is equal to q_d (0.025 m/d). The application of *Definition III* yields zero (numerically below zero) recharge as the water table is decreasing. As before, the drainage rate can be considered (0.025 m/d).

The results based on *Definition IV* can also be found in Figure 6 where fluxes extracted at different heights above the $h_p = 0$ plane are shown. As the height increases (approximating *Definition IV*), the extracted flux tends toward the specified infiltration flux in the soil column (0.02 m/d).

5. Discussion

5.1. Discussion of the Modeling Approach

The simulations described in this paper are based on homogenous 1D systems with constant boundary conditions. If more complex, 2D or 3D systems are considered, two additional factors can further complicate the analysis: (a) the water table might be inclined and not flat as in the 1D case; and (b) horizontal fluxes will affect the water table dynamics. Both of these complications can in principle be considered through appropriate postprocessing of the simulation results. The analysis is further complicated if transient boundary conditions, hysteresis, or heterogeneity are considered. In addition, for simple 1D models, the drainage flux can be easily considered in the context of the water fluctuation method. However, in the more complex, 2D or 3D setting, it is very difficult to associate the drainage fluxes to rivers or other discharge points to a specific recharge event or period, as the temporal dynamics of groundwater level change and drainage can be very different. While all of these aspects can be accounted for through an adequate model setup and appropriate postprocessing, all the issues highlighted above remain, thus preventing the unambiguous assessment of groundwater recharge.

5.2. Implications for Exacting Groundwater Recharge From Variably Saturated Subsurface Flow Models

It is becoming increasingly popular to examine how recharge changes under future climates (Crosbie et al., 2013; Ghazavi & Ebrahimi, 2019; McCallum et al., 2010; Mileham et al., 2009; Moeck et al., 2016). Variably saturated subsurface flow models, especially integrated surface and subsurface models, such as HydroGeoSphere represent all relevant hydrological processes and are thus, until closer examination, expected to be suitable to extract and observe recharge processes for current and future conditions. However, our analysis has clearly demonstrated that extracting groundwater recharge from physically based models yields ambiguous results even for very simple systems. The fundamental challenge is that the definition of recharge is anything but clear and thus cannot be implemented in a unique way in the postprocessing process of physically based models.

Hillel (1998, p480) eloquently highlighted the problems with identifying the water table and thus recharge: "*Groundwater is sustained (recharged) by percolation through the unsaturated zone, and the position of its surface (the water table) is determined by the relative rates of recharge versus outflow. Reciprocally, the position of the water table affects the moisture profile and flow conditions above it. One problem encountered in attempting to distinguish between the unsaturated and saturated zones is that the boundary between them may not be exactly at the water table but at some elevation above it, corresponding to the upper extent of the capillary fringe (at which the suction is equal to the air-entry value for the soil). Frequently, this boundary is diffuse and scarcely definable, particularly when affected by hysteresis*."

A quantity that can be uniquely quantified with variably saturated subsurface flow models is the flux below the root zone or extinction depth. Water below the root zone or extinction depth will not transpire or evaporate, the extinction depth is thus clearly defined, and can thus be used in an unambiguous way. This flux corresponds to the potential recharge and can be very useful. However, this approach does not work if the water table is above the extinction depth. Also, if the water table is very deep, as is typically the case in arid and semiarid areas, the time lag between deep infiltration and recharge can be very long (Nazarieh et al., 2018; Rossman et al., 2014). The potential recharge will eventually contribute to groundwater.

Another quantity that can be uniquely extracted and which is of direct use to many water resources management questions is the dynamics of the saturated volume. Note, however, that as illustrated above and previously highlighted in the literature (Gillham, 1984), the response of the water table and thus the dynamics of the saturated volume to infiltrating water will significantly depend on the antecedent soil moisture conditions above the water table (Gillham, 1984).

6. Conclusions

Recharge cannot always be unambiguously extracted from variably saturated subsurface flow models and so care should be taken when such models are employed to extract it. However, infiltration fluxes below the extinction depth can be extracted uniquely, e.g., to analyze how land use/cover or climate change affects the potential contribution to groundwater. Changes of saturated volumes can be easily extracted and provide direct and relevant information for water resources management. Since recharge is only of indirect interest to water resource management, the difficulty in accurately quantifying recharge in variably saturated subsurface flow models is not of concern. Rather, since the models simulate both surface water, unsaturated and saturated zone flows, they are able to accurately predict groundwater declines caused by land surface activities or climate change. They, therefore, are ideally suited to addressing water resource problems.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The input files of models in this research are available at: https://doi.org/10.6084/m9.figshare.23791467.v1 (Gong et al., 2023). A software HydroGeoSphere license would be required to run the models (cotact sales@aquanty.com).

Acknowledgments
This study is supported by the National Natural Science Fund of China (No. 52179026). Chengcheng Gong is very grateful to the Chinese Scholarship Council (201906560022) for providing an opportunity to be a visiting PhD student at the University of Neuchâtel. This research was also partially supported by the SAFEA: High-End Foreign Experts Project (G20200027030). We appreciate the insightful comments and constructive suggestions from anonymous reviewers and editors. Open access funding provided by Universite de Neuchatel.

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