Review

Assessment of Subsurface Drainage Strategies Using DRAINMOD Model for Sustainable Agriculture: A Review

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Abstract: Practicing agricultural drainage strategies is necessary to manage excess water in poorly drained irrigated agricultural lands to protect them from induced waterlogging and salinity problems. This paper provides an overview of subsurface drainage strategies and the modeling of their performance using the DRAINMOD model. Given that the DRAINMOD model considers a fixed value of the surface depression capacity (SDC) for the whole simulation period, which does not suit many agricultural practices, the paper then assesses the model's performance under time-variable SDC. It was revealed that adopting a fixed value of SDC for the whole simulation period in the DRAINMOD model causes it to produce improper predictions of the water balance in farmlands characterized by time-variable SDC. Such a model drawback will also adversely impact its predictions of the nitrogen and phosphorus fate in farmlands, which represent major inputs when managing both the agricultural process and agricultural water quality. Researchers should pay attention when applying the DRAINMOD model to farmlands characterized by time-variable SDC. Moreover, it is recommended that the DRAINMOD input module be improved by considering changes in SDC during the simulation period to ensure better management of the agricultural process and agricultural water.

Keywords: agricultural drainage strategies; agricultural water management; DRAINMOD; salinity; waterlogging; water distribution patterns

1. Introduction

Water is an indispensable element of agriculture. However, the oversupply of water results in severe losses in crop yield [1–3]. Providing agricultural lands with more water than crops need causes excess water to accumulate in these lands, resulting in a rise in groundwater tables. Under these conditions, water replaces oxygen existing in the soil profile, which may hinder, or stop, the respiration of crops' roots and thus result in severe damage to most crops [4,5]. This is referred to as the "waterlogging" condition (Figure 1). If excess water is salty enough and there are high evaporation rates, there is a great possibility that dissolved salts will accumulate on the soil surface when excess water evaporates. Over time, such a salt accumulation in the soil profile may hinder crops' growth, and this is known as the "soil salinization" problem (Figure 1) [6–8].

Excess water may also occur due to heavy precipitation events when the soil has low permeability and/or the rainwater is trapped in the land and cannot run off [9]. To

avoid these undesirable conditions, it is necessary to have a strategy that can mitigate any accumulation of excess water in the soil profile to ensure high agricultural productivity. Agricultural drainage strategies have been reported as an effective tool that allows both farmlands and urban areas to get rid of excess water [10,11], and subsurface drainage systems are well-known practices for ensuring the desired moisture conditions in crops' root zones [12–14]. Due to the importance of these systems, researchers have been interested in assessing their performance and developing new technologies and approaches that help to fully understand the way in which such systems impact farmlands' water balance.
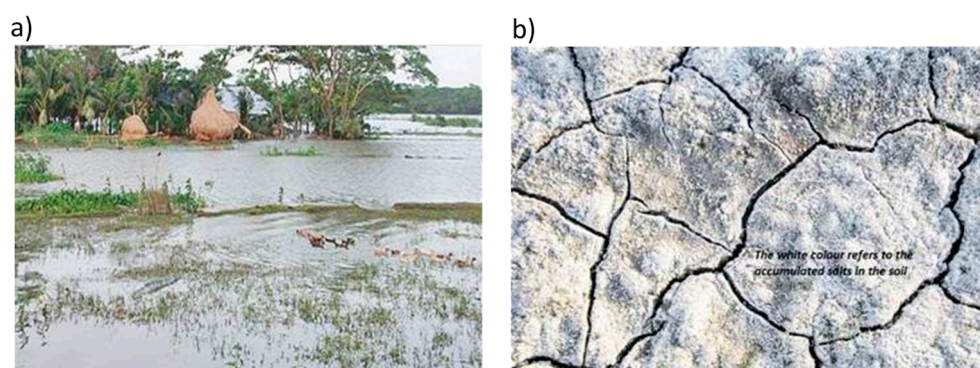

Figure 1. Waterlogging (**a**) and soil salinization (**b**) problems in agricultural lands.

Among all known methodologies and approaches for assessing the performance of subsurface drainage systems, mathematical models are superior since they save costs and time. DRAINMOD is one of the models that allow the quantification, on a continuous basis, of the performance of drainage and other related water management systems, as well as the assessment of various impacts of several field conditions and management practices on the performance of subsurface drainage systems [7,12].

This paper provides the following:

1. An overview of agricultural drainage strategies and subsurface drainage systems.
2. An overview of the DRAINMOD model and its application to simulating the performance of subsurface drainage systems and other related topics.

Additionally, this paper studies the DRAINMOD performance under a special practice that is common in many paddy lands and may affect the model's performance. For example, rice requires massive water amounts to grow optimally, and paddy lands are always characterized by their high water tables. However, during certain periods in the rice-growing season, it is necessary to practice so-called "mid-summer drainage practices" to change the land surface to non-ponding conditions to ensure sufficient oxygen for the roots, along with the draining of toxic substances such as sulfides and organic acids. This can be achieved by removing barriers around the land and smoothing the land surface. This, in return, causes the surface depression capacity to change.

In the DRAINMOD model, the surface depression capacity is input as a fixed value for the whole simulation period. So, there is no option in the model to consider any changes in the capacity of surface depression (such as under mid-summer drainage practices). Since the surface depression capacity is a major determinant of the water fate in farmlands [15,16], the DRAINMOD model's shortage in considering changes in the surface depression capacity may cause the model to produce improper water distribution patterns in agricultural lands. Therefore, this paper reviews the DRAINMOD model's performance in the study conducted by Awad et al. [15], who applied the model to predict the water fate in a paddy area where the surface depression capacity varies during the growing season due to mid-summer drainage practices. The aim is to investigate whether or not it is necessary to modify the input module of the DRAINMOD model and include the surface depression capacity as a time-variable value.

2. Agricultural Drainage

2.1. Why Agricultural Drainage?

Water that exists in farmlands may exceed the crop water requirements, and this may occur under the following conditions:

- An excessive water supply, such as flooding irrigation.
- Intense precipitation events.
- Upward water flux from an aquifer, or even lateral seepage or runoff from adjacent lands.

If the land cannot get rid of excess water naturally (e.g., through runoff or deep percolation to aquifers), it accumulates water on its surface, causing groundwater tables to rise. The more excess water, the greater the rise in groundwater tables. If groundwater tables rise to upper soil layers where crops' roots exist, water starts to replace oxygen in the soil profile, which hinders, or stops, the roots' respiration. This is the "waterlogging problem" in agricultural lands [2,17].

Waterlogging and soil salinization, known as the twin menace of poor drainage conditions, have been aggravated all over the world and have become a national threat to agriculture in many countries (Figure 2). Globally, it was estimated that more than 800 million hectares of land could be considered salt-affected [18–20].
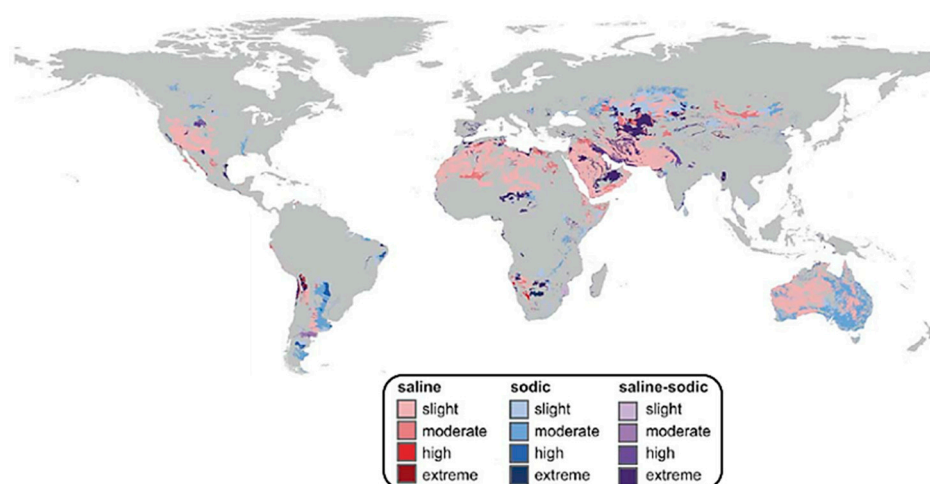

Figure 2. Global distribution of salt-affected soils. (Modified after Jothiman et al. [21]).

The above-mentioned threats of waterlogging and soil salinization highlight the great need for particular practices that help poorly drained lands get rid of their excess water to ensure the desired conditions for crops, soil, and the surrounding environment. Therefore, agricultural drainage has been practiced for decades in poorly drained farmlands to enhance their ability to get rid of the excess water through artificially constructed networks that are responsible for carrying and directing this excess water out of these lands [3,16].

In general, the benefits of practicing agricultural drainage include, but are not limited to, the following:

- It increases crop yield, as well as provides the ability to introduce new and improved cropping systems [22–24].
- Many studies have reported a direct relationship between poor drainage conditions and flooding susceptibility [25]. Hence, proper drainage practices can be an effective tool to mitigate flood risks and soil erosion as surface runoff decreases [26,27].
- It ensures better groundwater quality [28].
- It reduces the energy required for field machine operations, because soil compaction is decreased [3,22].

- Timelier field operations will be allowed. Consequently, crops can achieve full maturity by lengthening the growing season [3].
- As a result of the aforesaid benefits, farm income will increase while decreasing income variability.

The environment has also gained a host of benefits from the practice of agricultural drainage strategies, as follows [22]:

- It has improved the health of humans, plants, and farm animals.

Practicing agricultural drainage in wet and swampy areas led to a remarkable reduction in mosquito breeding sites, which causes a drop in the incidence and prevalence of important water-related and mosquito-transmitted diseases, e.g., malaria, yellow fever, and filariasis.

- The drainage of stagnant water results in eliminating foot rot in large animals.
- Practicing agricultural drainage mitigated nonpoint-source pollution caused by the movement of water-dissolved fertilizers from agricultural lands to the surrounding water bodies through runoff. Such mitigation helps to ensure better surface-water quality, which also reflects positively on human health.

2.2. What Is Agricultural Drainage and How Is It Being Practiced?

In simple words, agricultural drainage refers to practices that create a path for the excess water to be discharged from farmlands. Agricultural drainage has been practiced for centuries, and it helped shape many of the productive agricultural lands we see today. Modern drainage strategies were particularly prevalent toward the end of the 19th century. Between 1840 and 1890, it is estimated that around 4.9 million hectares of land were drained [3].

Practicing Agricultural Drainage

As agricultural drainage strategies aim to create a path for the excess water to be discharged from farmlands, this path can exist above or under the ground, and this is what distinguishes between so-called "Surface drainage practices" from "Subsurface drainage practices".

Surface drainage practices mainly aim to collect (through runoff) the excess water that exists on the land surface in a set of ditches that convey this water and discharge it from the farmland. To have an effective surface drainage system, the farmland topography has to be modified to create slopes toward ditches to allow excess water on the land surface to run off smoothly toward these ditches (Figure 3). On the other hand, subsurface drainage practices aim to create an underground path that collects excess water that exists in the soil profile and discharges it, whether directly to a spot outside of the farmland or to a ditch that then discharges it from the farmland. In the following section, we focus on some details related to subsurface drainage systems.
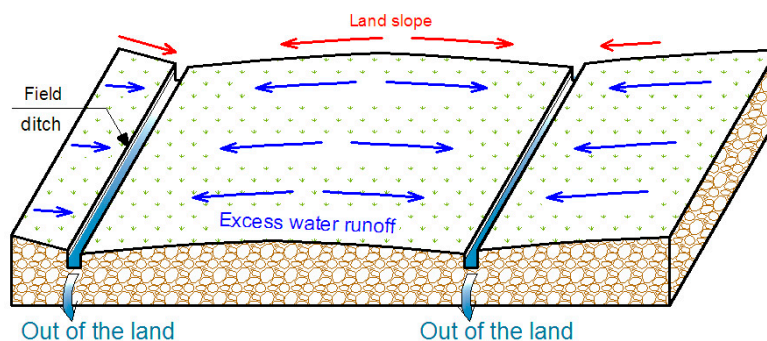

Figure 3. Surface drainage practices.

2.3. Subsurface Drainage Systems

For subsurface drainage practices, excess water is collected in underground perforated pipes that are installed at certain depths and slopes in such a way that allows this water to flow from laterals to main collectors until being discharged from the land (Figure 4). Sometimes, these underground pipes deliver excess water directly to ditches that are dug in the land, and then these ditches discharge this excess water from the land.
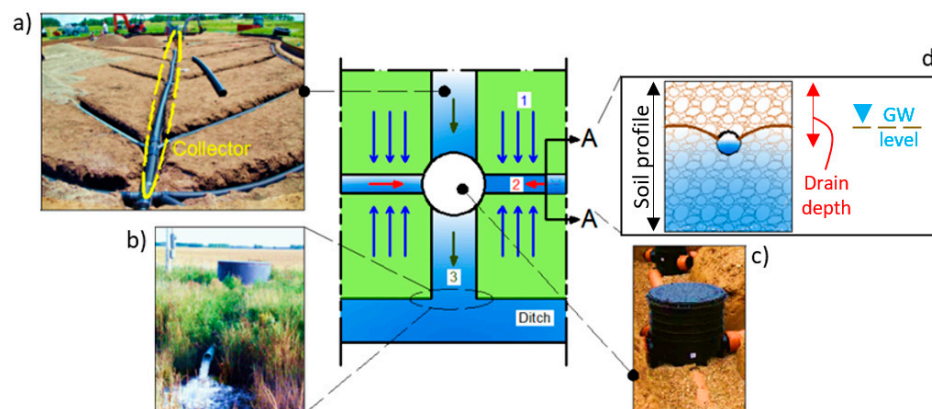

Figure 4. A typical layout of subsurface drainage systems showing (**a**) collectors, (**b**) outlets, (**c**) manholes, and (**d**) the cross-section A-A that shows drainpipes buried in the soil profile (at a certain drain depth) beside the GW table during the drainage process.

2.3.1. Layout and Components of Subsurface Drainage Systems

Figure 4 shows a simple layout of subsurface drainage systems. As shown in the figure, the main components of a subsurface drainage system are:

- Drainpipes (laterals), which are shown in section A-A (Figure 4);
- Drainpipes (collectors);
- Manholes;
- Outlets and drains.

- Drainpipes

Subsurface drainage systems are practiced mainly to get rid of the excess water that exists underground, so buried drainpipes are considered the backbone of such systems, as these pipes are the receivers and conveyors of the underground excess water. In large lands, subsurface drainage systems are designed in such a way that small-diameter drainpipes (laterals) discharge excess water into larger-diameter ones (collectors). Then, the largest-diameter pipes become responsible for conveying and discharging this water into any ditch or water body adjacent to the land. However, in small lands, laterals may be designed to discharge excess water directly into ditches or water bodies.

Drainpipes' surfaces are perforated in a way that allows underground excess water to enter these pipes (Figure 5). However, there is a high possibility that sand and/or silt soil particles enter from these perforations and accumulate in drainpipes, resulting in clogs in these pipes and thus hindering the drainage process. Therefore, in lands that have such soil structures, drainpipes are surrounded by proper filtering materials to prevent or mitigate any clogs in these pipes. There are plenty of filtering materials, and the choice of the proper one depends on many parameters, such as the availability of these materials, soil texture, etc. (Figure 6) [29,30].

- Collectors

Collectors are pipes with larger diameters than laterals and receive excess water from these laterals to discharge it to either larger pipes or any surrounding water body. It is preferable to have an irrigation canal at the beginning of the collector pipe (the pipe's highest elevation) and a drain at its end (the pipe's lowest elevation), as this helps in

performing maintenance work (known as the "washing process" of the network (Figure 7)). In such a case, water is pumped with high pressure at the beginning of the collector pipe, and as a result, water will flow in the network under high pressure to remove any clogs in the collectors to ensure the best performance of the drainage process.
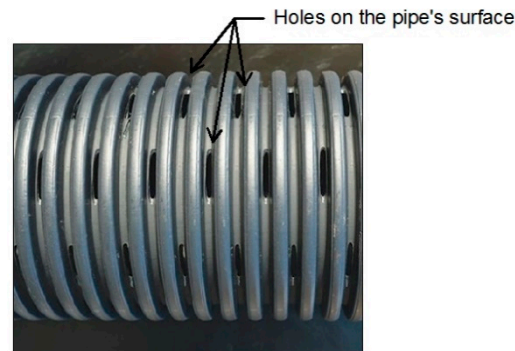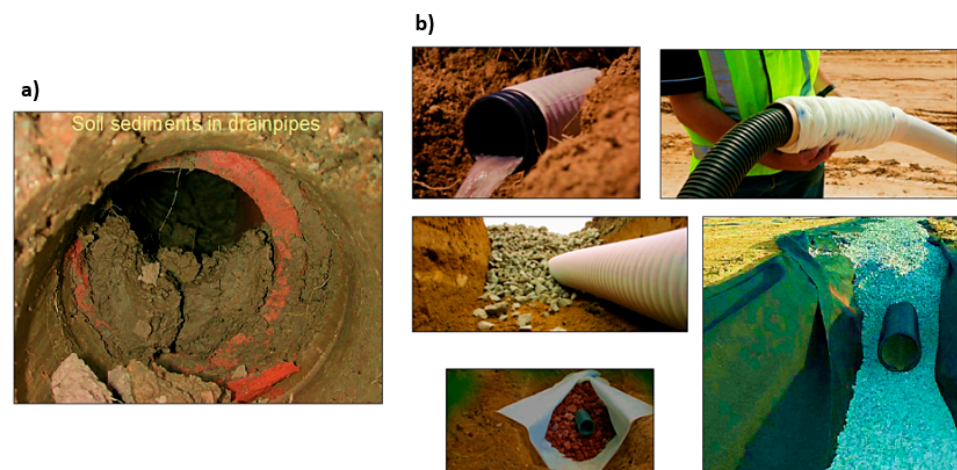

Figure 5. Drainpipe perforations.

Figure 6. Sediments in drainpipes: (**a**) sediment accumulation in drainpipes and (**b**) examples of filtering materials.
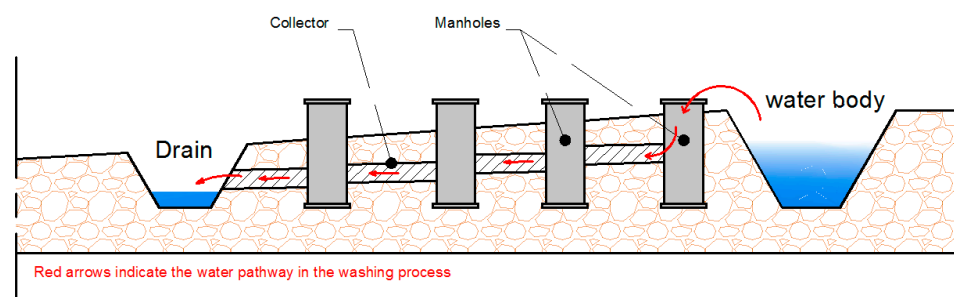

Figure 7. Washing process of the drainpipe network.

- Manholes

  Manholes are structures that are located at the intersections of two or more drainpipes (laterals with collectors/collectors with collectors) to mitigate the accumulation of sediments at these intersection points (Figure 8). Manholes are also implemented at specific spacings to divide the length of long collectors into smaller ones to facilitate the maintenance of these pipes. For example, if there is a certain issue (e.g., a clog) in the collector pipe, it is easy to check the sections between each adjacent manholes, rather than checking the whole length of the pipe.
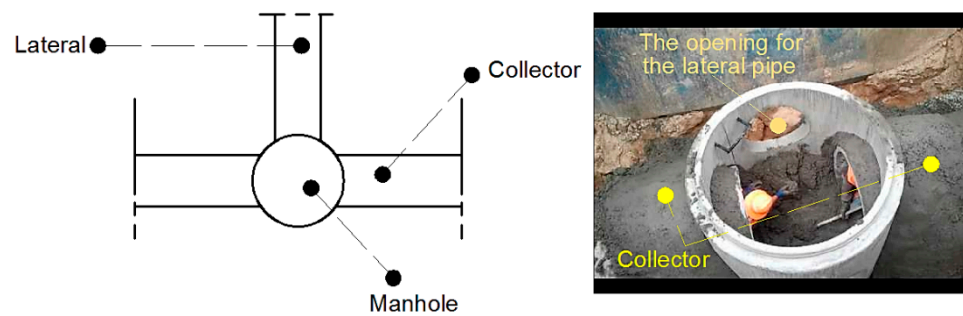
Figure 8. Manholes, showing their structure and location.

- Outlets and drains

A drainage outlet represents the point after which excess water leaves the subsurface drainage system to water bodies that surround the land. Such an outlet is mostly located at the end of a collector pipe, and, in most cases, this pipe discharges the excess water into open drains (Figure 9).
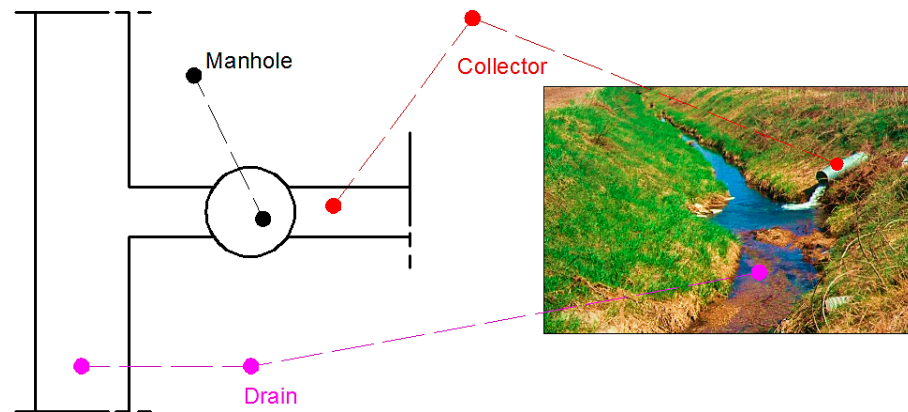

Figure 9. A typical layout showing the drainage outlet (which is mostly the end of a collector pipe).

To ensure the continuity of the drainage process, the highest designed water level in the drain or the water body (where collectors discharge excess water) should not be higher than the collector's bottom level to prevent the submergence of collectors (outlets) in these water bodies (Figure 10).
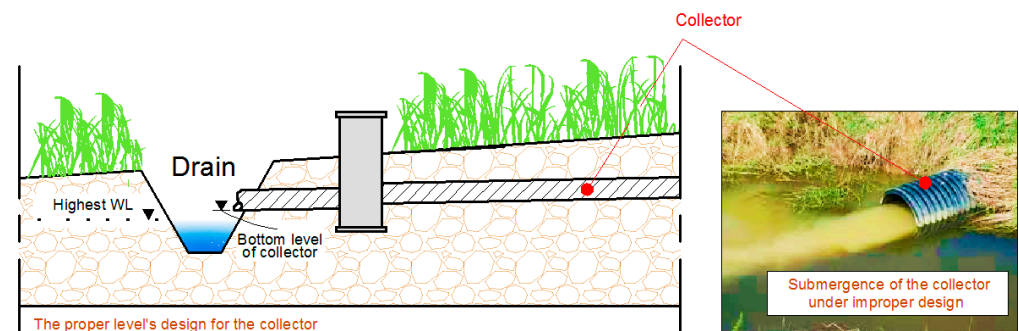
Figure 10. Design considerations to prevent the submergence of collector pipes.

2.3.2. Special Practices in Subsurface Drainage Systems

Subsurface drainage systems have mutated and developed from only a strategy for the removal of excess water to a tool that helps to better control groundwater tables and soil moisture in agricultural lands. In the following, a brief discussion is provided about so-called "Controlled drainage [31]" and "Subirrigation [32]" practices, which are two

examples of how to employ subsurface drainage practices for better control of groundwater tables and, thus, soil moisture.

Controlled Drainage Practices

Under common drainage conditions (conventional drainage), excess water moves from laterals to collectors and then is freely discharged into water bodies that surround the farmland. Therefore, under such conditions, any excess water in the soil is drained. Sometimes, there is a need to retain some or all of the excess water in the soil profile, and this occurs in the following cases:

- Crops that require large water amounts.

For example, rice and some other crops cannot grow well until the soil is sufficiently saturated. So, the soil must retain large water amounts to achieve such saturation conditions. Under conventional drainage practices, excess water is drained and lost from the land, which decreases the water availability and thus could adversely impact crop yields. Therefore, controlled drainage practices are applied under these conditions to decrease the drainage rate or stop any drainage flux to retain the desired water amount in the land and thus ensure high crop yields [24].

- After the application of fertilizers.

Fertilizers that are applied in agricultural lands dissolve in the soil water, and then crops' roots extract this water to meet their requirements from fertilizers and grow optimally. Under high and unmanaged drainage rates, large amounts of this water (which contains dissolved fertilizers) are lost from the soil before being extracted by crops' roots. This deprives crops of these fertilizers and increases the nonpoint-source pollution of surrounding water bodies that receive the drainage flux due to the dissolved fertilizers that exist in this flux. Therefore, it is sometimes preferable to decrease the drainage rate or stop any drainage flux after the application of fertilizers. Consequently, this allows crops to make the best use of these fertilizers while ensuring better quality for the surrounding water bodies [33].

Under the abovementioned cases, it is better to practice some control on the drainage flux. This can be achieved by setting a "Control structure" before the outlet. This control structure has something like a small gate that can be moved up and down to achieve the desired drainage rates (Figure 11).
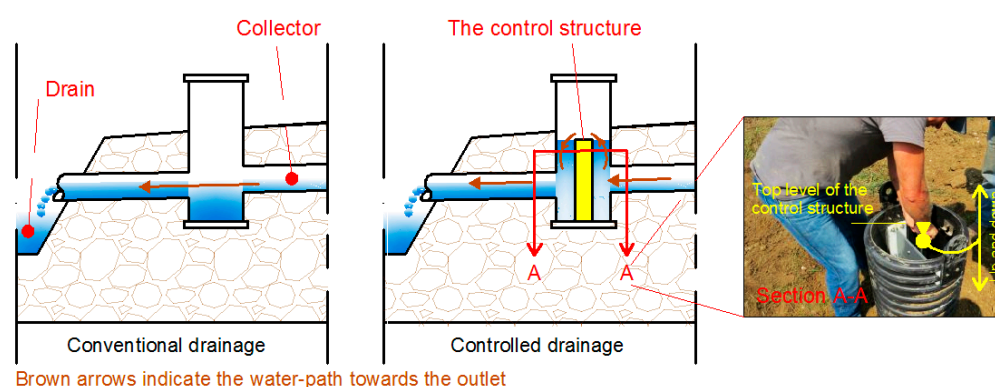

Figure 11. Conventional vs. controlled drainage practices.

Under controlled drainage practices, excess water does not flow directly to outlets. Rather, it accumulates in the control structure, or in the manhole that contains that control structure, until it reaches a level higher than the top of the control structure, and then drainage starts (Figure 11).

Subirrigation Practices

Apart from what is established in minds about drainage systems, namely, that they are installed to only lower groundwater tables in the soil profile, these systems can be managed in a different way (subirrigation practices) to exert the reverse action. Under subirrigation practices, water is pumped back into collectors to reach the laterals. As a result, water flows from these laterals to the soil profile (through the openings on the surfaces of these laterals). This increases the water availability in the soil profile, especially the root zone, and causes groundwater tables to rise (Figure 12).
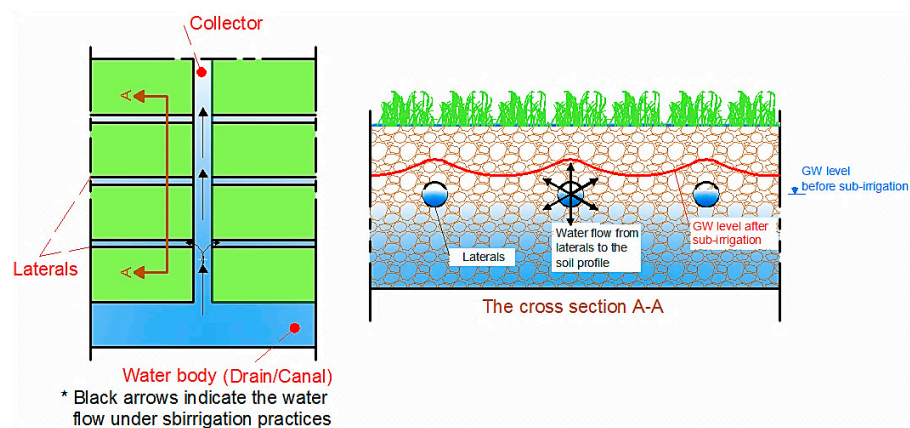

Figure 12. Subirrigation practices.

2.3.3. Advantages and Disadvantages of Subsurface Drainage Practices

Compared to surface drainage practices, the main advantage that characterizes subsurface drainage practices is the high control of the drainage rate, and this, in turn, results in several advantages [14,26]:

- Better control of groundwater tables.
- Mitigation of the degradation of water body quality that results from nonpoint-source pollution when fertilizers that are dissolved in drainage water discharge in these water bodies.

Most components of subsurface drainage systems exist underground, so the installation of these systems does not cause significant losses in the area of agricultural lands compared to surface drainage systems.

As previously stated, practicing subsurface drainage strategies mitigates the runoff to adjacent water bodies, which may save them from the so-called "gully erosion" and ensure better conditions for the maintenance of their cross-sections [34].

On the other hand, the major disadvantage of subsurface drainage systems is the high cost of installation. In addition, such systems require periodic maintenance to ensure the high performance of the drainage process.

2.4. Soil Type and Climate Patterns as Significant Determinants When Deciding the Best Drainage Strategy (Surface or Subsurface) in Agricultural Lands

To decide the best drainage strategy (whether surface or subsurface) for a particular land, it is necessary to have preliminary knowledge of the excess water fate in the land. Such a fate in agricultural lands depends largely on the soil characteristics and weather patterns. In principle, the excess water that exists in farmlands has two major fates: runoff and infiltration.

- If the soil is highly permeable, then excess water (which exists on the land surface) easily percolates into the soil profile in a relatively short time. In this case, subsurface drainage strategies are the ideal choice since most of the excess water will exist underground in the soil profile.

- For low-permeability soils, excess water (which exists on the land surface) takes a relatively long time to percolate into the soil profile, resulting in the accumulation of this water on the land surface. If this stagnant or retained water exceeds the surface depression capacity of the land, then runoff begins. Under such conditions, most of the excess water exists on the land surface and not in the soil profile, and thus, surface drainage strategies are the ideal choice in these lands to collect the excess water through runoff.
- Sometimes, we may have intense precipitation patterns in lands characterized by high-permeability soils. Under such conditions, the precipitation rate may exceed the percolation of excess water into the soil profile. This may result in excess water accumulation on the land surface, which makes surface drainage strategies necessary in these lands despite having relatively high-permeability soil in the land.
- If the climate pattern varies during the year in a particular land, it may be better to use a combination of both surface and subsurface drainage strategies to collect excess water runoff (e.g., due to heavy precipitation events) and get rid of underground excess water (when existing).

In addition to the abovementioned role of soils and climate patterns in deciding the best drainage strategies in agricultural lands, soil texture plays a dominant role in deciding the best design layout of drainage systems. Therefore, it is indispensable to properly consider different soil textures and climate patterns that exist in a particular area when deciding on the best drainage strategies and practices.

3. The DRAINMOD Model

In 1980, the computer model "DRAINMOD" was developed by Professor Skaggs at the Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC, USA [12]. DRAINMOD was developed as a field-scale model that predicts the performance and impacts of drainage strategies and associated water management practices on groundwater depths, soil water regimes, and crop yield. In addition, the model can be used to simulate the hydrology of lands that do not have underground drainpipes. DRAINMOD uses simple water balances and basic hydrology modeling approaches to calculate water balances and predict water fates on hourly and daily time scales for long periods of the climatological record [7].

The model was developed to be applied at field plot scales; however, many improvements have been made to the model to make it applicable at watershed scales of several thousand hectares [35,36]. Several researchers also improved DRAINMOD to fit more applications and field conditions (e.g., wetlands, snowy conditions, predictions of nitrogen (N) losses in the drainage flux, soil salinity affected by drainage strategies and irrigation management, and so on) [37–41]. More detailed information about the DRAINMOD model theory, description, and calculation sequence is available in Skaggs et al. [7].

In this review, we focus on the DRAINMOD model's applications to assess how agricultural drainage strategies impact the hydrology and water distribution patterns in agricultural lands. Table 1 summarizes the input parameters necessary to set up and run the model for hydrology simulations. Among these inputs, we discuss the effect of parameters related to the design layout of subsurface drainage systems on DRAINMOD hydrology outputs and the predicted water distribution pattern in agricultural lands. The table also lists the hydrology outputs of the model, which are represented by some parameters determining the water fate in agricultural lands.

Globally, the DRAINMOD model has been applied to manage farmlands' water balances from different aspects. For example, among others, the model was applied to assess how the spacing between drainpipes impacts crop yield and the water fate in agricultural lands [42–44]. Other researchers applied DRAINMOD to assess the impact of the drain depth on many farmlands' outcomes (including profitability and hydrology, salinity mitigation, and nitrate-N losses) [43,45–48]. The model is a vital tool that helps to decide the best drainage plans and irrigation schemes in agricultural lands [49]; many researchers have

applied DRAINMOD to assess the impacts of different drainage practices (e.g., controlled drainage [50–52]) and irrigation management techniques (e.g., subirrigation [53–55]) on farmlands' hydrology and crop yields.

Table 1. DRAINMOD inputs and outputs related to farmland water balance.

	Input Parameters		Outputs
Related to weather data	(1) Daily or hourly precipitation. (2) Daily maximum and minimum temperatures. (3) Daily evapotranspiration (users have the option to input it or calculated it in the model)		
Related to drainage system data	Design layout	(1) Installation depth of drainpipes. (2) Spacing between drainpipes. (3) Distance from the soil surface to the impermeable layer. (4) Drainage coefficient. (5) Initial depth to groundwater table. (6) Surface depression capacity.	• Daily, monthly, or yearly drainage. • Daily, monthly, or yearly evapotranspiration. • Daily depths to groundwater tables. • Daily, monthly, or yearly runoff.
	In case of controlled drainage	(1) Ditch's bottom depth. (2) Ditch's side slope. (3) The adopted scheme of controlled drainage practices.	
Other field conditions	Details of vertical and lateral seepage (if existing).		
Related to soil data	(1) Soil water characteristic curve. (2) Infiltration parameters. (3) Lateral saturated hydraulic conductivity.		
Related to crop data	Rooting depth of cultivated crops during different periods in the growing season.		

3.1. Subsurface Drainage Design Parameters: Determinants of Water Distribution Patterns in Agricultural Lands

Before discussing the role of subsurface drainage design parameters in determining the pattern of water distribution in farmland, we first recognize the relation between the different water fate patterns and how they impact each other. This will provide more understanding when assessing the impact of a certain subsurface drainage design parameter on the whole water fate. Figure 13 shows a simple illustration of the relationship between three of the most important outputs of the DRAINMOD model (drainage, runoff, and infiltration). Based on these outputs, the overall behavior of the water fate on the land can be recognized. The relation between drainage, runoff, and infiltration is represented as a seesaw that comprises two scenarios as follows (Figure 13):

- Scenario 1 represents the changes (in the design layout of the subsurface drainage system) that will increase the drainage flux. Under this scenario, the groundwater table drops rapidly, allowing more water on the land surface to percolate into the soil. This reduces excess water accumulation on the land surface, thus mitigating runoff. Therefore, properly designed subsurface drainage systems are a very common tool to mitigate high runoff rates [25,56].
- Scenario 2, in contrast to scenario 1, represents conditions in which drainage flux decreases (e.g., in poorly drained lands). This decreases infiltration rates as the soil is near/fully saturated. As a result, more water accumulates on the land surface, which increases the possibility of runoff when this excess water exceeds the depression capacity of the land. Therefore, high runoff is a common problem that characterizes poorly drained lands [6].

We next discuss the effect of the drain depth, drain spacing, and surface storage capacity on the drainage flux and thus on the whole water fate in agricultural lands.

3.1.1. Effect of Drain Depth

Under conventional drainage practices, many studies reported that the intensity of the drainage flux is proportional to the depth of drainpipes' installation. Therefore, increasing the drain depth increases the drainage flux [38–40] (as shown in scenario 1—Figure 13). In terms of the soil, increasing the drain depth will cause groundwater tables to drop

relatively rapidly, which increases the depth of unsaturated soil. This allows more gas exchange between soil and air, thus providing better conditions for crops that have deeper roots to grow optimally. In terms of the environment, increasing the drain depth mitigates runoff, but it is supposed to have high drainage fluxes, and that threatens the quality of adjacent water bodies that receive the drainage flux, as may it contain high concentrations of dissolved fertilizers and other sediments [57–59].
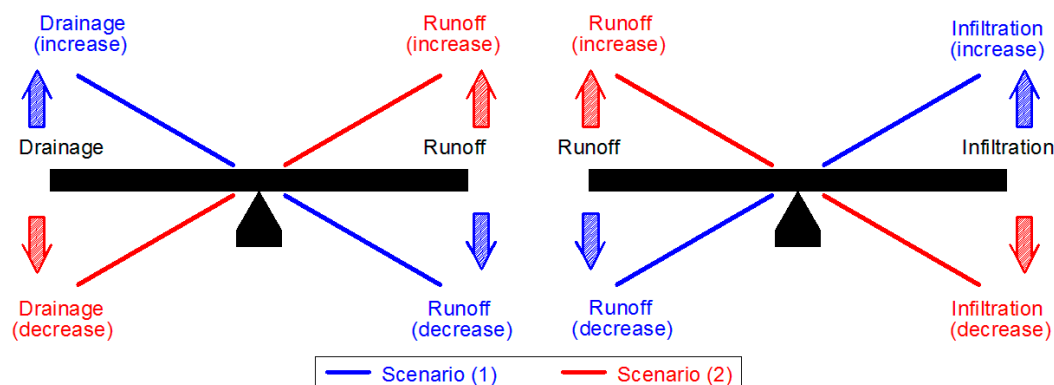

Figure 13. The balance between the different water distribution patterns in agricultural lands.

In contrast, shallow drainpipes result in a low drainage flux (scenario 2—Figure 13). Under such a condition, if there are intense rainfall or irrigation events and the land's depression capacity is low, there is an increasing possibility of having high runoff rates. This, in turn, harms many of the surrounding public properties and exposes lands to the threat of erosion [60]. On the other hand, such shallow drainpipes allow groundwater tables to rise, which is useful for some crops that grow optimally under saturation or near-saturation soil conditions.

3.1.2. Effect of Drain Spacing

At the same drain depths, the drainage flux intensity is reported to be inversely proportional to the spacing between drainpipes. Narrow spacing between drainpipes will result in higher drainage fluxes (scenario 1—Figure 13), compared to drainage fluxes from drainpipes installed with larger spacings [58,59,61].

3.1.3. Effect of Surface Depression Capacity
What Is a Land Depression?

In geology, the term "depression" refers to a landform that is sunken or depressed below the surrounding area [62]. During precipitation events, rainwater that falls in these depressions is retained and cannot run off to adjacent spots. Figure 14 shows an example of depressed areas (marked by the red line), where water is retained.
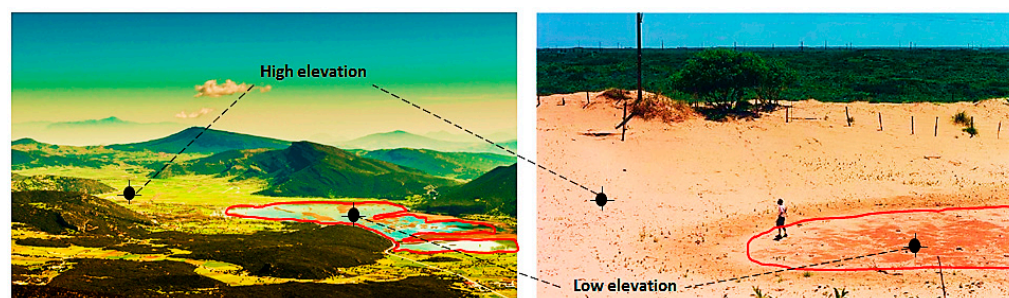

Figure 14. Examples of depressed lands.

Surface Depression in Agricultural Lands and Its Effect on Water Distribution Patterns

Surface depression in agricultural lands can be represented by the volume of water per unit area that can be retained in depression zones on the soil surface before runoff begins.

Therefore, as shown in Figure 15, semi-flat lands have a low depression capacity compared to meandering ones that can retain significant amounts of water before runoff begins.
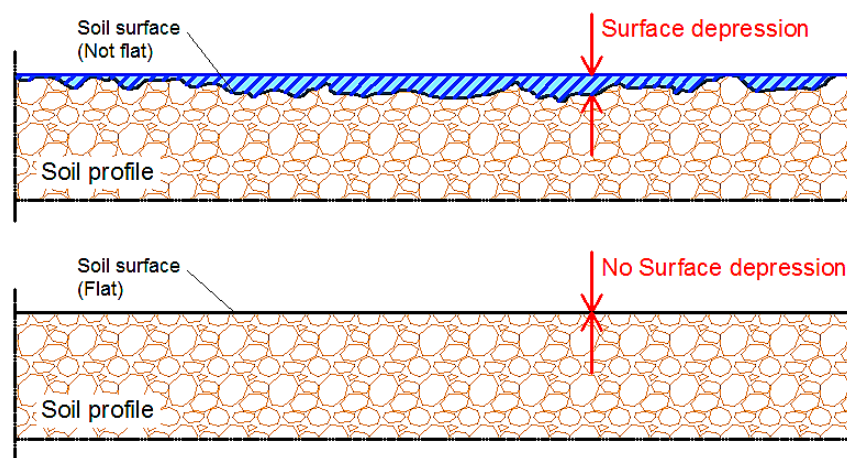

Figure 15. Examples of depressed land.

During rainfall or irrigation events, water accumulates on the land surface in depression zones. Then, this water starts to infiltrate into the soil. However, if the soil has low permeability or is saturated, the retained water accumulates more on the land surface. When the amount of this accumulated water exceeds the surface depression capacity of the land, runoff occurs. Therefore, the surface depression capacity is a very sensitive parameter when simulating the water cycle, as it is a major determinant of when runoff starts.

The lifetime of subsurface drainage systems is supposed to be very long (sometimes more than 30 years) because it is very costly to change their layouts after installation. Some parameters, such as the drain depth and spacing, are not subject to change due to human activities; however, some other parameters, such as the surface depression capacity, may increase/decrease due to human or agricultural activities. Paddy lands represent a good example of cases where the surface depression capacity is not constant and varies, even during the same growing season, due to the adopted agricultural practices, as follows.

Providing large amounts of water in paddy lands is necessary to raise groundwater tables to allow the rice to grow optimally. However, during some growing season periods, it is preferable to lower groundwater tables to suppress excessive tillering, encourage root growth, and enhance land accessibility. Such a practice is known as "mid-summer drainage". To achieve this, farmers remove barriers around the farmland and smooth its surface to allow stagnant water on the land surface to run off, thus preventing the accumulation of excess water (Figure 16). Such a practice can convert the land surface into a semi-flat one, thus changing (decreasing) the surface depression capacity of the land (Figure 15).
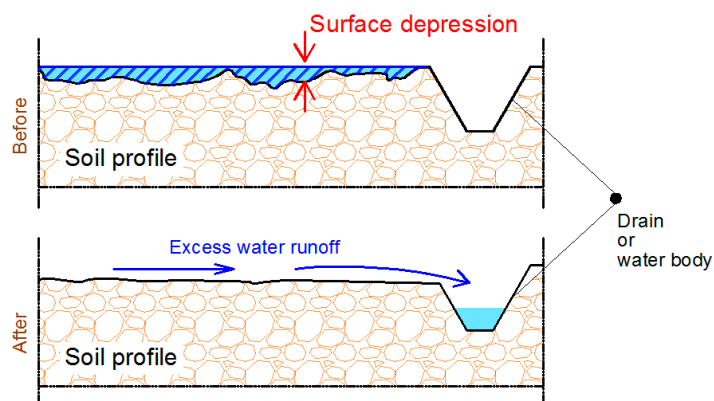

Figure 16. Changes in land's surface depression capacity before and after "Mid-summer drainage" practices.

Based on the above discussion about the critical role of the surface depression capacity in shaping the whole water fate (Section 3.1.3.) in farmlands, any changes in this capacity may result in new water distribution patterns.

In the DRAINMOD model, the surface depression capacity is input as a fixed value for the whole simulation period, and there is no option in the model to change it during the growing season. This could cause the model to produce improper predictions of the farmland water balance during the periods of mid-summer drainage practices (when the surface depression capacity varies due to agricultural practices). To assess such a problem, we review the results of the study conducted by Awad et al. [15], who applied the DRAINMOD model to predict the water fate in a paddy area that has mid-summer drainage practices. We aim to focus on the period during which the surface depression capacity changes. This is to assess the model's performance during this period and to evaluate whether or not it is necessary to modify the DRAINMOD model to consider changes in the surface depression capacity during the simulation period.

4. Evaluating the Performance of the DRAINMOD Model under Time-Variable Surface Depression Capacities

Awad et al. [15] applied the DRAINMOD model to assess its performance in predicting the water fate in a 6-hectare artificially drained paddy area located at the lower reaches of the Yangtze River, China (Figure 17). Mid-summer drainage practices are common in the study area, so it is a good choice to assess the impact of neglecting changes in the surface depression capacity on DRAINMOD outputs.
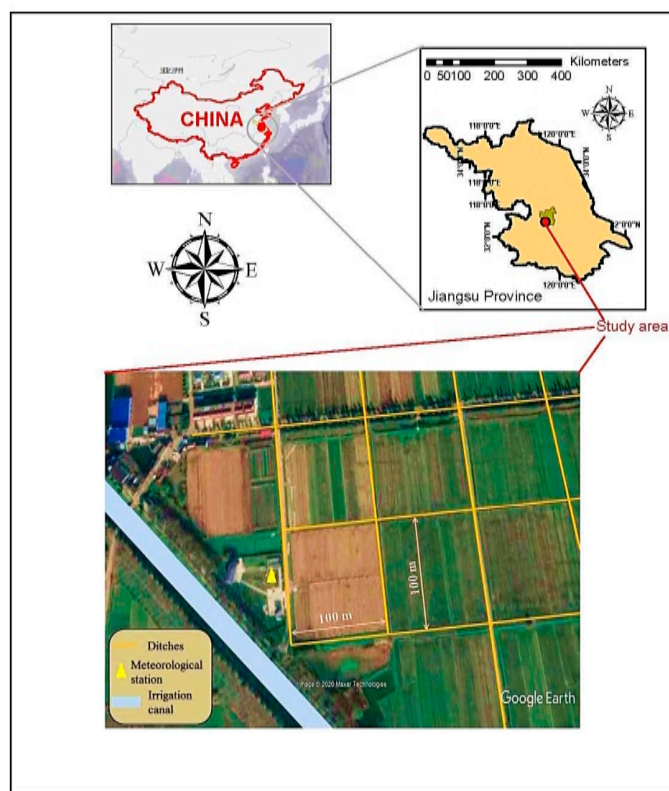

Figure 17. Changes in land's surface depression capacity before and after "Mid-summer".

The study area has a subsurface drainage system that comprises a set of buried drainpipes and some open ditches spaced at 100 m intervals. More information about field data and conditions in the study area are available in Awad et al. [15].

4.1. Mid-Summer Drainage Practices in the Study Area

Every July, farmers in the study area practice "mid-summer drainage" activities to achieve the desired field and crop conditions. As mentioned above, this results in changes (decreases) in the surface depression capacity of the land.

4.2. The DRAINMOD Performance in Predicting the Water Distribution Pattern in the Study Area

Figure 18 based on the reported simulation results [15], the overall performance of the DRAINMOD model is acceptable. The model performed well in predicting the depths of the water table in the study area, and some indicators (including the coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS) [63]) were used to evaluate the degree of agreement between observed and simulated groundwater tables:

- R^2 = 0.89, NSE = 0.84, and PBIAS = −3.7% → for calibration;
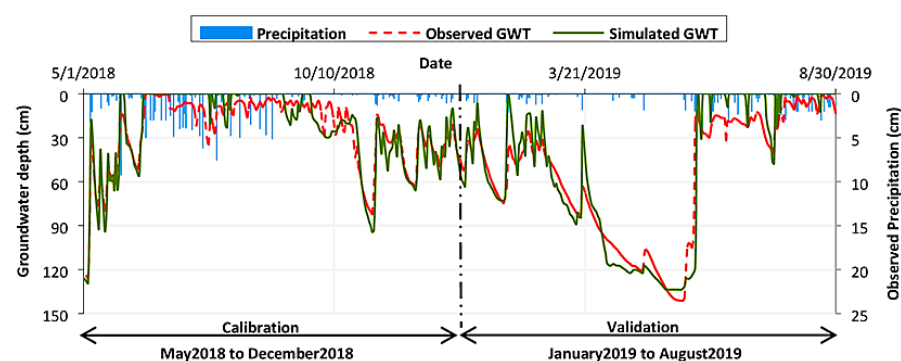- R^2 = 0.93, NSE = 0.89, and PBIAS = −6.5% → for validation.

Figure 18. Performance of the DRAINMOD model in predicting groundwater tables in the study area [15].

The overall performance of the model is good. However, during the period in which the surface depression capacity changes, the model predicts a water fate that is different from reality (Figure 19). During this period, there is a remarkable gap between observed and predicted groundwater tables (Figure 19). This gap occurs because of the following:

- Since the surface depression capacity is input into the DRAINMOD model as a fixed value for the whole simulation period, the model is not able to consider any changes in the surface depression capacity resulting from mid-summer drainage practices. As a result, the model considers that the excess water will continue to exist and accumulate on the land surface (despite the fact that this water will run off, in reality, due to mid-summer drainage practices). The model then considers this water to infiltrate into the soil profile and raise groundwater tables. However, in reality, during mid-summer drainage practices, there is mostly less/no water accumulated on the land surface, which decreases infiltration and thus lowers groundwater tables. This explains the remarkable gap between observed and simulated groundwater tables (Figure 19).
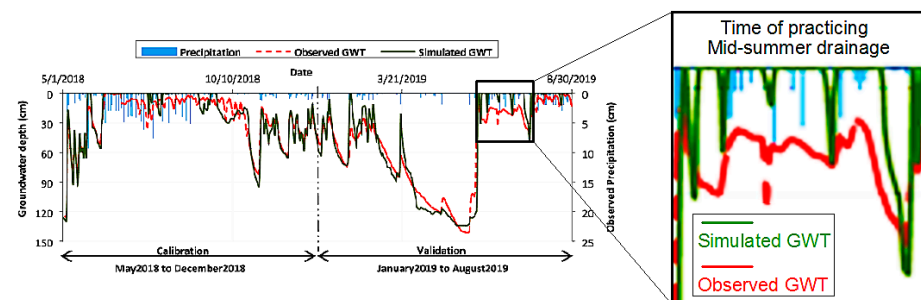

Figure 19. Effect of neglecting changes in surface depression capacity in the DRAINMOD model on the model's efficiency.

Based on the aforesaid factors, the fixed input value of the surface depression capacity in the DRAINMOD model resulted in predicting a water fate that is different from reality. Since the model is a well-known tool that is used to predict the nitrogen (N) dynamics and turnover in the soil–water–plant system in agricultural lands, such a shortcoming in predicting the real water fate (when the surface depression capacity changes) may adversely impact the model's efficiency in predicting the actual N-fate.

5. Conclusions

Having the proper agricultural drainage strategies has become indispensable in irrigated farmlands to mitigate excess-water hazards on crop yields while ensuring better conditions for the surrounding environment and water bodies. Besides the presented overview in this paper of these strategies and the assessment of their performance using the DRAINMOD model, we reported an important drawback of the model, represented by its inability to consider changes in the surface depression capacity (SDC) when simulating farmlands' water balances. Such a drawback causes the model to predict unrealistic water distribution patterns in farmlands characterized by time-variable SDC, which consequently also adversely affects the model's outputs related to the fate of nitrogen and phosphorus in farmlands. Researchers must pay attention when applying the DRAINMOD model to manage agricultural water in farmlands characterized by time-variable SDC.

6. Recommendations for Future Research Work

Considering that many decision-makers rely on the DRAINMOD model's outputs to decide on appropriate management strategies for the agricultural process, we recommend improving the model's input module to allow users to input the "surface depression capacity" as a time-variable value. This ensures accurate outputs from the model and thus better management of agricultural water and high agricultural productivity.

The authors also recommend expanding the applicability of DRAINMOD modules (e.g., wastewater application management and urban modeling) for better management of agricultural water and water resources as a whole.

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