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ESTIMATION OF DEPTH TO THE GROUNDWATER TABLE FLUCTUATION WITH HYDRUS-1D MODEL

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ABSTRACT Field scale measurement and mapping of the spatiotemporal variability of depth to the groundwater table (DGWT) is difficult. HYDRUS-1D is a public domain hydrological model for simulating one-dimensional movement of spatial or temporal variability of water, heat, and solute in a porous media. This study evaluated the accuracy of HYDRUS-1D model for predicting DGWT. In achieving this goal, HYDRUS-1D model was calibrated using observed DGWT data of 320 consecutive days and validated using 120 consecutive days data in Newfoundland, Canada. Precipitation data from the nearest weather station and observed DGWT data from a monitoring borehole located in the study site were used. Deep drainage parameters, A_{qh} and B_{qh} were found as the sensitive parameters to predict DGWT. A_{qh} and B_{qh} parameters were adjusted manually during the calibration and found to be -0.60200 cm/day and -0.00840 1/cm, respectively. Resultant A_{qh} and B_{qh} parameters were used for validation. Root mean square error and coefficient of determination between observed and simulated DGWT values during model calibration were 15.85 cm and 0.75 and during validation were 13.35 cm and 0.87, respectively. Simulated DGWT underestimated during both calibration and validation. It was also found that simulation results did not respond to precipitation peaks. If long-term field observations covering higher variability with multiple boreholes together with detailed soil information for the entire profile were available, calibration of the model and the resultant prediction to DGWT could be achieved with higher accuracy.

Keywords: Calibration, Groundwater, Hydrus-1D, Validation

INTRODUCTION In the hydrologic cycle, groundwater recharge plays a major role since it is the largest usable freshwater storage, and its ability to purify water through filtration as well as moderate dry weather flow. Groundwater recharge rate depends on several factors like surface and subsurface conditions (topography, soil water content, porosity, permeability soil texture, and bulk density), climate conditions (precipitation, evaporation, and transpiration) and land use (land use management and vegetation type).

Groundwater recharge fluctuates with barometric pressure changes, earth tides, regional flow, and pumping (Todd, 1959; Bredehoeft, 1967; Roeloffs, 1988; Healy and Cook, 2002; Zeumann et al., 2009; Cutillo and Bredehoeft, 2011). Estimation of groundwater recharge is essential for water resources development, management, and groundwater hydrology investigations (De Silva, 2014). Understanding the processes that cause groundwater recharge and monitoring of the groundwater level fluctuation is crucial in groundwater recharge process (De Silva, 2014).

Direct measurements, water balance method, tracer techniques such as chloride profile, geophysics and hydrological model simulations are the most prominent methods that can be used to estimate groundwater recharge or groundwater level fluctuation. However, these methods have inherent uncertainties and limitations (Vries and Simmers, 2002; Likens, 2009). Accurate estimation of groundwater recharge and its spatiotemporal variability at field level is much more difficult in areas having deeper groundwater table and complex terrain conditions (Sophocleous, 2002; Winter, 1998). If field data; terrain conditions, physical properties of soil, vegetation and meteorological data are available, numerical modelling can be used to estimate groundwater recharge with an acceptable accuracy. Development of hydrological models are alternative methods for expensive, time consuming and labours field works, but the applied model must be pertinent to the actual field conditions (Vries and Simmers, 2002).

HYDRUS-1D software package is a public domain hydrological model considers the coupled water, heat, and solute transport in the soil under physical processes such as precipitation, irrigation, capillary rise, runoff, evapotranspiration, percolation, vegetation characteristics and chemical processes such as soluble salts (van Genuchten and Wagenet, 1989; Simůnek and van Genuchten, 2008). The HYDRUS-1D model numerically solves the Richards equation for variably saturated media and the convection-dispersion equation for heat and solute transport based on Fick's law (Simůnek and van Genuchten, 2008). The accuracy of simulation outputs of the model is generally dependent on the availability and reliability of input parameters. The accuracy of input data such as thermal properties, meteorological variables, and soil's physical and hydraulic properties highly determine the accuracy of the model output (Simůnek and van Genuchten, 2008).

The quantification of water fluxes is essential in agriculture, water supply, environmental science, engineering, and hydrology; thus, need to acquire continuous monitoring of groundwater recharge and spatiotemporal variability of water table fluctuation. Less groundwater recharge means the dropping of groundwater table; hence, it may negatively impact on agricultural and domestic water supplies as well as the sustainability of ecosystems. For efficient and sustainable water resource management, information on groundwater recharge and spatiotemporal variability of groundwater level fluctuation is important. Hydrological models can predict the fluctuation of groundwater table effortlessly with acceptable level of accuracy when input data are reliable. On the other hand, when input data are not reliable or accurate, model predictions might give completely erroneous outputs. If we can acquire in-situ field measurements of inputs such as soil texture, bulk density, and climate data such as precipitation and evaporation, site specific groundwater level fluctuations can accurately be simulated by using hydrological models such as HYDRUS-1D. Overall goal of this study was to evaluate the accuracy of HYDRUS-1D model for predicting depth to the groundwater table (DGWT). Specific objectives were to; (i) identify sensitive parameters that effect on estimation of DGWT by using HYDRUS-1D model, (ii) calibrate HYDRUS-1D model using observed DGWT in 2017 and 2018, and (iii) validate DGWT simulated using HYDRUS-1D with observed values in 2018.

METHODOLOGY The studied site was a grass field in Pynn's Brook Research Station (PBRS) located in Pasadena (49.073 N, 57.561 W), Western Newfoundland, Canada. The site contains reddish brown to brown coloured podzolic soil and depth to the bedrock is more than 1 m with 2 – 5% slope (Badewa et al., 2018; Illawathure et al., 2020).

Data Collection Field data such as type of soil, soil texture and bulk density of the PBRS were collected from literature to be used as input parameters for the HYDRUS-1D model. The upper soil layer from surface to 35 cm is a loamy sand soil. The average bulk density of the loamy sand soil is 1.31 g cm^{-3} and sand, silt and clay percentages are 82%, 11.6% and 6.4%, respectively (Badewa et al., 2018; Illawathure et al., 2020). Below is a well sorted sandy soil layer continue further down to more than 4 m (Badewa et al., 2018). Since the bulk density and soil textural data were not available for the sandy soil layer, model input parameters for sandy soil were taken from Saxton and Rawls (2006) model.

Observed values of DGWT was obtained from a 3.47 m deep, shallow groundwater monitoring borehole located at the PBRS (Illawathure et al., 2020). For the present study, observed DGWT data were considered for 320 days; from, Julian date 174 (23rd June, 2017) to 493 (8th May, 2018) for calibration and 120 days; from, Julian date 494 (9th May, 2018) to 613 (5th September, 2018) for validation (Figure 5, APPENDIX A). Meteorological data for the studied site were collected from the Environment and Natural Resources Canada (www.canada.ca). The daily precipitation data were obtained from the nearest weather station, Deer Lake-A (49.213 N, 57.392 W), Western Newfoundland, Canada. The annual precipitation at the studied site in the year 2017 was 1166 mm with 428 mm falling as snow and in the year 2018 was 1463.7 mm with 576.4 mm falling as snow. (https://climate.weather.gc.ca/historical_data/.html) (Figure 5, APPENDIX A).

HYDRUS-1D Model Simulation of water flow through the vadose zone and recharge of groundwater was the main process since the present study focused on groundwater level fluctuation without considering root water uptake. A period of 320 days (two third of the available observed data) was considered for model calibration and a period of 120 days (one third of the available observed data) was considered for model validation. In this study, the HYDRUS-1D model was run separately as two different simulation exercises for calibration and validation.

The HYDRUS-1D model contains the generalized relationship between the groundwater recharge rate and groundwater table established by Ernst and Feddes (1979) as given in Eq. 1. q_L is the impose lower boundary flux, h_L is transient pressure head or water table elevation at the lower boundary, A_{qh} and B_{qh} are adjacent parameters with the units of cm day^{-1} and cm^{-1}, respectively and h_{gw} is loge-term equilibrium water table position (cm) relative to the lower boundary (Hopmans and Stricker, 1989; Simunek et al., 2008).

$$q_L(t) = A_{qh} \exp\left[-B_{qh}\left|h_L - h_{gw}\right|\right] \qquad (1)$$

According to the literature and by performing trial-and error, the most sensitive parameters were identified to calibrate HYDRUS-1D model for the studied site. Deep drainage parameters, A_{qh} and B_{qh} were identified as sensitive parameters. These two parameters were adjusted manually to minimize the difference between observed and model simulated values of DGWT. This was achieved, initially by plotting observed and simulated values, and then by comparing the differences statistically (Neto et al., 2015; De Silva 2014; Saâdi et al., 2018; Jiménez-Martínez et al., 2009; Golmohammadi et al., 2021). The best fitting values of A_{qh} and B_{qh}, were defined for the studied site and then were applied for the model validation.

For the model calibration and validation, a 400 cm deep soil profile was considered having two soil layers. Atmospheric boundary condition with surface runoff was considered as the upper boundary condition and deep drainage was considered as the lower boundary condition. Initial conditions were used in pressure heads. The soil hydraulic parameters for two soil materials; loamy sand soil and sandy soil, were derived with available field data by the HYDRUS-1D from van Genuchten model according to the input data.

Table 1. Input information of the HYDRUS-1D model for calibration and validation

Input Information	Parameters	Inputs/Values	
		Calibration Model	Validation Model
Geometry Information	Number of soil materials	2	2
	Number of layers	2	2
	Depth of soil profile (cm)	400	400
Time Information	Initial time (Days)	0	0
	Final time (Days)	320	120
	Time variable BC	320	120
Irritation Criteria	Maximum number of irritations	200	200
	Water content tolerance	0.005	0.005
	Pressure head tolerance (cm)	0.005	0.005
Soil Hydraulic Model	Hydraulic model	van Genuchten-Mualem	van Genuchten-Mualem
Water Flow BC	Upper BC	Atmospheric BC with surface runoff	Atmospheric BC with surface runoff
	Lower BC	Deep drainage	Deep drainage
	Initial conditions	In pressure heads	In pressure heads

Note: BC – Boundary Condition

Under the profile discretization, the whole 400 cm soil profile was divided into 201 nodes at 2 cm intervals. During the calibration exercise, DGWT of the first day (Julian date 174) was set at 250 cm, and it was considered as the initial water table depth for model input. During the validation, 180 cm was applied as the initial water table depth of the first day (Julian day 494).

Data were analyzed qualitatively and quantitatively. Qualitative data analysis was done by observing graphs and comparing observed and simulated DGWT data with 1:1 line. Statistical analysis such as root mean square error (RMSE) and coefficient of determination (R^2) was applied to analyze data quantitatively.

RESULTS AND DISCUSSION

Model Calibration According to the literature, A_{qh} and B_{qh} parameters were the sensitive parameters for the calibration of DGWT (Neto et al., 2015; De Silva, 2014; Saâdi et al., 2018; Jiménez-Martínez et al., 2009). Results of simulated DGWT obtained with a number of trial-and-error runs completed using different A_{qh} and B_{qh} values and observed groundwater table data are shown in Figure 1 and Table 2 (APPENDIX A). Visually and statistically, the best fitting of observed and model simulated DGWT was found when A_{qh} parameter in q(GWL) was at -0.60200 cm day^{-1}, B_{qh} parameter in q(GWL) was at -0.00840 cm^{-1} and the reference groundwater level position was at 248 cm. RMSE and R^2 between the observed and simulated values of best fit DGWT was 15.85 cm and 0.75, respectively (Table 2, APPENDIX A). Initial days of the simulated period (Days from 174 to 350) observed and model simulated values of DGWT was fit closely, but the peaks of observed values were not simulated accurately by the model. In general, simulated results underestimated the DGWT, but followed the pattern of observed DGWT fluctuation (Figure 1 and 2).

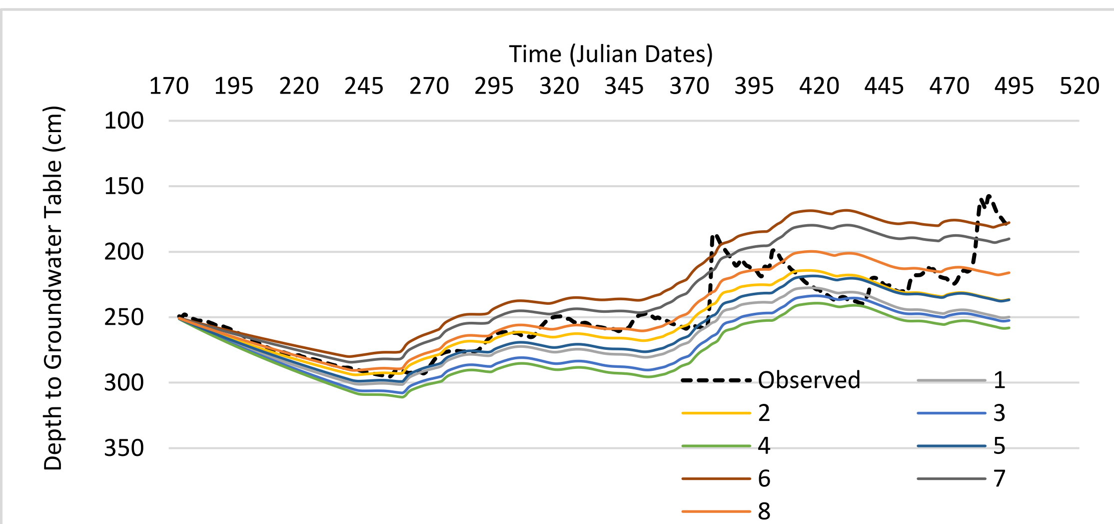

Figure 1. Variation of the simulated depth to the groundwater table (DGWT) during the calibration exercise

(X axis is in Julian dates starting the 1st January 2017 as the day 1)

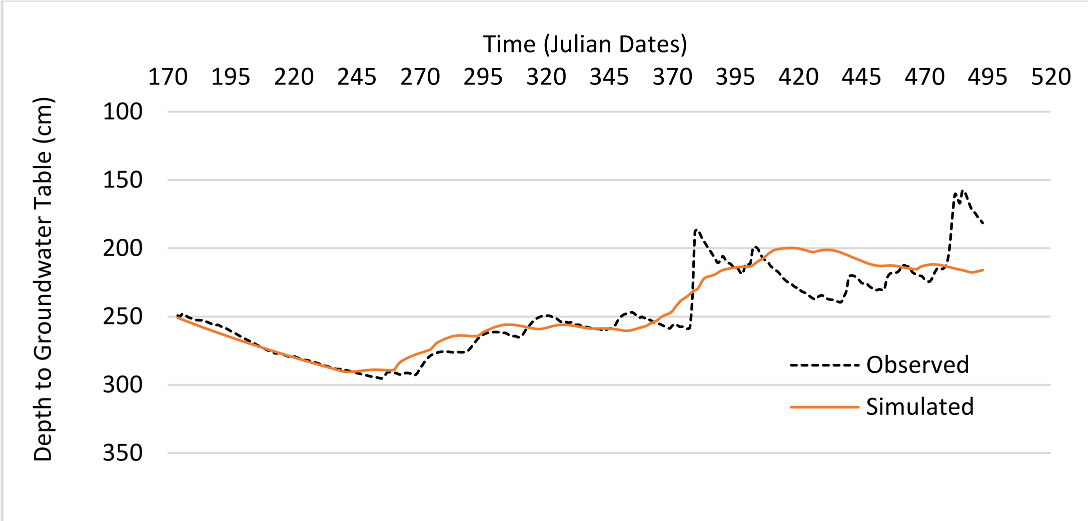

Figure 1. Observed and simulated depth to the groundwater table (DGWT) fluctuation during the calibration exercise based on the best values of A_{qh} and B_{hq} parameters

(X axis is in Julian dates starting the 1st January 2017 as the day 1)

Model Validation In the initial days of the validated period (Days from 494 to 530), observed and model simulated patterns of DGWT closely matched; however, the rest of the simulated results had some deviation from the observed values with the best fit values of the sensitive parameters (A_{qh} and B_{qh}) obtained during the calibration process (Figure 3). RMSE and R^2 between the observed and simulated values of DGWT was 13.35 cm and 0.87, respectively. Similar to the calibration results, the model simulated results of validation also underestimate the DGWT.

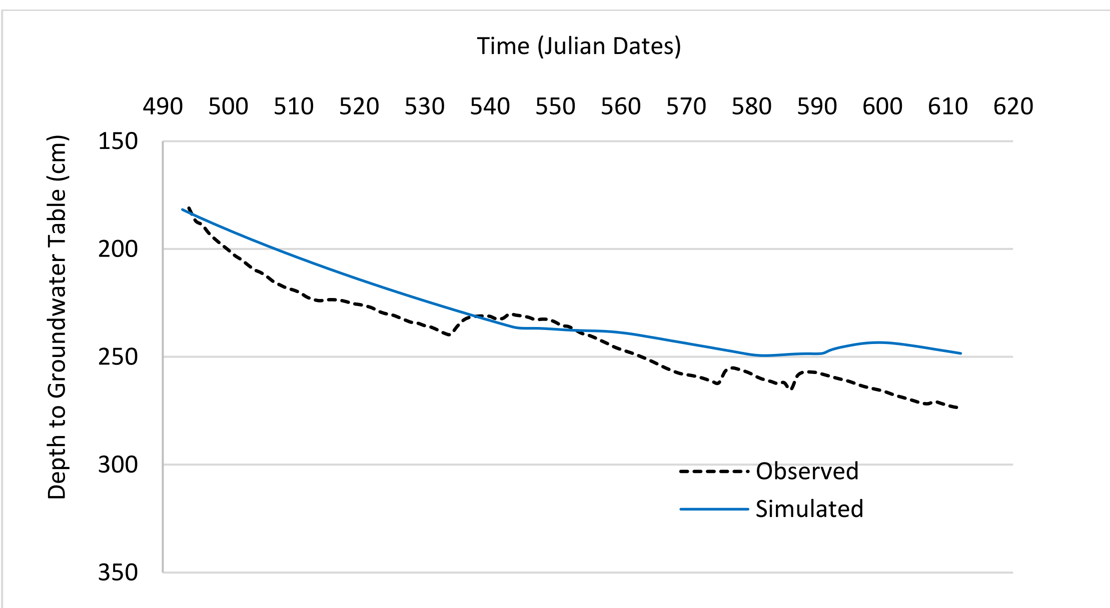

Figure 2. Observed and simulated depth to the groundwater table (DGWT) fluctuation during the validation exercise

(X axis is in Julian dates starting the 1st January 2017 as the day 1)

Further Analysis A further analysis was carried out to improve the fitting between observed and simulated DGWT values using the validation data set. This process was done by changing A_{qh} and B_{qh} parameters by +5% from the calibrated values. When the A_{qh} value was changed by 5% increments until a 25% changed, RMSE decreased and R^2 increased slightly; however, changing of the B_{qh} at the same percentage did not decrease RMSE or increase R^2 much (Table 3, APPENDIX A). This might be due to a very small value of B_{qh} compared to A_{qh}, and comparatively lower sensitivity.

Both visually and statistically, the best match between the observed and model simulated DGWT for the validation period was found when A_{qh} parameter in q(GWL) was at -0.7525 cm day^{-1} (when the calibrated A_{qh} was increased by 25%) and B_{qh} parameter in q(GWL) was at -0.00840 cm^{-1} (similar to the calibrated value). After adjusting these sensitive parameters, RMSE and R^2 between the observed and simulated DGWT were 7.96 cm and 0.89, respectively.

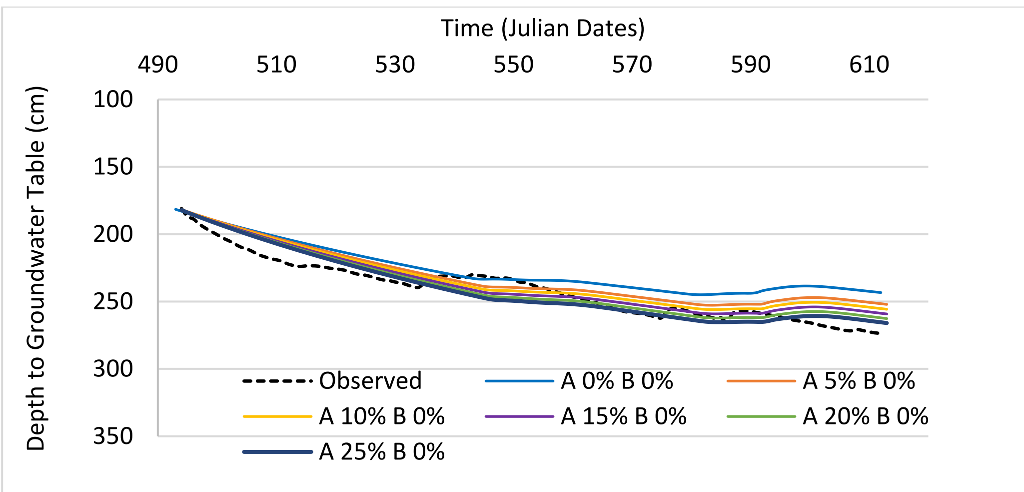

Figure 3. Variability of groundwater table during the validation period by adjusting parameter A

(X axis is in Julian dates starting the 1st January 2017 as the day 1)

In the present study, field data were available only in loamy sand soil (upper soil layer, 0-35 cm) and bulk density and soil textural data were not available for the second layer (35-400). Therefore, hydraulic parameters for the sandy soil layer (saturated hydraulic conductivity, saturated water content and residual water content) were derived assuming a general soil type (sandy soil). On the other hand, the impact of the second layer on water storage and deep drainage must have been higher since this layer is much thicker (higher weightage) compared to the topsoil layer. This study shows the importance of the availability and accuracy of input data.

CONCLUSION Groundwater recharge and spatiotemporal variability of DGWT is essential for efficient and sustainable water resource development and management for domestic, agricultural, environmental and engineering purposes, and climate studies. This study assessed the potential of HYDRUS-1D model to estimate the variability of depth to the groundwater table (DGWT) in boreal region and its accuracy. Results obtained using the

HYDRUS-1D model during calibration and validation often matched with observed data in the studied site. Statistical results of the validation showed higher accuracy with observed DGWT values than during the calibration.

According to the present study, model simulated DGWT was not fitted well with spikes (higher precipitations) of the rainfall pattern as shown by the observed DGWT. It showed that the HYDRUS-1D model needed extensive calibration to obtain accurate DGWT and its fluctuations due to rapid recharge and discharge processes. Overall results of both calibration and validation processes showed underestimation of DGWT.
The advantage of applying the HYDRUS-1D model in soil hydrology is that it gives not only the DGWT, but also other important hydrological processes like soil water storage, infiltration, runoff, surface fluxes, and bottom fluxes. If accurate field data, climate data, and initial depth to ground water table data were available, the HYDRUS-1D model would be able to predict DGWT with an acceptable accuracy.

REFERENCES

Badewa, E., Unc, A., Cheema, M., Kavanagh, V., and Galagedara, L. (2018). Soil moisture mapping using multi-frequency and multi-coil electromagnetic induction sensors on managed podzols. Agronomy, 8(10), 224. https://doi.org/10.3390/agronomy8100224

Bredehoeft, J.D. (1967). Response of well-aquifer systems to earth tides. Journal of Geophysical Research, 72(12), 3075–3087. https://doi.org/10.1029/jz072i012p03075

Cutillo, P.A., and Bredehoeft. J.D. (2011). Estimating aquifer properties from water level response to earth tides. Ground Water, 49(4), 600–610. https://doi.org/10.1111/j.1745-6584.2010.00778.x

De Silva, C.S. (2014). Simulation of potential groundwater recharge from the Jaffna Peninsula of Sri Lanka using HYDRUS-1D Model. OUSL Journal, 7(0), 43. https://doi.org/10.4038/ouslj.v7i0.7307

de Vries, J.J., and Simmers, I. (2002). Groundwater recharge: An overview of processes and challenges. Hydrogeology Journal, 10(1), 5–17. https://doi. org/10.1007/ s10040-001-0171-7

Ernst, L. F., and Feddes, R. A. (1979). Invloed van grondwateronttrekking voor beregening en drinkwater op de grondwaterstand (No. 1116). ICW.

Golmohammadi, G., Rudra, R. P., Parkin, G. W., Kulasekera, P. B., Macrae, M., & Goel, P. K. (2021). Assessment of impacts of climate change on tile discharge and nitrogen yield using the drainmod model. Hydrology, 8(1), 1–16. https://doi.org/10.3390/hydrology8010001

Healy, R.W., and Cook, P.G. (2002). Using groundwater levels to estimate recharge. Hydrogeology Journal, 10(1), 91–109. https://doi.org/10.1007/s10040-001-0178-0

Hopmans, J.W., and Stricker, J.N.M. (1989). Stochastic analysis of soil water regime in a watershed. Journal of Hydrology, 105, 57–84.

Illawathure, C., Cheema, M., Kavanagh, V., & Galagedara, L. (2020). Distinguishing capillary fringe reflection in a GPR profile for precise water table depth estimation in a boreal podzolic soil field. *Water (Switzerland)*, *12*(6). https://doi.org/10.3390/W12061670

Jiménez-Martínez, J., Skaggs, T.H., van Genuchten, M.T., and Candela, L. (2009). A root zone modelling approach to estimating groundwater recharge from irrigated areas.

Journal of Hydrology, 367(1–2), 138–149. https://doi.org/10.1016/j.jhydrol.2009.01.002
Likens, G., Benbow, M.E., Burton, T.M., Van Donk, E., Downing, J.A., and Gulati, R.D. (2009). Encyclopaedia of Inland Waters. Elsevier B.V. 0-12-370626-2
Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research, 12(3), 513–522. https://doi.org/10.1029/WR 012i003p00513
Neto, D.C., Chang, H.K., & van Genuchten, M.T. (2016). A mathematical view of water table fluctuations in a shallow aquifer in Brazil. Groundwater, 54(1), 82–91. https://doi.org/10.1111/gwat.12329
Rassam, D., Šimůnek, J., Mallants, D., and van Genuchten, M.T. (2018). The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media: Tutorial. Riverside: CSIRO Land and Water.
Roeloffs, E.A. (1988). Hydrologic precursors to earthquakes: a review. Pure and Applied Geophysics, 126(2–4), 177–209. https://doi.org/10.1007/BF00878996
Saâdi, M., Zghibi, A., and Kanzari, S. (2018). Modeling interactions between saturated and un-saturated zones by Hydrus-1D in semi-arid regions (plain of Kairouan, Central Tunisia). Environmental Monitoring and Assessment, 190(3), 170. https://doi.org/10.1007/s10661-018-6544-3
Sophocleous, M. (2002). Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal, 10(1), 52–67. https://doi.org/10.1007/s10040-001-0170-8
Saxton, K.E., and Rawls, W.J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of America Journal, 70:1569–1578 (2006). https:// doi:10.2136/sssaj2005.0117
Schaap, M.G., Leij, F.J., and van Genuchten, M.T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology, 251(3–4), 163–176. https://doi.org/10.1016/S0022-1694(01)00466-8
Šimůnek, J., van Genuchten, M.T., and Šejna, M. (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. Vadose Zone Journal, 7(2), 587–600. https://doi.org/10.2136/vzj2007.0077
Todd, D.K. (1959). Groundwater Hydrology. New York, John Wiley and Sons.
van Genuchten, M.T., and Wagenet, R.J. (1989). Two-site/two-region models for pesticide transport and degradation: Theoretical development and analytical solutions. Soil Science Society of America Journal, 53(5), 1303–1310. https://doi.org/10.2136/sssaj1989.03615995005300050001x
Winter, T.C. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal, 7(1), 28–45. https://doi.org/10.1007/s100400050178
Zeumann, S., Weise, A., and Jahr, T. (2009). Tidal and non-tidal signals in groundwater boreholes in the KTB area, Germany. Journal of Geodynamics, 48(3–5), 115–119. https://doi.org/10.1016/j.jog.2009.09.037

APPENDIX A

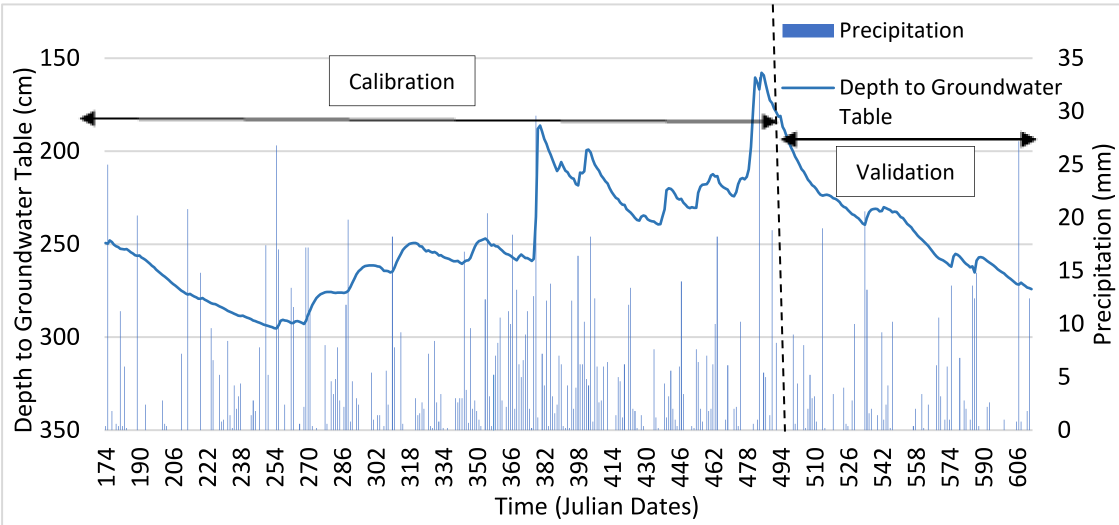

Figure 4. Daily precipitation and daily observed depth to the groundwater table fluctuation during the studied period

(X axis is in Julian dates starting the 1st January 2017 as the day 1)

Table 2. Summary of the sensitive fitting parameters, RMSE and R^2 between observed and simulated depth to the groundwater table during the calibration process

Model Run	Deep Drainage Parameters		RMSE (cm)	R^2
	A_{qh} (cm day^{-1})	B_{qh} (cm^{-1})		
1	-0.96320	-0.01008	24.54	0.69
2	-0.90300	-0.01092	17.88	0.72
3	-0.72900	-0.00714	29.24	0.66
4	-0.72900	-0.00672	3312	0.63
5	-0.69863	-0.00798	20.09	0.73
6	-0.41600	-0.00798	30.14	0.75
7	-0.45270	-0.00750	23.18	0.75
8	-0.60200	-0.00840	15.85	0.75

Table 3. Summary of the adjusting parameters, RMSE and R^2 between observed and simulated depth to the groundwater table during further studies

Percentage Change		Values		RMSE (cm)	R^2
A_{qh} (%)	B_{qh} (%)	A_{qh} (%)	B_{qh} (%)		
0	0	-0.6020	-0.0084	13.35	0.87
5	0	-0.6321	-0.0084	11.33	0.89
10	0	-0.6622	-0.0084	09.64	0.88
15	0	-0.6923	-0.0084	08.42	0.89
20	0	-0.7224	-0.0084	07.83	0.89
25	0	-0.7525	-0.0084	07.96	0.89