




Review

Dripping Rainfall Simulators for Soil Research— Design Review

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Abstract: Dripping rainfall simulators are important instruments in soil research. However, a large number of non-standardized simulators have been developed, making it difficult to combine and compare the results of different studies in which they were used. To overcome this problem, it is necessary to become familiar with the design and performances of the current rainfall simulators. A search has been conducted for scientific papers describing dripping rainfall simulators (DRS) and papers that are thematically related to the soil research using DRS. Simulator design analysis was performed integrally, for simulators with more than one dripper (DRS_{>1}) and with one dripper (DRS₌₁). Descriptive and numerical data were extracted from the papers and sorted by proposed categories, according to which the types and subtypes of used simulators are determined. The six groups of elements that simulators could consist of have been determined, as well their characteristics, representation and statistical analyses of the available numerical parameters. The characteristics of simulators are analyzed and presented, facilitating the selection of simulators for future research. Description of future simulators in accordance to the basic groups of simulator elements should provide all data necessary for their easier replication and provide a step closer to the reduction of design diversification and standardization of rainfall simulators intended for soil research.

Keywords: dripping rainfall simulator; drippers; rainfall simulators review; soil research; rainfall simulator construction



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1. Introduction

Simulation of rainfall is often a necessary and unavoidable part of experimental soil research, both in laboratory conditions and in the field [1–5]. The advantage of research using rainfall simulators is that it is possible to generate precipitation when, where and how much we want. This is especially important for research in arid areas where rainy events are rare, saving time and money. On the other hand, there are some difficulties in simulations, such as the limited size of the wetted surface, the difference in the size distribution of raindrops and the kinetic energy of simulated and natural precipitation [6–10].

Rainfall simulators are used in wide specter of mutually related research as are hydrology, soil erosion, runoff, infiltration, evaporation, chemical transport, aggregate stability etc. so the same simulators could suits to different research requirements. In an attempt to make a rainfall simulator that would closely mimic natural precipitation and meet the requirements of specific methods of research, different types of simulators have been developed and they can be divided into simulators that generate drops in a processes of spraying [11–16] and dripping [5,17–19]. Dripping rainfall simulators have very little head pressure associated with their creation and gravity is the main force for its acceleration. Whereas spraying rainfall simulators use pressure heads and nozzles to create raindrops and typically throw the drops outwards upwards or downwards, creating nonlinear drop

paths. According to [20], dripping rainfall simulators are used in about 20% of the total number of rainfall simulation experiments. In addition to these two basic groups of simulators, there is a group of simulators that generate drops by the combined action of the mentioned processes, created in an attempt to compensate for the shortcomings of simulators from the two previously mentioned groups or as a consequence of specific research methodology [8,21–26].

The design of rainfall simulators is based on the requirements of future and the analysis of previous scientific research during which rainfall simulators were applied and/or described, available resources and personal ideas of researchers. Accordingly, different criteria are given on the basis of which the simulators are designed [7,17,27–32].

Parr & Bertrand (1960), Mutchler & Hermsmeier (1965), Yakubu & Yusop, (2017), Ngasoh et al., (2020) [33–36] classified rainfall simulators. A description of their design and individual performances or a description of the basic groups to which they belong were obtained. Also, [37,38] conducted an exhaustive inventory of rainfall simulators, presented the historical development of simulators, the basic features of classification groups and individual factors of design and performance of simulators. However, a detailed design analysis and a comparative analysis of individual simulator design elements are lacking.

The aim of this review is to provide information needed for adequate design of future rainfall simulators and implementation of research under identical conditions of simulated precipitation. The analysis of technical specifications of elements of non-standardized simulators will also provide the necessary data for their development and reduce diversification of design of future simulators, used in soil research. Given the scope of the task, this scientific paper will analyze the design of rainfall simulators with drippers, which generate primary drops exclusively by drippers, together with a group of simulators that generate drops by the combined processes of spraying and dripping.

2. Materials and Methods

Internet research databases Research Gate, Google Scholar, KoBSON, COBISS, Academia.edu, JSTOR and Scopus were used in the research. A search has been conducted for available scientific papers describing dripping rainfall simulators (DRS), generating drip in a process of dripping and papers covering a wide range of thematically related to the soil research using DRS from 1941 to the present. The analysis includes the design of simulators that generate primary drops exclusively by drippers and those that generate drops by the combined action of spraying and dripping processes, with data on elements of their design that differ from DRS excluded from the analysis.

Simulator design analysis was performed integrally, for simulators with more than one dripper ($DRS_{>1}$) and with one dripper ($DRS_{=1}$), through determination of different elements that can make one DRS simulator, their frequency of application and statistical analysis of their numerical parameters.

In order to facilitate the analysis of DRS design, descriptive and numerical data were derived from the articles, sorted by categories for each type and subtype of simulator, as follows:

- general data: year of publication, author and title of the scientific paper in which the simulator was applied or described, simulator type designation,
- structural support: role, conditions in which it is placed (laboratory or field), existence of wind protection, portability, shape of elements, material of which the structural support elements are made, type of support, number of support points, height at which the water tank with drippers is placed, existence and type of water tank with drippers levelling system,
- water tank: role, shape, form, material of which it is made, position in relation to other elements of the simulator, volume,
- water moving mechanism: type,

- mechanism of water flow regulation and simulator operation: type, existence of oscillations of water tank with drippers, type of measuring equipment, position of measuring equipment,
- water tank with drippers: type, shape, material of which it is made, dimensions, modularity, type of its connection with drippers, number of drippers, distance between drippers,
- drippers: designation of the type and subtype, diameter.

Determining the types and subtypes of simulators is the basis for analysis. The type of simulator is determined on the basis of a complete or partial description of the design elements or performance factors of the simulator, which appear for the first time in the scientific literature. The simulator subtype was determined based on the similarities with certain type of simulator and determined simulator type modification. The design types of simulators are made up of the capital letter of the first author's last name and the year of publication of the paper in which some of the simulators are listed for the first time (example: K-1974). If the beginning of the author's surname and the year of publication of the papers with different simulators coincide, more capital letters in the type designation are added until a difference is established (example: RI-1985). To the simulator types that has a one or more simulator subtypes is adding a lowercase letter "a" (example: A-1957 a). The lowercase letters that come next are added in alphabetical order after the year and indicate the order of occurrence of the subtypes (example: A-1981 c). Since not all types or subtypes of the simulator had all the data available according to the selected categories, an independent comparative analysis of the available data within the categories was conducted.

The collected data were classified, analyzed statistically and presented using the software packages LibreOffice and IBM SPSS Statistics 20.

3. Results and Discussion

Out of a total of 188 scientific papers included in the analysis, 51 different types and 27 subtypes of $DRS_{>1}$ were singled out in 149 papers (Table 1), and in the remaining 39 papers as many as 25 different types 4 subtypes of $DRS_{=1}$ (Table 2), so it can be noticed that rainfall simulators $DRS_{>1}$ are almost four times more represented than $DRS_{=1}$.

DRS is an apparatus that can consist of several elements, namely:

- structural support,
- water tank,
- water moving mechanism,
- mechanism of water flow regulation and simulator operation
- water tank with drippers and
- drippers.

3.1. Structural Support

The primary role of the structural support is to enable the installation of water tank with drippers in the appropriate position and height. In addition to this, the structural support can also support the hydraulic water supply tank [39,40], wind protection in the form of a curtain [41–43] or pipes [28,44–47], water supply hoses, various measuring equipment and accessories. It can be made of metal, plastic or wooden profiles, beams, slabs, pipes, cables and chains of different dimensions [4,8,19,29,40,48–53]. The structural support can rest on a surface, over legs whose ends can be pointed or over plates of different dimensions. It can also be attached to the wall or ceiling of a room (Figure 1a) or off-road vehicle (Figure 1b). The water tank with drippers can be supported or hung from the bracket, where, if the tank hangs, the connection between the structural support and the tank it can be rigid or loose [18,23,49,54–58].

The structural support usually rests over the 4 legs placed vertically or at an angle with the possibility of levelling the water tank with drippers (Figure 1c), interconnected with cables, braces and horizontal prismatic elements to increase stability and strength of

the structure [22,50,59]. The 3-leg structural supports (Figure 1d) are usually placed at an angle, connected at the ends by a ring, which allows easy height adjustment of water tank with drippers [18,28,39,45–47,60,61].

The structural support can also occur in the form of a vertically placed pipe carrying (Figure 1e) or passing through a water tank with drippers attached to it [62,63] (Figure 1f). The support must be rigid enough to prevent unwanted oscillations of the water tank with drippers during the simulation. Field simulators usually have a structural support that is portable and collapsible [29,40,46,50], which makes it easier for researchers to work. Another distinction between field and laboratory simulators is the windshield, although its presence in laboratory conditions does not necessarily exclude it. However, there is very little data available about windshield presence when it comes to DRS.

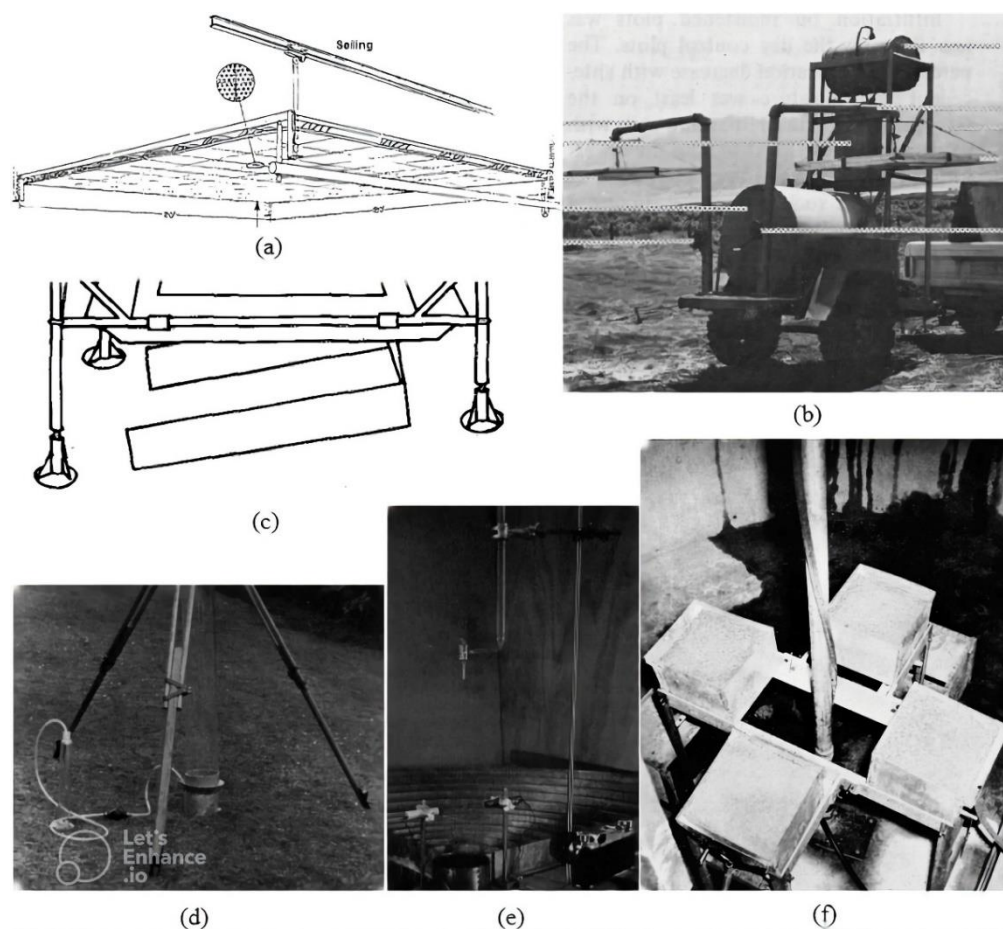


Figure 1. Six examples of simulators structural support: (a) Structural support attached to the laboratory ceiling [54] (Reprinted/adapted with permission from Ref. [Israelsen et al., 1979]); (b) Structural support attached to an off-road vehicle [64] (Reprinted/adapted with permission from Ref. [Epstein & Grant, 1966]); (c) Four-legged simulator support [50] (Reprinted/adapted with permission from Ref. [Munn & Huntington, 1976]); (d) Three-legged simulator support [39] (Reprinted/adapted with permission from Ref. [Tricker, 1979]); (e) Structural support of DRS₌₁ [65] (Reprinted/adapted with permission from Ref. [Riezebos & Epema]); (f) Structural support in the form of a rotating vertical pipe [63] (Reprinted/adapted with permission from Ref. [Blackburn et al., 1974]).

Depending on the height of the structural support, i.e., the height at which the water tank with drippers can be placed, the drops of simulated rain can reach a certain percentage of the terminal fall velocity [9]. Most often, the heights are up to 2 m. The number of simulations with a drop height over 2 m gradually decreases to a height of 5 m. The number of simulations with drop heights over 5 m is relatively uniform, while the highest recorded drop height is 14 m (Figure 2).

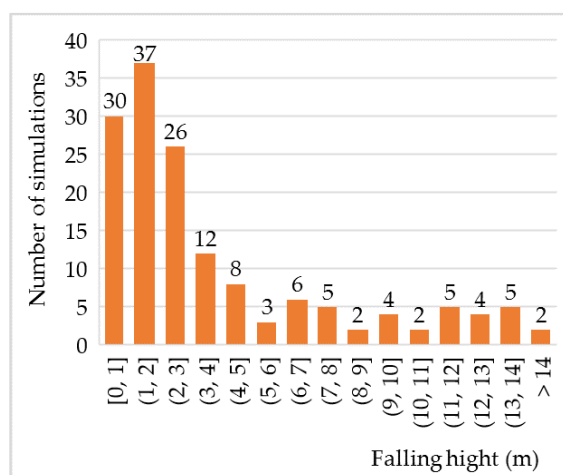


Figure 2. Number of conducted simulations at different drops falling heights. Note: data whose values are given in ranges in analysed papers are not included in the analysis.

3.2. Water Tank

The water tank provides the water for the water tank with drippers (Section 3.5) [61,66,67] and sometimes there is only one tank with dual function [68–71]. It is usually cylindrical or rectangular shape, made of plastic (Plexiglas or clirit) or metal (aluminium, stainless steel or brass), open or closed, with a volume of several liters to several thousand liters. It could be placed on the ground, structural support, specially made structural support or off-road vehicle, in close proximity to other simulator elements [29,49,51,54,61,72]. The amount of water in the tank is finite or conditionally infinite in the case when the tank is constantly replenished with water.

3.3. Water Moving Mechanism

The water moving mechanism can be water or air pumps, the mechanism of gravitational movement of water [28,69] or specific mechanisms [73] (Table 1). Pumps could be powered with electric motor supply from the electric mains, power generators [61,74] or batteries [19,49] and internal combustion engine [16]. It has been noticed that peristaltic water pumps are very often used during simulations. Pumps with internal combustion and gravitational movement of water from the tank are more suitable for field use than electric pumps due to lower power requirements [10,16,29,52,58,61,67,75,76]). The mechanism of gravitational movement of water involves establishing water levels above the drippers level, which is gradually released through the drippers while reducing the water level in the water tank with drippers [8,43,77]. There are also specific types of water-starting mechanisms, such as a battery of water-filled syringes, whose pistons are gradually moved by a special mechanism and push water through the opening at the end [73].

3.4. Mechanism of Water Flow Regulation and Simulator Operation

Regulation of water flow can be done through the mechanism of water moving in the form of pumps and specific mechanisms [73,78] (Figure 3a–c), by gravitational movement of water according to the Mariotte’s bottle principle [50] (Figure 3e), using pipe or hose systems, valves and fittings [16] (Figure 3d) or by changing the number, type and size of drippers [40,56,79,80], where the regulation of the entire hydraulic system could be analogue or digital [54,76,81].

Some pumps have the ability to regulate the power of their work, which can directly regulate the flow of water in closed and open hydraulic systems [52,58,61,76]. On the other hand, the flow in open box water tank with drippers can be maintained by adjusting the height of the water column through the opening on the side of the tank or reaching their maximum height after which water overflows [62] (Figure 3a,b).

If a simulator with one dripper is used with a large enough surface of the tank and a constant inflow of water is not necessary, then it is possible to ignore the change in water level that occurs due to drip consumption for a certain amount of water consumed.

Regulation of the flow of specific mechanisms depends on the intensity of the water movement mechanism work [73] (Figure 3c).

The principle of operation of the Mariotte’s bottle enables uniform release of water regardless of the level in the water tank or in the water tank with drippers. By changing the height at which the tube of the Mariotte’s bottle or the bottle itself relative to the drippers is located, the pressure and flow of water can be regulated [80]. Since this mechanism of regulating the flow of the water involves storing the final amount of water at a certain height, above the drippers, the amount of water available for an individual simulation is relatively small. However, it is possible to use several smaller water tanks, which would be alternately filled and emptied, thus overcoming the problem of limited simulation duration [8,40,43] (Figure 3e).

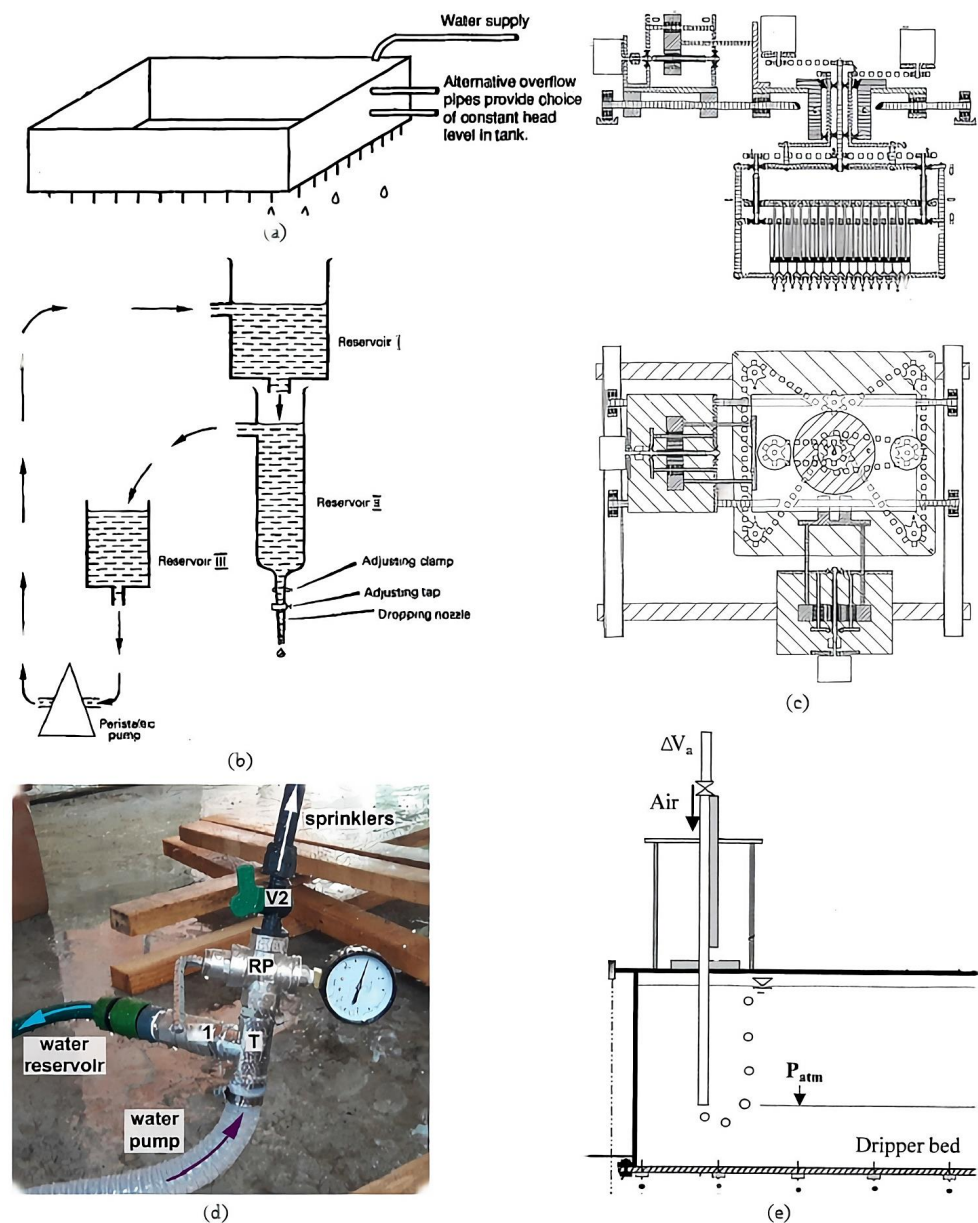


Figure 3. Different water flow regulating mechanisms: (a) Pump flow control and water level maintenance in the water tank with drippers [82] (Reprinted/adapted with permission from

Ref. [Terry & Shakesby, 1993]); (b) Flow control by pump, maintenance of water level in the water tank with drippers and adjustable valves [83] (Reprinted/adapted with permission from Ref. [Cousen & Farres, 1984]); (c) Specific mechanism of flow control and simulator operation [73] (Reprinted/adapted with permission from Ref. [Römkens et al., 1975]); (d) Mechanism in the form of hose system with valves and fittings [16]; (e) The mechanism of gravitational motion of water according to the principle of a Marriott bottle [80] (Reprinted/adapted with permission from Ref. [Regmi & Thompson, 2000]).

All elements of the hydraulic system of the rainfall simulator are connected by a system of pipes and hoses of different diameters, connectors, valves, extensions, reducing diameters, forked and T connectors and rails, thus forming a complete system. Flow control can be done directly by means of a T-pipe or hose system by directing the water into the water tank with drippers with one arm, in the path of which there is a flow control valve, and the other arm returns to the water tank [8,16,18,42,84].

The size of the generated drops and the flow of water in the hydraulic system are dominantly regulated by the number, size of the opening and the length of the drippers, as well as by the type of drippers. The larger the diameter of the drippers in the form of a tube is, the lower flow resistance is considerably, providing greater flexibility in applying a wide range of intensities for a small change in pressure [40,80]. When regulating the flow and the operation of the simulator in general, it is important to point out some difficulties that may arise, especially in terms of proper operation of the drippers. The use of thread drippers (see Section 3.6. Drippers) involves the use of simulators with high water consumption, which also makes it difficult to regulate the intensity of precipitation [50]. The main problem that occurs with simulators with tube drippers is the uniformity of the operation of the drippers due to their clogging with dirt or air bubbles.

Clogging of needles with dirt can be prevented to some extent by using distilled water or filters [18], while clogged needles can be cleaned with a smaller needle [85]. The release of needles from air bubbles can be carried out by applying a vacuum to the needle with a hypodermal needle syringe [81] or a higher water or air pressure can be applied for a short period of time [40].

Filling of box tanks water tank with drippers can be done by immersing the tank in water or turning it on its back and pumping water and then returning it to its original position [42]. Also, filling can be carried out by applying a vacuum in a box tank with simultaneous filling with water, which prevents dripping and the appearance of bubbles in the caps during filling [81]. Flow control can be performed by simultaneously regulating the water and air pressure in the water tank with drippers [1] (Figure 4a).

Depending on the design of the structural support, it is possible to change the position of the water tank with drippers, along the vertical axis [29,85] in order to regulate the kinetic energy of precipitation. Also it is noticed a horizontal repositioning in order to equalize the spatial distribution of drops, in the horizontal plane by circular [69,86] or translational motion [58,87,88] (Figure 4b,c). Also, some simulators have vibration motors mounted on a water tank with drippers, which increase the spatial uniformity of precipitation [59].

Hydraulic and pneumatic pressure or hydraulic flow meters are important elements of rainfall simulators [41,48,87,89] which are regulated by flow control mechanisms, so that the regulation of the hydraulic system of the simulator is done in accordance with their measurement data [16,18,90]. Pressure gauges come in the form of manometers or Venturi tubes with measuring scale and can be digital or analogous as flow gauges [8,58] (Figure 4b,d). Water pressure and flow are closely related, so the appropriate water flow can be determined on the basis of pressure measurements, by calibrating the simulator. Meters are usually placed between the water tank and the water tank with drippers, or are attached directly to the water tank with drippers [1,48,58] (Figure 4e,f).

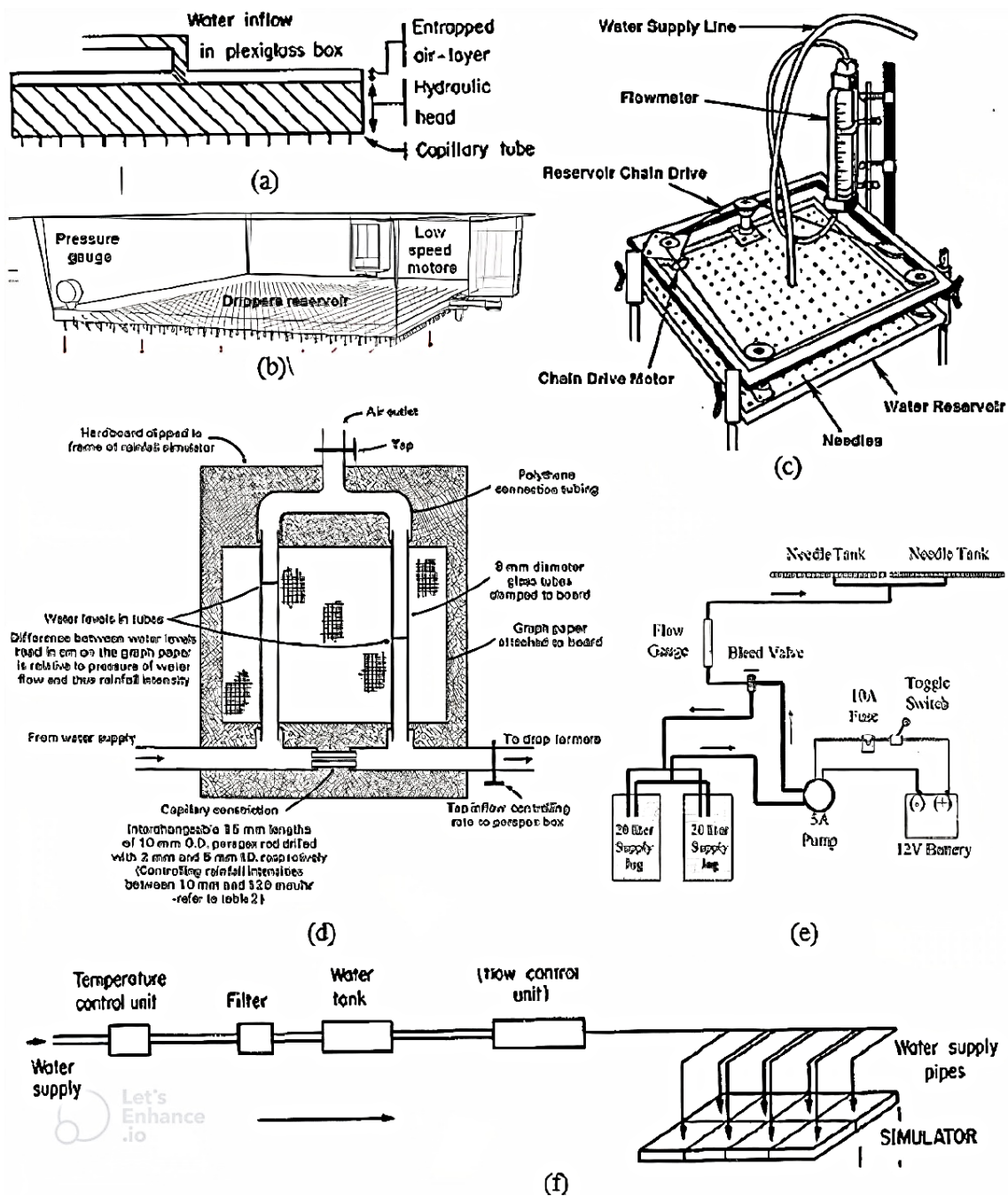


Figure 4. Different mechanisms of simulator operation: (a) Air and water medium inside the water tank with drippers [1] (Reprinted/adapted with permission from Ref. [Riezebos & Seyhan, 1977]); (b) Low speed motors rotating mechanism of drippers reservoir with pressure gauge [58] (Reprinted/adapted with permission from Ref. [Wang et al., 2018]); (c) DRS_{>1} with flow meter and water tank with drippers rotation mechanism [87] (Reprinted/adapted with permission from Ref. [Guerrant et al., 1990]); (d) Water pressure gauge with control valves [8] (Reprinted/adapted with permission from Ref. [Bowyer & Burt, 1989]); (e,f) Schematic representation of the order of DRS_{>1} elements [1,19] (Reprinted/adapted with permission from Ref. [Riezebos & Seyhan, 1977; Battany & Grismer, 2000]).

3.5. Water Tank with Drippers

The water tank with drippers is an element of the simulator to which the drippers are attached and which directly supplies them with water. It can consist of a curtain of fabric placed on a metal mesh [91–93], interconnected system of plastic pipes or hoses [22,53,94] and boxes [46,95,96].

The fabric placed on a metal mesh at a certain distance from the surface is soaked with water from a sprayer, which will collect in the depressions of the fabric formed at the openings of the mesh, after which the water would be further transferred to the drippers in the form of hanging threads. The water tank with drippers in the form of a pipe system consists of parallel plastic pipes of round or rectangular profile, with two vertical pipes for water supply. The drippers are mounted along these pipes (Figure 5a). The water tank with drippers can also appear in the form of dendritically connected fork hoses that start from one water supply hose and end with a large number of hoses connected to the drippers, placed on a plate with holes [22] (Figure 5b). A rainfall simulator with a box water tank with drippers is most commonly used and can occur as an open or closed box [50] (more common), cylindrical (Figure 5d,g), rectangular (Figure 4a,b and Figure 5c) or complex shape (Figure 5e,f) (Table 1), made of plastic, PVC or Plexiglas. A box water tank with drippers may have an inlet through which water is delivered to it and an outlet through which air is released [18,19,61,97] (Figure 5h).

Box water tank with drippers elements can be interconnected by bonding materials, aluminium profiles or screws [51,81,98]. Teflon tape, silicone or adhesives of different composition are most often used for sealing connection hoses, meters and drippers. The drippers themselves can be glued directly to the bottom plate of the box or removed, if necessary, from a fixed adapter or with it if connected via a thread [56,80,85,99] (Figure 6a,b).

The oldest type mentioned E-1944 is a bit special: it uses a water pump, and cloth on chicken wire and the WTD box type shape is not specified. Almost all $DRS_{>1}$ after 1944. use a Box as the “Dripping Reservoir Type”, with a few exceptions. Until 1963 most WTD box type shape were cylindrical. After that rectangular is the most common type, but sometimes also cylindrical is used. The water moving mechanism often is not specified, but when it is specified it is almost always a water pump or gravity (Table 1).

Although $DRS_{=1}$ are included in the integral analysis, data on their water movement mechanism are often not given, while the shape of the water tank with drippers is excluded from the analysis since it is a single dripper, so only the types and subtypes of simulators are presented (Table 2).

In a cylindrical box water tank with drippers, box is between 0.15 and 1.37 m in diameter, while their height is up to 0.35 m [45,63,69]. The cylindrical box water tank with drippers is less common than the rectangular. Reservoirs of complex shape are usually a combination of rectangular and Cylindrical boxes, in which water moves gravitationally according to the principle of a Mariotte’s bottle [100].

The length of the long edge of the rectangular box water tank with drippers usually does not exceed 1.50 m, while the length of the largest number of simulators is in the range from 0.50 to 1.00 m. Simulators with a long edge greater than 1.50 m are only used rarely, with a maximum length of 4.00 m (Figure 7a). Most rectangular water tank with drippers are square (length/width ratio 1.0) (Figure 7b). The highest length/width ratio was 4. The height of the tank usually ranges from 20 to 30 mm and from 40 to 50 mm, while higher tanks are less often used (Figure 7c).

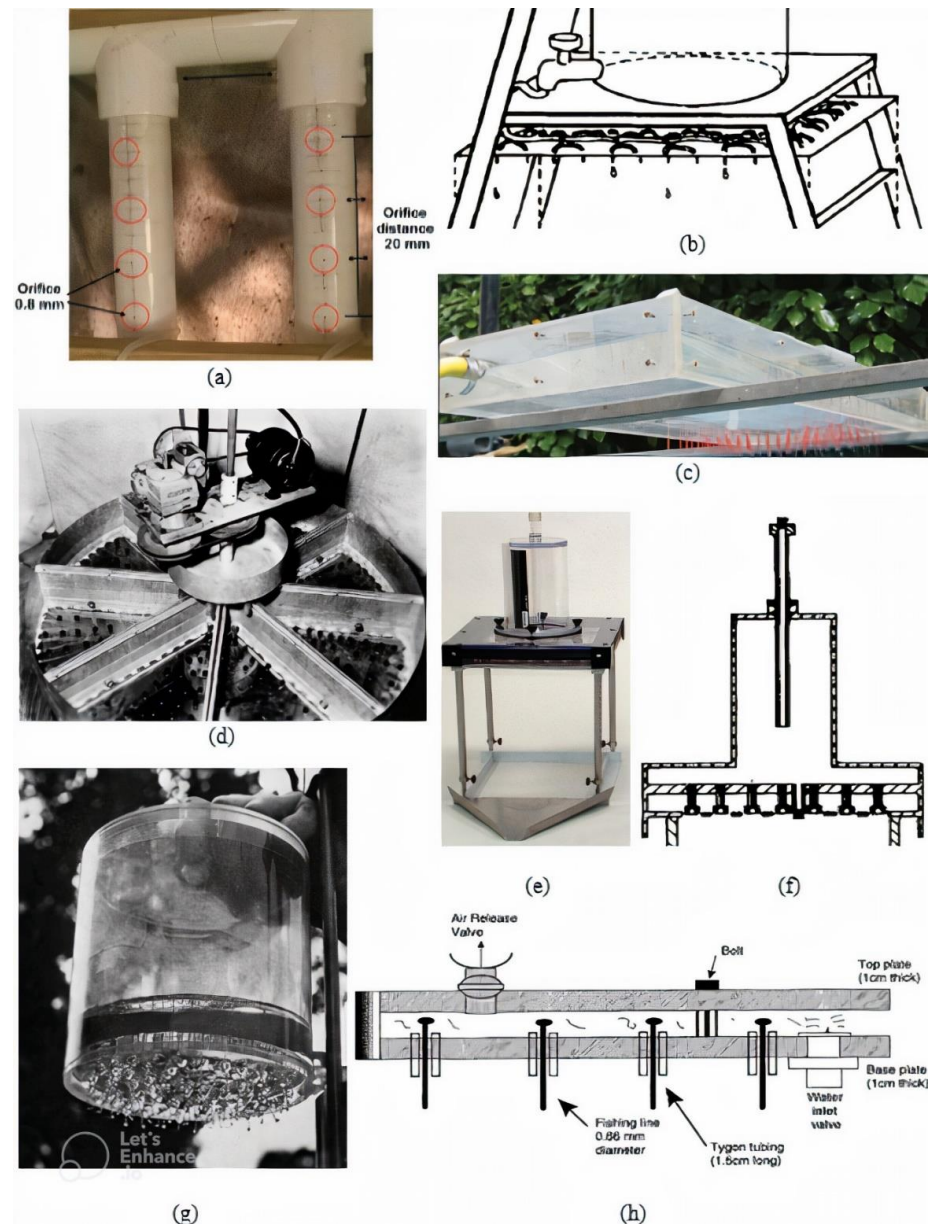


Figure 5. Different water tanks with drippers: (a) The water tank with drippers in a form of tubes [53] (Reprinted/adapted with permission from Ref. [Nampulá et al., 2016]); (b) Dendritic plastic tubes water tank with drippers [22] (Reprinted/adapted with permission from Ref. [Imeson, 1977]); (c) Closed rectangular box water tank with drippers [10] (Reprinted/adapted with permission from Ref. [Corona et al., 2013]); (d) Open cylindrical box water tank with drippers [63] (Reprinted/adapted with permission from Ref. [Blackburn et al., 1974]); (e,f) Complex box water tank with drippers [101,102] (Reprinted/adapted with permission from Ref. [Kamphorst, 1987; Eijkelkamp, 2018 (Eijkelkamp—Laboratory equipment. Available online: https://www.royaleijkelkamp.com/products/?gclid=Cj0KCQjw166aBhDEARIsAMEyZh7B0oWCwK61ruEC4Ex0SFSpnAGOWcLCIIa915RXHzgnKfzxq8rk6MMaAuh3EALw_wcB (accessed on 7 July 2018))); (g) Closed cylindrical box water tank with drippers [39] (Reprinted/adapted with permission from Ref. [Tricker, 1979]); (h) Closed rectangular box water tank with drippers with opening for air and water [60] (Reprinted/adapted with permission from Ref. [Andersen, 1999]).

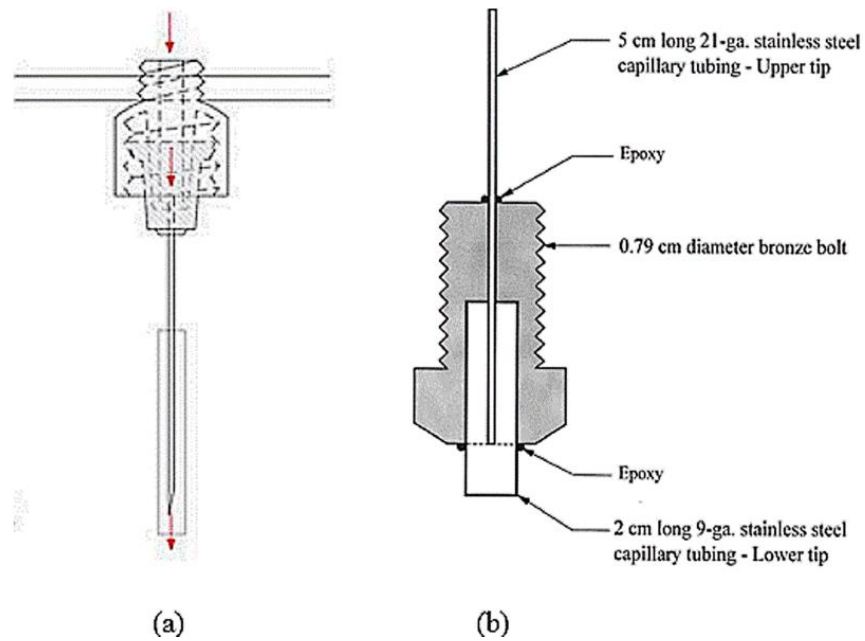


Figure 6. Drippers with threads for connection to the water tank with drippers and additional tubes for modification of their performances: (a) Metal tube dripper with plastic threaded adapter at the end and plastic tube at the other end [58] (Reprinted/adapted with permission from Ref. [Wang et al., 2018]); (b) Dripper in the form of a metal tube with a metal adapter with a thread at the end and a metal tube at the other end [80] (Reprinted/adapted with permission from Ref. [Regmi & Thompson, 2000]).

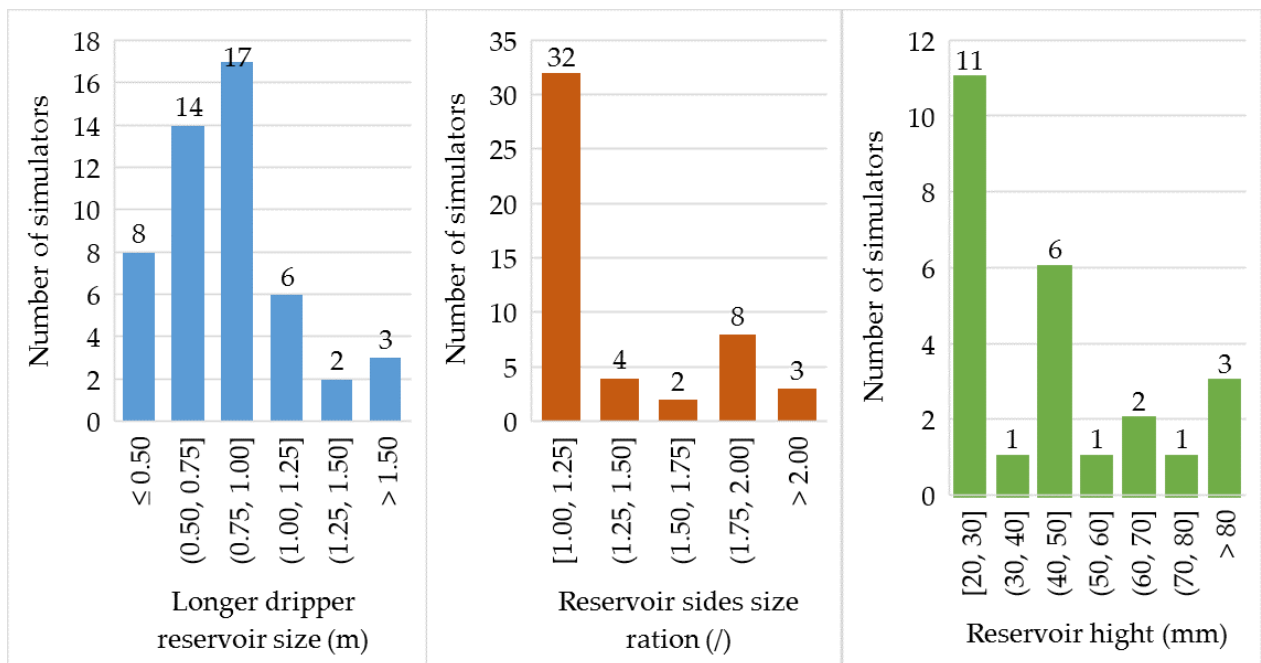


Figure 7. Rectangular box water tank with drippers size: (a) Number of different simulators of a certain size of the long side of a rectangular box water tank with drippers; (b) Number of different simulators of certain values of the ratio of the long and short; (c) Number of different simulators of certain height.

Table 1. Classification of DRS_{>1} according to water moving mechanism and water tank with drippers type and shape, with listed literature sources of papers in which simulators are described or applied (W. pump—water pump; CCW—cloth on chicken wire; Not Spec.—not specified; WTD—water tank with drippers). Note: background colours signify different groups in a classification table only to make it easier for reader to observe data.

Type or Subtype of DRS	Water Movement Mechanism	Water Tank with Drippers	WTD Box Type Shape	
E-1944 a	W. pump	CCW	/	[91,103]
E-1944 b	W. pump	CCW	/	[104]
E-1944 c	W. pump	CCW	/	[105]
E-1944 d	W. pump	CCW	/	[92]
E-1944 e	W. pump	CCW	/	[93]
E-1944 f	W. pump	CCW	/	[106]
E-1948	Gravity	Box	Complex	[107–109]
R-1953	Air pump	Box	Cylindrical	[110]
A-1957 a	Gravity	Box	Cylindrical	[111,112]
A-1957 b	Gravity	Box	Cylindrical	[28,47]
A-1957 c	Gravity	Box	Cylindrical	[113]
A-1957 d	Gravity	Box	Cylindrical	[46]
R-1960	Not Sp.	Box	Cylindrical	[79]
M-1963	W. pump	Box	Cylindrical	[62,63,114–117]
C-1965 a	Not Sp.	Box	Rectangular	[17,118]
C-1965 b	Gravity	Box	Rectangular	[18]
C-1965 c	Gravity	Box	Rectangular	[49,64,119]
C-1965 d	Gravity	Box	Rectangular	[50,120]
C-1965 e	W. pump	Box	Rectangular	[1,121–124]
C-1965 f	Gravity	Box	Rectangular	[51,87,125,126]
C-1965 g	Not Spec.	Not Spec.	Not Spec.	[127]
C-1965 h	Not Spec.	Not Spec.	Not Spec.	[128]
C-1965 i	Not Spec.	Box	Rectangular	[24,90,129]
S-1966	W. pump	Box	Rectangular	[24]
B-1971	Gravity	Box	Rectangular	[85]
W-1973 a	W. pump	Box	Rectangular	[41,130–132]
W-1973 b	W. pump	Box	Rectangular	[32,133]
W-1973 c	Not Spec.	Box	Rectangular	[134]
K-1974	W. pump	Box	Rectangular	[81,84,135–147]
D-1975 a	Not Spec.	Not Spec.	Not Spec.	[21,148,149]
D-1975 b	Gravity	Dendritic	/	[22,150]
G-1975	Not Spec.	Not Spec.	Not Spec.	[151]
R-1975	Specific	/	/	[73]
H-1976	Not Spec.	Box	Rectangular	[152,153]
W-1976	Not Spec.	Not Spec.	Not Spec.	[154]
I-1979	W. pump	Box	Rectangular	[54]
T-1979	Gravity	Box	Cylindrical	[39]
C-1984	W. pump	Tubes	/	[155]
R-1985 a	Gravity	Box	Rectangular	[40];
R-1985 b	Not Spec.	Box	Rectangular	[97,156]
T-1985	Not Spec.	Box	Cylindrical	[56]
F-1987 a	W. pump	Box	Rectangular	[23]
F-1987 b	W. pump	Box	Rectangular	[82]
K-1987 a	Gravity	Box	Complex	[96,100,101,157–160]
K-1987 b	Gravity	Box	Complex	[161]
C-1988	Gravity	Box	Rectangular	[57]
B-1989 a	Gravity	Box	Rectangular	[8,43,77]
B-1989 b	Gravity	Box	Rectangular	[89,162]
B-1989 c	Air pump	Box	Rectangular	[60]
B-1989 d	Gravity	Box	Rectangular	[163,164]
L-1991	W. pump	Box	Rectangular	[95,165]
B-1992	Gravity	Box	Cylindrical	[45,86,166]
A-1994	Not Spec.	Box	Rectangular	[167]
H-1996	Not Spec.	Not Spec.	Not Spec.	[168]
L-1998	Not Spec.	Box	Rectangular	[66,169,170]
B-2000	W. pump	Box	Rectangular	[19]
R-2000	Gravity	Box	Rectangular	[80,98]
D-2001	Not Spec.	Box	Rectangular	[171]
H-2001 a	Gravity	Box	Cylindrical	[69]
H-2001 b	W. pump	Box	Cylindrical	[88,172,173]
H-2001 c	W. pump	Box	Cylindrical	[67]
J-2001	W. pump	Box	Rectangular	[42]
W-2001	W. pump	Box	Rectangular	[25]
A-2006	W. pump	Box	Rectangular	[174]
C-2007	Gravity	Box	Rectangular	[99]
D-2008	W. pump	Box	Rectangular	[76,175]
F-2008	W. pump	Box	Rectangular	[61]
V-2008	Gravity	Box	Rectangular	[4]
B-2012	Not Spec.	Box	Rectangular	[26]

Table 1. Cont.

Type or Subtype of DRS	Water Movement Mechanism	Water Tank with Drippers	WTD Box Type Shape	
R-2012	W. pump	Box	Rectangular	[74]
C-2013	Not Spec.	Box	Rectangular	[10]
H-2013	Gravity	Box	Rectangular	[59]
N-2016	Not Spec.	Tubes	/	[53]
F-2017	Not Spec.	Box	Cylindrical	[70]
M-2017	Gravity	Box	/	[94]
X-2017	Not Spec.	Box	Cylindrical	[78]
W-2018	W. pump	Box	Rectangular	[58]
N-2020	Not Spec.	Tubes	/	[5,176]

Table 2. DRS₌₁ with the listed sources of papers in which they are described or applied.

Simulator Type Mark	Research Paper Authors and Year of Publishing
L 1941	[177]
M 1944	[178]
L 1947	[48]
G 1949	[179]
M 1954	[180]
M 1956	[181]
P 1962	[75]
M 1963	[182]
P 1963	[183,184]
M 1965	[44,185,186]
M 1967	[187,188]
B 1975	[189]
R 1976	[190]
A 1981 a	[191–194]
A 1981 b	[72,195]
A 1981 c	[196]
B 1981	[197]
S 1981	[55]
F 1983 a	[198]
F 1984 b	[83]
F 1984 c	[68]
RI 1985	[65]
G 1988	[199]
R 1990	[200]
M 2003	[201]
F 2007	[202]
R 2012	[52,203]
Y 2016	[204]
YA 2016	[205]

Modular design of a small number of rainfall simulators with a rectangular box water tank with drippers implies the simultaneous application of a number of identical water tank with drippers within a single system, with the aim of easier handling, transport, installation

and maintenance of simulators while multiplying the area covered by the simulator of 4, 6 or even 10 m² (Figure 8a,b).

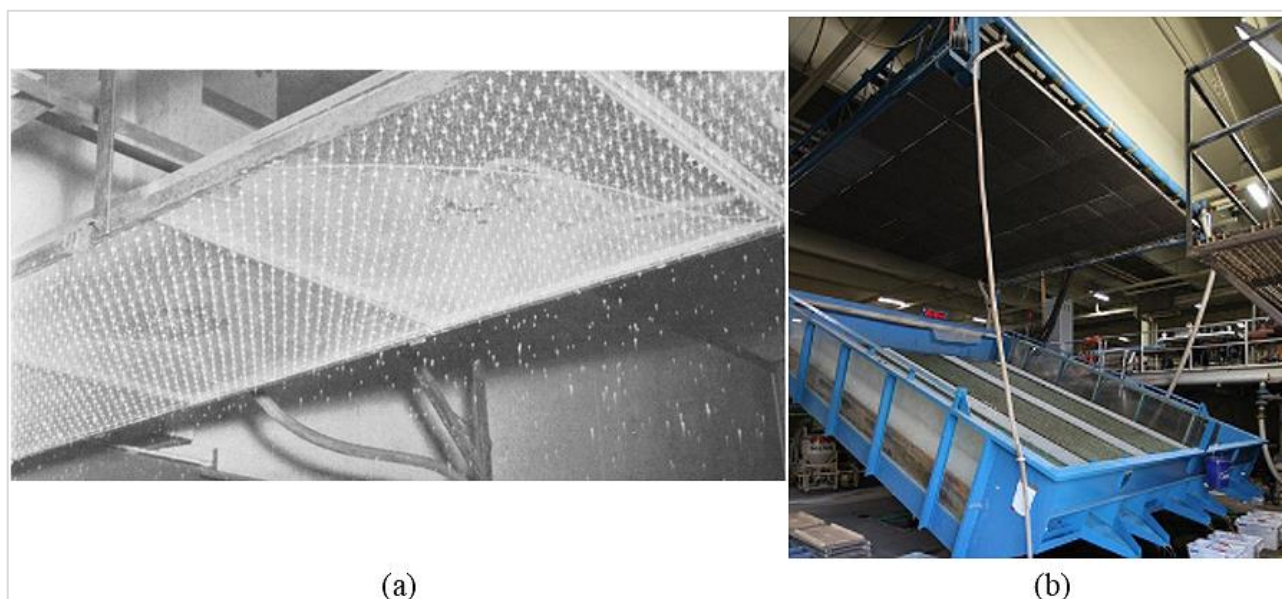


Figure 8. (a,b) Modular design of rectangular box water tank with drippers [17,206] (Utah State University/Utah Water Research Laboratory. Available online: <https://uwrl.usu.edu/hydraulics/hydraulic-testing> (accessed on 19 August 2022)).

Several simulators that use airflow during the simulation to control droplet size or specific raindrop research, have a special system with an additional chamber into which air is pumped and released in the immediate vicinity of the drippers during the simulation [32,41,54,84,110,134] (Figure 9).

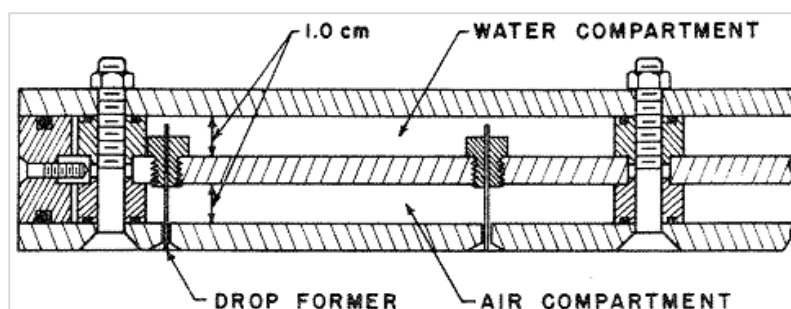


Figure 9. Box tank with drippers with air and water chambers [32] (Reprinted/adapted with permission from Ref. [Onstad et al., 1981]).

Drippers could be arranged according to a rectangular [87] (Figure 10a), triangular [18] (Figure 10b) or circular [86] (Figure 10c) pattern. With a rectangular pattern, the distance of drippers within a row can be the same as, or different from the distance between the rows. In the triangular pattern [18], each dripper is equidistant from the neighboring ones, increasing the number of rows of drippers parallel to the direction of water runoff, which reduces the possibility of forming concentrated flows on the experimental plot compared to the rectangular pattern. The circular pattern occurs in simulators with a Cylindrical shape of the water tank with drippers and is determined by the distance between the radii of the circular lines by which they are arranged and the distance between the drippers on the same circular line [62,75].

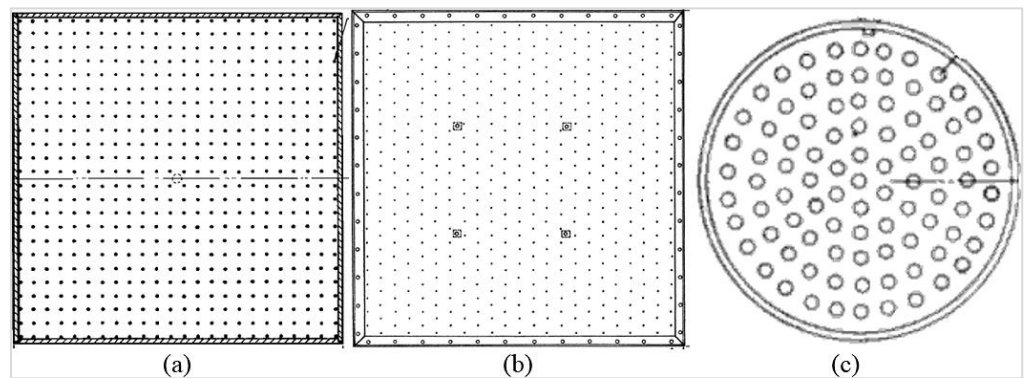


Figure 10. Patterns of drippers arrangement: (a) Rectangular [17] (Reprinted/adapted with permission from Ref. [Chow et al., 1965]); (b) Triangular [18] (Reprinted/adapted with permission from Ref. [Meeuwig et al., 1971]); (c) Circular [28] (Reprinted/adapted with permission from Ref. [Steinhardt & Hillel, 1966]).

The distance between the drippers arranged according to the rectangular and triangular pattern commonly ranges from 15 to 30 mm. Few simulators apply a drippers distance of less than 15 mm or in the range from 30 to 40 mm. The minimum and maximum recorded distance are 12.7 mm and 200 mm respectively (Figure 11).

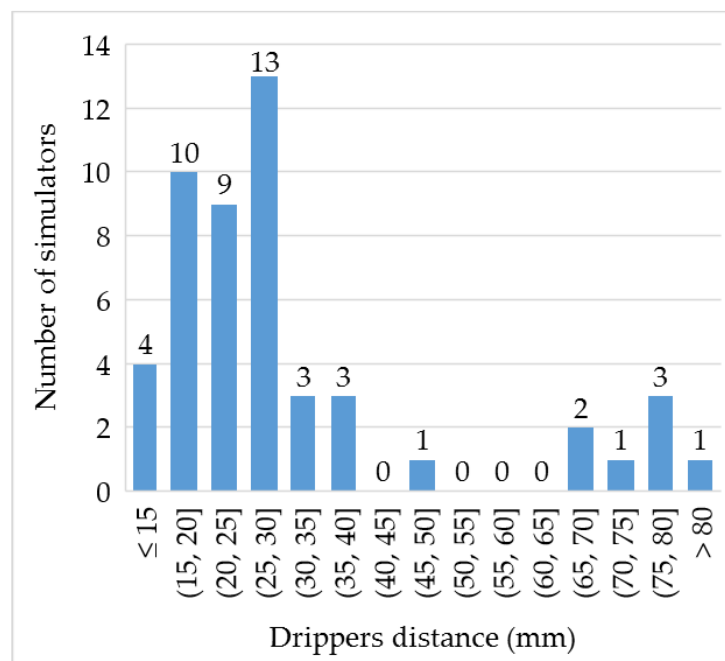


Figure 11. Number of different simulators of a certain value of the mutual spacing of the drippers. Note: the analysis also includes individual simulations with different values of the drippers distance of one simulator.

With a smaller distance between the drippers, their number per unit area will be larger. The number of drippers is determined by the size of the wetted surface and the distance between the drippers. Figure 12 presents the values of the dripper density of the analyzed simulators.

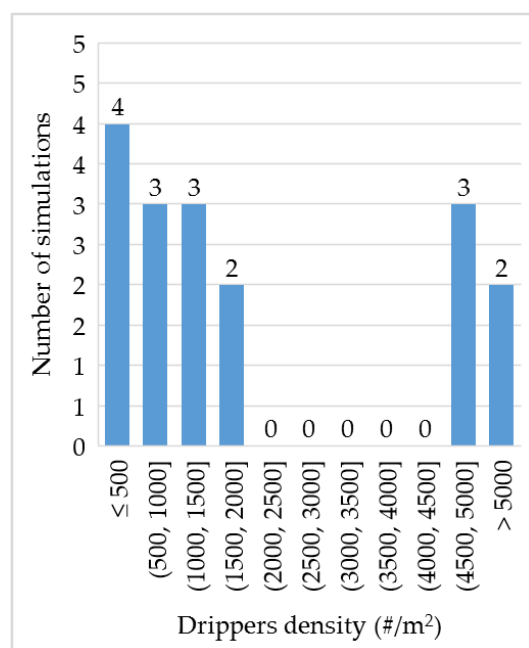


Figure 12. Number of different simulators of a certain value of the density of the drippers arrangement. Note: the analysis also includes individual simulations with different values of the drippers density of one simulator.

3.6. Drippers

Rainfall simulator drippers are the last in a series of simulator elements, on which end water drops are formed. They are also mentioned in scientific literature as drop formers, drop producers, dripping valves, nuzzles, orifices, and they appear in a form of:

- tubes,
- metal tubes (MT) (hypo needle tubes, hypodermic syringe needles, syringe needles, hypodermic needles with rectangular tip, protruding needles, blunted needles, hypodermic tubing, stainless steel tubing, stainless steel tubes, milled stainless steel tubing, stainless steel capillary tubes, drip needles made from hypodermic tubing, cooper tubing, cooper tubes, brass tubes) [62,75,135,174,194],
- glass tubes (GT) (glass burette, glass capillary tubes, glass capillaries) [107,108,178,201],
- plastic tubes (PT) (plastic capillary tubes, plastic needle caps, polyethylene tubes, polyethylene catheter tubes, tygon tubes, nylon tubes, Teflon capillary tubes, micro syringe) [17,58,129,136,152],
- holes in dripper reservoir (HO) [39,53,101,157],
- irrigation drippers (ID) (standard plastic irrigation dripper, PCJ-CNL drippers [5,76]
- hanging yarn (YA) (woolen string, woolen yarn) [91,103,104,106] and
- drippers of unspecified type and material (UN) [26,55,154,199].

For some drippers the performance is modified by the use of the thin threads of different materials that are placed inside the tubes or holes (80–20 nickel-chromium alloy wire, chromium alloy wire, chromium plated brass wire, 1.016 mm tick chromium alloy wire, stainless steel or plated wire, double 0.2 mm tick nylon thread, 0.55, 0.60, 0.66 mm tick fishing line) (index “wire”) [47,48,89,111,164]. Also, performance is changed by the influence of air flow (index “air”) and vibration (index “vib”), or by the simultaneous influence of air flow and threaded wire on the drops during the simulation [48,59,134,179,181].

Until the beginning of the 1960’s, drippers in the form of glass tubes, hanging yarn and metal tubes were mostly used. After that, the use of drippers in the form of metal tubes became dominant, and from the second half of the 1970s, drippers in the form of plastic pipes began to be used in large numbers. Later, drippers in the form of holes in

water tank with drippers and irrigation drippers were used on several occasions. Also, the use of drippers of unknown type was noted (Figure 13).

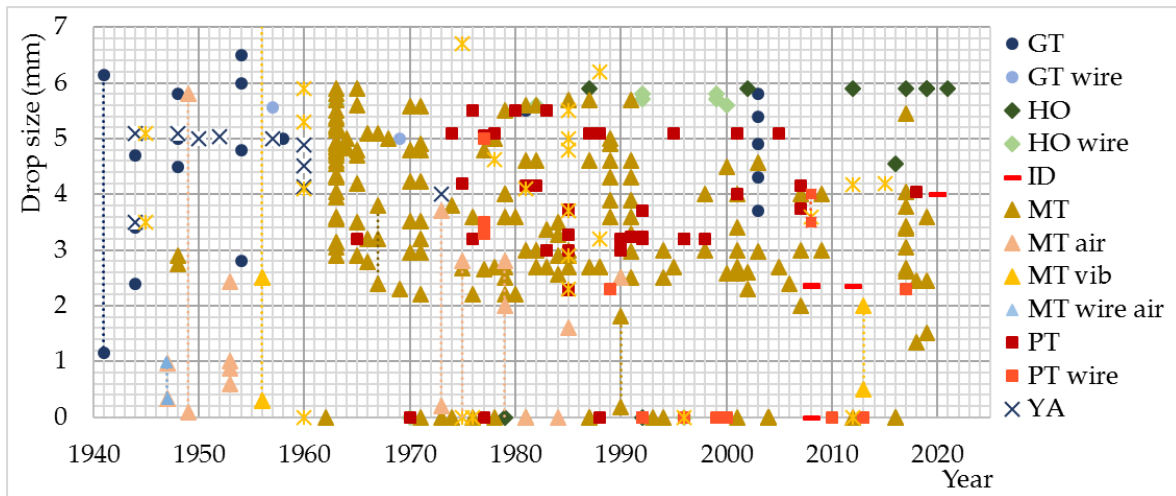


Figure 13. Type and subtype (modified performance drippers) of drippers and corresponding sizes of generated drops applied in previous rainfall simulations (GT—Glass tubes, GT wire—Glas tubes with threads, HO—Holes in dripper reservoir, HO wire—Holes in dripper reservoir with threads, ID—Irrigation drippers, MT—Metal tubes, MT air—Metal tubes under influence of air flow, MT vib—Metal tubes under influence of vibration, MT wire air—Metal tubes with threads under influence of air flow, PT—Plastic tubes, PT wire—Plastic tubes with threads, YA—Hanging yarn and UN—unspecified drippers type). Note: for markers that are on a horizontal line with a value of 0, they are not given values of the corresponding diameter of the generated drop.

By far the most common are drippers in the form of metal pipes, followed by drippers in the form of plastic pipes, the same number of drippers in the form of glass pipes and holes in tanks and the smallest number of drippers in the form of hanging threads and irrigation drippers. Modified performance drippers appear in significantly smaller numbers within their groups and subgroups. In addition to the above, there is a relatively small number of drippers for which no description has been given on the basis of which they could be classified into any of the groups (Figure 14).

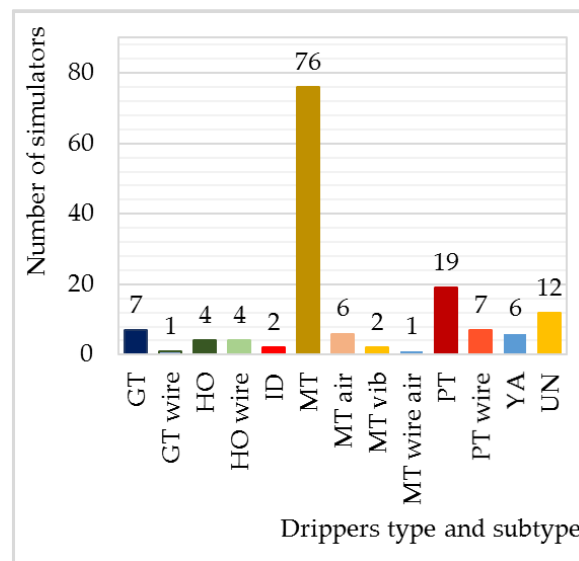


Figure 14. Number of different simulators with drippers of a certain type and subtype. Note: the analysis also includes individual simulations with different types of drippers of one simulator.

4. Conclusions

The paper presents the so far used DRS applied in soil research. Based on the conducted classification, it was determined that a relatively large number of different types DRS and their modified versions were used. Simulators with one dripper were used significantly less than simulators with multiple drippers. The analyzed data provide insight into the most commonly used types or subtypes of simulators, as well as the numerical values of some of the elements that define their design. Research has determined six basic groups of elements that these simulators can consist of: structural support, water tank, water moving mechanism, mechanism of water flow regulation and simulator operation, water tank with drippers and drippers. For each of the groups, the basic purpose and forms in which the elements of the simulator appear are presented. Also, a statistical analysis of the numerical parameters of the elements for which the data was available was carried out. This approach to the analysis of the DRS design should provide insight into the design of simulators used and facilitate the selection of future simulators. In addition to descriptive and numerical descriptions of the basic elements of the simulator according to the classification categories in which the data on them are grouped, a graphic presentation and technical drawings of the simulator in future works should also be provided. This would provide almost all the information necessary for other researchers to make an identical simulator, which should in the future reduce the appearance of simulators of different design and performance. In addition to saving resources during the construction of the simulator, this would bring a step closer to the standardization of rainfall simulators with drippers, which would provide consolidation and comparative analysis of data from different soil research under equal conditions of simulated rainfall. It is important to keep in mind that simulators design and performances are mutually conditional, so to understand the simulator design completely it is needed to analyzed also their performances.

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