Assessing the Performance of WaSim and DRAINMOD Models for Subsurface Drainage Design and Analysis in a Data-Scarce Environment

Collection
Research

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Highlights

- Simulation models are useful decision-support tools for the design and analysis of drainage systems.
- Pedotransfer functions can estimate soil hydraulic inputs to drainage models.
- The DRAINMOD model performed well and can be used as a subsurface drainage design tool.
- WaSim model performed satisfactorily and can also be used as a subsurface drainage design tool.

Abstract. *Simulation models are useful decision-support tools for designing and analyzing subsurface drainage systems in irrigated lands. However, the challenge is determining the soil hydraulic data inputs required by models to achieve reliable and accurate simulation of water table depths (WTDs) and drainage discharges (DDs) at various drain depths and spacing combinations. This is particularly important for data-scarce areas, such as middle- and low-income countries (MLICs), that lack facilities to determine in-situ soil hydraulic properties. We evaluated the performance of WaSim and DRAINMOD models to simulate WTDs and DDs at a field scale in KwaZulu-Natal, South Africa. Saturated hydraulic conductivity (K_{sat}) and soil water retention ($\theta(h)$) values were determined using the in-situ pumping test and a pressure plate apparatus. Pedotransfer functions (PTFs) in the Rosetta computer program also estimated these soil parameters. The DRAINMOD and WaSim models were calibrated using the in-situ measured K_{sat} and laboratory-measured $\theta(h)$ data, while the validation exercise used the PTFs-estimated K_{sat} and $\theta(h)$ data as soil hydraulic inputs. The models' performance in simulating WTDs and DDs was assessed using Nash-Sutcliffe Model Efficiency (NSE), Modified Index of Agreement (d), Coefficient of Determination (R^2), and Mean Absolute Error (MAE). During validation, DRAINMOD simulated WTDs with NSE, d, R^2, and MAE of 0.86, 0.81, 0.89, and 5.3 cm, respectively, whereas, for DDs, the model registered NSE, d, R^2, and MPE of 0.81, 0.79, 0.83, and 0.17 mm.day^{-1}, respectively. During the validation period, the WaSim model simulated WTDs with NSE, d, R^2, and MAE of 0.76, 0.74, 0.78, and 9.0 cm, respectively. For the same validation period, the WaSim model simulated DDs with NSE, d, R^2, and MAE of 0.74, 0.73, 0.77, and 0.2 mm.day^{-1}, respectively. The results suggest that both models, with either in-situ measured and laboratory-measured soil data or PTFs-estimated soil data, can be used to design and analyze drainage systems in data-scarce environments with a reasonably high confidence level. Designers of subsurface drainage systems in Pongola, South Africa, can use any of the two drainage models as decision support tools. We recommend using DRAINMOD and WaSim models with PTFs-estimated hydraulic soil data based on soil textural information, soil particle size data, bulk density, and θ(h) data at field capacity and permanent wilting point.*

Keywords. *Deep percolation, Irrigation, Pedotransfer functions, Water management, Water table.*

Poor agricultural drainage threatens irrigated agriculture's long-term sustainability (Gurovich and Oyarce, 2015). The problem is more pronounced in arid and semi-arid areas with low-permeable soils (Singh, 2018). Providing artificial subsurface drainage systems in such areas constitutes one of the critical determinants for a successful irrigation system (Oosterbaan, 2020).

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Subsurface drainage systems assist in lowering root-zone soil salinity below threshold levels, beyond which crop growth is negatively affected (Skaggs, 2017). Furthermore, they facilitate reducing waterlogging by lowering shallow water tables to soil layers below the root-zone (Skaggs, 2017). The goal is to maintain a soil-water-air-salt balance that optimizes root-zone oxygenation and root-water and -nutrient uptake (Gurovich and Oyarce, 2015; Tao et al., 2019; Hauda et al., 2020). Of critical importance is to design and install a subsurface drainage system that will timely lower water table depths before saturated soil conditions in the root-zone become toxic to plant roots (Gurovich and Oyarce, 2015). The challenge, however, is to accurately determine the appropriate (1) drain depth (d), (2) drain spacing (L), (3) hydraulic head (h_d), and (4) drainage discharge (q) that correspond well with existing soil types, recharge rate to the soil system (R), and design water table depth (Ds), which is a function of the type of crop being grown.

Until the 1980s, the determination of subsurface drainage design parameters depended on the team's experience with the system's design (ASABE Standards, 1999). Unfortunately, this design approach is prone to many errors. It has often resulted in over- or under-designed subsurface drainage systems, negatively impacting investment costs and crop growth (Oosterbaan, 2000). Also, the soil system is complex, and its behavior can be better understood using mechanistic or process-based comprehensive tools such as simulation models (Wang et al., 2006). This could explain the development of a good number of subsurface drainage simulation models that have taken place within the past five decades. The models have significantly simplified the design of subsurface drainage systems by allowing designers to analyze the performance of the systems at various combinations of drain depth (d) and spacing (L) before installation (Malota et al., 2022). According to Jeantet et al. (2021), simulation models are useful decision-support tools that provide a timely and cost-effective determination of optimal drainage system design parameters.

Most subsurface drainage models require inputs such as weather data, crop information, soil surface characteristics, soil layering, and soil properties for each layer (e.g., soil texture and bulk density) (Halbac-Cotoara-Zamfir et al., 2022). Nearly all models require soil hydraulic inputs such as saturated soil hydraulic conductivity (K_{sat}), soil water fractions (θ), and their corresponding pressure heads (h), which are derived from Soil Water Retention Curves (SWRCs) (Hess et al., 2000; Hirekhan et al., 2007; Oosterbaan, 2020). Usually, drainage models are very sensitive to both K_{sat} and $\theta(h)$ (Skaggs et al., 2012). Therefore, they must be accurately estimated to minimize the prediction uncertainty of drainage simulation models. However, precise measurement of K_{sat} and $\theta(h)$ is achieved using in-situ measurement methods, which are expensive and often unavailable, particularly in many developing countries (Salazar et al., 2008). Unfortunately, laboratory methods, which are an alternative to in-situ methods, tend to overestimate these parameters (Moriasi et al., 2007). Owing to these challenges, researchers developed indirect methods that estimate both K_{sat} and $\theta(h)$ from surrogate data, e.g., soil particle size distribution data and bulk density (Schaap et al., 2001). The common term given to these indirect methods is called Pedotransfer Functions (PTFs) (Bouma and van Lanen, 1987). Notable examples of PTFs have been reported by Rawls and Brakensiek (1985), Rawls et al. (1991), and van Genuchten and Liej (1992).

Since the development of PTFs, the irrigation and drainage community has benefited from the wide choice of methods and approaches for estimating soil hydraulic parameters for various uses. The Rosetta computer program (Schaap et al., 2001) presents good examples of popular PTFs that users can employ to estimate $\theta(h)$ and $K_{sat,}$ even with limited soil data. Rosetta estimates these parameters using any of the following options, which represent different levels of soil data availability: (1) soil textural class (STC) only; (2) STC + % sand, silt and clay (%SSC) + soil bulk density (SBD); (3) STC +%SSC + SBD + $\theta(h)$ values at field capacity (SWR_{fc}); or (4) STC +%SSC + SBD + SWR_{fc} + $\theta(h)$ values at permanent wilting point (SWR_{pwp}).

Like PTFs, drainage simulation models exhibit significant variations in data input requirements, user-friendliness, and level of complexity (Diaconu et al., 2017). Therefore, providing a wider choice of simulation models to meet different user needs and contexts is paramount (Gurovich and Oyarce, 2015). Selected examples of drainage models are DRAINMOD (Skaggs, 1980), WaSim (Hess et al., 2000), SALTMOD (Oosterbaan, 2000), EnDrain (Ebrahimipak et al., 2019), and SWAP (Halbac-Cotoara-Zamfir, 2022). Of the many drainage models, WaSim and DRAINMOD are the two models that have been widely applied as decision-support tools when designing and analyzing subsurface drainage systems in many parts of the world (e.g., Hirekhan et al., 2007; Dayyani et al., 2009; Skaggs et al., 2012). The wide adoption of the two models is largely based on their suitability for application in a wide range of soil types and water table conditions (Salazar et al., 2008; Ebrahimipak et al., 2019). The strength of the WaSim model is that it is user-friendly (with a graphical interface), in addition to having a minimal data input requirement (Hirekhan et al., 2007). Though not as easy to use as the WaSim model, the strength of the DRAINMOD model is its applicability in different climatic regions, i.e., humid, arid, and semi-arid regions (Skaggs et al., 2012).

In common with many countries that depend on irrigated agriculture for food production, South Africa has also seen substantial agricultural drainage improvements over the past two decades (Reinders et al., 2016). Despite this, nearly 42% of the total 16.7 million hectares of arable land in South Africa is still waterlogged with elevated salinity levels and is in urgent need of well-designed subsurface drainage systems (Ojo et al., 2011; Reinders et al., 2016). Addressing this challenge timely and cost-effectively would require using drainage models as decision-support tools. However, the performance of the drainage models needs to be thoroughly assessed before they can be used to design drainage systems. Similarly, challenges caused by the limited availability of soil hydraulic data inputs to drainage models must be addressed promptly and effectively, specifically in certain parts of South Africa where such data is unavailable. The objective of this study was to evaluate the performance of the WaSim and DRAINMOD models for the design and analysis of subsurface drainage systems using soil hydraulic inputs estimated by PTFs at a field scale in KwaZulu-Natal, South Africa.

Materials and Methods

Study Site

This field scale study was conducted on an irrigated sugarcane field (32 hectares) located in Pongola, KwaZulu-Natal Province, on the north-eastern side of South Africa, near the Swaziland border (coordinates 27° 23′ 0″ South and 31° 37′ 0″ East) (fig. 1). Crop production in the area relies on irrigation during April-October and depends on rainfall during November-March. Sugarcane was planted at the study site in August 2011 and harvested in June and July 2012. The sugarcane crop was irrigated using a sprinkler irrigation system with a 20 mm design gross irrigation depth every 7 days.

The area is considered arid, with an aridity index of 0.2 (Malota and Senzanje, 2015). KwaZulu-Natal is dominated by podzol soils that require long-term fertilization to facilitate arable cropping (Lambrechts and MacVicar, 2004). The far northern part of the field (A9 and A10) is dominated by clay-loam soils, while the rest of the field is dominated by clay soils (fig. 1) (van der Merwe, 2003; Malota, 2013; Malota and Senzanje, 2015). In common with many government agricultural offices in South Africa, the Pongola Agricultural Office conducts soil analyses to determine the most easily measured soil data under laboratory conditions, e.g., % sand, silt and clay, and laboratory-determined soil water retention data. The soil surface slopes at the irrigation scheme are between 2 and 2.8% in all directions.

Analysis of the soil profile from five trenches dug down to the drain depth in the field (north, south, east, west, and center) revealed the presence of two soil profile layers. The mean thickness of the topsoil profile layer is 0.40 m, whose spatial variation across the field is insignificant (coefficient of variation = 3.41%). The bottom profile layer is more than 1.9 m thick. The current drainage system was installed in 2003 with 54 m drain spacing, 1.8 m drain depth, and a 5 mm.day^{-1} design discharge. Despite installing the drainage systems, the irrigation scheme continued to experience shallow water tables less than 0.5 m deep from the soil surface. This warranted further investigation of the performance of the subsurface drainage system.

Brief Description uf the WaSim and Drainmod Models

WaSim Model

WaSim is a process-based model jointly developed by Cranfield University and HR Wallingford, UK. The model simulates the fluctuation of soil water fractions and WTDs, considering inputs of rainfall, irrigation, and/or seepage from canals whenever relevant (Hess et al., 2000). The development of the model was based on a water balance of a four-layered soil profile extending from the soil surface (upper boundary layer) down to the impermeable layer (lower boundary layer) (fig. 2) (Hess et al., 2000). Lateral and vertical seepage are estimated using Darcy's equation. Potential evapotranspiration is calculated by the WaSim ET utility using the Penman, Penman-Monteith, or FAO Modified Penman-Monteith equations.

Infiltration is calculated using the Green-Ampt equation. In this case, the soil is assumed to be homogenous, with the matrix flow assumed to be dominant. The wetting front is approximated as a step function, and precipitation intensity is assumed to be constant over the entire time step. Soil water moves from the upper layer to the lower layer when the soil moisture content in the upper layer exceeds field capacity (FC). Thus, the drainage rate is the function of the amount of excess water in the upper soil layers (fig. 2).

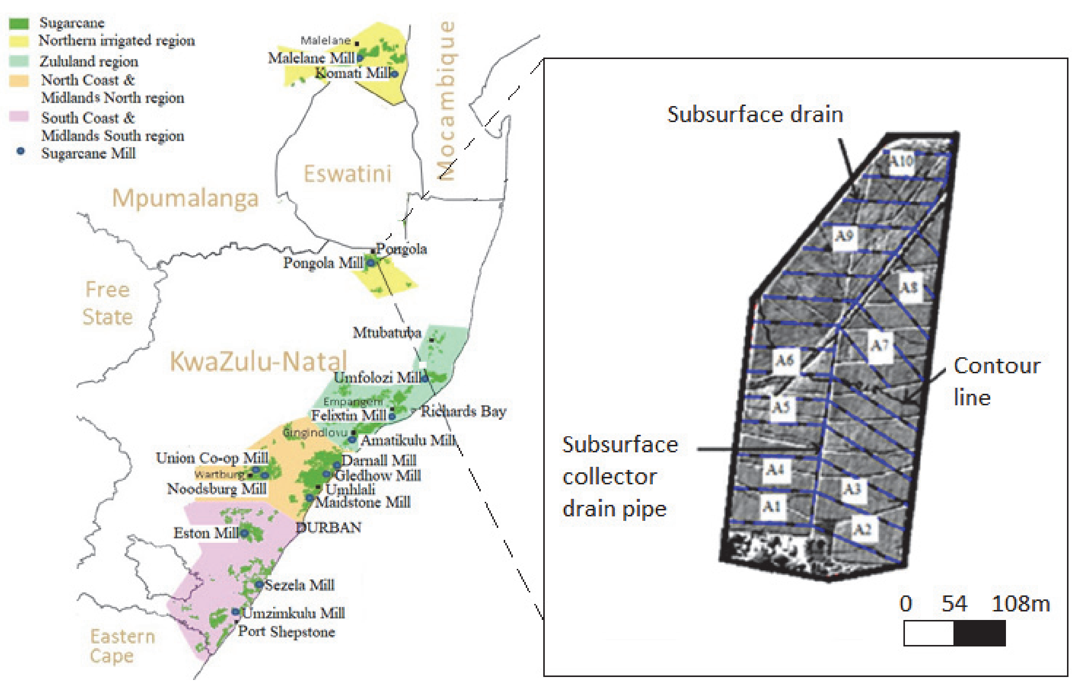

Figure 1. Location of the study site, soil sampling, and WTD measurement points (A1 – A10) in the sugarcane field in South Africa (Malota, 2013; Otim et al., 2020).

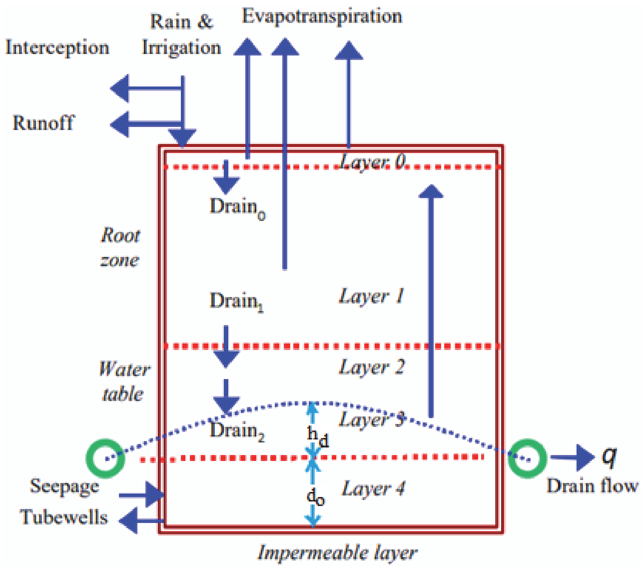

Figure 2. Overview of the soil water balance in the WaSim model (after Hess et al., 2000).

Daily surface runoff due to irrigation and/or rainfall is estimated using the US SCS curve number technique (USDA, 1969). The soil water movement from upper soil layers to lower layers constitutes deep percolation, which forms an input into the subroutine for predicting water table depth and drainage discharge. The calculation of drainage discharge (q) (mm.day^{-1}) considers various mathematical and physical approximations, which is generally common with many physical-based equations (Lovell and Youngs, 1984). In this regard, WaSim uses empirical equation 1 (after Youngs et al., 1989), which assumes a steady-state subsurface drainage system and that the subsurface drain pipe diameter (φ) (m) is large enough not to cause head losses that would increase the water-table height (h_d) (m) midway between two drains (0.5L).

$$q = 1000\left\{\frac{K_{sat}}{(0.5L)^{\beta}}\left[(0.5\varphi)^{\beta} - h_d^{\beta}\right]\right\} \tag{1}$$

where

K_{sat} = saturated hydraulic conductivity (m.day^{-1})

L = drain spacing (m)

β = an exponent (dimensionless) that is calculated using equation 2.

$$\beta = 2\left[d_0 / (0.5L)\right]^{d_0/(0.5L)} \quad \text{for} \quad \frac{d_0}{(0.5L)} < 0.35 \tag{2}$$

Or else,

$$\beta = 1.36$$

where d_0 is the depth to the impermeable layer (m).

WaSim simulates the contribution of groundwater to transpiration and evaporation (capillary rise) as a function of the differences between root depth (for transpiration) and soil surface (for evaporation), water table depth, and the hydraulic properties of the soil (Hess et al., 2000). A summary of the inputs and outputs of the WaSim model is given in table 1. Further details of the model can be found in Hess et al. (2000).

DRAINMOD Model

DRAINMOD is a process-based hydrological model that simulates the performance of subsurface drainage, controlled drainage, and/or sub-irrigation systems over a long climatological period (Skaggs, 1980; Skaggs et al., 2012). Skaggs et al. (2012) provide the following description of the DRAINMOD model: The model computes a day-by-day and hour-by-hour water balance of a vertical soil column that exists mid-way between two drains. DRAINMOD predicts the outputs of hydrologic processes such as infiltration, subsurface drainage, surface runoff, evapotranspiration, vertical and lateral seepage, water table depth, and water-free pore space in the soil. Output summaries of these processes are given on a daily, hourly, monthly, and yearly time step as defined by the user.

Infiltration is predicted using the Green-Ampt equation (Green and Ampt, 1911). Surface water storage is characterized by the average depth of depressions on the soil surface that must be filled before runoff can begin (Gayle and Skaggs, 1978) (see S1 in fig. 3). Potential evapotranspiration (PET) can be inputted directly as an input data file. Otherwise, DRAINMOD calculates PET using the Thornthwaite method. The calculation of PET depends on weather data such as daily rainfall, temperature, relative humidity, and wind speed. The distribution of soil water in the soil is assumed to be in two zones. First, water is distributed in the wet zone, which is assumed to extend from the water table level to the root zone. Secondly, soil water is distributed in the dry zone, where water is assumed to have been removed due to the inadequate water supply to meet the evapotranspiration demand in the root-zone. The soil water distribution and the volume of water-free-pore space in the soil profile above the water table are computed and given as an output at a user-defined time step.

DRAINMOD uses Hooghoudt's steady state equation (eq. 3) to calculate drain outflow from the saturated soil zone (Skaggs et al., 2012). DRAINMOD also uses Kirkham's equation to estimate drainage outflow when the soil profile is completely saturated, and surface water ponding allows water to move freely on the soil surface. See Skaggs et al. (2012) for more information. The parameters in equation 3 are as defined in figure 3.

$$q = \frac{8K_{sat2}d_e h_d + 4K_{sat1}h_d^{2}}{L^2} \tag{3}$$

Table 2 summarizes the inputs and outputs of the DRAINMOD model. More details about the DRAINMOD model can be found in Skaggs et al. (2012).

Description of the Rosetta Computer Program

Rosetta is a computer program that contains five hierarchy PTFs to estimate θ(h) values and saturated (K_{sat}) and unsaturated hydraulic conductivities (K_{unsat}) (Schaap et al., 2001). In addition, Rosetta contains a sub-program known as the RETention Curves (RETC) that describes the hydraulic properties of saturated and unsaturated soils and predicts soil water retention values. The PTFs in Rosetta estimate θ(h) values and saturated and unsaturated hydraulic conductivity parameters using surrogate data such as particle size

Table 1. Summary of Wasim model inputs and outputs (Hess et al., 2000).

Inputs	Outputs
Weather and irrigation data (actual irrigation depths, daily rainfall, PET, and temperature)	Crop transpiration
Soil data (lateral hydraulic conductivities, soil water retention values, and soil layer depths)	Water table depths
Crop-related inputs (crop type, daily root elongation rate, and daily root-water uptake)	Drainage discharge
Drainage systems parameters (drain depth, drain spacing, depth to impermeable layer, and design drainage discharge)	Capillary rise Surface runoff Open water and soil evaporation

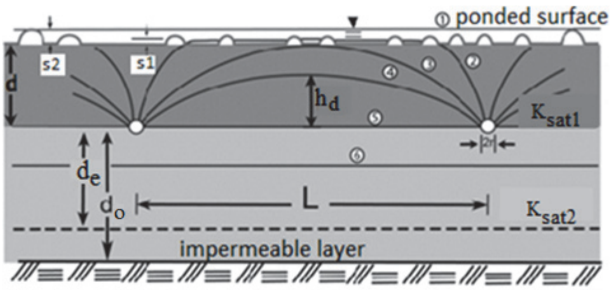

Figure 3. A schematic presentation of the DRAIMOD model (after Skaggs et al., 2012) (L = drain spacing (m), K_{sat1}, K_{sat2} = saturated hydraulic conductivity (mm.day^{-1}) above and below the drainage base, respectively, d_e = equivalent depth (m), S1 is the average depth of depressions on the soil surface (mm), S2 is the maximum depth of depressions on the soil surface (mm), d is the drain depth (mm), h_d = hydraulic head (m), and d_o = depth to impermeable layer (m)).

distribution (i.e., % sand, silt and clay), bulk density, and/or soil water retention values at one or two known points on the soil water retention curve (SWRC) (i.e., soil water fractions at -33 kPa (Field Capacity (FC)) and -1500 kPa (Permanent Wilting Point (PWP)). Saturated hydraulic conductivity values are estimated using the van Genuchten-Mualem soil hydraulic model presented in equation 4 (Schaap et al., 2001).

$$K_r\left(S_e\right) = K_0 S_e^{L_x}\left\{1-\left[1-S_e^{n/(n-1)}\right]^{1-(1/n)}\right\}^2 \tag{4}$$

where

S_e = effective saturation (cm^3.cm^{-3})

K_r = relative hydraulic conductivity (dimensionless)

n (>1) = measure of pore-size distribution

L_x (<0) = an empirical connectivity parameter, in most cases taken as 0.5 (Mualem, 1976)

K_0 = matching point at saturation (m.day^{-1}) and is comparable, but not entirely equal to K_{sat}.

A summary of inputs to the five hierarchy PTFs contained in Rosetta and their respective outputs is provided in table 3. Schaap et al. (2001) highlight that better estimation of K_{sat} values by Rosetta is associated with more detailed soil data inputs and information. Thus, the fifth PTF in table 3 is likely to better estimate K_{sat} values than the rest of the PTFs.

Study Approach

This study involved the collection of weather and irrigation data, measurement of soil properties, water table depths, and drainage discharges, determination of soil hydraulic properties using PTFs within Rosetta, calibration and validation of the WaSim and DRAINMOD models, and finally, performance assessment of the two drainage models to simulate WTDs and DDs using various statistical indices. Figure 4 provides a flow diagram of the methodology adopted in the study.

Measurement of Soil Physical and Hydraulic Properties

Saturated soil hydraulic conductivity (K_{sat}) values were measured using the in-situ auger-hole method (van Beers, 1983). The locations of the auger-holes (piezometers) were selected randomly. Three 70 mm diameter piezometers were drilled in each of the upper and middle sections of the scheme, while the lower section had four piezometers. All piezometers were augured to a depth of 1.7 m, well below the observed water table depth level. A step-by-step measurement procedure of the in-situ auger-hole method followed in this study is provided by van Beers (1983) and Ritzema (2014).

The soil water retention values were determined using soil samples collected using soil cores at random points across the field (refer to fig. 1). The soil samples were collected from the second soil profile layer, within which the water table depth fluctuated at the piezometer locations. The soil samples were carefully handled to ensure minimal disturbance before analysis. The soil samples were placed in a pressure chamber of a pressure plate apparatus and subjected to pressure heads (*h*) of 0 m, 20 m, 40 m, 120 m, and 150 m. With a pressure gauge set at zero, the rise in water level draining from the soil samples through the pipette was left to stabilize, after which the soil cores were then removed from the pressure chamber, weighed, and placed back in the pressure chamber. This procedure was repeated for the rest of the pressure levels (i.e., 20 m, 40 m, 120 m, and 150 m). The soil cores were oven-dried at 105 °C for 24 hours to determine soil moisture (θ) at each pressure level (*h*). The θ(*h*) data were fitted to the van Genuchten soil water retention model (VGM) in the RETention Curves (RETC) computer program (van Genuchten and Leij, 1992), from which soil water retention curves (SWRCs) were developed.

Table 2. Summary of DRAINMOD model inputs and outputs (Skaggs, 1980).

Inputs	Outputs
Weather and irrigation data (daily rainfall, temperature, PET, and irrigation depths)	Infiltration rate
Soil data (lateral hydraulic conductivity, surface water ponding depth, soil water retention values, and soil layer depths)	Water table depth
Crop-related inputs (crop type, and tabulated root depth function)	Drainage discharge
Drainage system parameters (depth to impermeable layer, drain depth, drain spacing, effective radius of the subsurface drain pipe, and design drainage discharge)	Hydraulic head at mid-drain spacing Surface runoff Vertical and lateral seepage

Table 3. Summary of input parameters and outputs for various PTFs contained in the Rosetta program (Schaap et al., 2001).

PTF	Inputs
1	Soil textural class
2	Soil textural class and % sand, silt and clay
3	Soil textural class, % sand, silt and clay, and soil bulk density
4	Soil textural class, % sand, silt and clay, soil bulk density, and soil water retention values at FC
5	Soil textural class, % sand, silt and clay, soil bulk density, and soil water retention values at FC and PWP

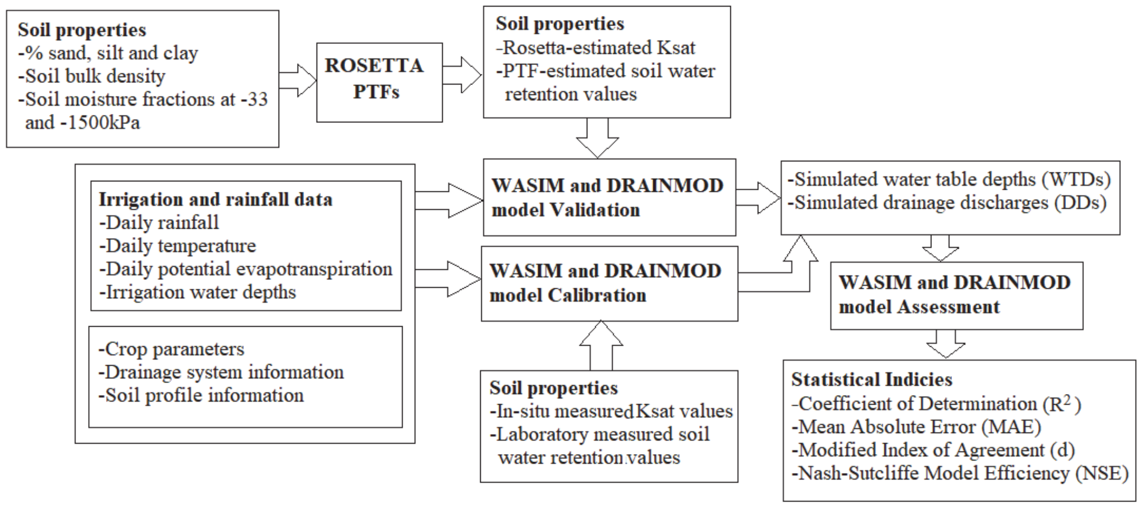

Figure 4. A schematic of the WaSim and DRAINMOD performance assessment approach adopted in this study (after Malota, 2013).

Using the same soil samples described above, % sand, silt and clay were obtained under laboratory conditions. The methods used for particle size analysis were the thermo-gravimetric and pipette methods (Warrick, 2002). The soil samples were analyzed for particle size distribution and soil textural class determination using the USDA classification system (Warrick, 2000). After that, the soil particle size distribution data, bulk density, and the values of soil water fractions at -33 and -1500 kPa for each of the ten soil samples were inputted into the Rosetta computer program to estimate K_{sat} and $\theta(h)$ values for each soil sample.

Measurement of Water Table Depth and Drainage Discharges

Five piezometers augured at mid-drain spacing (fig. 5) were randomly selected to measure water table depths (i.e., locations A2, A4, A5, A7, and A9 in fig. 1). The daily WTDs were measured using a dip meter with a beeper, as shown in figure 6. The measurement error of the dip meter was found to be ±0.5 cm. Daily DDs (mm.day^{-1}) were measured at five randomly selected drain outlet points (manholes) (fig. 7). The DDs were measured only at manholes corresponding to piezometers where WTDs were measured.

Regarding figure 5, drainage discharge from a drain pipe is generated from half of the drainage area on either side of a drain lateral pipe. For example, the drainage discharge (q) at manhole X in figure 5 is generated from a drainage area A (A = LS). The measurement of DDs at a manhole was done using a bucket and a timer. The measurement period for both DDs and WTDs was from September 2011 to February 2012.

Calibration and Validation of the WaSim and DRAINMOD Models

The calibration and validation procedure adopted in this study is similar to that of Salazar et al. (2008). The irrigation and weather data for the period October 1998 to September 1999, obtained from the irrigation scheme personnel, were used to prepare weather data files for calibrating the WaSim and DRAINMOD models. The scheme collects daily weather data using automatic weather instruments. The weather data include daily potential evapotranspiration (PET), rainfall, and minimum and maximum air temperatures. Daily PET data were determined using the Thornthwaite method (Malota, 2013). In-situ-measured K_{sat} and laboratory-measured $\theta(h)$ data were used as soil hydraulic inputs to both the WaSim and DRAINMOD models. During model calibration, the lateral hydraulic conductivity values (K_{Lsat}) were set at twice the Rosetta-estimated vertical hydraulic conductivity values (K_{Vsat}) because lateral hydraulic conductivity values are generally twice or more than the vertical K_{sat} values (Skaggs, 1978). The maximum ponding depth on the soil surface was set at half the observed depth because there were very few areas where ponding was observed, and most of the ponds were also rarely full. Table 4 summarizes the parameters that were iterated during the calibration of the WaSim and DRAINMOD models. Daily WTDs and DDs data for the 1998 to 1999 period obtained from irrigation scheme personnel were compared with simulated WTD and DDs data for the same 1998 to 1999 period.

The validation of the two models used weather and irrigation data from September 2011 to February 2012. The weather data were obtained from an automatic weather station about 3 km from the irrigation scheme. In contrast, the irrigation water depth data were measured using rain gauges installed at the scheme. The Rosetta-estimated K_{sat} and $\theta(h)$ data were used as soil hydraulic inputs for both the WaSim and DRAINMOD models. This was followed by comparing the observed and simulated WTD and DDs data from September 2011 to February 2012.

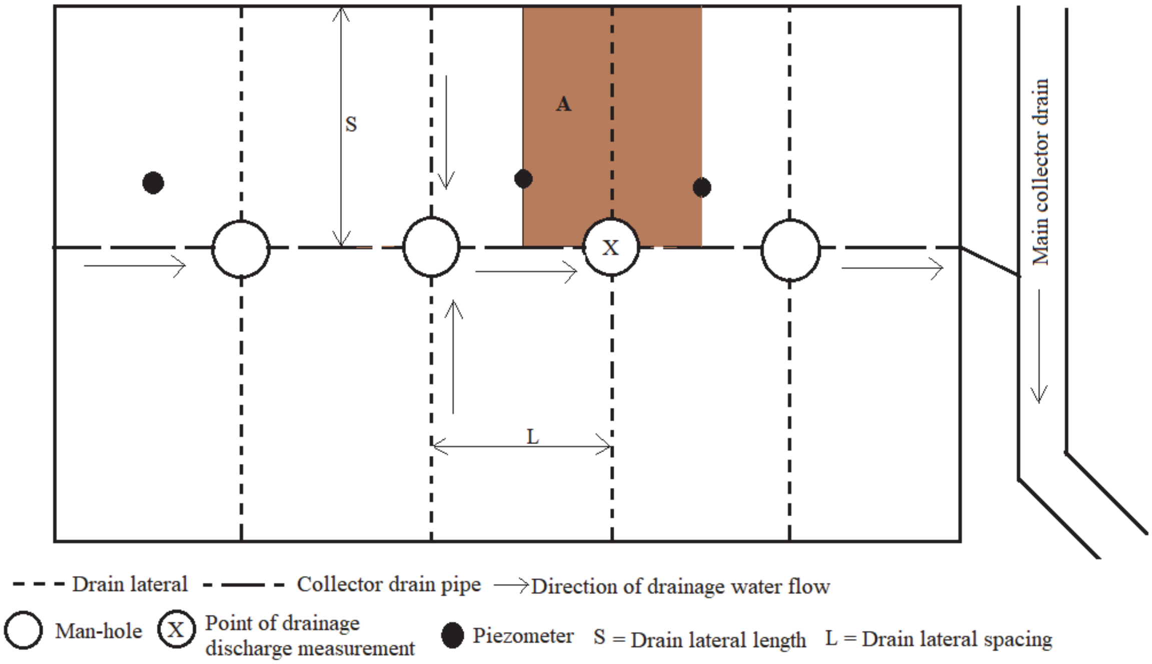

Figure 5. A schematic presentation of the layout of piezometers at mid-drain spacing (Malota, 2013).

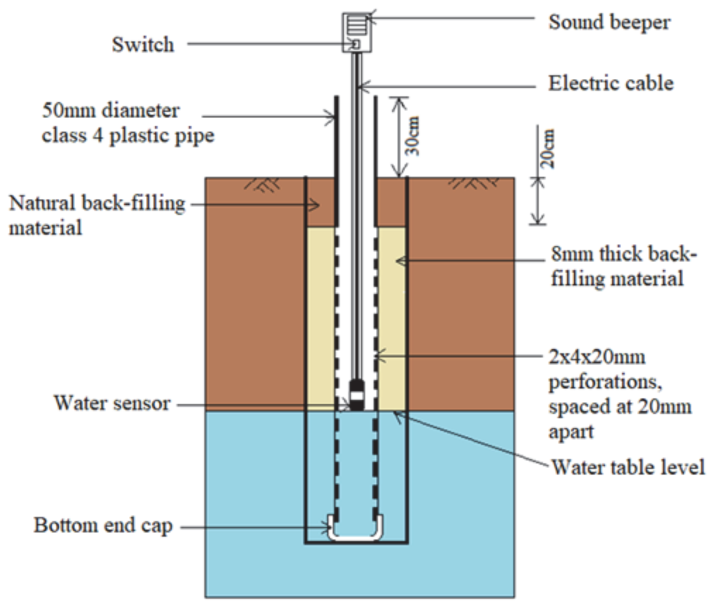

Figure 6. A detailed cross-section of one of the piezometers with an electronic dip meter lowered in the piezometer to locate the WTD from the soil surface (Malota, 2013; Malota and Senzanje, 2015).

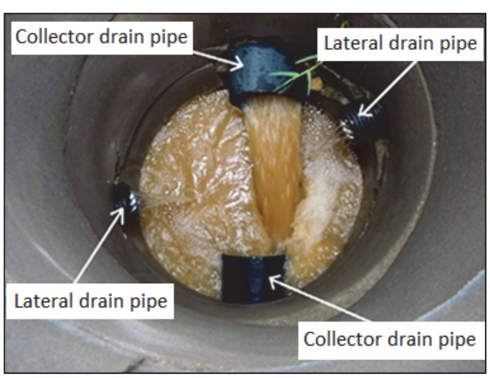

Figure 7. One of the drainage discharge outlet points where DDs were measured from lateral drain pipes (Malota, 2013).

Table 4. Summary of WaSim and DRAINMOD model calibration parameters.

Input Parameter	Iteration	Calibrated Values
Lateral hydraulic conductivity ($K_{L\text{-}sat}$)	Set as twice PTF-estimated vertical K_{sat}	0.42 m.day^{-1}
Maximum ponding depth	Set at half the observed depth	5 cm

Model Evaluation

The performance of both the WaSim and DRAINMOD models was assessed using (1) the Coefficient of Determination (R^2) (eq. 5), (2) the mean Absolute Error (MAE) (eq. 6), (3) the Nash-Sutcliffe model Efficiency (NSE) (eq. 7) (Wang et al., 2006), and (4) the Modified Index of

Agreement (d) (Legates and McCabe, 1999) (eq. 8). R^2, d, and NSE values range from 0 to 1, with values closer to 1 depicting excellent agreement between simulated and observed data sets (Legates and McCabe, 1999). MAE values closer to zero indicate very minimal differences between simulated and observed values. Details of the statistical measures of agreement between predicted and observed water table depths and drainage discharges are presented in table 5.

$$R^2 = \left[\frac{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2}\sqrt{\sum_{i=1}^{N}\left(P_i - \bar{P}\right)^2}} \right]^2 \tag{5}$$

$$MAE = \frac{\sum_{i=1}^{N}\left|\left(O_i - P_i\right)\right|}{N} \tag{6}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(O_i - P_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2} \tag{7}$$

$$d = 1 - \frac{\sum_{i=1}^{N}\left|O_i - P_i\right|}{\sum_{i=1}^{N}\left(\left|P - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)} \tag{8}$$

where

P_i = simulated value

O_i = observed value

$\bar{P}$ and $\bar{O}$ = mean simulated and observed values, respectively

N = total number of data points.

Results and Discussion

Soil Particle Size Distribution

The results of the physical properties of different soil samples collected from the study site are shown in table 6. The bottom soil layers at locations A9 and A10 are both characterized as clay-loam soil with a mean bulk density of 1.80 g.cm^{-3}. The rest of the locations are characterized as clay soil with a mean bulk density of 1.90 g.cm^{-3}. The soil textural classification results in table 6 matched very well with the classification for the same irrigation scheme reported by van der Merwe (2003). However, the soil moisture fractions at PWP in table 6 were higher than expected, resulting in minimal values of available water (FC – PWP). Gee et al. (2002) found that the pressure plate apparatus sometimes fails to reach equilibrium, especially at soil water pressure heads of 1500 kPa (i.e., PWP), even after a couple of weeks of attempted equilibrations. As such, Gee et al. (2002) suggest using more reliable methods, such as a thermocouple psychrometer, or dew point meter, to determine more accurate soil water retention values at PWP.

Similarly, PTFs are known to overestimate soil water fractions, particularly at PWP. For example, in the semi-arid environment of Jordan Valley, Mohawesh (2013) obtained soil moisture fractions of up to 0.51 – 0.55 cm^3.cm^{-3} at PWP when measured soil water retention data were fitted to the Vereecken PTF. Mohawesh (2013) found measured available water values ranging from 0.01 – 0.38 cm^3.cm^{-3}, which are not very different from the available water values of 0.01 – 0.12 cm^3.cm^{-3}, found in this study.

Performance of the Van Genuchten (1980) Soil Water Retention Model

The results of the performance of the VGM are presented in figure 8. All the soil samples had excellent agreement between laboratory-measured and VGM-estimated $\theta(h)$ data ($R^2 > 0.90$). Pressure heads increased with decreased soil moisture fractions, which aligned with our expectations.

Measured and Rosetta-Estimated Saturated Hydraulic Conductivity

The K_{sat} values measured using in-situ and laboratory methods and those estimated by PTFs in the Rosetta computer program are presented in figure 9. There were no significant differences between laboratory-, in-situ, and Rosetta-estimated K_{sat} values at a 95% confidence level. Locations A9 and A10 registered relatively high K_{sat} values (mean K_{sat} = 0.55 m.day^{-1}) compared to the rest of the locations (mean K_{sat} = 0.30 m.day^{-1}). These two locations corresponded to the scheme section, whose soil type is clay loam, whereas clay soil dominated the rest. The general variation in the in-situ-measured K_{sat} values observed in figure 9 is common in soil properties surveys (Zhang et al., 2013). The slightly high K_{sat} values obtained under laboratory conditions were not very different from our initial expectations. Previous research findings by Moriasi et al. (2007) also show that laboratory methods of measuring K_{sat} values generally overestimate K_{sat} values.

Table 5. Measures of agreement between predicted and observed water table depth and drainage discharges.

Parameter	Statistic	Criteria: Acceptable	Good	Excellent	Reference
Daily water table depth	R^2	>0.50	>0.70	≥0.8	(Morias et al., 2007; Saraswat et al., 2015)
	NSE	>0.40	>0.60	>0.75	(Skaggs et al., 2012)
	MAE (cm)	<20	<15	<10	(Skaggs et al., 2012)
	d	>0.70	>0.75	>0.8	(Moriasi et al., 2007)
Daily drainage discharge	R^2	>0.50	>70	≥0.8	(Skaggs et al., 2012)
	NSE	>0.4	>0.6	>0.75	(Skaggs et al., 2012)
	d	>0.70	>0.75	≥0.8	(Moriasi et al., 2007)

Table 6. Summary of soil physical properties from various sampling locations.

Location	Bulk Density ($g.cm^{-3}$)	Moisture Fraction at FC ($cm^3.cm^{-3}$)	Moisture Fraction at PWP ($cm^3.cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	Soil Textural Class
A1	1.87	0.45	0.43	22.7	31.2	46.1	Clay
A2	1.87	0.47	0.43	22.3	31.0	46.7	Clay
A3	1.99	0.47	0.43	20.0	30.1	49.9	Clay
A4	1.95	0.48	0.42	22.1	29.6	48.3	Clay
A5	1.97	0.44	0.43	21.8	34.2	44.0	Clay
A6	1.89	0.55	0.44	23.0	28.3	48.7	Clay
A7	1.86	0.53	0.41	22.7	32.0	45.3	Clay
A8	1.82	0.37	0.33	20.2	30.1	49.7	Clay
A9	1.76	0.49	0.42	31.3	50.5	18.2	Clay-loam
A10	1.84	0.33	0.27	48.4	50.5	31.3	Clay-loam

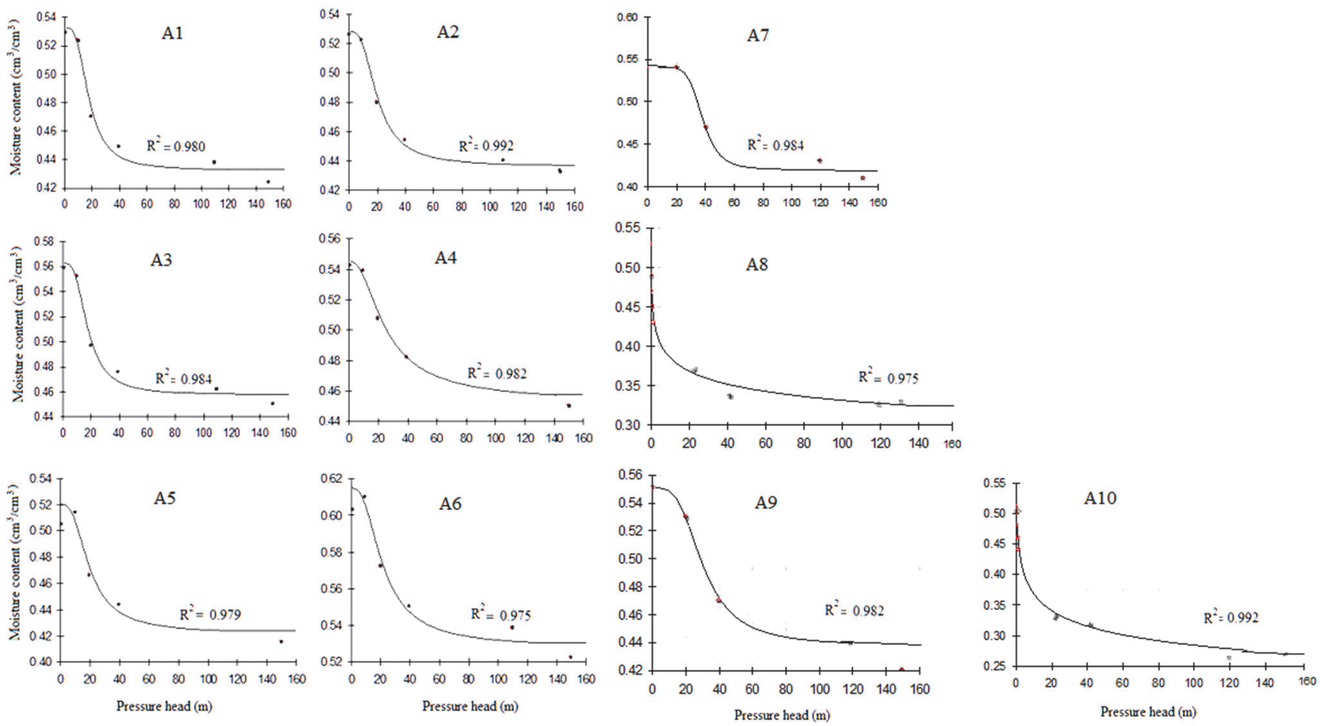

Figure 8. RETC performance in fitting laboratory-measured soil retention values to the van Genuchten (1980) soil water retention model.

Spatial analysis of the results in figure 9 revealed that all the K_{sat} values measured by the three methods varied spatially with Coefficient of Variation values (CV) of 0.55, 0.53, and 0.51 for the in-situ method, PTFs, and laboratory methods, respectively. As already highlighted, this is normal in soil properties studies since soil physical and hydraulic properties tend to vary in space (Zhang et al., 2013). The current drain spacing of 54 m and 72 m in clay and clay-loam soils, respectively, was determined based on K_{sat} values of 0.85 $m.day^{-1}$ in clay-loam soils and 0.45 $m.day^{-1}$ in clay soils, which were slightly higher than the K_{sat} values presented in figure 9. Thus, designing new subsurface drainage systems at the scheme using the K_{sat} values presented in figure 9, while maintaining the drain depth of 1.8 m, will likely reduce the drain spacing, which will also alleviate the waterlogging condition being experienced at the scheme (Skaggs et al., 2012).

Performance Of WaSim And DRAINMOD Models During Calibration And Validation Periods

A summary of observed and simulated water table depth and drainage discharge during the calibration and validation of the WaSim and DRAINMOD models is presented in table 7. During calibration, the DRAINMOD and WaSim models predicted cumulative drainage discharges of 230 mm and 236 mm, respectively. Both models predicted an average drainage discharge of 2 $mm.day^{-1}$. DRAINMOD and WaSim models predicted an average water table depth of 81 cm and 91 cm, respectively. During the same calibration period, the observed cumulative drainage discharge was 267 mm (average drainage discharge of 2.2 $mm.day^{-1}$) and the observed average water table depth of 92 cm. In the validation period, the DRAINMOD and WaSim models predicted cumulative drainage discharges of 270.1 mm and 272.5 mm, respectively. The DRAINMOD and WaSim models predicted average drainage discharges of 2.2 $mm.day^{-1}$ and 2 $mm.day^{-1,}$ respectively. DRAINMOD predicted an average water table depth of 78.2 cm, while WaSim predicted an average depth of 82.2 cm, respectively. During the same validation period, the observed cumulative drainage discharge was 270 mm, while the average drainage discharge and water table depth were 2.1 $mm.day^{-1}$ and 77.1 cm, respectively. There were minimal differences between the average water table depth and drainage discharge simulated by the two models.

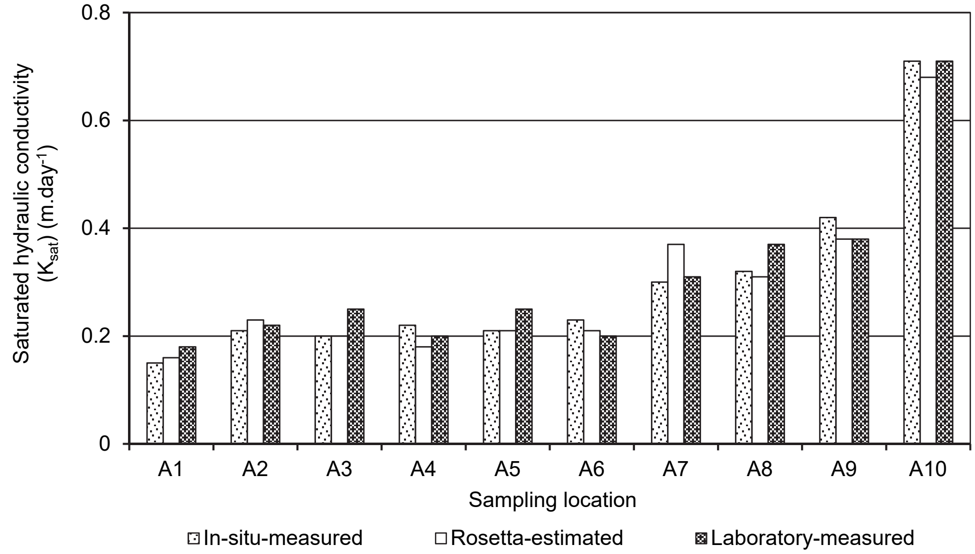

Figure 9. Saturated hydraulic conductivity (K_{sat}) values determined using different methods

Table 7. A summary of observed and simulated water table depth and drainage discharges during calibration and validation.

Stage	Model/ Criteria	Cumulative Precipitation and Irrigation (mm)	Cumulative Drainage (mm)	Average Drainage Discharge (mm.day^{-1})	Average Water Table Depth (cm)
Calibration	DRAINMOD		230	2	81
	WaSim		236	2	91
	Observed	496	267	2.2	92
Validation	DRAINMOD		270.1	2.2	78.2
	WaSim		272.5	2	82.2
	Observed	531	270	2.1	77.1

Similarly, there were minimal differences between the cumulative drainage discharge simulated by the two models during calibration (230 mm and 236 mm for DRAINMOD and WaSim, respectively) and the validation period (270.1 mm and 272 mm for DRAINMOD and WaSim, respectively).

Results of the fluctuation of observed and simulated WTD and drainage discharges during calibration and validation of the WaSim and DRAINMOD models are presented in figures 10, 11, 12, and 13. In all cases, pairs of time series of simulated and observed WTD and DD followed each other relatively well. A summary of the statistical performance indices of the DRAINMOD and WaSim models during the calibration and validation periods is presented in tables 8 and 9, respectively. For the DRAINMOD model, both pairs of simulated and observed daily WTDs and DDs values matched very well and registered NSE and $R^2 \geq 0.80$. The model also registered d values > 0.80 during the calibration period when simulating WTDs and DDs. Similarly, the model registered a high d value of 0.81 during the WTD simulation in the calibration period. A d value of 0.79 was registered during the validation exercise of the WaSim model to simulate DDs. All these results indicate excellent agreements between pairs of simulated and observed WTDs and DDs. DRAINMOD simulated WTDs and DDs with low relatively MAE values, again indicating excellent agreement between pairs of simulated and observed WTDs and DDs both during the calibration and validation periods. Comparing the NSE and d values of the two models' performances in tables 8 and 9 with the NSE and d values reported by Skaggs et al. (2012) indicates that both the WaSim and DRAINMOD model performances in this study were quite satisfactory.

The good performances of the two models could partly be attributed to the use of detailed soil properties (soil bulk density, soil particle size distribution data, soil water retention values at FC and PWP) as inputs to the Rosetta computer program to estimate the K_{sat} values, which were later used as inputs to the two models. Notably, the Pongola Agricultural Office has a well-equipped soil laboratory where easily measured soil data and information such as soil textural class, soil particle size distribution, bulk density, and soil water retention values can be measured. In the absence of in-situ measured K_{sat} and soil water retention values, data-scarce areas such as Pongola can, therefore, use the easily accessible soil data as inputs to PTFs to estimate K_{sat} and soil water retention values. Oosterbaan (2000) noted that the performance of empirically developed simulation models largely depends on how well the input parameters best represent the natural system being modeled. The WaSim and DRAINMOD models partition the soil profile into a multi-soil-layer water balance, similar to the finite element method for numerically solving mass transfer-related processes (Tekkaya and Soyarslan, 2014). As opposed to modeling the

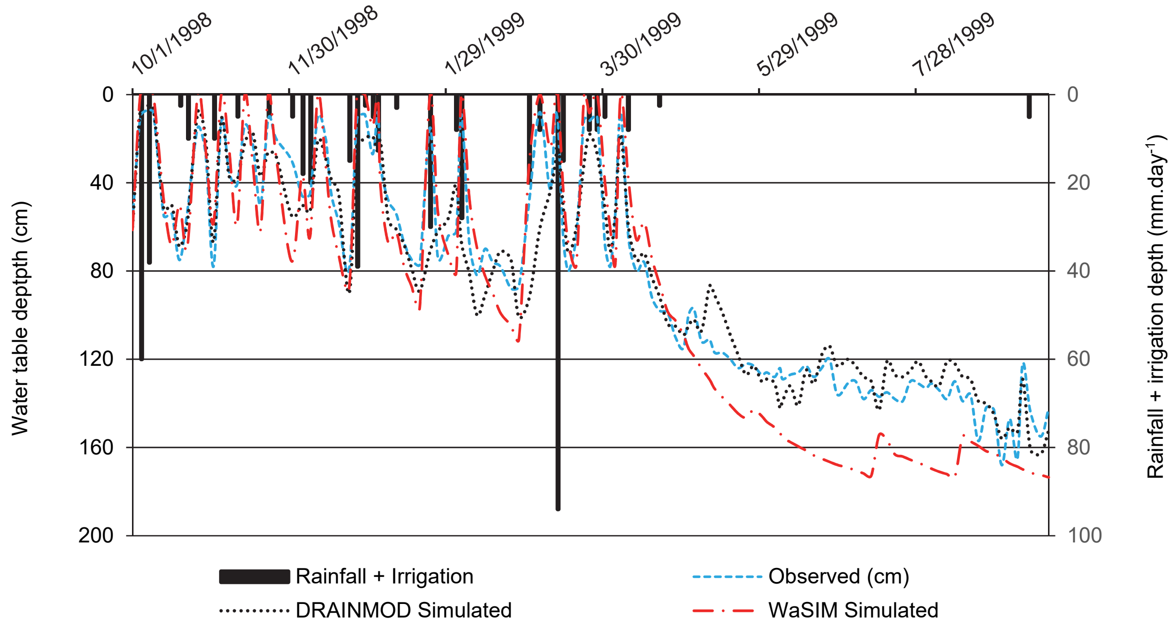

Figure 10. Fluctuation of water table depth during calibration of the WaSim and DRAINMOD models.

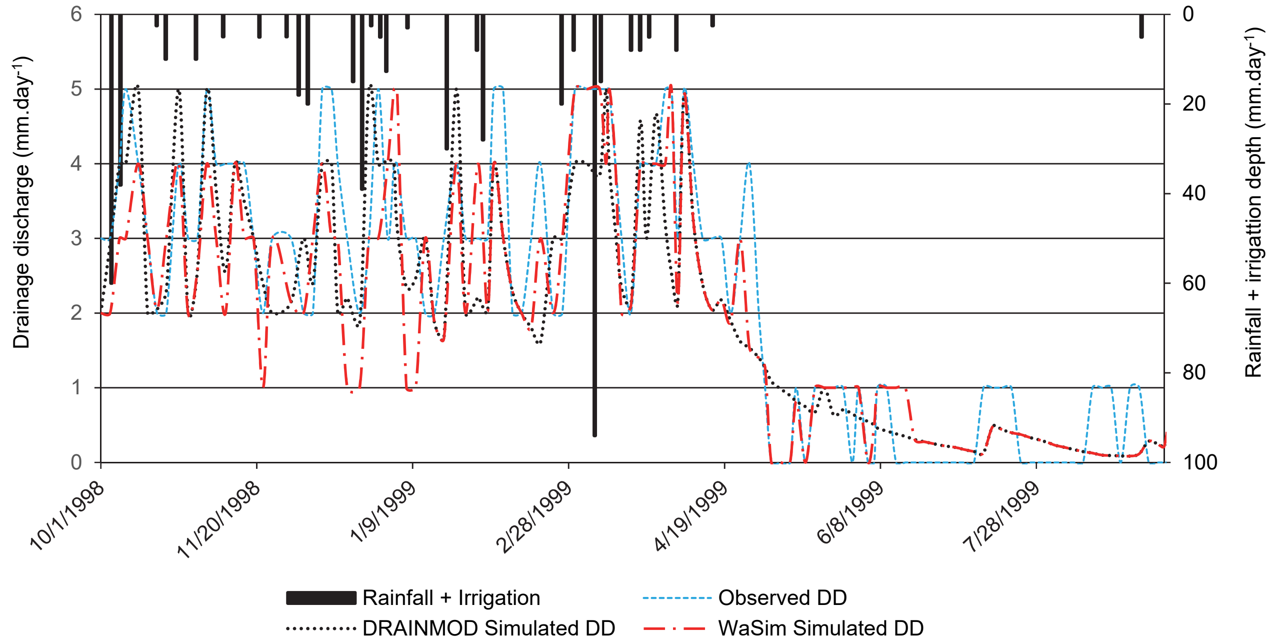

Figure 11. Fluctuation of drainage discharges (DD) during calibration of the WaSim and DRAINMOD models.

soil system as a homogenous entity, this partitioning of the soil profile by the WaSim and DRAINMOD models might have also contributed to the accurate simulation of the soil system.

Many model simulation studies generally accept NSE and R^2 model calibration and validation results greater than 0.5 (Moriasi et al., 2007). However, Skaggs et al. (2012) highlight that model adoption for subsurface drainage system design must be cautiously approached. In this regard, Skaggs et al. (2012) explain that DDs and WTDs are critical determinants of the performance of both subsurface drainage and crop production systems and are, therefore, required to be simulated with high accuracy. Thus, the R^2, d, and NSE values of > 0.8 obtained during DRAINMOD calibration and validation imply that the model can reliably be used to design and analyze subsurface drainage systems with soil hydraulic inputs estimated by the PTFs in the Rosetta computer program. The WaSim model has a graphical user interface that makes it easier to use than the DRAINMOD model. Thus, its application may still be recommended, particularly where designers may not be more conversant with using the DRAINMOD model.

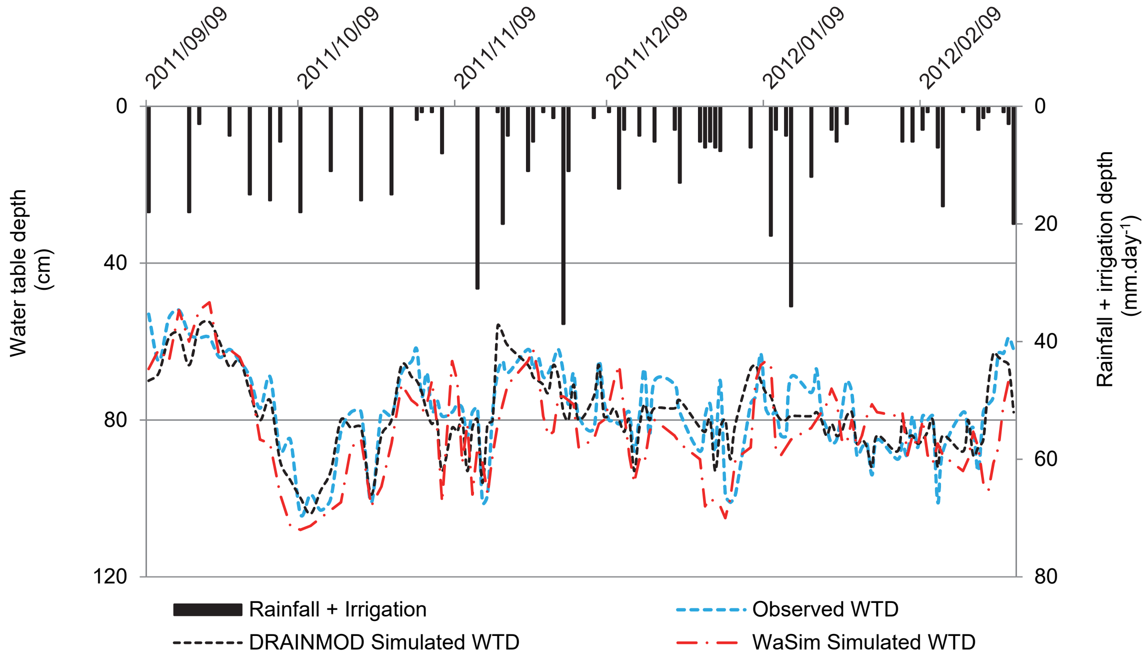

Figure 12. Fluctuation of water table depths (WTD) during validation of the WaSim and DRAINMOD models.

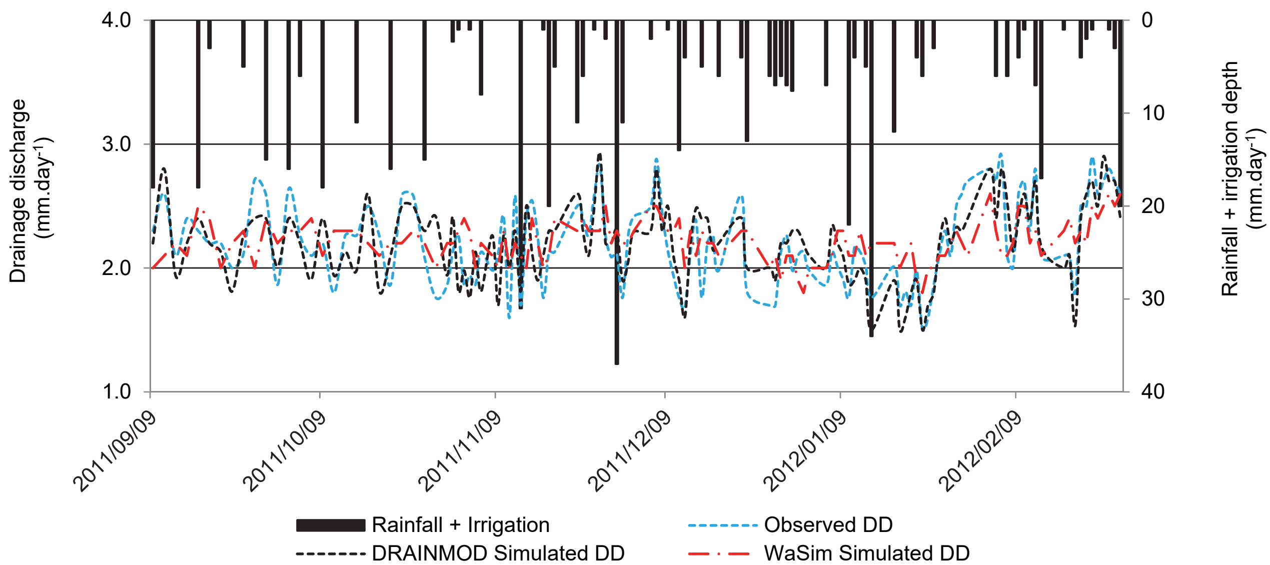

Figure 13. Fluctuation of drainage discharges (DD) during validation of the WaSim and DRAINMOD models.

Table 8. DRAINMOD model performance parameters during the calibration and validation exercises.

Statistical Parameter	Calibration Period: Water Table Depth (cm)	Calibration Period: Drainage Discharge (mm.day^{-1})	Validation Period: Water Table Depth (cm)	Validation Period: Drainage Discharge (mm.day^{-1})
R^2	0.85	0.89	0.89	0.83
d	0.82	0.85	0.81	0.79
MAE	4.1	0.13	5.3	0.17
NSE	0.81	0.88	0.86	0.81

Table 9. WaSim model performance parameters during the calibration and validation exercises.

Statistical Parameter	Calibration Period: Water Table Depth (cm)	Calibration Period: Drainage Discharge (mm.day^{-1})	Validation Period: Water Table Depth (cm)	Validation Period: Drainage Discharge (mm.day^{-1})
R^2	0.78	0.81	0.78	0.77
d	0.78	0.79	0.74	0.73
MAE	5.2	1.8	9.0	0.2
NSE	0.76	0.78	0.76	0.74

CONCLUSIONS

This study evaluated the performance of the WaSim and DRAINMOD models to simulate WTDs and DDs using K_{sat} and soil water retention data estimated by PTFs in the Rosetta computer program. The results showed that the DRAINMOD model simulated both the WTDs and DDs with a reasonably high level of accuracy (R^2, d and NSE > 0.8), and the model can be used for the design and analysis of subsurface drainage systems using soil hydraulic inputs estimated by PTFs in the Rosetta computer program. The WaSim model simulated WTDs and DDs with a relatively lower level of accuracy (R^2, d, and NSE < 0.8) than the DRAINMOD model. However, considering the user-friendliness of the WaSim model, which still performed well in the calibration and validation periods, it may still be used to design and analyze subsurface drainage systems.

We recommend using this design approach when the PTFs that estimate K_{sat} and $\theta(h)$ based on soil textural class, particle size distribution data, bulk density, and soil water retention values at PWP and FC are used. The impacts of different levels of soil physical and hydraulic data availability on the performance of the two models need to be assessed. Also, we recommend further studies to investigate the impacts of drainage system performance on crop yields and the impacts of climate change and different soils on the performance of subsurface drainage systems. Lastly, the WaSim and DRAINMOD models' performance may need to be assessed over a longer period and for different climates and soils than the conditions considered in this study.

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