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REVIEW

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Drainage models: An evaluation of their applicability for the design of drainage systems in arid regions

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Abstract

Only 5%–10% of irrigated lands in least developed countries (LDCs) are currently drained. Although drainage simulation models (DSMs) are used to evaluate alternative designs, it is unclear which drainage model is suitable for LDCs' arid and semi-arid regions. This study evaluates selected DSMs (ADAPT, RZWQM2, DRAINMOD, EPIC, HYDRUS-1D, WaSim and SWAP) and critically assesses their applicability to arid and semi-arid areas. Also, establish and apply selection criteria based on the availability of data in LDCs with Libya as a case study, and identify the most suitable model for application in Libya. DRAINMOD had the highest overall score, and alternative methods to predict missing input parameters for DRAINMOD are discussed. Evaluating the feasibility of using predicted input parameters for DSMs to design drainage systems in LDCs would help farmers, planners and decision-makers to reduce the overall cost of drainage system and, also, make DRAINMOD a more accessible tool to evaluate different drainage designs.

KEYWORDS
drainage, integrated water management, simulation modelling, sustainability

1 | INTRODUCTION

Food production is expected to rise by up to 100% by 2050 to fulfil demand because of an increase in the world population (Prăvălie et al., 2021). However, as a consequence of soil salinization, desertification, soil erosion and urbanization, the world's arable lands are degrading (FAO, 2002). Water use efficiency is a key challenge in arid and semi-arid countries because of increased cross-sector demand for limited water supplies (Elshemy, 2018). It is consequently critical for long-term agricultural development and economic growth in arid and semi-arid regions that drainage system design and management emphasize water use efficiency, particularly in places where the water resource is non-renewable (Qadir et al., 2003; Scheumann & Freisem, 2002). For example, by the 1950s, water needs in arid Libya had exceeded water resources for food self-sufficiency, and similar situations were noted throughout the Middle East and portions of Africa (Qadir et al., 2003).

Only 25 to 50 million ha of irrigated lands (<30% of the total irrigated area requiring drainage) is currently drained (Smedema et al., 2000), and according to Smedema et al. (2000), the proportion of agricultural land drained in least developed countries is 5%–10% compared with 25%–30% in developed countries. These differences are due to low levels of agricultural and rural development, adoption of crops and varieties that can tolerate adverse drainage conditions such as salinity and waterlogging. In addition, the cost of installing and maintaining drainage systems and more traditional (i.e. less innovative, more risk-averse and less competitive) farming attitudes in least developed countries compared with developed countries prohibit drainage system installation. In Libya, for example, it was estimated that in 2000, only 9000 ha (around 2% of all croplands) of irrigated land was equipped with some form of drainage (FAO, 2016). This is due to a fundamental lack of expertise in the country, lack of knowledge on which drainage models are applicable to arid and semi-arid regions, lack of data for key input parameters for drainage models and the high cost of drainage installation.

Drainage simulation models such as DRAINMOD, SWAP, ADAPT, RZWQM2, EPIC, WaSim and HYDRUS-1D can potentially be used to provide reliable predictions of multi-component systems to evaluate drainage system design, over long periods (1–100 year). These models have been applied and tested in many areas of the world such as the Netherlands (Kroes et al., 2000), Canada (Huang et al., 2011), Egypt (Kandil et al., 1995), USA (Ayars & Evans, 2015), Turkey (Kale, 2011), China (Luo et al., 2009), Brazil (Meriguetti et al., 2015) and Australia (Bennett et al., 2013). However, these models require extensive temporal as well as spatial input data sets for soils, hydrology, topography, climate and crop variables, which is a problem for many least developed countries where the availability and temporal and spatial incoherence of data are limited. In addition, operating the models requires trained and experienced users. To meet the dual challenge of sustainable agriculture and water use efficiency in Libya and to optimize yields in irrigated areas, rehabilitation and improvements to existing drainage systems as well as the design of new drainage systems need to be urgently implemented. To enable this, there is a need to determine which drainage simulation models are most appropriate for Libya. This review (1) evaluates selected drainage simulation models and their applicability to arid and semi-arid areas, (2) establishes and applies selection criteria based on the availability of data in least developed countries such as Libya and (3) identifies the most suitable model for application in Libya.

2 | DRAINAGE SIMULATION MODELS FOR ARID AND SEMI-ARID REGIONS

Drainage simulation models, also known as 'Agro-Hydrological Models', can evaluate and predict the soil–water condition, soil salinity and water table depths under given water management, crop rotation and climatic conditions (Skaggs, 1999). In addition, drainage simulation models allow multiple scenarios to be applied by considering the effect of capillary rise and deep percolation on the drainage design as well as the effects of drain spacing and depth on crop yield and water table depth. Models such as DRAINMOD and SWAP can be used to evaluate alternative designs such as the effects of various irrigation strategies and drain spacing and depth on crop yield (Kandil et al., 1995; Meriguetti et al., 2015), whereas ADAPT and HYDRUS can simulate soil moisture status/waterlogging (Gowda et al., 2012; Šimůnek et al., 2012). In the next section, seven simulation models will be reviewed, namely, ADAPT, RZWQM2, DRAINMOD, EPIC, HYDRUS-1D, WaSim and SWAP. Table 1 illustrates the applications of each model in arid and semi-arid areas.

TABLE 1 The drainage simulation models applications in arid and semi-arid countries with the references.

Model name	Applications in arid and semi-arid area
ADAPT	The model has not been applied.
RZWQM2	China (Chen et al., 2020; Zenghui et al., 2019) and USA (Kisekka et al., 2017)
DRAINMOD	India (Gupta et al., 1993) and Egypt (Abdel-dayam & Skaggs, 1990; Kandil et al., 1995; Wahba et al., 2002; Wahba & Christen, 2006)
EPIC	Argentina (Bernardos et al., 2001), France (Cabelguenne et al., 1990), Australia (Jones et al., 1989), China (Gao et al., 2017) and USA (Gassman et al., 2005; USDA, 1990)
HYDRUS-1D	Oman (Al-Maktoumi, 2021), China (Chen et al., 2021; Qian et al., 2021), Morocco (Er-Raki et al., 2021) and Tunisia (Kanzari et al., 2021)
WaSim	India (Hirekhan et al., 2007) and Colombia (Depeweg & Fabiola Otero, 2004)
SWAP	Pakistan (Sarwar & Feddes, 2000), India (Bastiaanssen et al., 1996; Verma & Gupta, 2014; Verma & Isaac, 2010) and Argentina (Bastiaanssen et al., 1996)

2.1 | The Agricultural Drainage and Pesticide Transport (ADAPT) model

The ADAPT model is a one-dimensional, daily time step, field-scale simulation model created by the Department of Agricultural Engineering of Ohio State University (Chung et al., 1992). The ADAPT model has three components: hydrology, erosion and pesticide transport. In the hydrology component, the model is capable of simulating the quantity and quality of drainage water linked to water table depth. The ADAPT model integrates two models: The first model is the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Leonard et al., 1987), and the second is DRAINMOD (Skaggs, 1982). The ADAPT model can predict hydrology and water quality components such as subsurface drainage volume and nitrate losses from subsurface drainage (Gowda et al., 2012). The ADAPT model requires climatic data, drainage design information, soil water content data and crop information (Table 2).

One of the strengths of using the ADAPT model is that it has been applied extensively, especially around the Midwest United States (humid areas), and is considered to accurately describe hydrological components such as water table depth, nitrate losses in subsurface drainage and subsurface drainage flow in heavy soil types (heavy soils contain more clay and are sticky and hard to work but tend to be more fertile) (Anand et al., 2007; Gowda et al., 1999a; Gowda et al., 2007; Gowda et al., 2008; Johansson et al., 2004; Petrolia & Gowda, 2006a, 2006b; Sands et al., 2003; Sogbedji & McIsaac, 2006; Updegraff et al., 2004). Also, the accuracy of the ADAPT model has been evaluated to predict the water table depth in comparison with other widely used models such as DRAINMOD and SWAT (Desmond et al., 1996). The results show that in heavy soil types and humid agroclimatic zones,

TABLE 2 Minimum input parameters required to run the Agricultural Drainage and Pesticide Transport (ADAPT) model.

Input data requirement	
Climatic data	Daily precipitation, average daily temperature, radiation, relative humidity, wind speed and potential evapotranspiration
Drainage design	Drain depth and spacing, distance from drain to impermeable layer, initial depth of water table and maximum surface storage
Soil water content	Bottom depth of each soil layer and soil layer saturated hydraulic conductivity, water characteristics, water table–volume drained–upward flux, Green–Ampt parameters for different water table depths, percentage of rainfall that penetrates to the water table and surface cracking parameter
Crop	Planting and harvesting dates, root depth, tillage and fertilizer and pesticide applications. In some cases, leaf area index parameter

the performance of ADAPT to predict water table depth is comparable with the results obtained from DRAINMOD and SWAT (Desmond et al., 1996; Gowda et al., 2012). The ADAPT model was accurately applied to evaluate water flow and nutrient discharge at the field scale and catchment scale in northern Ohio and Minnesota (Dalzell et al., 2004; Davis et al., 2000; Gowda et al., 1999b). In more recent studies conducted in southern Minnesota, the model was applied to evaluate the impacts of subsurface drain spacing and depth (Nangia et al., 2010b), the rate and timing of N application (Nangia et al., 2010a, 2008) and changes in precipitation (Nangia et al., 2010c) on N losses. However, and critically, the model has not been applied in arid areas to design and/or evaluate drainage systems. Also, ADAPT has not been tested in areas where the soil texture is predominantly sandy, and the rate of saturated hydraulic conductivity (K_{sat}) is high, such as in Libya. For example, the highest value of K_{sat} applied in the ADAPT model is 2.0 m d^{-1}, whereas in a study in Libya, the highest value of K_{sat} was 38.0 m d^{-1} (Ellafi et al., 2021). Therefore, the model needs to be tested in more diverse environments, including arid areas, before it can be recommended to design drainage systems in new areas such as in Libya. Limited technical support is available for users, and there is no GIS user interface available for ADAPT (the script cannot be directly input into a GIS-compatible format). It is a DOS-based model that uses a text editor to create input files (ADAPT was written in FORTRAN with modular programming techniques), which makes it hard to identify errors, especially for inexperienced users (Gowda et al., 2012).

2.2 | Root zone water quality model 2 (RZWQM2)

RZWQM2 is a one-dimensional model that focuses on the effects of water management practices on water quality, water quantity and crop yields. RZWQM2 model can simulate the soil stratigraphy of up to 30-m depth including the root zone for one specific crop at any given time (simulating crop growth and the movement of water, nutrients and pesticides over, within and below the crop root zone of a given unit area). The model includes crop growth parameters for >20 field crops from the Decision Support System for Agrotechnology Transfer (DSSAT) crop modules (Ma et al., 2011). RZWQM2 uses daily steps for crop growth and considers the soil water content, pesticide movement and heat transfer; in addition, it can obtain and utilize up to 10 stratigraphic layers (Ma et al., 2012). To design a drainage system, RZWQM2 requires climatic site description, soil and pesticide property, crop, initial soil condition and management practice input parameters (Table 3).

TABLE 3 Minimum input parameters required for the RZWQM2 model.

Input data requirement	
Climatic data	Daily precipitation (amount and intensity), minimum and maximum daily temperature, solar radiation, relative humidity and wind speed
Site description	Latitude, elevation, longitude and slope
Soil properties	Soil horizon delineation, soil texture and bulk density. Soil hydraulic properties: soil water content at 33 and 1500 kPa suction and saturated hydraulic conductivity
Pesticide properties	General pesticide data such as common name, half-life, adsorption constant and dissipation pathways
Management practices	Estimate of dry mass and age of residue on the surface, tillage, irrigation, planting/harvest, fertilization, etc.
Crop	Specifying a crop cultivar from supplied database
Initial soil condition	Initial soil water content/water table; initial soil temperatures; initial soil pH and cation exchange capacity values

RZWQM2 has some strengths that make it unique. First, it can be combined with other models such as the DSSAT crop growth model (Jones et al., 2003), the Simultaneous Heat and Water (SHAW) model (Flerchinger & Pierson, 1991; Flerchinger & Saxton, 1989) and the Parameter Estimation Software (PEST) (Doherty, 2010). This combination helps RZWQM2 to improve the accuracy of simulations in the crop root zone. The RZWQM2 model has been shown to generate accurate predictions across a range of soil types including sandy located in Minnesota (Wu et al., 1999), clay located in Thailand (Shrestha & Manandhar, 2014), silt loam located in Kentucky (Malone et al., 2004) and sandy loam located in New Jersey (Ahmed et al., 2007). It has been applied to humid (Ahmed et al., 2007), tropical (Shrestha & Manandhar, 2014) and semi-arid areas in the United States (Kisekka et al., 2017) and arid areas in China (Chen et al., 2020; Zenghui et al., 2019). The development of a Windows-based user interface has made it more accessible for researchers and drainage managers to use as it does not require expertise in coding (Ma et al., 2000, 2007a). RZWQM2 is one of the few models that simulate pesticide uptake by plants, equilibrium and kinetic adsorption, degradation and irreversible adsorption, volatilization and macropore transport of pesticides. In addition, RZWQM2 has a unique ability to estimate chemical losses (e.g. nitrogen) because of runoff. RZWQM2 is also able to simulate subsurface drainage flow, the fluctuation of water table depth and nutrient losses from agricultural fields through subsurface drains (Ma et al., 2007b, 2007c, 2007d; Qi et al., 2011). RZWQM2 also has some weaknesses; for example, when the field is heterogeneous, the model should be used either by simulating a sub-field or by using average values for the soil inputs. RZWQM2 is unable to estimate the runoff for each sub-field or able to simulate water retention due to surface roughness. Despite the model including a soil equilibrium chemistry module, the simulation of changes in soil pH and EC is not fully evaluated and the model cannot simulate more than one crop at the same time (Ma et al., 2012).

2.3 | DRAINMOD

DRAINMOD is a widely adopted simulation model that describes the hydrology of poorly, or artificially drained, shallow water table soils. The first version of DRAINMOD was published in the 1970s (Skaggs, 1977, 1978, 1980). Since then, the model has been modified to include sub-models such as the soil salinity model DRAINMOD-S (Kandil et al., 1995) and field-scale models for predicting nitrogen transformation and fate DRAINMOD-N (Breve-Reyes, 1994) and DRAINMOD-NII (Youssef et al., 2005). DRAINMOD has been used extensively in humid areas (Ale et al., 2012; Breve-Reyes et al., 1998; Sanoja et al., 1990) and by the United States Department of Agriculture–Natural Resource and Conservation Service (USDA-NRCS) to design and evaluate drainage systems in the United States (Ayars & Evans, 2015). DRAINMOD has also been applied successfully in semi-arid areas to predict water table fluctuation in India (Gupta et al., 1993) and salt load, water table depth and drainage discharge in Australia (Wahba & Christen, 2006). DRAINMOD was evaluated in Egypt to simulate the water table depth under two management practices (conventional and controlled drainage) (Wahba et al., 2002). For arid areas, DRAINMOD was first applied to simulate soil salinity changes during irrigation of one crop season, and the results showed that the model could be extended to simulate drainage systems in arid areas (Abdel-dayam & Skaggs, 1990). DRAINMOD has also been successfully applied to predict the effect of soil salinity on crop yield and to evaluate the impact of different irrigation strategies and drainage designs on crop yields (Kandil et al., 1995). The input requirements to design a drainage system using DRAINMOD include climatic and soil water content data, drainage design information and crop information (Table 4).

A key strength of DRAINMOD is its wide adoption in many areas of the world and accurate predictions. In arid and semi-arid areas, DRAINMOD was accurately applied to predict soil salinity, water table depth and relative crop yield. DRANMOD is a one-dimensional model, and lateral and downslope seepage can be taken into account (Smedema et al., 2004). Also, DRAINMOD shows potential in predicting hydrologic variables such as infiltration rates, subsurface drainage, surface runoff, evapotranspiration, vertical and lateral seepage, water table depth and drained or water-free pore space in the soil profile (Skaggs et al., 2012). DRAINMOD outputs are summarized in a user interface as either daily, monthly, or yearly formats depending on end-user requirements. Additional outputs can be predicted such as crop yields (e.g. rotations of five crops; Kandil et al., 1995), salinity status, the depth of irrigated water and variables indicating wetland hydrological status (i.e. the number of continuing days with water table close to the surface). DRAINMOD supports the use of outputs from pedotransfer function (PTF) models (such as ROSETTA [Schaap et al., 2001]) as a source of key soil input data including saturated and unsaturated hydraulic conductivity.

TABLE 4 Minimum input data required to design a drainage system using DRAINMOD.

Input data requirement	
Climatic data	Hourly precipitation, daily maximum and minimum air temperature and potential evapotranspiration
Drainage design	Drain depth and spacing, distance from drain to impermeable layer, initial depth of water table and maximum surface storage
Soil water content	Bottom depth of each soil layer and soil layer saturated hydraulic conductivity; water characteristics; water table–volume drained–upward flux; Green–Ampt parameters for different water table depths
Crop	Root depth, yield, stress due to high-water table and trafficability parameters

2.4 | The Environmental Policy Integrated Climate (EPIC) model

EPIC (Williams, 1990; Williams et al., 1984, 1996) includes hydrological and environmental models produced by USDA-ARS and Texas AgriLife Blackland Research and Extension Centre (BREC) laboratories in Temple, Texas (Williams et al., 2008). EPIC combines the GLEAMS model (Leonard et al., 1987), the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992) and Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980). EPIC can be applied to simulate drainage areas that are characterized by homogeneous weather, soil, crop rotation and agricultural management practices for detailed field simulations (Wang et al., 2012). The input requirements to design a drainage system using EPIC include potential evapotranspiration, runoff, crop growing season, soil property and irrigation parameter variables (Table 5).

TABLE 5 Minimum input data required to design a drainage system using Environmental Policy Integrated Climate (EPIC).

Input data requirement	
Potential evapotranspiration	Hargreaves: maximum and minimum temperature, or Penman–Monteith: daily maximum and minimum temperature, relative humidity, wind speed and solar radiation
Runoff	Curve Number, rainfall amount, potential maximum retention after runoff begins and initial infiltration rate
Crop growing season	Fixed dates schedule, planting and harvesting dates, water stress, plant population, winter dormancy, maximum potential leaf area index, harvest index and biomass-energy ratio
Soil property	Bulk density, soil field capacity and wilting point and saturated hydraulic conductivity
Irrigation	Irrigation ratio, floodplain saturated conductivity, maximum groundwater storage, groundwater residence time, return flow, deep percolation and groundwater storage threshold

The EPIC model can be subdivided into subarea components including weather, hydrology, erosion-sedimentation, nutrient, pesticide fate, plant growth, soil temperature, tillage economic budgets and plant environment control (Williams, 1990). Sabbagh et al. (1993) modified the hydrology component to simulate daily water table fluctuations and the effect of subsurface drainage systems. EPIC is an open-source code written in FORTRAN that has been maintained by the BREC development and user support team. Therefore, EPIC has several Windows and GIS-based versions with detailed user manuals (BREC, 2012). For management practices, EPIC has been calibrated and validated for several studies such as Gassman et al. (2010) and Wang et al. (2011). In arid and semi-arid areas, EPIC was accurately applied to predict the crop yield in many areas in the world including Argentina (Bernardos et al., 2001), south of France (Cabelguenne et al., 1990) and Australia (Jones et al., 1989). EPIC was successfully applied in arid China, to predict maize yield and the contribution of shallow groundwater to evapotranspiration (Gao et al., 2017). EPIC has also been applied to predict crop yield in semi-arid areas in Texas and California (Gassman et al., 2005; USDA, 1990). However, and critically, EPIC has limited ability to estimate drainage volume and changes in water table depth because of the volume of water applied (via rainfall and/or irrigation) (Wang et al., 2012). In addition, EPIC needs further development to be able to accurately estimate the volume of water removed from the soil profile through subsurface drainage, which is a key design requirement for drainage systems in arid and semi-arid areas (Gassman et al., 2010).

2.5 | HYDRUS-1D

The HYDRUS-1D model and its related models such as SWMS-2D, CHAIN_2D, HYDRUS-2D, HYDRUS (2D/3D), UNSATCHEM, HP1 and CW2D have been widely applied to estimate water flow and solute transport in soil profiles and groundwater movement (PC-PROGRESS, 2020a, 2020b; Šimůnek et al., 2011). In 2010, the HYDRUS website (PC-PROGRESS, n.d.) claimed that there were >1000 peer-reviewed journal references in which the HYDRUS programs had been applied (Šimůnek et al., 2012). Critically, HYDRUS has only been applied once for drainage design in an arid area (Qian et al., 2021). Qian et al. (2021) assessed the influence of subsurface drainage parameters on soil desalination and salt discharge using HYDRUS-1D. However, HYDRUS-1D was successfully applied in arid and semi-arid areas for other purposes such as monitoring the shallow water table in arid urban zone in Oman (Al-Maktoumi, 2021), estimating groundwater recharge and evapotranspiration in arid inland in China (Chen et al., 2021), predicting soil moisture at different depth, actual evapotranspiration and deep percolation of semi-arid area in Morocco (Er-Raki et al., 2021) and evaluating the soil salinization risks under different climate change scenarios in a semi-arid region of Tunisia (Kanzari et al., 2021). HYDRUS-1D software is free to download either from the HYDRUS or USDA-ARS website. The general approach in the HYDRUS-1D model is to choose an objective function to serve as a level of the agreement between measured and predicted data, and which directly or indirectly is related to the adjustable parameters. By minimizing this objective function, the best-fit parameters are determined (Simunek et al., 1998). The HYDRUS-1D models can be used to simulate the movement of water and solute transport (Šimůnek et al., 2012). In addition, HYDRUS-1D can be applied to estimate flow by solving the Richards equation (Richards, 1931). To describe unsaturated or partially saturated soil hydraulic properties, HYDRUS-1D uses PTFs developed by van Genuchten (1980) and Brooks and Corey (1964), as modified by Durner (1994), Kosugi (1996) and Vogel and Císlerová, 1988). To predict the saturated hydraulic conductivity, the Rosetta PTF model (Schaap et al., 2001) is installed inside HYDRUS-1D. These PTFs were developed mainly on heavier soils unlike the sandy soils existing in Libya (Ellafi et al., 2021). HYDRUS-1D considers both equilibrium and nonequilibrium flow by assuming a fraction of the liquid phase as being mobile and immobile respectively (Šimůnek et al., 2003; Šimůnek & van Genuchten, 2008). HYDRUS-1D has an underlying equation called the Marquardt–Levenberg algorithm (Marquardt, 1963). The Marquardt–Levenberg algorithm is used for inverse estimation of soil hydraulic properties, solute transport and/or heat transport parameters from the measured transient or steady-state flow and/or transport data (Marquardt, 1963; Šimunek & Hopmans, 2002). A major weakness of the Marquardt–Levenberg algorithm is that the algorithm only searches for a local minimum of the objective function (Šimůnek et al., 2012). This potentially could lead to a problem when running HYDRUS-1D in multiple soil horizons where uncertain initial and boundary conditions are involved (Šimůnek et al., 2012). The input data required to design a drainage system using HYDRUS-1D include climatic data, drainage design information, irrigation data, soil water content and crop information (Table 6).

2.6 | Water Simulation (WaSim) model

WaSim model is a one-dimensional daily water balance simulation model developed by Cranfield University and HR Wallingford (Hess & Counsell, 2000). WaSim simulates soil water storage in the root zone and water table depths by predicting the infiltration rates, evapotranspiration and drainage discharge in response to precipitation, irrigation and canal seepage as applicable. WaSim was first developed as a teaching and demonstration tool for irrigation, drainage and salinity management. WaSim can also predict the soil salinity status in response to different management practices such as drainage design and environmental scenarios including soil type and cropping patterns (Counsell & Hess, 2001). WaSim has been successfully applied to simulate water use, runoff and deep percolation under different environmental conditions (Stephens et al., 2001). For semi-arid areas, WaSim was successfully used to predict water table depth, drainage discharge and soil salinity in India (Hirekhan et al., 2007). WaSim was also successfully applied in a semi-arid irrigation district in Colombia to determine irrigation requirements, yield reductions and drain discharge (Depeweg & Fabiola Otero, 2004). WaSim requires a minimal input dataset as compared with other drainage simulation models (Hess & Counsell, 2000). The input data required to design a drainage system using WaSim include climate data, crop and soil information, irrigation and salinity data and drainage information (Table 7).

A strength of WaSim is that it does not require intensive input data and training compared with other drainage simulation models (Hess & Counsell, 2000). WaSim can be run on a daily time-step, to simulate a drainage scheme for up to 30 years, including up to three crops in rotation, and can simulate water table depths under both drained or undrained conditions (Hess & Counsell, 2000; Taguta, 2017). However, WaSim has not been widely applied and validated in drained lands. Also, WaSim does not accept initial soil salinity of >12 dS m^{-1}, which limits the applicability of WaSim in saline areas (Hirekhan et al., 2007). In addition, when scheduling the irrigation, irrigation dates can only be added as a fixed date and cannot be modified in response to lower or higher evapotranspiration (Hirekhan et al., 2007).

2.7 | The Soil–Water–Atmosphere–Plant (SWAP)

SWAP is a physically based, detailed, agro-hydrological model that simulates the movement of water and solutes in the vadose zone in response to plant growth (Van Dam et al., 1997). SWAP is a widely applied 1-D simulation model that designs and evaluates drainage systems (Samipour et al., 2010). The model uses the Richards equation (Richards, 1931) and includes root water extraction, to compute soil moisture movement in variably saturated soils (Kroes et al., 2008). SWAP has been used in semi-arid Pakistan, to simulate the impacts of land drainage (12 scenarios of drain depth and spacing) on soil moisture conditions in the root zone and their effect on crop yield and soil salinization in the Fourth Drainage Project, Punjab, Pakistan (Sarwar & Feddes, 2000). SWAP was also applied to predict the impact of fresh and saline irrigation waters on crop yield in semi-arid region in the state of Uttar, India (Verma & Gupta, 2014) and to predict the relative yield and salinity profile under various management options to manage saline drainage effluents under shallow water table conditions in a semiarid monsoon climate (Verma & Isaac, 2010). SWAP has also been successfully applied to predict crop yield, soil salinity and soil moisture conditions in arid areas of India and Argentina (Bastiaanssen et al., 1996). The input data required to design a drainage system using SWAP include climatic, drainage design, soil water content and crop parameters (Table 8).

SWAP adheres to the open-source philosophy. This allows other research teams to integrate the model into a variety of Decision Support Systems for example the Pesticide Emission Assessment at

TABLE 6 Minimum input data required to design a drainage system using HYDRUS-1D.

Input data requirement	
Climatic data	Daily precipitation, daily air temperature and potential evapotranspiration
Drainage design	Drain depth and spacing, entrance resistance, saturated hydraulic conductivity above and below drains, depth of impervious layer and wet perimeter of the drain
Irrigation	Observation node triggering irrigation, pressure head triggering irrigation, irrigation flux, duration of irrigation and lag time when irrigation triggered after signal is reached
Soil water content	Saturated water content, residual water content, saturated hydraulic conductivity, pore-connectivity parameter and unsaturated hydraulic conductivity
Crop	Root depth, initial time of the root growth period, yield reduction due to salinity, pressure head when root can and cannot extract water from soil and potential transpiration

TABLE 7 Minimum input data required to design a drainage system using Water Simulation (WaSim).

Input data requirement	
Climatic data	Daily rainfall and reference evapotranspiration
Drainage design	Drain depth, spacing, diameter and distance to impermeable layer
Irrigation and salinity	Irrigation time and amount, irrigation water quality and leaching requirement
Soil water content	Water retention, infiltration rates and saturated hydraulic conductivity
Crop	Cover development and rooting depths

Regional and Local scales (PEARL) model for pesticides and the Agricultural Nutrient Model (ANIMO) for nutrients (Ayars & Evans, 2015; Marinov et al., 2005). However, recent versions of the model are distributed without a Graphical User Interface, which makes it hard for new and inexperienced users to use SWAP effectively.

3 | MODEL SELECTION

3.1 | Simulation model approaches

Simulation models can be categorized based on their spatial (e.g. 'Field' or 'Catchment') and temporal scales (Radcliffe et al., 2015). The spatial scale of most drainage simulation models is usually the field scale, but in some catchment-scale models such as SWAT, the drainage system is part of the water routing function (Radcliffe et al., 2015). The field scale is the decision-making scale for farmers, whereas the catchment scale is appropriate for managing and planning water resource allocations (Flury, 1996; USEPA, 2014). In this review, the focus will be on field scale models (field scale ranges between 10 m^2 and 10 ha) as this is the scale at which farmers make decisions, and the surface and subsurface drainage offer convenient sampling points that integrate small-scale processes (Radcliffe et al., 2015). Simulation models range in temporal scale from minutes to year (Table 9), and daily values of weather data are recommended, because the records are more available from widely distributed meteorological stations (Skaggs et al., 2012).

TABLE 8 Minimum input data required to design a drainage system using Soil–Water–Atmosphere–Plant (SWAP).

Input data requirement	
Climatic data	Radiation, precipitation, temperature, vapour pressure, reference evapotranspiration and wind speed
Drainage design	Drain depth and spacing, depth of impervious layer, drain entry resistance, level of drain bottom, vertical and horizontal hydraulic conductivity above and below drains and soil profile depth
Soil water content	Initial moisture condition, ponding, soil evaporation and soil hydraulic functions
Crop	Crop height, growing period, irrigation time and depth, yield respond, rooting depth, leaf area index, salt stress, interception, root density, root distribution, root growth and crop water use

The infiltration equations used in drainage simulation models include the Curve Number method (National Resource Conservation Service [NRCS], 2004), the Green–Ampt equation (Green & Ampt, 1911) and the Richards equation (Richards, 1931). The Curve Number method is an empirical parameter used to predict runoff and can also be used to predict the infiltration rate from rainfall. The Curve Number was developed by the NRCS in 1985 by knowing the amount of rainfall, runoff and the potential maximum soil moisture retention after runoff begins. This method is widely adopted to predict infiltration rates in drained lands at the catchment scale (King et al., 1999). The Green–Ampt equation depends on the availability of key input variables such as soil suction head, water content and saturated soil hydraulic conductivity. The Green–Ampt equation is widely adopted in many hydrological models such as HEC-HMS (USACE, 2000) and in drainage models such as DRAINMOD and RZWQM2. Other drainage models such as HYDRUS-1D use the Richards equation, which depends on the intensity of rainfall, evaporation and soil hydraulic properties.

TABLE 9 Summary of model properties related to simulating drainage systems in arid and semi-arid regions.

	Model						
Model properties	ADAPT	RZWQM2	DRAINMOD	EPIC	HYDRUS-1D	WaSim	SWAP
Spatial scale	Field	Field	Field	Field	Field	Field	Field
Temporal Scale	Day	Minute-day	Hour-day	Day-year	Minute-year	Day-year	Hour-day
Infiltration rate	CN	GA	GA	CN or GA	Richards[b]	CN	Richards
Management practices	Limited	Extensive	Extensive	Extensive	Limited	Extensive	Extensive
Monitoring water table[a]	Yes	Yes	Yes	Yes	No	Yes	Yes
Salinity status[a]	No	Yes[c]	Yes	Yes	Yes	Yes	Yes
Ditches/Pipes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Availability	Free	Free	Free	Free	Free	Free	Free
References	(Chung et al., 1992)	(Ma et al., 2009)	(Skaggs, 1977)	(Williams et al., 1984)	(Simunek et al., 1998)	(Hess & Counsell, 2000)	(Kroes et al., 2000)

Abbreviations: ADAPT, Agricultural Drainage and Pesticide Transport; RZWQM2, Root Zone Water Quality Model 2; EPIC, Environmental Policy Integrated Climate; WaSim, Water balance model; SWAP, Soil–Water–Atmosphere–Plant; CN, Curve Number; GA, Green–Ampt.
[a]Critical in arid and semi-arid regions.
[b]Richards equation.
[c]Have not been tested at all.

Water management practices have been applied to minimize the negative water quality impacts of agricultural drainage. They include the installation of a control structure at drain outlets, conventional drainage systems without a structure to control the flow discharging through the drain outlets, the applications of subsurface irrigation either through the subsurface drains or open ditches and/or a combination of these water management practices. The extent to which various water management practices are included within the model is classified as limited or extensive. Drainage simulation models can also be categorized based on their ability to monitor water table and salinity status, which is the main concern in arid areas. In addition, some models can simulate surface drainage, subsurface drainage or both, which means it can be useful for managing the water sources in the area, especially if the area such as Libya has water scarcity issues. Finally, the availability of the model, based on economic cost (open source or commercial model), is also another category by which these models can be judged (Table 9). Table 9 shows model properties and the different approaches applied in each simulation model such as the spatial and temporal scale classification, how the infiltration rate is determined, the management practices, monitoring water table depth and salinity status, simulating ditches and/or drains and the availability of each model (open source or commercially paid).

3.2 | Model selection criteria

The aim of this review was to identify a suitable drainage model that could be used to design and/or evaluate drainage systems in arid regions, specifically drainage schemes in Libya. A key requirement was that the selected model should meet the minimum criteria established by Skaggs (1999). Firstly, model selection was based on the models' capability (the ability to design a successful drainage system in an arid area to prevent salinity and waterlogging problems) and the cost of its application (Skaggs, 1987). The selection of the model depends on the nature of the problem to be solved. In arid areas, the key aspect of drainage system design is defining the optimum water table depth and drain spacing. These are essential to prevent soil salinity and waterlogging affecting crop yield. Therefore, the selected model has to be able to accurately predict the fluctuations of water table depths in response to irrigation amount and the prevailing climatic conditions including rainfall and evapotranspiration on a daily basis.

Moreover, the selected model was required to accurately predict the soil salinity status of the root zone and the amount of irrigation required to maximize crop yield and optimal leaching requirements. In addition, the cost implications of applying the model and the risk of inaccurate predictions must be considered when choosing the model based on applying different alternative designs and choosing the most cost-effective drainage design. The model selection process also considered how frequently each model appeared in the scientific literature as well as whether the application of the model to drainage scheme design was accurate/validated and whether it had been applied to arid regions and soil textural classes typically found in arid regions and Libya, specifically. The availability and cost of generating the input data required by each model and how many input parameters were required to design a drainage system using each model is also an important aspect of the selection criteria.

In addition, the computer requirements and training requirements also need to be considered. In developed countries, usually, these requirements are not a major concern, and model input data of suitable spatial and temporal frequency and quality are available from multiple sources. However, for least developed countries, the selected model needs to be capable of accommodating data availability limitations that may be encountered (Table 10). If the input data are un- or partially available, of poor quality and/or spatially or temporally discontiguous the selected model must support data mining techniques as alternative methods for input data generation. For example, PTFs and artificial neural networks (ANNs) are widely adopted to predict soil water properties such as saturated hydraulic conductivity (K_{sat}). Therefore, the selected model should support the output from or have built-in PTFs and/or ANNs to generate the required input data. In addition, it is preferable that the selected model has the ability to be combined with open-source software applications such as QGIS, to pull in remote sensing (RS) data to identify the areas that need to be drained.

Finally, the selected model should consider the effects of other factors on the performance of drainage systems. These factors include drainage water discharge and quality, soil infiltration rates, actual evapotranspiration and relative crop yield. As mentioned previously, the minimum performance requirement for the selected model is that it can address the key irrigation/drainage issues of arid areas namely soil salinity and waterlogging. Therefore, the model needs to be able to accurately predict water table depth, water quality, soil salinity and infiltration rate. Therefore, the more factors that can be described by the model, the lower risk of errors. The key selection criteria used to determine the suitability of the selected models for application in Libya are listed in Table 10.

In Table 10, the model selection criteria are divided into key model characteristics required to design drainage systems in Libya and user requirements. The key model characteristics include conditions such as the availability of input data required by each model and the ability to be applied in arid regions such as Libya. The users' requirements include conditions such as the cost of the model, minimum computer requirements and level and availability of the technical training required and user support. Each model was scored against all selection criteria. More positive responses were scored higher than negative ones, for example, if a model has been applied in arid regions, that model was given a score of (1). If the model was not applied in arid areas, it was given a score of (0). The sum of the score of each criterion gave the overall model criteria total score with the selected model having the highest total score.

The selection criteria total scores in Table 10 show that DRAINMOD had the highest total score of 14 points (comprising nine key model characteristic requirement points and five user requirement points). HYDRUS-1D and SWAP had the second-highest total scores

TABLE 10 Suitability criteria for drainage model selection

Selection criteria	Model						
	ADAPT	RZWQM2	DRAINMOD	EPIC	HYDRUS-1D	WaSim	SWAP
A. Key model characteristics required in order to design drainage systems in Libya							
Has the model been applied and validated to simulate drainage systems in arid regions	0	1	1	1	1	1	1
Has the model been applied to simulate soil salinity status and waterlogging in arid regions	0	0	1	0	1	1	1
Has the model been applied in the least developed countries	0	0	1	1	1	1	1
Does the model have the potential to be applied in arid regions	1	1	1	1	1	1	1
Is all input data available in Libya	0	0	0	0	0	0	0
Model supports input data derived from data mining techniques (i.e. PTFs, ANNs and/or remote sensing)	1	1	1	1	1	1	1
Does the model consider the effects of other factors (e.g. lateral flow, ET, deep percolation, working days and crop growth affected by waterlogging and salinity)	1	1	1	1	1	1	0
The model uses widely accepted equations used in the development of drainage simulation models (Richards equation, water balance approach, Curve Number and/or Green–Ampt)	1	1	1	1	1	1	1
Has the model been combined with GIS programs	0	1	1	1	1	0	1
Is the model widely referenced and validated for drainage applications (based on publications >20)	0	0	1	0	0	0	1
Total score of *A. Characteristic requirements*	4	6	9	7	8	7	8
B. User requirements							
Is the model open source	1	1	1	1	1	1	1
Computer requirements (can run under minimum computer requirements in the least developed countries '£500')	1	1	1	1	1	1	1
Technical support is available for users	0	1	1	1	1	0	1
Tutorial available to learn how to apply the model	0	1	1	1	1	1	1
The model does not require intensive training is intuitive to use, errors are easy to recognize (e.g. windows interface models preferred over the Dos-based model)	0	1	1	0	0	1	0
Total score of *B. User requirements*	2	5	5	4	4	4	4
Total score *A* + *B*	6	11	14	11	12	11	12

Note: Justification for criteria are shown in brackets and original objectives are shown in italics (the model score 1 if it can achieve the defined characteristic, and will score 0 if it has not achieved the defined characteristic).

with 12 points each. This was followed by RZWQM2 and WaSim, which had a total score of 11 points each. The model with the lowest total score in Table 10 was ADAPT with a total score of 6 points. Although RZWQM2 scored well in individual criteria, DRAINMOD had a greater number of publications related to drainage applications, which means greater validation under peer review and was applied more times in arid and semiarid regions. Based on this selection criteria, DRAINMOD was identified as the most suitable model to design and evaluate drainage systems in Libya and other data-poor arid regions.

4 | DRAINMOD INPUT DATA AVAILABILITY AND QUALITY OF INPUT DATA IN LIBYA

DRAINMOD considers the effect of salinity, excess water and drought on crop yield (Wahba et al., 2002). DRAINMOD like other models discussed in this review is dependent on input data, such as daily precipitation and temperature, soil water characteristics (Table 4), land use and topography. Without these data, applying DRAINMOD to design a drainage system in a given target location will

TABLE 11 DRAINMOD inputs data required for drainage system design adopted from (Skaggs et al., 2012).

Input data	Expected range	Data sources in Libya[a]	DRAINMOD prediction[b]	Alternative methods of measurements
Drain depth	50 to 300 cm	Drainage maps and reports for HAP and EAP: the source is the archive at the General Water Authority located in Tripoli and the data was produced by (Cornelius-Brochier, 1981; Danenco, 1980; Holzmann-Wakuti, 1974; Italconsult, 1976)	No	Field measurements
Drain spacing	5 to 200 m		No	Field measurements
Depth to restrictive layer	50 to 1000 cm		No	Field measurements
Profile layer depths	5 to 200 cm		No	Field measurements
Drainage coefficient (DC)	0.5 to 10 cm d^{-1}	Unavailable	No	Field measurements
Surface depressional storage (S1)	0.25 to 10 cm	Unavailable	No	Field measurements
Minor surface depressional storage (S2)	0.25 to 10 cm	Unavailable	No	Field measurements
Crop or vegetation inputs[c]	Evans et al. (1991)	Reports (GWA, 1999) and literature such as (Allen et al., 1998; Evans et al., 1991; Kandil et al., 1995)	No	Experiments
Root depth versus time (cm vs. days)	0 to 100 cm		No	Experiments
Saturated hydraulic conductivity by layer	0.05 to 100 cm h^{-1}	Field and laboratory measurements for HAP and EAP: available at the General Water Authority (Cornelius-Brochier 1981; Holzmann-Wakuti, 1974; Italconsult, 1976)	No	These inputs can be predicted by applying widely adopted PTFs such as Rosetta and/or developing ANNs using easily measured data such as soil texture and bulk density
Soil water retention curve by layer h(Θ)	Skaggs (1980)		Yes	
Soil water content at saturation (Θs)	0.3–0.9 $cm^3\ cm^{-3}$		No	
Soil water content at lower limit (Θll)	$(\Theta_s - 0.10)$ to $(\Theta_s - 0.26)\ cm^3\ cm^{-3}$		No	
Drainage volume versus water table depth (Vd)	Skaggs (1980)	Unavailable	Yes	Laboratory and/or field measurements
Upward flux versus water table depth (Upflux)	Skaggs (1980)	Unavailable	Yes	Laboratory and/or field measurements
Infiltration parameters versus water table depth	Skaggs (1980)	Unavailable	Yes	Laboratory and/or field measurements
Initial soil salinity by layer	0 to 18 millimhos cm^{-1}	Survey and reports for HAP and EAP: the source is the archive at the General Water Authority located in Tripoli and the data was produced by (Cornelius-Brochier, 1981; Danenco, 1980; Holzmann-Wakuti, 1974; Italconsult, 1976).	No	Field measurements or developing ANNs using easily data obtained from remote sensing images from Landsat images.
Groundwater salinity	Measured		No	
Irrigation water salinity	Measured		No	
Irrigation amount	Kandil et al. (1995)		No	Experiments
Daily but preferred hourly precipitation	Observed	Meteorological stations nearby HAP and EAP: the source is the Libyan National Meteorological Centre; however, the daily datasets are partly available with missing values on some days.	No	Meteorological data can be obtained on hourly basis with no missing values from ERA5-Land (Muñoz Sabater, 2019)
Daily maximum and minimum air temperature	Observed		No	
Daily potential evapotranspiration (PET)	0.0 to 2 cm^{-1}		No	

[a]The data sources focused on two agricultural projects located in Libyan arid areas namely, Hammam Agricultural Project (HAP) and Eshkeda Agricultural Project (EAP).
[b]Is DRAINMOD able to predict the input parameters within the model?
[c]The impact of different factors on yield such as excess water stress, deficit water stress, planting delay and salinity stress. PTFs are the pedotransfer functions. ANNs are the artificial neural networks.

not be possible, which is the case in many least developed countries including Libya. Therefore, these data need to be measured or interpolated using PTFs or ANNs to run DRAINMOD. Table 11 illustrates the input data required to run DRAINMOD for designing a drainage system in arid areas. Table 11 also shows the assessment undertaken by Skaggs et al. (2012) including the expected range by DRAINMOD for each input parameter. The availability of data input sources for least developed countries and Libya specifically is also included. Table 11 also illustrates the ability of DRAINMOD to predict each of the input parameters and other alternative approaches that can be used to predict the required input parameters.

5 | METHODS TO OBTAIN INPUT DATA FOR DRAINMOD IN DATA-POOR ARID REGIONS

As discussed in this study, DRAINMOD would be the recommended option for the design and evaluation of drainage systems in arid regions. However, even though DRAINMOD has the ability to predict input data such as the unsaturated hydraulic conductivity, upward flux versus water table depth and infiltration rates, the model is not suitable to design and evaluate drainage systems in data-poor areas. However, it is crucial to note that DRAINMOD users can maximize the use of DRAINMOD in areas where there are insufficient datasets. DRAINMOD is driven by input data (Table 10); these data may be partially or completely unavailable in data-poor low-income countries because of the economic cost and time and expertise required to collect the data. However, utilizing alternative ways of generating the required data can make the use of DRAINMOD viable. One such alternative method to accurately generate the missing data is to use ANNs.

ANNs have been successfully applied to several agricultural engineering problems, including yield prediction such as corn yield (Uhrig et al., 1992; Uno et al., 2005), soybean growth (Zhang et al., 2009) and wheat yield (Ruβ et al., 2008). In water management, ANNs have been applied to simulate the groundwater levels in coastal aquifers (Taormina et al., 2012), to predict water table response to change in precipitation (More, 2018), to predict drainage water and groundwater salinity at various drain depths and spacing (Nozari & Azadi, 2017) and to estimate evapotranspiration (Feng et al., 2017). In soil management studies, ANNs have been used to determine soil temperature (Nahvi et al., 2016), to estimate total soil nitrogen, organic carbon and moisture content (Morellos et al., 2016) and to estimate soil hydraulic properties such as soil water content, saturated and unsaturated hydraulic conductivity (Ellafi et al., 2021; Schaap et al., 2001) and reduction in hydraulic conductivity (Ezlit et al., 2014). However, further research is needed to assess how successfully missing input data for DRAINMOD and other models can be derived from ANNs to support drainage system design. Key input parameters for DRAINMOD often absent in data-poor regions include the following.

5.1 | Saturated hydraulic conductivity (K_{sat})

Saturated hydraulic conductivity is a key input parameter to evaluate drainage system designs. Direct methods of estimating K_{sat} are often difficult, time-consuming and expensive. In DRAINMOD, K_{sat} for each horizon above the restricting layer is an essential parameter because (1) K_{sat} in DRAINMOD is used to calculate other input parameters such as infiltration rates by applying the Green–Ampt equation (Equation 3) and the capillary rise water table depth relationship. (2) K_{sat} is also integral to Hooghoudt's steady state equation to calculate drainage flux, water table depth and spacing between drains (Equation 4). In addition, K_{sat} is considered the most sensitive input parameter in DRAINMOD in terms of predicting the annual subsurface drainage volume, growing season and relative crop yield. Research is needed into the application of indirect methods to estimate K_{sat} such as utilizing existing PTFs and/or developing ANNs to estimate K_{sat} from more readily available soil measurements (Cosby et al., 1984; Dane & Puckett, 1994; Julia et al., 2004; Puckett et al., 1985; Saxton et al., 1986; Schaap et al., 2001). Thereafter, validation is required by applying the predicted K_{sat} values in DRAINMOD to design drainage systems as compared with the design based on measured K_{sat}.

5.2 | Evapotranspiration (ET)

Evapotranspiration is a main component in the water balance equation applied by DRAINMOD (Equation 1). Accurate prediction of ET is also important to justify the crop water requirements and leaching requirements. ET can be directly measured from the soil water balance in lysimeters (Allen et al., 1998). However, such measurements are rarely available in low-income countries, for a given time and location, even within data-rich areas. Alternatively, ET can be calculated from climatological data such as net radiation, temperature, humidity and wind speed. DRAINMOD can determine ET by inputting the daily maximum and minimum temperature and precipitation. Yet, within data-poor areas, these meteorological data are often absent or discontinuous. Research is needed into alternative methods to estimate these missing values, for example, applying ANNs to predict the missing meteorological data needed for ET calculation, such as the daily maximum and minimum air temperature (Ustaoglu et al., 2008). Other methods have predicted the missing meteorological data using the Arithmetic Averaging of Neighbouring Stations (AANS) (Xia et al., 1999), predicting daily maximum and minimum air temperature from average monthly data (Liu et al., 2008), or using calculated meteorological data such as ERA5-Land (Muñoz Sabater, 2019). Also, ANNs can be developed to predict ET from limited climate data (Zanetti et al., 2007). The predicted ET based on each method should be applied in DRAINMOD to evaluate the impact of using each method on crop yield and water table depth in comparison with the ET calculated from observed data.

5.3 | Soil electrical conductivity (EC)

Soil electrical conductivity is a measure of the amount of salt in a given soil (soil salinity). By knowing the EC with depth, DRAINMOD is able to predict long-term effects of different irrigation and drainage practices on crop yield (Equation 5). Direct measurements of EC are expensive and time consuming. Therefore, research is needed to find an alternative method to predict EC of soil with depth. A potential method may be to develop an ANN model to predict EC from more readily available soil measurements such as groundwater depth and quality, soil texture and irrigation water quality (Bouksila et al., 2010). However, such data may not be available in many areas, especially within the least developed countries. Therefore, the potential of using remote sensing images such as Landsat coupled with ANNs to develop a model that can predict soil salinity might be a solution in data-poor areas (e.g. Libya) (Sahbeni, 2021).

6 | CONCLUSIONS

Drainage simulation models such as DRAINMOD, SWAP, ADAPT, RZWQM2, EPIC, WaSim and HYDRUS-1D have been applied to predict the daily performance of drainage systems and to monitor and control water table levels (Malakshahi et al., 2020; Shrestha & Manandhar, 2014; Verma & Gupta, 2014). These models have been developed to describe a specific field condition, such as a shallow water table (Skaggs et al., 2012), drainage water management practices and their impacts on crop yield (Ma et al., 2012; Verma & Gupta, 2014) and monitoring soil salinity and irrigation strategies in arid and semi-arid areas (Wahba et al., 2002; Wahba & Christen, 2006). In this study, the applicability of these models to design drainage system in arid and semi-arid areas located in the least developed countries was evaluated and against a selection criterion. The most applicable model was DRAINMOD. Evaluating the feasibility of using predicted K_{sat}, ET and EC as input parameters for simulation models to design drainage systems in data-poor areas would help farmers, planners and decision-makers to reduce the overall cost of drainage system design. Also, it would make these simulation models more accessible tools to evaluate different drainage designs.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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