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Technical paper

A Rainfall Simulator Used for Testing of Hydrological Performances of Micro-Detention Permeable Pavement

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Abstract

A rainfall simulator for laboratory experimentation is developed to test hydrological performances of micro-detention pond permeable pavement, MDPP. Rainfall characteristics consisting of rainfall intensity, spatial uniformity, raindrop size, and raindrop velocity show that natural rainfall is simulated with sufficient accuracy. The rainfall simulator used pressure nozzles to spray water for rainfall intensity from 40 to 220mm/hr. Uniformity distribution test gives coefficient of uniformity of 95% over an area of $1m^2$. The raindrops falling at velocity ranging from 0.5 to 15m/s with drop sizes diameter between 2 to 5mm. Free drainage system below the rainfall simulator is accompanied with outlet tanks attached with ultrasonic sensor devices to record the outflow data. During the experiments, the outflow received is 98% in average. Experiment results in typical runoff hydrograph and percolation rate of the MDPP system. This shows the ability of the rainfall simulator to obtain initial hydrology data to aid in the design of the MDPP prototype.

Keywords: *On-site detention; Raindrop size; Raindrop velocity; Rainfall uniformity; Runoff.*

1. Introduction

Rainfall simulator had been extensively used for study on rainfall, runoff, soil erosion, and infiltration for laboratory and field experiments [1-3]. Rainfall simulators are devices to duplicate the physical characteristics and reproduction of natural rainfall. The advantages include the possibility to vary the system configuration for simulating different scenarios of rainfall field characteristics [4]. Other than that, the advantages encompass the fact that rainfall can be produced quickly on demand, wherever necessary without having to wait for natural rain at the intensity and duration required, thereby, eliminating the erratic and unpredictable variability of natural rain [5], as well as the rapid data collection under relatively uniform conditions [6].

Rainfall characteristics for rainfall simulators applied in hydrological studies include drop size, spatial uniformity and terminal velocity [7]. Other important criteria are the accurate control of rainfall intensity, repeatability of applying the same simulated rainstorms, and ease of operation within the research area covered [8]. Rainfall intensity varies according to the study area, where most researchers choose to investigate in an area that is less than $5m^2$. Many rainfall simulators are designed with the nozzle at a height of 3 m or less to replicate the velocity and kinetic energy of natural rain [9]. There are two types of rainfall simulators; namely, drop former and nozzle simulators. Drop former is a drop-forming type, which simulates the rainfall through a drip tank with uniform arrays of holes. The water flow produces a distribution of drops with an intensity that is controlled by the diameter of the holes and the pressure in the tank. Its limitations are drop size distribution, velocity of the drops that is dependent on tank height, and impractical for large area. On the other hand, the nozzle type generates drops that force water into the nozzles and produce higher velocities and rainfall intensities at larger scales with uniform spatial distribution and reasonable drop size distribution [4]. As for spatial uniformity, it is calculated based on Christiansen uniformity coefficient (CU) where higher than 80% is considered as uniform [5].

Rainfall simulator model parameterization was designed and fabricated by designers to provide no limitation on frequency, duration and intensity for the objectives of their research [10-11]. Designers will make comparisons between study of rainfall simulators in use; its specifications and performance characteristics, standard evaluation and test methodology from data collected by various studies [5],[12-13]. It is factual that no standard rainfall simulator that is applicable for all situations exists. Thus, the design of each rainfall simulator is specific for each condition and for the aim of the study. Investigation on urbanization and sustainability awareness on green pavement leads to the usage of the rainfall simulator as a tool to evaluate hydrological performance of green pavement system [12],[14-17]. Furthermore, rainfall simulator offers the database needed for computational model simulation; runoff and infiltration process for permeable pavement surfaces [18-19].

In this study, a rainfall simulator was needed for an artificial rainfall experiment done within a laboratory scale that is used to simulate infiltration processes and rainfall hydrograph of a new design of permeable pavement named micro-detention permeable pavement (MDPP) system. The advantage of laboratory investigations in comparison to field measurements is the ability to control the determining factors and to concentrate research on specific processes to fill the existing knowledge gaps [11]. The required properties of the simulator consist of producing: i) A wide range of rainfall intensity varying from 40 to 220 mm/hr; ii) An acceptable reproduction of the rain on the plot area; and iii) A satisfactory design for the green pavement box as an important component for the rainfall simulator, in order to place the heavy material of MDPP and compacted subgrade, and transparent sheet to monitor the storage capacity of the MDPP. Thus, this research aimed to design and test a new rainfall simulator for green pavement application and verify the chosen configuration that would satisfy the above properties.

2. Materials and Methods

Rainfall simulator is designed with consideration on appropriate size, pump, flowmeter, pipe network, nozzles, frame, green pavement box, gutter system and outlet discharge. Ultrasonic sensor device is developed to ease in reading the results obtained. It is installed at outlet to produce results of outflow discharge.

2.1. Design of the Rainfall Simulator

Rainfall simulator components include: Water tank, pumping and piping system, flow meter, nozzles, green pavement box, ultrasonic sensor device and outlet tank (Fig. 1).

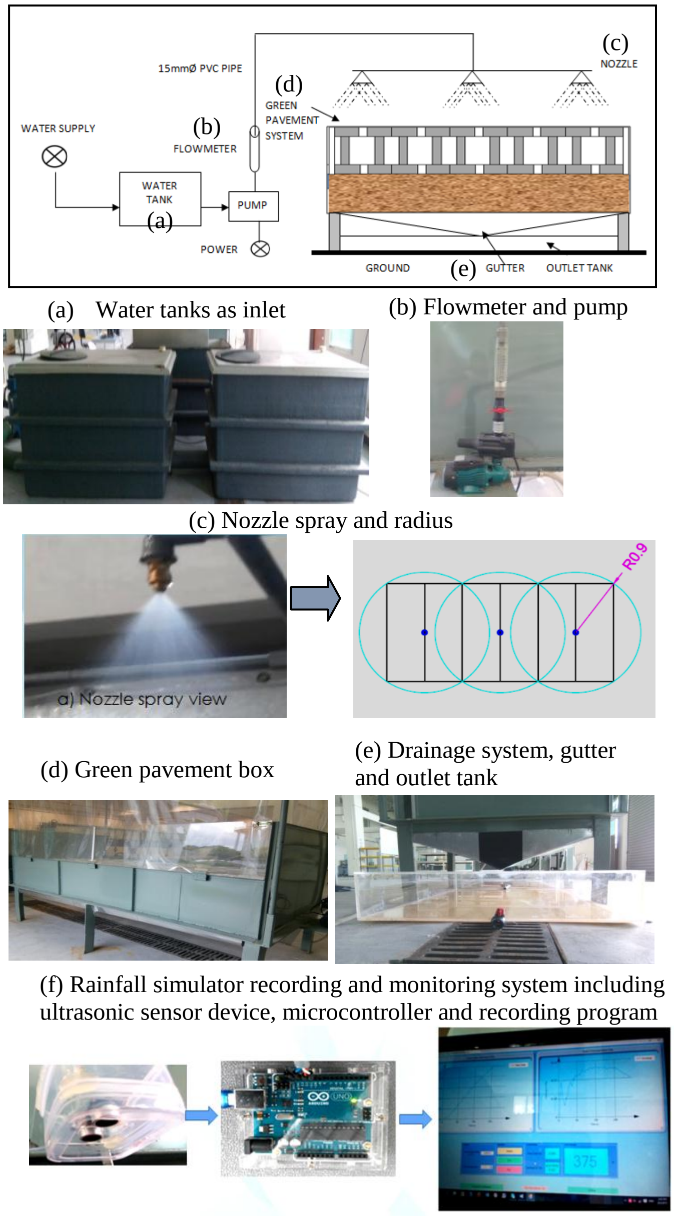

Figure 1: Rainfall simulator and green pavement box

The length and width of the frame are 3.16 m and 1.47 m, respectively. For this research, height is adjustable, where the maximum height is 3m from the surface of green pavement box to offer a variety of height in the experiments.

Rainfall dropping from the nozzles comes from the water tanks. The water tanks, 3 set with volume of 3 m^3, are connected with pump and piping system to flowmeter and nozzles. The pumping system gives a stable pressure to avoid variations in intensity during the simulated rainfall events. The simulator uses three nozzles (Full jet S. S 3/4HH-30WSQ) to cover the catchment area of 3x 1.305 m plot. Full cone nozzles give circular spray pattern to the catchment area. PVC plastic cover is fitted around the apparatus to limit the spray and ensure that the rainfall is within the catchment area. Adjustable valve is attached to the flowmeter to control the flow at maximum reading of 35 LPM@ 10 GPM. Height of the nozzles from the surface of the green pavement system is set at 1.55 m with nozzles coverage diameter of 1.8m.

The size of the green pavement box is 3 x 1.305 and 0.5 m (H). Perspex sheet (of 10 mm thick and 0.45 m height is extended to the box for transparent view. Bottom catchment is built with a rigid framework of 30 nos. steel rod and beams of 50 mm Ø with parallel beam arrangement. It is then closed with a fine nylon mesh, supported on galvanized steel mesh. A brown fabric is attached to the underside of the fine nylon mesh to prevent soil sedimentation. The box is able to sustain huge loads of the pavement and the subgrade soil (5 tonnes). Gutter is attached below the box to collect the discharge water. The gutter is built from ductile iron of 2 (width) x 3 m (length). It is bended in triangle shape to ensure that the water will be directed to the outlet tank. The rainfall simulator output device, RS Output Monitoring GUI program detects the depth of discharge water using ultrasonic sensor. The sensor reads the differences of water level in every 5 s to 1 min onwards with a maximum of 1hr interval. The reading is then transferred to the micro controller. It gives the result of the outlet discharge as a unit of hydrograph and in an Excel file in table form that consists of time, depth and discharge.

2.2. Calibration of Rainfall Simulator

The amount of design storm is set based on Intensity-Duration-Frequency (IDF) curve for Kota Samarahan, Sarawak, Malaysia. Rainfall range is from 155 to 210mm/hr for duration of 15 min to 1 hr. Inflow and outflow capacities of rainfall simulator are tested. Percentage of outflow received is calculated based on water balance equation, equation 1.

$$\frac{\partial ds}{dt} = i - q_1 \tag{1}$$

where,

d1 is the depth of storage water (m),t is time (s),I is externally supplied rate of precipitation (m/s), and q1is overflow (m/s).

To check uniformity distribution of the rainfall simulator catchment area, 200 cylinder cups is arranged in the green pavement box. Rainfall intensity of 210mm/hr, 150mm/hr and 80mm/hr is applied for 7 min. Equation 2 is used to calculate Christiansen's coefficient of uniformity, CU is:

$$CU = 100\left(1 - \frac{\Sigma\left|x - \bar{x}\right|}{n\bar{x}}\right) \tag{2}$$

where,

x is the rainfall depth, n is number of measurements and $\bar{x}$ is an average of all the measurements. The depth of water collected in cylinder cups is measured, as shown in Fig. 2.

CU for rainfall intensity of 210mm/hr, 150mm/hr and 80mm/hr are 97%, 95% and 93%, respectively.

Drop size distribution ranging from 2 – 5mm falls within velocities of 0.5 – 15m/s.

Figure 2: Calibration on uniformity distribution and drop sizes

Table 1 simplifies the techniques and measurements method of manual techniques reviewed by [2]. The manual technique is mostly used due to its simplicity, low cost and availability of material. In this study, drop sizes are measured using oil immersion technique.

Table 1: Techniques and users on drop size distribution [2]

Remaks	Techniques	Methodology
14 drop sizes calibration of rainfall simulators from 1892 - 2012	Stain method: measurement of stains on dyed absorbent paper	Chemically treated paper is used for raindrops size measurement. Rain drops are allowed to fall on a sheet of absorbent paper (e.g. filter paper, blotting paper, blueprint paper, paper toweling, photographic paper, and adding machine tape) with a water-soluble dye. Embedded dye will react with rainfall and leaves permanent marks on paper. The marks is measured and counted for rainfall size distribution.
From 1940s to 2012 of 11 reported papers ca**librated using this technique**	Flour pellet method: measurement of rain drops into finely sieved flour and produce dough pellets	The dough pellets will be oven dried. Pellets were sized with sieves and weighed. It is then calibrated by weighing dried pellets produced by drops of a known size.
From 1937-2016 from 14 rainfall simulators; calibrated using oil immersion techniques.	Oil immersion method: measurement of rain drops in a vessel containing oil.	Raindrops is collected in glass/vessel trough containing mixture of lightly viscose liquids; Vaseline®, treatment oil and mineral oil. Using a camera and microscope low viscosity and hydrophobic nature of the oil causes rain drops to form discreet spherical shapes, allowing drop counting and measurement by microscope or via photograph

Three basins of 60cm Ø are placed in the centre of the nozzles. Oil is prepared using the mixtures of 2:1, consisting of engine oil treatment and mineral oil. The readings are taken at rainfall intensity of 210mm/hr, 150mm/hr and 80mm/hr. Water droplets are suspended in a spherical shape in the basin due to the viscous oil mixture, as in Fig 3. The diameter of the droplets is measured and recorded.

3. Results and Discussion

3.1. Performance of the Rainfall Simulator

Table 2 shows the performance of the rainfall simulator. The rainfall intensity is converted to inflow and controlled by flowmeter in litre per minute. The outflow discharge is recorded and percentage of outflow received is calculated. From the experiments, the outflow received is almost 98%.

Table 2: Inflow and outflow capacities of rainfall simulator

ARI	2	5	10	20	50	100
Rainfall intensity (mm/hr)	155	170	170	185	200	210
Inflow (LPM)	10	11	11	12	13	14
Volume (L)	150	165	165	180	195	210
Outflow (m^3)	0.140	0.159	0.165	0.181	0.196	0.210
Outflow received (%)	93	96	98	98	98	98

3.2. Comparison of Rainfall Simulators

Figure 3 illustrates the collection of spatial uniformity in the form of Christiansen's coefficient of uniformity (CU), drop size distribution, types of simulator, range of rainfall intensity, and simulation area covered. The two types of rainfall simulators can be found in literature, consisting of drip former and nozzles.

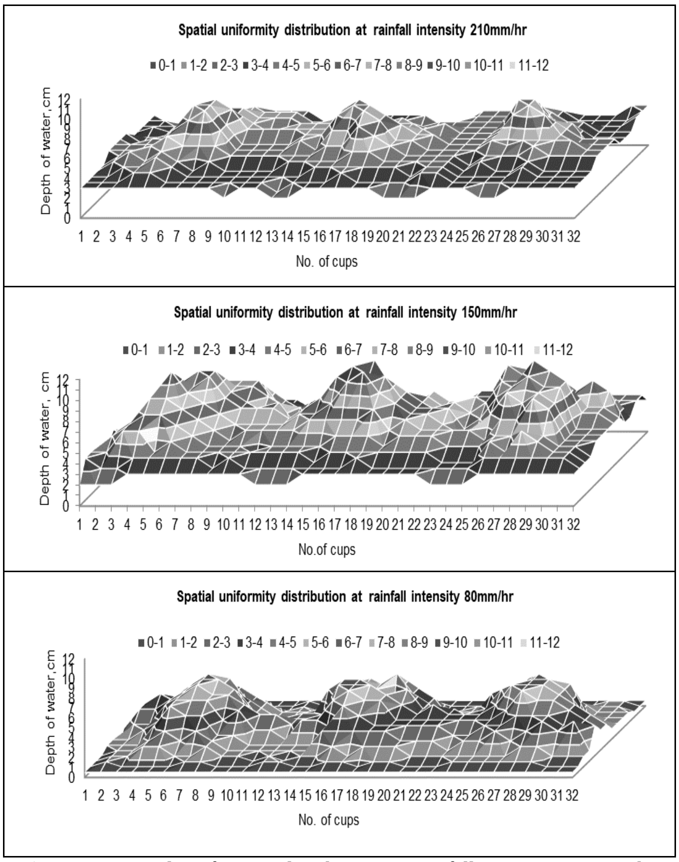

Figure 3: Spatial uniformity distribution at rainfall intensity 210mm/hr, 150mm/hr and 80mm/hr

Table 2 is presented to make a comparison with the rainfall simulator of this study. The nozzle-type and laboratory-scale rainfall simulators are presented in this study. Characteristics listed are fall height, rainfall intensity, medium diameter of raindrops, spatial uniformity of rainfall over the plot, and the plot size. Considerable differences are observed between the rainfall simulators. For example, rainfall drop height changes from 0.4 to 6m. Rainfall intensities ranging from as small as 0.5 mm/min to 360mm/hr are simulated. The median diameter of raindrops changes from 0.25m to 6.5mm. Whereby, the rainfall simulator being design resulted in drop size distribution ranging from 2 – 5mm falls within the velocities of 0.5 – 15m/s. The size of plots is considerably different from a minimum of 0.05 to $12m^2$. All simulators produce an almost uniform rainfall over the plots with a CU ranging from 80 to 97%, excluding 2 studies that started at 60% coefficient. Closer CU value to 100% shows a more uniform pattern of the rainfall. For the rainfall simulator in study, CU value for the rainfall intensity of 210mm/hr, 150mm/hr and 80mm/hr are 97%, 95% and 93%, respectively.

When these characteristics are considered, it can be said that the rainfall simulator of this study is in accordance with its counterparts. The rainfall simulator developed in this study has a considerable plot size of $4m^2$. One notable feature of the rainfall simulator is its capability to monitor the performance of green pavement systems for its infiltration and permeability capacity and storage performance.

Table 2: Hydrological characteristics of rainfall simulator

Ref.	**Spatial Uniformity (CU, %)**	**Drop size (mm)**	**Types of Nozzles**	**Rainfall Intensity (mm/hr)**	**Catchment Dimension Area (m x m x height)**
[1]	>80%	0.48-0.51	NZ	50 to 150	2 x 6 x 3.5
[4]	62- 76	0.25 -3.3	DF	61.6 & 31	4 × 4 × 2
[3]	>80%	0.5–2	DF	0.5, 0.75, 1.0, 1.5 and 2.0 mm min−1	1.5 x 1 x 1.2
[12]	0.001, 0.007, 3.91, 14.58, and 81.44	0.69–8.97	DF	600	2.30 × 1.801 × 1.60
[5] from 3 rainfall simulator	86, 87-91,97 & 95	2.2, 3.0, 2.25 & 1.6	NZ	47.5-52.5, 13-178,67 & 54	2 x 3 x 3, 2-$12m^2$(2-3m),0.65 x 0.94 x 3.25 & 0.5 x 0.8 x 4.5
[5]	82 and 89	2.2–3.1	NZ	45- 105	6.5 x 1.36 x 1.15
Review on artificial rainfall generated by 13 rainfall simulators based in various European research institutions from Germany, the Netherlands, Spain and Switzerland **[10]**.	61–98	0.38–6.5	Both	37–360	Area: $0.05m^2$-1.5 m^2 Height from 0.4-3.43
[6] from 1967-2003 of 7 rainfall simulator.	80-90	1.2-2.25	NZ	10-142	0.24-$3.5m^2$
Review of RS characteristics from **studies between 1990 and 2010 [13] are** summarized herein.	Lowest: 58-73 of [20] Highest: 95 of [21]	Smallest: 0.42mm of [22] by Nozzle and 1.9mm of [23] Largest: 3.7mm of [24] by Nozzle & 6.7mm of [24] by Drop former	NZ : 59 researchers DF: 17 researchers	Smallest: 2-86mm/hr [25] Highest: 94-573mm/hr [26] *both using nozzles	Simulation area: $<1m^2$: 34 researchers $\geq 1m^2$- $4m^2$: 15 researchers $>4m^2$: 12 researchers Height: 1.4-3.0m: 47 researchers 3.1m-5m: 10 researchers ≥6m: 7 researchers

4. Conclusion

The analysis of the rainfall characteristics including rainfall intensity and its spatial uniformity, raindrop size, raindrop velocity, and kinetic energy shows good performances and indicates that natural rainfall conditions are successfully simulated to test the MDPP system.

The main advantages of this rainfall simulator are: 1) The compact structure for laboratory-scale despite that it can put huge loads on the green pavement system and compacted subgrade (about more than 5 tonnes); 2) The simple and inexpensive construction and as it uses local material; 3) The green pavement box with transparent view using Perspex sheet for easy monitoring; and, 4) That it can be operated by one person, where the runoff collection is monitored using electronic devices.

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References

[1] Lora M, Camporese M, Salandin P (2016), Design and performance of a nozzle-type rainfall simulator for landslide triggering experiments. *Catena* 140, 77–89. http://doi.org/10.1016/j.catena.2016.01.018

[2] Kathiravelu G, Lucke T, Nichols P (2016), Rain drop measurement techniques: a review. *Water* 8(2), 29. http://doi.org/10.3390/w8010029

[3] Huang J, Wu P, Zhao X (2013), Effects of rainfall intensity, underlying surface and slope gradient on soil in filtration under simulated rainfall experiments. *Catena* 104, 93–102. http://doi.org/10.1016/j.catena.2012.10.013

[4] Corona R, Wilson T, D'Adderio LP, Porcù F, Montaldo N, Albertson J (2013), On the estimation of surface runoff through a new plot

scale rainfall simulator in Sardinia, Italy. *Procedia Environmental Sciences* 19, 875–884. http://doi.org/10.1016/j.proenv.2013.06.097

[5] Aksoy H, Unal NE, Cokgor S, Gedikli A, Yoon J, Koca K, Inci SB, Eris E (2012), A rainfall simulator for laboratory-scale assessment of rainfall-runoff-sediment transport processes over a two-dimensional flume. *Catena* 98, 63–72. http://doi.org/10.1016/j.catena.2012.06.009

[6] Abudi I, Carmi G, Berliner P (2012), Rainfall simulator for field run-off studies. *Journal of Hydrology* 454–455, 76–81. http://doi.org/10.1016/j.jhydrol.2012.05.056

[7] Meyer LD (1994), Rainfall simulators for soil erosion research. In: Lal R (Ed.), *Soil Erosion Research Methods* (2nd Edition, p. 127). Soil and Water Conservation Society (U.S.), St. Lucie Press, Delray Beach, FL.

[8] Clarke MA, Walsh RPD (2007), A portable rainfall simulator for field assessment of splash and slopewash in remote locations. *Earth Surface Processes and Landforms* 32, 2052–2069.

[9] Humphry J., Daniel TC, Edwards DR, Sharpley AN (2002), A portable rainfall simulator for plot scale runoff studies. *American Society of Agricultural Engineers* 18(2), 199–204.

[10] Iserloh T, Ries JB, Arnáez J, Boix-fayos C, Butzen V, Cerdà A, Echeverríae MT, Fernández-Gálvez J, Fister W, Geißler C, Gómez JA, Gómez-Macpherson H, Kuhn NJ, Lázaro R, León FJ, Martínez-Mena M, Martínez Murillo JF, Marzen M, Mingorance MD, Ortigosa L, Peters P, Regüés D, Ruiz-Sinoga JD, Scholten T, Seeger M, Solé-Benet A, Wengel R, Wirtz S (2013). European small portable rainfall simulators: a comparison of rainfall characteristics. *Catena* 110, 100–112. http://doi.org/10.1016/j.catena.2013.05.013

[11] Fister W, Iserloh T, Ries JB, Schmidt R (2012), A portable wind and rainfall simulator for in situ soil erosion measurements. *Catena* 91, 72–84. http://doi.org/10.1016/j.catena.2011.03.002

[12] Nnadi EO, Newman AP, Duckers L, Coupe SJ, Charlesworth S (2012), Design and validation of a test rig to simulate high rainfall events for infiltration studies of permeable pavement systems. *Journal of Irrigation and Drainage Engineering ASCE*, (June), 553–558. http://doi.org/10.1061/(ASCE)IR.1943

[13] Grismer ME (2011), *Rainfall Simulation Studies – A Review of Designs , Performance and Erosion Measurement Variability*.

[14] Gianni Vesuviano VS (2013), A generic hydrological model for a green roof drainage layer. *Water Science and Technology* 68(4), 769-75. http://doi.org/10.2166/wst.2013.294

[15] Yong CF, McCarthy DT, Deletic A (2013), Predicting physical clogging of porous and permeable pavements. *Journal of Hydrology* 481, 48–55. http://doi.org/10.1016/j.jhydrol.2012.12.009

[16] Ni et al., 2011; Ni, Tong-yuan, Yang, Y. (2011). A New Test Mehtod for Pervious Concrete Permeability. Institute of Electrical and Electronics Engineers, IEEE, 950–953. http://doi.org/978-1-61284-774-0/11/$26.00 ©2011 IEEE

[17] Zhang, 2006) Zhang, J. (2006). A laboratory scale study of infiltration from Pervious Pavements. RMIT University.

[18] Langhans et al., 2011; Langhans, C., Govers, G., Diels, J., Leys, A., Clymans, W., Putte, A. Van Den, & Valckx, J. (2011). Experimental rainfall – runoff data : Reconsidering the concept of infiltration capacity. Journal of Hydrology, 399(3–4), 255–262. http://doi.org/10.1016/j.jhydrol.2011.01.005

[19] Illgen, 2008 Illgen, M. (2008). Infiltration and surface runoff processes on pavements : Physical phenomena and modelling, 1–10.

[20] Munster CL, Taucer PI, Wilcox BP, Porter SC, Richards CE (2006), An approach for simulating rainfall above the tree canopy at the hillslope scale. *Trans. ASABE* 49(4), 915- 924.

[21] Herngren L, Goonetilleke A, Sukpum R, de Silva DY (2005), Rainfall simulation as a tool for urban water quality research. *Environmental Engineering Science* 22 (3), 378 - 383.

[22] Schiøtz IG, Veihe A, Miyashita T, Larsen J (2006), A winter rainfall simulation study of sediment and phosphorus loss in arable land in Denmark. *Geografisk Tidsskrift, Danish Journal of Geography* 106(1).

[23] Regmi TP, Thompson AI (2000), Rainfall simulator for laboratory studies. *Applied Engineering in Agriculture* 16(6):641-647.

[24] Gifford GF (1968), *Influence of Various Rangeland Cultural Treatments on Runoff and Sediment Production from the Big Sage Type, Eastgate Basin, Nevada*. Ph.D Thesis, Utah State University, Logan.

[25] Liu L, Bringi VN, Caylor IJ, Chandrasekar V. (1993), Intercomparison of multiparameter radar signature from Florida storms. In Preprints *26th Int. Conf. Radar Meteorol. Norman, OK: Amer. Meteorol. Soc.*, pp. 733–735.

[26] Miller WP (1987), A solenoid-operated, variable intensity rainfall simulator. *Soil Sci. Soc. Am. J.* 51(3):832-834.

[27] Sobrinho TA, Go´mez-Macpherson H, Go´mez JA (2008), A portable integrated rainfall and overland flow simulator. *Soil Use and Management* 24, June, 163-170.