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DEVELOPMENT OF DESIGN CRITERIA FOR PITCHER IRRIGATION

MSc Dissertation
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Development of Design Criteria for Pitcher Irrigation

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Water spilt on the ground ...
cannot be gathered up again ...

Samuel II, 14:14.

Abstract :

Through practical work with pitcher irrigation it was found that little was published about design criteria which would allow the production of pitchers suitable for specific site and crop conditions.

The theoretical base of the functional principles of pitcher irrigation was elaborated and the three main interacting components, pitcher, soil and environment were extracted and formed the basis for further experiments.

Two laboratory experiments were conducted investigating the saturated hydraulic conductivities of 14 pitchers and the glasshouse soil. The hydraulic conductivities of pitchers ranged from 0.0006 cm/day to 0.5333 cm/day and those from the sandy loam soil were determined to average of 31.3 cm/day for 4 disturbed samples and 115.1 cm/day for one undisturbed sample.

One pitcher with a hydraulic conductivity of 0.034 cm/day and a capacity of about 2.5 litres was selected and used in the glasshouse monitoring daily seepage rates under a constant water level. Seepage rates varied between 1.25 l/day when installed under very dry condition and levelled out to about 0.5 to 0.6 l/day. Tensiometer readings were taken at 3 radial distances from the pitcher wall of 2, 7 and 12 cm at 15 cm depth. Seepage rates from the pitcher were found to be significantly influenced by evaporation at the 0.001 level measured through a Class A Pan.

A two dimensional pitcher model was developed based on theoretical and empirical analysis of water fluxes through porous media under saturated and unsaturated flow conditions from a cylindrical-type source. The conditions from the glasshouse experiment were used as inputs. The model showed reasonable results concerning the sensitivity of inputs and flow prediction. The evaluation however has to be done in separate field experiment.

No general valid design criteria could be developed but a theoretical and practical base was created on which more directed future research can be based.

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TABLE of CONTENTS :

LIST of FIGURES :

LIST of TABLES :

1. Introduction

In 1981 UNESCO launched its major project on the use and conservation of water in rural areas of Latin America and the Caribbean. "...the Project specifically recognizes the value of incorporating traditional materials and methods into water-resource technology. Traditional techniques cost relatively little and, when combined with appropriate modern technology, can prove extremely effective." GISCHLER and JAUREGUI, (1984). The advantage of pitcher irrigation for the developing world technologists is that the system can be used at varying levels of sophistication and that most of the components can be manufactured locally POWER, (1985)[28]. Water practices which were developed for temperate climates may not work as well in arid regions due to technological, environmental, economic and cultural reasons.[27] This should be considered when new technologies are to be introduced.

1.1 Project Objectives

Little is published about design criteria which allow the production of irrigation pitchers for specific site conditions.

The objectives of this project were therefore directed towards the establishment of design criteria for irrigation pitchers with special emphasis put on the:

- Determination of the saturated hydraulic conductivities of pitchers;
- Assessment of the interaction of the environment and the pitcher;
- Development of a model which allows the prediction of pitcher performance;

To achieve this laboratory experiments were conducted, a model developed and a preliminary test was run in the glasshouse to compare the results of the model with the performance of one pitcher.

1.2 Introduction to Pitcher Irrigation

1.2.1 Definition and Classification

<u>Definition of Pitcher Irrigation</u> :

Pitcher irrigation consists, in its simplest form, of unglazed baked earthen pitchers which are buried to their neck in the soil and filled with water[27]. The water gradually seeps out through the porous walls into the root zone under hydrostatic pressure and/or suction, to maintain plant growth around the pitchers [27][35].

Classification by the location of application :

As water is applied slowly in low volumes in the plant root zone, and only part of the soil is wetted, it may be classified as a localized irrigation system. It can be further sub classified as a subsurface irrigation system as the "emitter" is located under the soil surface [38][35][5].

Sub classification by means of replenishment :

According to the means of replenishment pitcher irrigation can also be divided into three categories: Manual, semi-automatic and (fully)automatic systems.

- Manual systems are filled manually with a watering can, bucket or a flexible hose.
- Semi-automatic systems have a pipe system which connects the pitchers, with outlets into each pitcher. After pitchers have been refilled the water is turned off again.
- Automatic systems consist of pitchers or capsules as part of a closed system interconnected with pipes. Water is applied constantly under a hydrostatic head [5].

Definition: Pitcher Irrigation System :

- Macro scale :

Comparing with other localized irrigation systems [38], pitchers can be defined as emitters which form a discharge unit delivering water to the base of the plant. They form part of the total irrigation system consisting of laterals, submains, the main, the control head and the water delivery unit consisting of an elevated tank, a pump or other source of water, as described by SILVA et al.(1987), BARTH (1988) and others.

- Micro scale :

On the micro scale side, the pitcher itself forms a complete (micro) system, incorporating the above mentioned emitter and water storage unit which are normally distinct elements of the system. OLGUIN (1975) and GARCIA (1977)[in 35] even found that the system had 'capabilities' of (auto)regulating the quantities of water released based on the principles of suction.

This micro scale approach shall be followed up throughout this dissertation when examining the system during the experiments.

1.2.2 History and Distribution

Pitcher irrigation is an ancient irrigation system which originated in northern Africa but became forgotten over the years[5]. First trials on this old system were conducted in 1972 in India [22] and were followed by Iran with the "Kuzeh Pot" in 1977 [5][3]. The system started to spread also into other countries like Bukina Fasso, Senegal, Tunisia, Nigeria [5], Ghana, Morocco, Tanzania, Kenya, Botswana [11] and Zimbabwe [7]. An especially interesting area of distribution became Latin America where the use of pitcher irrigation was reported from Brazil, Bolivia, Mexico, Chile, Argentina and Ecuador [5][35]. SP

In most of these countries the system was mainly used in the experimental stage or on micro scale. In Brazil where the system had already been tested on areas of 5000 m^2, a great effort was made to extend it to larger areas [5][14].

A summary of different pitchers and the crops grown, reported in the literature, is given in Table 1.

According to BARTH (1988), pitchers were used for a great variety of crops not mentioned in Table No.1, like cabbage, carrot, radish, sunflower, jojoba, rizinus, peanut, passionfruit, millet, aromatic plants and herbs. In addition also olive growing in Tunisia and a UNESCO project of afforestation in Chilean desert is mentioned where pitchers were used for irrigation with good success.

The latest news of research into pitcher irrigation was reported in October 1989 from Zimbabwe where the British Institute of Hydrology in Wallingford, in conjunction with the Lowveld Research Station, compared different small-scale irrigation systems, of which one was pitcher irrigation [7].

Table No. 1: A summary of different pitchers and the crops grown in different countries

Country	Volume or Dimensions Pitcher (l)(cm)	Crops grown	Distances between Pitchers (m)	Seepage Rates of Pitcher (l/day)	Hydrostatic Pressure used (Yes/No)
ECUADOR	15	-Apple		3.5-20	N
	2	-Onion			
		-Onion seed		< 2	Y/N
		-Vegetables			
CHILE	0.9				
INDIA	10	-Pumpkin	1.30 x 1.30	3.0	N
		-Melon			
		-Bottle gourd	3.00 x 3.00		
		-Watermelon			
		-Pepper,-Knol Khol			
		-Cucumber			
		-Tomatoes	1.43 x 1.43		N
		-Radish			
	24	-Vegetables	2.00 x 2.00	≈1.6-2.0	N
BRAZIL	12				
	0.7	-Watermelon	2.00 x 2.00	4.30-5.40	Y
		-Muskmelons		3.14-2.45	Y
		-Corn		10	
		-Beans			
IRAN	Ø=8 cm				N
	h=15 cm				
	0.950			3.12	N
ZIMBABWE	0.6	-Common Bean	0.3 along bed		N
	2.4	-Common Bean	0.3 along bed		N

Explanation: Blanks, Information not stated
Sources: [5][32][35][23][7][28][14][6][24][1][26]

2. Interacting Components of Pitcher Irrigation

From the functioning principles pitcher irrigation can be divided into three major interacting components which are the pitcher and its properties, the soil surrounding the pot and the environment consisting of the climate and the crop grown.

In 1979 to 1980 a wide ranging experiment was conducted at the Bebedouro Experimental Station in Brazil where one of the objectives was to investigate the technical feasibility of irrigation by porous capsules. 50 porous capsules were used under different hydrostatic pressures of 35, 50 and 70 mbar. The mean daily seepage rates varied significantly (at 0.01 level) with different pressures applied. In addition it was found that the release of water with this method was not uniform throughout the growing season of corn. "It brings out the fact, that the proposed method does not work solely under hydrostatic pressure, but also autoregulated by the plant water demand like irrigation by suction..." OLGUIN et al.(1976), SANTOS (1977)[in 35]. This was found to be more relevant for the treatments with the smallest hydraulic head and during periods of highest crop water demands.[35]

This interaction of crop water requirements and seepage rates out of pitchers was also stated by MAHDAVI, (1977)[in 3] for the "Kuzeh" in Iran, and by OLGUIN (1975) and GARCIA (1977)[in 35] in Mexico.

2.1 The Pitcher

Different authors used different names to describe the emitter. "Porous capsules" (which are closed capsules with two holes for the pipe connections) or "porous pots" is used by GISCHLER and JAUREGUI (1984), SILVA et.al.(1988), "earthen pitcher" or "pitcher" is used by MONDAL (1982), the INSTITUTE OF HYDROLOGY (1990) and others. The pitcher produced in Iran is called the "Kuzeh" pot, MAHDAVI (1977)[in 3]. But not all the names used conform e.g. SAHU (1983) describes pitcher irrigation of watermelons whereas the pitcher serves as a reservoir only placed on bricks outside the soil. The irrigation is done by small syphon tubes primed and inserted with the end in a plastic tube in the soil [30].

2.1.1 Size and Forms

Pitchers are used with different sizes and forms. The volumes range from 0.6 l in Zimbabwe to over 15 l in Ecuador (Table No. 1) to even 24 l reported by OSWAL and SINGH (1975)[in 11]. The first pitcher generation consisted of common clay pitchers with an average diameter of 30 cm and a more spherical form. The Kuzeh, which was designed for irrigation purposes, was about 15 cm high and 8 cm in diameter with a narrow neck and opening [3] to prevent high evaporation. Form and size was similar to the 'small pitcher' used in the experiment in Zimbabwe [7].

A large effort was put into the design of the Brazilian enclosed porous capsule which was casted in gypsum moulds. It is a trapezoidal shape in the form of a truncated cone with two integrated moulded-in clay pipe pieces at the top for the pipe connections [34][35][32]. Problems were reported by BARTH (1988) as the moulding worked under laboratory conditions but not with all clay types under field conditions [6][5].

Good results were reported from Ecuador with a hand made small cylindrical/round pitcher (Vol.= 2 l, ø=14cm, h=21cm), with a neck opening of about 6 cm in diameter. Two indentations in the top allowed a pipe to pass through for replenishment. This pitcher was used under manual filling as well as under semi- and fully automatic filling whereas for the latter the lid and the pipe were glued and sealed to the pitcher.(see. also Chapters 3.1.3 and 3.1.4 where one of these was used [5][34]

Probably the only commercially manufactured and available 'pitcher' is the "Blumat"[R] automatic irrigator which works as well under the principles of suction as under slight hydrostatic pressure. It was designed for use in flower pots and beds on terraces and balconies. It consists of a conical downwards pointing ceramic cup glued to a removable tight fitting plastic lid and a 3 mm flexible pipe. The ceramic cup is 56 mm high and has a maximum diameter of 21.5 mm.[33]

Although most authors stated the size or volume of pitchers, only BARTH (1988) recommends the use of small pitchers of 2 l for home gardens for manual filling and recommends the use of bigger pitchers for orchards and afforestation. No information was found about reasons which lead to specific designs of pitchers concerning their different sizes and shapes.

The volume, shape and surface area of a pitcher are important properties of the pitcher. The combination of these three factors depends on the purpose and circumstances of use and can be defined as followed:

- <u>Volume</u> : The volume is determined by the crop water requirements in combination with the planned irrigation - or replenishment - interval during periods of peak water requirements. For systems under constant hydrostatic pressure the storage component within the pitcher becomes less important as the storage is done by a central tank.

- Shape : The shape of a pitcher is mainly determined by the designed region of application, e.g. near the soil surface for shallow rooted crops, with a conical pitcher pointing downward. But the volume requirement, rigidty and production limitations playing an important role. Further, the combination of volume and shape determines the average positive head applied.

- Surface area : The surface area forms the conducting or emitting component of the pitcher, the link between the water and the soil. Assuming a constant flow per unit area of pitcher wall then the total water applied increases with the increase in surface area.

2.1.2 Materials and their Properties

2.1.2.1 Composition, Porosity and Firing Temperature

The functioning of the system is based on the ability of the pitcher wall to transmit the right amount of water into the root zone. Therefore different porous materials and mixtures have been examined and used.

Clay was used as the basic material in all reports. To increase the porosity, cow dung [39], sand [4][5], wood shavings [5][11], weakly meta phorsed shale, talc and calcite [32][35][33][34] were mixed with clay or different clay minerals. BARTH (1988) reported very good results by mixing sand and clay in the ratio of 1 : 2 , after experimentation with different mixing ratios.

SILVA et al. (1985) used different mixing ratios of a local clay called 'Taguá'(B) on the one hand to a mixture of talc, chalk and 'chamota'(A) on the other. By varying the hydrostatic pressure he obtained flow rates from 0.1 to 36 l/day/capsule for the different capsules with a volume of 0.7 l. The best performance was exhibited by the capsule with a mixing ratio of A:B of 40:60, with a porosity of 20 % - 22 % and a water release of about 3 l/day under a positive head of 0.25 m. A summary of these results is given in Table No. 2.

Table No. 2: Daily water releases per porous capsule of different material mixing proportion (A: Talc, chalk and 'chamota' mixture; B: Local clay 'Taguá') under different hydrostatic pressures.

Mixing propor-tions (%) A : B	Daily water release/capsule (l) Hydrostatic pressure (m) 1.00	0.75	0.50	0.25
20 : 80	0.30	0.20	0.17	0.10
30 : 70	3.62	3.02	2.03	0.82
35 : 65	5.44	3.94	2.47	1.62
40 : 60	7.72	6.32	4.34	2.83
50 : 50	36.00	29.00	19.00	9.50

Source: Modified after SILVA et al.(1988)[34]

Beside the material composition, the firing temperature has an influence on the permeability of fired clay materials (slabs) as reported by USMAN (1986). With increasing firing temperature a decrease of the permeability was found. Too low firing temperatures of 750° C. led to material weakness and breakdown of the slabs.[37]

SILVA et al. (1988) reports best results with firing temperatures of 900 °C, when the decomposition of CO_2 occurs which is responsible for the final porosity of the $CaCO_3$ rich material.[34]

2.1.2.2 Hydraulic Conductivity

The hydraulic conductivity (K) is a measure of the permeability of a porous medium and forms an important constant in the flow equation. In 1856 the first description of water flow through a porous medium was given by Henry DARCY, a French hydraulic engineer, who examined the flow of water through horizontal beds of sand. Darcy's Law states that the rate of flow through a porous media is proportional to the head loss and inversely proportional to the length of the flow path and may be written as:[36][21]

Darcy's Law:

$$Q = - K A \frac{dh}{dl} \qquad \{1\}$$

Where:

Q	=	Flow rate	(m^3/day)
K	=	Hydraulic conductivity or proportionality constant of the porous medium	(m/day)
A	=	Cross sectional area of flow	(m^2)
dh/dl	=	Hydraulic gradient	(m/m)

Saturated hydraulic conductivity values of pitchers have been reported from different authors to vary between 0.0240 cm/day and 0.1368 cm/day according to the materials and firing temperatures [34]. During experiments at Silsoe College saturated hydraulic conductivity values of 0.0063 cm/day to 0.548 cm/day for slabs were obtained which were from the same material and treatments as the pitchers used in the experiments [37][11]. A summary of different hydraulic conductivity values is given in Table No. 3 .

2.2 The Soil

2.2.1 Water Movement and Wetting Patterns

Pitchers can be considered as the emitters of drip irrigation, a point source of water delivery. The spread and movement of the water through the soil depends therefore mainly on capillary and gravitational forces. In fine textured soils like clays and clay loams the capillary forces are stronger and the gravitational forces can be almost neglected. The wetting patterns sometimes have a greater lateral than a vertical component[38].

In sandy soils gravity plays a relatively stronger role than capillary action, which causes a more elongated shaped wetting pattern [38].

As the calculations of the distribution patterns on the basis of physical properties of the soil are complicated and unreliable JOBLING (1974) recommends empirical prediction and guide-lines for the first approximation as shown in Fig. 1 and 2 [38][17]. BURGESS & CARR (1988) recommend the use of a simple portable test rig for trickle irrigation [10] which could be modified for use in pitcher irrigation by replacing the emitters with porous capsules with different water release characteristics. This would allow the prediction of the wetting radius of different pitchers.

Table No. 3: Saturated hydraulic conductivity values (K) for pitchers as reported by different authors.

SOURCE	Sat. Hydraulic Conductivity (cm/day)	Pitchers or Materials Specified
OLGUIN & SANTOS (1977)	0.096 - 0.192	N/A
SILVA et al.(1978)	0.024 - 0.072	Dep. on firing temp and ?
SILVA et al.(1985)	0.1296	A:B = 40:60 (+)
RENDON (1979)	0.1368	N/A
BARTH (1988)(*)	0.5333(*)	Sand : Clay = 1 : 2
CLIFT-HILL (1985)(#)	0.0063	Stoneware
	0.0045	Grogged terracotta
	0.0089	Grogged terracotta + stoneware
	0.0548	Grogged terracotta + stoneware + wood shavings
USMAN (1986)(#)	0.7520	Red clay + woodshav. at 750°C
	0.2510	Red clay+ grey clay + woodshav. at 850°C
	0.0900	Red clay + grey clay + woodshav. at 950°C

(+) Compare with Table No. 2

(*) Pitcher was provided by BARTH from the project described (Ecuador), and the hydraulic conductivity tested by the author (see chapter on laboratory experiments)

(#) MSc dissertation, unpublished

SOURCE: [34][37][11]

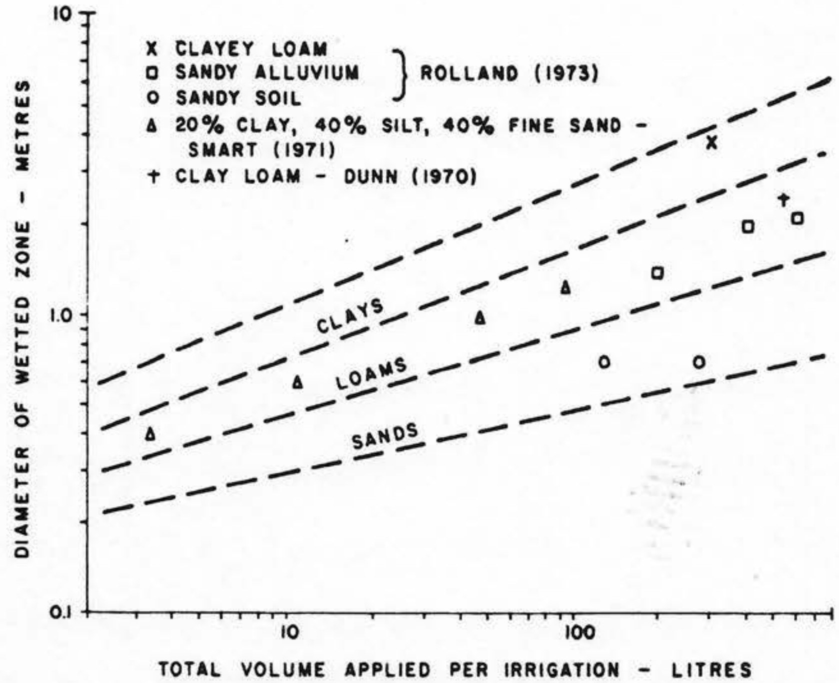


Fig. 1 : **Approximate guide for estimating the diameter of the wetted zone**
Source : **[38]**

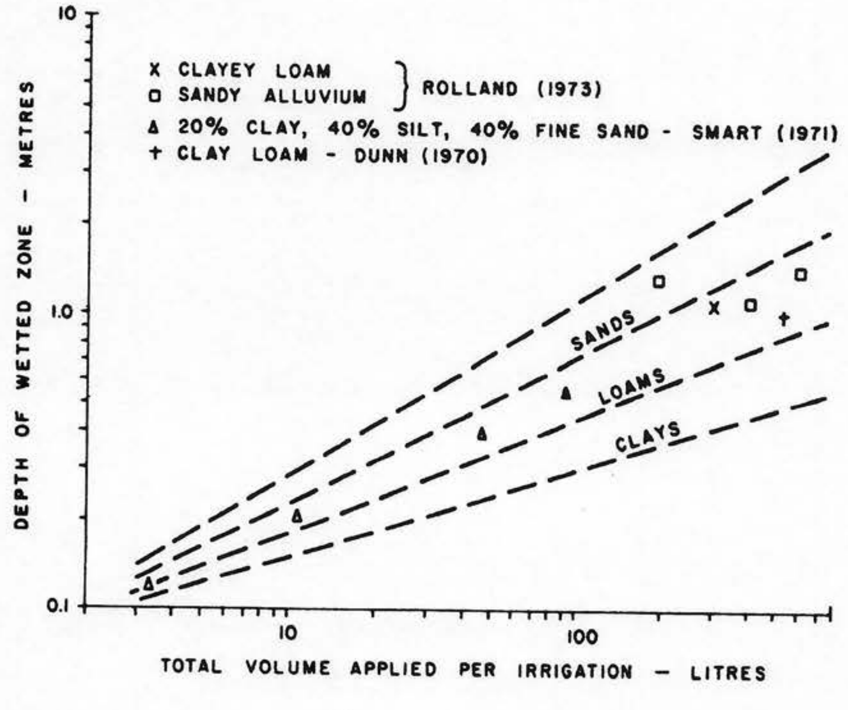


Fig. 2 : **Approximate guide for the estimating depth of wetted zone**
Source : **[38]**

2.2.2 Soils used in Pitcher Irrigation

SILVA (1985) and (1988) described the soils to be sandy loams and loamy sand in which trials have been conducted. ALEMI (1980) reported good results in irrigating saline sandy loam soils. MONDAL (1974) used saline sandy loams using good quality water and in sodic soils using saline water. Different authors recommend the mixing of farmyard manure or cow dung into the soil and to "tramp" it down. On heavy soils a thin layer of sand is placed around the pitcher while packing the soil [22].

2.2.3 Hydraulic Conductivity of Soils

No information was found on the topic of hydraulic conductivities of soils in which pitcher irrigation was practised.

Most flow of water in the field especially in the rooting zone of most crops is under unsaturated conditions. It involves complex relations like variable soil moisture, suction and conductivity. The unsaturated hydraulic conductivity is therefore a function of the negative pressure head and the water content of the soil. With drying of the soil (entry of air) the conductive proportion of the soil cross-sectional area decreases, hence the hydraulic conductivity decreases. [36][15] The unsaturated flow is widely expressed by using different empirical equations. One where the unsaturated hydraulic conductivity under a negative pressure head is related to the saturated hydraulic conductivity with empirical constants representing specific soils as shown in equation {2} [18][40][2]:

$$K_{(p)} = K_o \, e^{(CP)} \qquad \{2\}$$

Where:

$K_{(p)}$	=	Unsaturated hydraulic conductivity in (m/day) related to the matric potential
K_o	=	Saturated hydraulic conductivity as measured (m/day)
C	=	Empirical exponent (m^{-1}) see Table No. 4

Table No. 4 : Typical values for the saturated hydraulic conductivity (K_o) and the empirical exponent (C) as used in equation {2}.

Soil Description	Saturated Hydraulic Conductivity (m/day)	Exponent 'C' (m^{-1})
Sandy loam	1.80	18.0
Silty loam	0.85	4.0
Fine sand	1.10	2.0
Structured clay	0.50	1.0
Peat	0.75	6.5

Source: [18][12]

More values, found through curve fitting by using the same equation {2}, are given by AMMOOZEGAR-FARD et al. (1984) for 39 soils.

2.3 The Environment

OLGUIN et al. and SANTOS (1977) found that the release of water out of porous capsules was not solely influenced by the hydrostatic pressure applied, but also by the crop water demand [in 35]. Similar observations were reported from two experiments, where pitchers were used without hydrostatic pressures. USMAN (1986) and CLIFT-HILL (1985) observed that an increase in temperature and open pan evaporation increased seepage rates from the pitchers. CLIFT-HILL (1985) added that the seepage rates from cropped pitchers were significantly higher than those placed in bare soil.

The transpiration flux of water vapour from the crop surface into the atmosphere is the final stage of a process that began with the water movement through the soil towards the roots, MARSHALL and HOLMES(1988). The pitcher with its porous wall can be considered as being part of this soil-water-plant-atmosphere continuum forming a lower conducting layer in a stratified soil. A theoretical conclusion can therefore be drawn that there should be a positive correlation between crop water demand and hence the soil water status and the water flux out of the pitcher.

3. Experimental Design

3.1 The Pitcher

3.1.1 Laboratory Experiments, Hydraulic Conductivity

The objective of this project was to develop some design criteria for pitchers which enable the design of pitchers with a specified output. The objectives of the hydraulic conductivity measurements were to make a comparison with values published (see Table No. 3) and to have a range of values to choose from for further experiments.

As shown in Darcy's equation {1} the property of the water-conducting porous material is defined by the constant K, the saturated hydraulic conductivity. The following experiment was set up to determine the saturated hydraulic conductivity of a range of pitchers by using the pitcher as a whole. A modified falling head permeameter was developed and used.

SILVA et al. (1985) used a constant head device measuring the porous capsule as a whole. By measuring the flow rate under a constant head with a known internal and external surface area of the capsule (the average was taken) and the wall thickness, the saturated hydraulic conductivity could be calculated by rearranging Darcy's equation {1}(see also Table No. 2).[34]

CLIFT-HILL (1985) and USMAN (1986) used a falling head permeameter and glued a plastic funnel on slabs which were produced and treated in the same way as the pitchers, to measure the saturated hydraulic conductivity.[37][11]

In this experiment a combination of these two methods was used. It was decided to use the pitcher as a whole as the hydraulic conductivity value obtained would be more representative for the pitcher as a conducting unit, with its natural slight variations in material composition. This is especially important since the pitcher as a unit was to be used in further experiments. The falling head permeameter was used as the hydraulic conductivity was expected to be very low and therefore the test procedure would have been very time consuming under a constant head.

3.1.2 Calculations and Formulae

In the falling head permeameter, a fine manometer tube, which serves as a reservoir of water flow as well as a variable head device, is connected to the presaturated test sample. In the test the rate of fall of the water level in the manometer tube is recorded.

The hydraulic conductivity can be calculated by noting the flow rate in the manometer tube which is given by:[36][21]

$$Q_t = \pi r_t^2 \frac{dh}{dt} \qquad \{3\}$$

The flow through the manometer tube must be equal to the flow through the sample which is given by Darcy's law {1} :

$$Q_s = \pi r_s^2 K \frac{h}{l} \qquad \{4\}$$

πr_t^2 and πr_s^2 are the cross sectional areas of the manometer tube and the sample and can be written as 'a' and 'A' respectively. By equating equations {3} and {4} and integrating, the hydraulic conductivity can be obtained:

$$K = \frac{a * l * \ln (h_1 / h_2)}{A (t_2 - t_1)} \qquad \{5\}$$

Where:

K	=	Saturated hydraulic conductivity in (m/s)
Q_t, Q_s	=	Flow through manometer tube and test sample
r_t, r_s	=	Radius of manometer tube and sample (m)
a,A	=	Cross sectional area of manometer tube and test sample (m^2)
l	=	Length of sample (m)
h1/h2	=	Ratio of start head to finish head during readings
t2-t1	=	Elapsed time from start to end of reading (s)

By using the whole pitcher as a test sample, the cross sectional area (A) and the length of sample (l) are changed to:

A	=	Average surface area of the pitcher (internal area + external area)/2 (m^2)
l	=	Average wall thickness (m)

3.1.3 Pitcher Selection and Surface Area Estimation

A range of pitchers were used which had partly been used for other experiments by CLIFT-HILL (1985) and USMAN (1986). Four pitchers were provided by the author. As it was not possible to determine which pitcher had been used in the previous experiments, a visual selection was done to remain with a wide range of different pitchers. The pitchers were visually classified into 7 groups for better description (which doesn't impose a performance indication). The grouping for means of description is given below for 14 pitchers:

Visual grouping and short description of the pitchers used

Group		Description and No. used in this experiment
I	:	Pitcher with apparent wood shavings mixed into the clay before burning (UK) No.: 10, 11, 12
II	:	Pitcher probably made from red clay as marked with 'red' (UK) No.: 1, 2, 5
III	:	Pitcher with same appearance and shapes like II but without 'red' (UK) No.: 4, 7
IV	:	Pitcher described to come from Africa by CLIFT-HILL No.: 8, 9
V	:	Pitcher described by BARTH (1988) from the same project in southern Ecuador with an approximate sand : clay ratio of 1 : 2 No.: 6
VI	:	Pitcher produced in Sam Borondon in the coastal area of Ecuador with a higher sand content No.: 3
VII	:	'Blumat'^{R} automatic drip irrigator, commercially available (prod.in Austria) No.: 13, 14

The specifications of the pitchers used in this experiment are given in Table No. 5 in chapter 3.1.5 .

<u>Estimation of the Surface Area and the Wall Thickness</u>

Pitchers are produced in a variety of different shapes and sizes. To calculate the surface area a method was adopted, which proved to be suitable for symmetrically shaped pitchers like those thrown on a wheel. Pitchers were marked at fixed height increments (10 mm) along the axis of rotation, the diameters were taken and the surface areas of the segments integrated. The surface areas of the segments were approximated by using the formula for the lateral surface area of a truncated cone.

The wall thicknesses were taken along the segments and averaged to use in equation {5}. By subtracting the wall thickness from the diameters measured at the equivalent segment the internal diameter was found and thus the internal surface area. For the surface area (A) in equation {5} the average of the internal and external surface area was calculated.

3.1.4 Experimental Procedures

The falling head permeameter was slightly modified to serve this requirement. A plastic funnel was glued (two component glue) to the neck of every pitcher pointing outwards and the manometer tube (ø = 2 mm) connected to the funnel point.

Pitchers were checked for leakages during the first fill and later under a positive head of 1.6 m. Because of the very low porosity of the material it was found to be necessary to soak the pitchers for 3 days to ensure fully saturated conditions.

14 pitchers were tested in random order every day and on 5 following days which gives 5 replications for every pitcher. Pitchers were checked for apparent leakages (blowholes) after every test run.

3.1.5 Results of Laboratory Experiments

A summary of the results obtained from the laboratory experiments of the 14 pitchers tested, together with the specifications, is given in Table No. 5.

Pitcher No. 8 could not be tested as the joint of the funnel didn't hold. The same problems occurred for pitcher No. 4 after 4 replications. Pitcher No. 10 started to leak at a small formerly sealed off crack after two replications. Sealing the leakages under wet conditions was not possible.

Table No. 5 : Summary of pitcher specifications and average hydraulic conductivities of 14 pitchers tested

No. of Pitcher	Volume (ml)	Height (total) (mm)	Wall thickness AVG (mm)	Diameter MAX (mm)	Surface Area INTERN. (cm^2)	Surface Area EXTERN. (cm^2)	Surface Area AVG. (cm^2)	Hydraulic Conductivity AVG. (cm/day)
1	4152	208.8	7.0	218.0	1226.27	1349.07	1287.67	0.00124
2	3880	216.8	8.3	207.0	1181.77	1314.21	1247.99	0.00074
3	**2492**	**191.9**	**8.2**	**173.0**	**833.72**	**921.60**	**877.66**	**0.03449**
4	4225	236.8	7.6	209.9	1251.48	1396.95	1324.21	0.00059(*)
5	4571	229.1	8.7	220.5	1313.88	1486.68	1400.28	0.00109
6	1364	170.0	9.1	132.0	563.08	682.55	622.81	0.53329
7	4943	245.7	6.7	229.5	1421.56	1557.72	1489.64	0.00057
8	3835	209.8	7.8	204.6	1168.86	1293.72	1231.29	N.A. (+)
9	4039	211.8	7.7	208.8	1194.90	1311.71	1253.30	0.01053
10	3265	211.1	10.4	199.1	1053.06	1234.30	1143.68	0.00450(#)
11	3920	210.7	9.3	211.4	1179.41	1352.34	1265.88	0.00134
12	4227	235.8	10.8	208.8	1259.10	1476.26	1367.68	0.00096
13	6.4	56.0	3.7	21.5	6.00	19.26	12.63	0.36854
14	6.4	55.0	3.7	21.5	6.00	19.26	12.63	0.44934

(*) Pitcher No. 8 : A leakage at the joint of the funnel and the pitcher neck was found.
(+) Pitcher No. 4 : Hydraulic conductivity value from 4 replications, leakage at funnel joint.
(#) Pitcher No.10 : Hydraulic conductivity value from 2 replications, leakage at a sealed off crack.
Bold Pitcher used for further experiments in the glasshouse.

OLGUIN & SANTOS (1977) reported values for K between 0.096 - 0.192 cm/day, SILVA et al. (1985) 0.1296 cm/day and RENDON (1979) 0.1368 cm/day. Comparing these with the hydraulic conductivity values found, the published values were higher than the values found for pitcher No. 3 (K = 0.0345 cm/day), and lower than those found for pitcher No. 13 (K = 0.3685). But SILVA et al. (1978) used porous capsules with a permeability of 0.024 to 0.072 cm/day which would cover the range of pitcher No. 3. For better comparison the test results are listed in ascending order of the average values found, in Table No. 6. [34]

A few pitchers showed slightly increasing hydraulic conductivities with time which might be explained by initially not fully saturated flow due trapped air. In particular pitcher No. 6 showed a steady increase in hydraulic conductivity for about 160 % . This could be explained by the very fragile structure of the pot which was handmade under farm conditions and had been fired in a simple stove with a relatively low firing temperature.[6] USMAN (1986) also reported the dissolving of clay slabs of low firing temperatures when hydrostatic pressure was exerted. SILVA et al. (1985) found capsules with mixing proportions of A:B of 50:50 % (Table No. 2) unsuitable for use under field conditions as they showed low mechanical resistance [34].

Table No. 6 : Saturated hydraulic conductivity values for 14 pitchers tested, in ascending order of the average values from 5 replications

No. of Pitcher	HYDRAULIC CONDUCTIVITY (cm/day) 1.Rep.	2.Rep.	3.Rep.	4.Rep.	5.Rep.	Average	St.Dev.
8	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7	0.0005	0.0006	0.0005	0.0006	0.0007	0.0006	0.00005
4	0.0005	0.0007	0.0006	0.0006	N.A.	0.0006	0.00005
2	0.0007	0.0007	0.0007	0.0008	0.0008	0.0007	0.00004
12	0.0009	0.0009	0.0009	0.0009	0.0012	0.0010	0.00013
5	0.0010	0.0011	0.0011	0.0010	0.0013	0.0011	0.00011
1	0.0011	0.0012	0.0012	0.0013	0.0014	0.0012	0.00009
11	0.0015	0.0012	0.0012	0.0015	0.0013	0.0013	0.00016
10	0.0050	0.0040	N/A	N/A	N/A	0.0045	0.00049
9	0.0086	0.0090	0.0108	0.0114	0.0129	0.0105	0.00159
3	0.0255	0.0283	0.0347	0.0398	0.0441	0.0345	0.00693
13	0.3618	0.3654	0.3678	0.3616	0.3862	0.3685	0.00912
14	0.4342	0.4215	0.4052	0.4827	0.5031	0.4493	0.03731
6	0.2701	0.4896	0.5860	0.6166	0.7043	0.5333	0.14842

Note: Missing data through leakages

3.2 The Soil

3.2.1 Hydraulic Conductivity Determined for the Glasshouse Soil

<u>The Glasshouse Soil</u>:

The glasshouse soil was not a naturally grown soil. The previous soil (clay) had been replaced by a sandy clay loam a few years ago to a depth of about 0.6 m. Different experiments have been conducted over the years and the soil exhibited different degrees of compaction through digging and establishing pathways, and different moisture contents. The soil was determined to be a sandy clay loam with 61 % sand, 20 % silt and 19 % clay.

Sampling and Hydraulic Conductivity Determination:

The soil samples were taken randomly from the project area of about 2.5 m x 2.5 m. Undisturbed sampling failed, except for one case, through dryness and lack of soil stability. Four cylinders (conductivity cells) with an internal diameter of 9.98 cm and a height of 13.03 cm were filled with well mixed soil of a gravitational moisture content of 9.9 % . Together with the undisturbed sample they were saturated for 48 hours.

The falling head permeameter was used with a manometer tube of an internal diameter of 5.26 mm . Three replications were done on every sample and the results together with the dry bulk densities are shown in Table No. 7.

Table No. 7 : Hydraulic conductivity and dry bulk density results for the glasshouse soil (Silsoe College)

No.of Sample	Hydraulic Conductivity (m/d)					Dry Bulk Density (g/cm^3)
	1.Rep	2.Rep.	3.Rep	Average	Std.Dev.	
GL-1	0.296	0.296	0.296	0.296	0.00000	1.40
Gl-2	0.345	0.332	0.332	0.336	0.00602	1.39
Gl-3	0.338	0.338	0.326	0.334	0.00569	1.36
Gl-4	0.284	0.284	0.284	0.284	0.00022	1.37
* Gl-5 (undist.)	1.201	1.126	1.126	1.151	0.03540	1.42
- Average of Gl-1 to Gl-4 (disturbed) :				0.313	0.00288	1.38
- Average of all samples :				0.480	0.01322	1.39

Results and Applicability of the Measurements:

When using disturbed repacked samples for the saturated hydraulic conductivity measurements, care has to be taken when interpretating these results and applying them to field conditions. The structure is destroyed and shrinking and swelling during handling as well as microbiological activity may lead to changes in comparison with field conditions [8].

The results of the average saturated hydraulic conductivity of 0.31 m/day for the repacked sample and of 1.15 m/day for the undisturbed sample lie within results reported for a sandy clay loams [2]. But still, under normal field conditions the use of these results would have to be questioned, and different methods for undisturbed sampling or field methods should be adopted.

For this particular case however the results may still be valid and applicable as similar conditions existed in the lab as well as in the glasshouse, both the sample and the soil structure having been disturbed. As described earlier the soil was not found to be homogeneous through compaction and different treatments. To achieve homogeneity around the pitcher, the glasshouse soil in the project area was dug out to a depth of about 0.5 m, thoroughly mixed and refilled after the hole was lined with plastic sheeting to prevent water seepage in from outside.

3.2.2 Unsaturated Hydraulic Conductivity under Varying Matric Potentials for the Glasshouse Soil

By using equation {2} and the empirical exponent 'C', values from Table No. 4, the change in the unsaturated hydraulic conductivity for the glasshouse soil (sandy clay loam), with decreasing matric potentials near the pitcher, is plotted in Fig. 3.

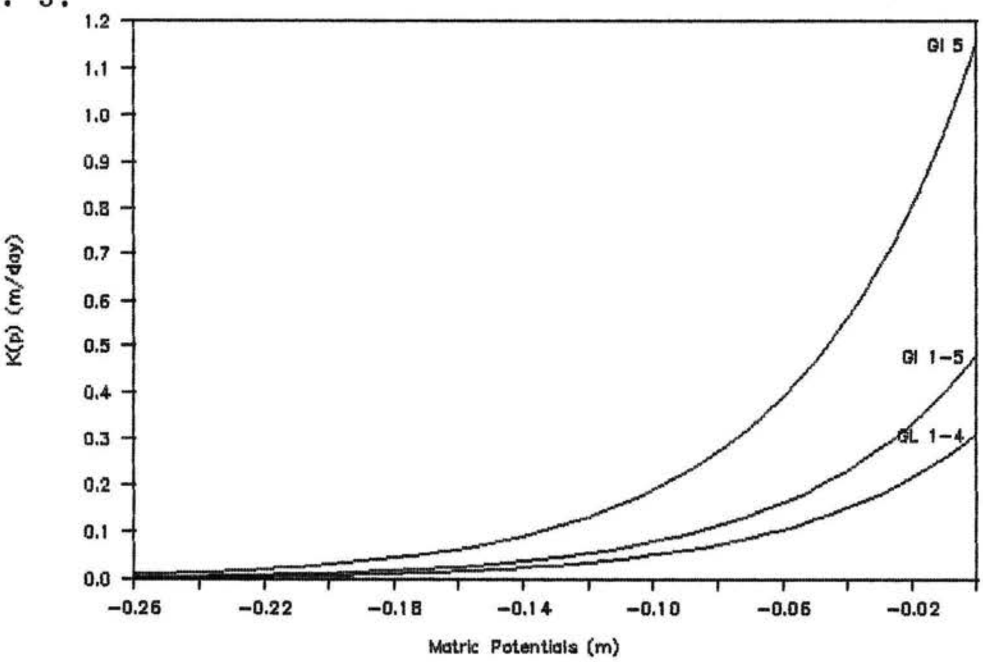


Fig. 3 : Change in hydraulic conductivity K (m/day) under the effect of matric potential (m) for the glasshouse soil; explanations in the text

3.3 The Environment

3.3.1 The Glasshouse Experiment and its Objectives

The objectives of the glasshouse experiment were to examine the pitcher behaviour in its environment and to study the interaction of the climate (crop), soil and pitcher. The conditions (also from the laboratory experiments) should be used as input values for the model so that the model results could be compared with the observations made and results obtained.

Limitations of this Experiment :

This experiment was considered to be a preliminary study with limited numbers of observations and replications. It was meant to build a base for future research and to indicate the direction for further experiments. It was not meant to produce statistically sound generally applicable results, which would have been outside of the scope of this study due to time limitations.

3.3.2 Experimental Procedures

Location and Soil :

The glasshouse was chosen as the location of the experiment as it allows an easier monitoring of the water movement from the pitcher without the interference of rainfall. At the project location a pit was excavated of about 2.5 m x 2.5 m to a depth of about 0.5 m. To prevent water seepage from outside into the project soil the pit was completely lined with plastic sheeting and the soil, after it had been thoroughly mixed, was refilled to its former height. The refilling was done by piling up the soil from the centre until it reached the desired height of 0.4 m from the plastic. The gravitational moisture content was determined to be quite homogeneous with an average of 3.84 % (St.dev. 0.038) from 7 randomly picked samples.

The Pitcher :

Pitcher No. 3 was chosen as the test pitcher as its hydraulic conductivity value fell into the range of those published by SANTOS et al. (1978) (s. Table No.6) and had the following specifications: Height = 19 cm, ø (max) = 17 cm, volume = 2.49 l, K = 0.0345 cm/day. Pitchers with higher hydraulic conductivities would also have been suitable but could not be used as No. 13 and 14 were too small and No. 6 was too inconsistent in its K value.

The plastic funnel was cut off level, leaving 1 cm above the pitcher rim to give a good closing fit for the constant water level device. The pitcher was embedded to its neck in the centre of the plot and filled with water.

The Constant Water Level and Flow Rate Monitoring Device :

As changes in water levels would influence the seepage rates through decreasing heads and surface areas, the functioning principle of the "chicken water feeder" was used to maintain a constant water level in the pitcher and to monitor the daily seepage rates. A 1 l (total 1150 ml) conical glass flask was used as a reservoir and turned upside down on the neck of the pitcher, being fixed by a rubber bung, which on one side sealed the flask and on the other was glued to a plexi glass plate of 140 mm x 140 mm x 5 mm supporting the stand. A rigid plastic tube with a ø of 12 mm and a length of 50 mm was inserted through a hole in the rubber bung (tight fit) and a centred hole in the plexi glass plate (glued to prevent being pushed in) and allowed to protrude by 15 mm. A second "finger hole" of 23 mm in diameter was drilled into the plexi glass beside the bottle neck which was sealed by a rubber bung to prevent evaporation. The constant water level device is illustrated in Fig. 4 .

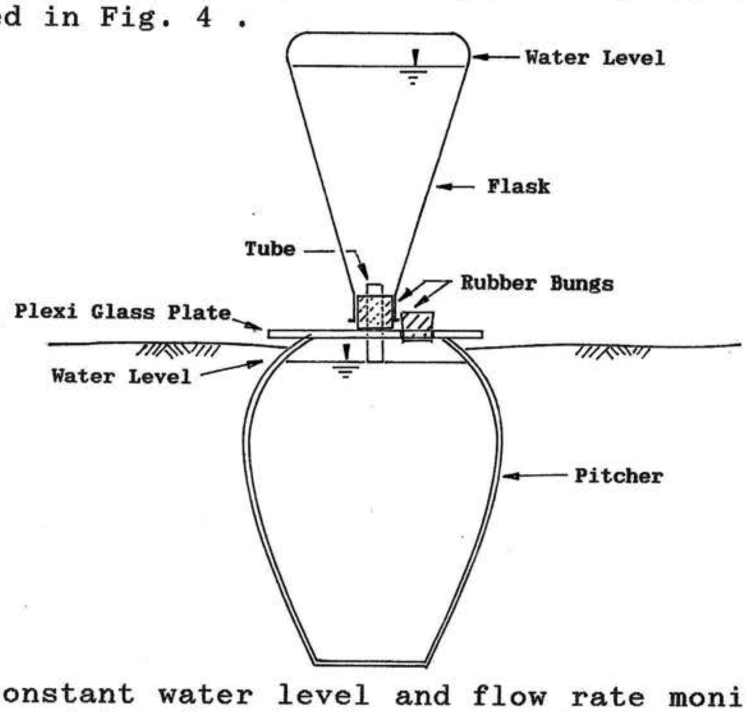


Fig. 4: The constant water level and flow rate monitoring device developed for the glasshouse experiment

The refill was done in the following way: The rubber bung from the "finger hole" was removed and the forefinger inserted from outside into the hole tapping the tube end at the water surface inside of the pitcher. This prevented air coming in and water coming out of the flask while it was removed from the pitcher neck. The flask was then refilled to the top of the tube and the amount replaced monitored. The flask was then reinstalled in the same way tapping the tube exit with the finger until it had a fix stand on the pitcher.

Tensiometers :

12 mercury tensiometers were installed at radial distances of 2, 7 and 12 cm from the point of maximum pitcher radius at a depth of 15 cm measured from the soil surface to the middle of the ceramic cup. Every array therefore had 4 replications.

Class 'A' Evaporation Pan :

A class 'A' evaporation pan was sited on a wooden open frame platform with its centre about 3 m away from the pitcher.

Readings :

All reading were taken once a day at 10 o'clock in the morning (at 09.00 G.M.T.).

3.3.3 Results and Observations from the Glasshouse Experiment

Seepage Rates from Pitcher No. 3 :

The seepage rates were measured from the moment of the first filling at 24.07.90 at 9 o'clock in the evening. The initial water releases were very high starting with 1252 ml/day (extrapolated to 24 h) and then steadily declining with the wetting up of the soil reaching 662 ml/day after the 7th day at 30.07. At the 31. of July the first change occurred with a rise in the seepage rate to 720 ml/day and 749 ml/day on the following days. The following days were the hottest of the year reaching a peak at the 3 rd of August.

The seepage rates together with the open pan evaporation are summarised in the graph in Fig. 5. By comparing these values it could be found that whenever the open pan evaporation increased or decreased to the value observed the day before, they were followed by the seepage rates from the pitcher but with a much lower magnitude. It may be noted that the pitcher neck was covered by the plexi glass inhibiting evaporation losses from the water surface in the pitcher. The plexi glass was resting on the plastic rim and formed a good fitting lid.

Matric Potentials Around the Pitcher :

The tensiometers formed three concentric circles around the pitcher with four tensiometers at the same distance from the pitcher. The two inner circles were installed at the 26th of July and the outer circle on the following day when the wetting had advanced further outwards. The initial phase was accompanied with air entry and breakdown of the tensiometers. This occurred especially at the outer ring where the tensiometers were placed at the quite sharply differentiated wetting front with the very dry soil (θ_m = 3.8 %). In the beginning the breakdowns were related to the dry soil and the installation and the tensiometers were refilled. This forced water into the soil which might have influenced the reading of the nearby tensiometer. Later it was found that 5 had to be replaced as the ceramic cups had very fine cracks at the joints which had not been detected when checked before installation.

The readings have therefore to be considered to be unreliable especially during the initial phase, which can be easily detected when observing the graphs in Fig. 6. The objective of the tensiometer installation was to obtain average values at radial distances from the pitcher. This could still be achieved even with lower numbers of observations as not all tensiometers broke down simultaneously. It was also easy to detect the malfunctioning ones as they gave 0 readings.

In Fig. 6 the average matric potentials at three radial distances are plotted together with the seepage rates. A general tendency could be observed that decreasing matric potentials caused an increase in the seepage rates out of the pitchers. It may be noted that the tensiometers were installed at 15 cm depth (middle of ceramic cup), which is further away from the soil surface than the outer tensiometer ring is away from the pitcher wall. This would explain the relatively small changes in matric potentials at that depth even under higher evaporation rates. Tensiometer depths of 5 cm to 10 cm would have been more appropriate in this case.

Open Pan Evaporation :

Open pan evaporation data were taken together with the matric potentials from the 26 th of July on. Ordinary tap water was used to fill the pan which seemed not to be sufficiently decontaminated as algae growth developed especially during the hot period of the experiment. Replacement of the water was therefore carried out more frequently.

On the 15 th and the 18 th of August the evaporation data had to be rejected as through failure of the ventilation window, water dripped from the roof into the evaporation pan during heavy rains. The faulty automatic window setter was switched on accidently and the windows stayed jammed open. The experimental plot was not affected. Both values for seepage rates and pan evaporation of those days, were not used when computing the correlation.

Relation between Seepage Rates and Evaporation :

The pitcher with its porous wall can be considered as being part of this soil-water-plant-atmosphere continuum forming a lower conducting layer in a stratified soil. Therefore the relation of the daily seepage rates to the evaporation was examined to prove whether the null hypothesis, that there is no correlation between the evaporation rate and the seepage rates, could hold or not. For the comparison of the two parameters the relative numbers were important and no conversion of the pan evaporation to ETo or bare soil evaporation was done.

It was observed that the initial phase of wetting up the soil volume, indicated by a steady decrease in seepage rates, must have come close to a steady state situation around the 30 th of July. The pitcher showed for the first time a reaction on fluctuating evaporation data (there had been changes before) which was indicated by the first rise in seepage rates on the 31 st of July, following a steady decay since installation. It was therefore assumed that the pitcher had come to a steady state situation with the soil and the external environment at the 31 st.

Seepage rates were plotted against pan evaporation on a scatter diagram for 19 days and the result are shown in Fig. 7. The correlation coefficient was calculated to be 0.74 which showed a positive correlation to be highly significant (at 0.001 level for 17 degrees of freedom) [19]. The null hypothesis, that there is no correlation between seepage rates and the bare soil evaporation, can therefore be rejected.

A linear regression line was calculated using the least-squares method with the following equation, as also shown in the graph in Fig. 7 : $y = 0.346 + 0.050\ x$

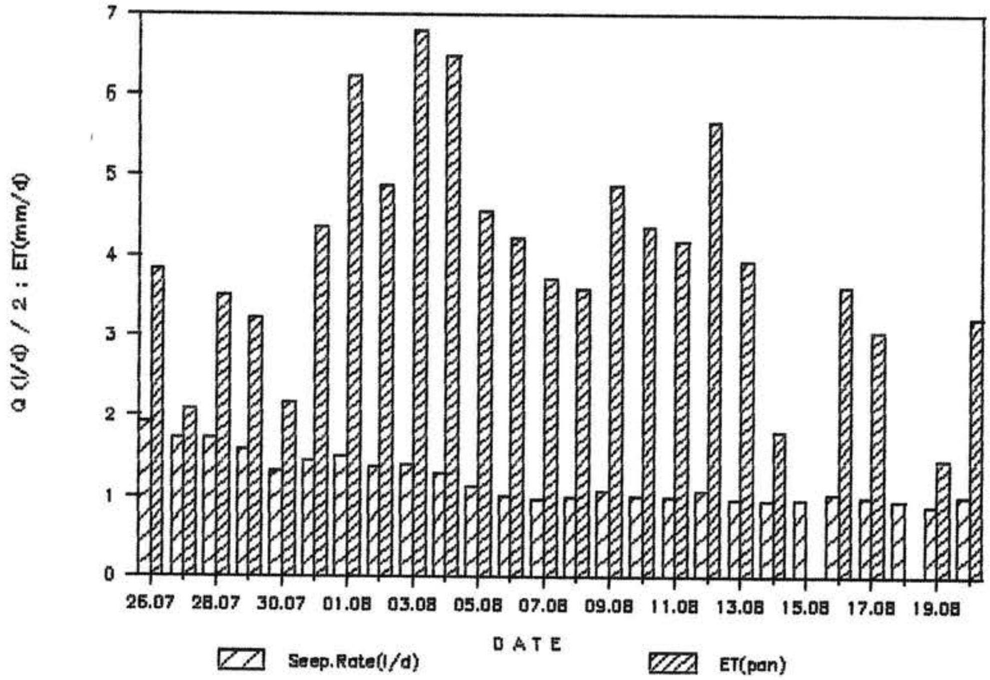


Fig. 5 : Seepage rates (l/d) and pan evaporation (mm/d) for the project period (Missing values are explained in the text)

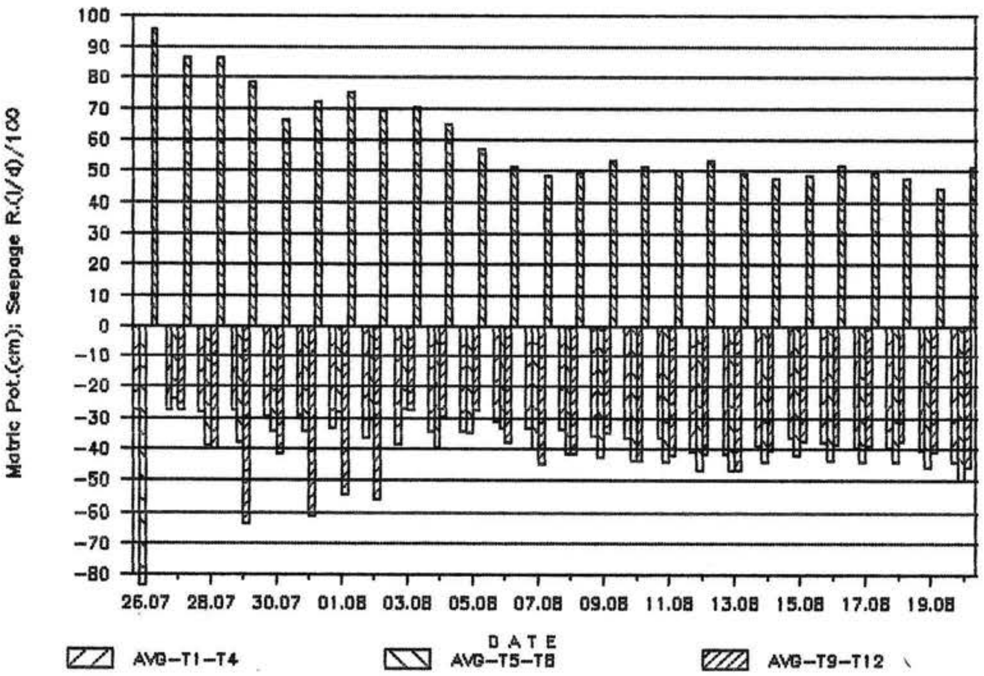


Fig. 6 : Average matric potentials (cm) at radial distance of 2, 7 and 12 cm from the pitcher wall at a depth of 15 cm, against daily seepage rates from the pitcher

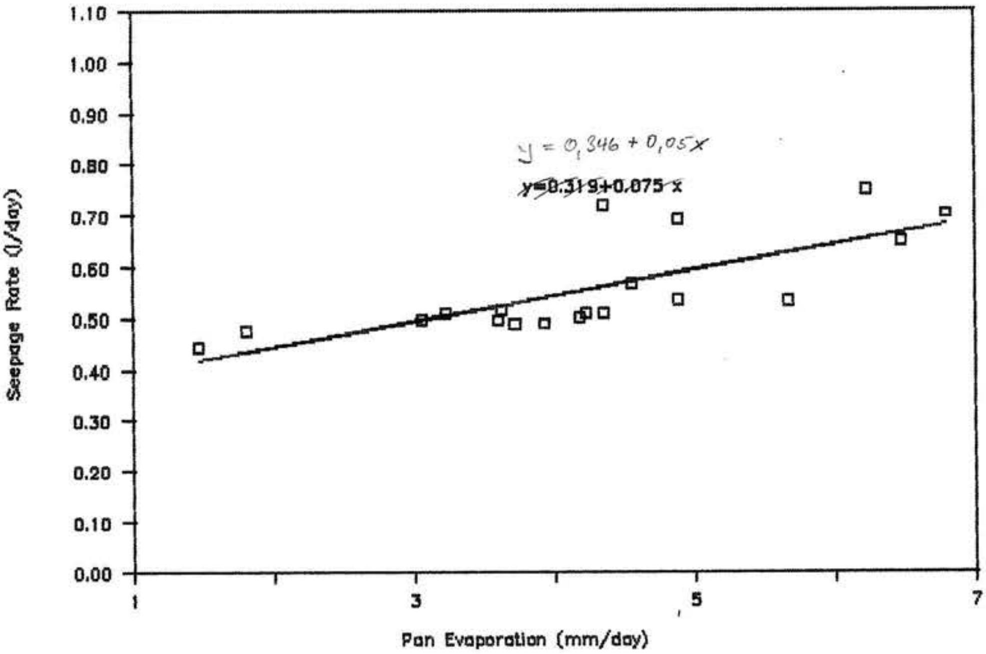


Fig. 7 : Correlation of seepage rates against pan evaporation; r = 0.74

4. The Pitcher Model

4.1 Objectives of the Pitcher Model

The objectives were, to develop a model which would allow the prediction of seepage rates and limits of performance for pitchers under a specific situation. It should be a practical tool for those concerned with the design and development of pitchers as well as for those applying this system under field conditions.

4.2 Development of the Model

The model incorporates the three major interacting components of pitcher irrigation elaborated in the previous chapters. It was based on the soil-water-plant-atmosphere continuum, a link between the pitcher, the soil and the environment, with the driving force of a potential- or hydraulic gradients throughout the system.

The model and its components are schematically described in Fig. 8 .

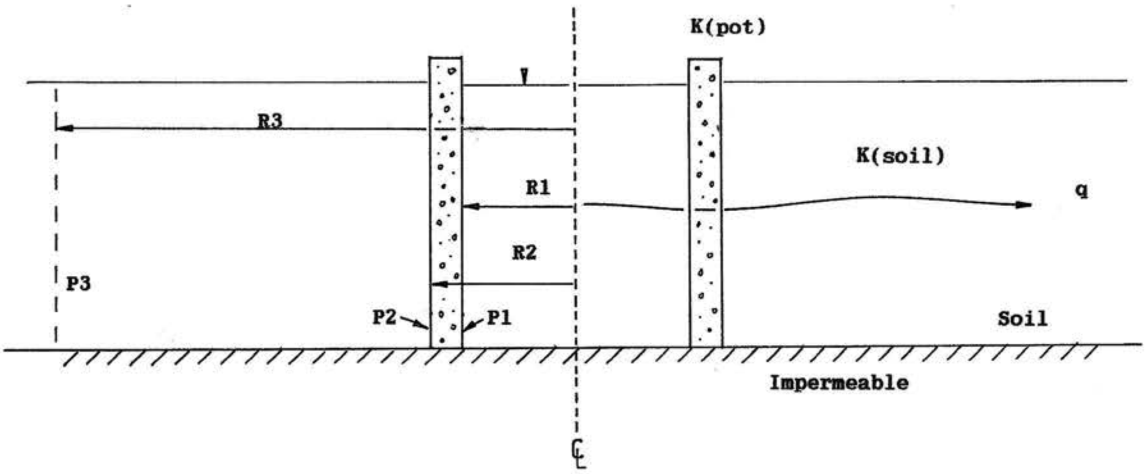


Fig. 8 : Schematic layout of model components for water movement from a cylindrical pitcher

The following symbols were used throughout this model:

R1	=	Internal radius from centre line of pitcher (m)
R2	=	External radius from centre line of pitcher (m)
R3	=	Radius to point of measured or assumed potential in the soil from centre line of pitcher (m)
P1	=	Potentials at R1 (m) at inside pitcher wall
P2	=	Potentials at R2 (m) at outside pitcher wall
P3	=	Potentials at R3 (m)
Kp	=	Saturated hydraulic conductivity of pitcher wall (m/day)
K	=	Hydraulic conductivity of soil (m/day)
q	=	Flux out of the pitcher (m^2/day)

X

The following simplified assumptions were made for the modelling approach which are assumed to hold for most practical conditions under which pitcher irrigation is applied:

Assumptions :

- A steady state situation is assumed;
- Pitchers are assumed to be cylindrical or could be adjusted;
- The ~~the~~ pitcher wall is always saturated;
- The flow through the soil may be saturated as well as unsaturated:
- The hydraulic conductivity of the pitcher is lower than the hydraulic conductivity of the soil;
- The relation between matric potentials and soil wetness is the same on a drying and wetting cycle; hysteresis is neglected;
- The pitcher rests on an impermeable layer (e.g. plough pan) and therefore the water movement is horizontal.

For the Soil:

The hydraulic conductivity of the soil is described by the following empirical relationship [18][2]:

$$K_{(p)} = K_o \ e^{(CP)} \qquad \{2\}$$

Where:

$K_{(p)}$	=	Unsaturated hydraulic conductivity in (m/day) related to the matric potential p (m)
K_o	=	Saturated hydraulic conductivity as measured (m/day)
C	=	Empirical exponent (m^{-1}) see Table No. 4

From Darcy's Law for a steady state situation it is given:

$$q = 2 \pi K_{(p)} \frac{dp}{dr} \qquad \{6\}$$

Where:

q	=	Flux per unit height (m^3/day/m)
r	=	Radius (m)
p	=	Potentials (m)

When substituting $K_{(p)}$ through equation {2}:

$$q = 2 \pi K_o e^{cp} \frac{dp}{dr} \quad \{7\}$$

And by rearranging and integrating between the limits R2, R3 and P2, P3 for the soil it can be shown that:

$$\ln \frac{R3}{R2} = \frac{2 \pi K_o}{q} * \frac{1}{C} \left[e^{CP3} - e^{CP2} \right] \quad \{8\}$$

Rearranging {8} for q, the flux through the soil is described by:

$$q = \frac{2 \pi K_o}{\ln R3/R2} * \frac{1}{C} \left[e^{CP3} - e^{CP2} \right] \quad \{9\}$$

<u>For the Pitcher</u>:

Applying Darcy's Law to the pitcher:

$$q = 2 \pi Kp \frac{dP}{dr} \quad \{10\}$$

As the flow through the pitcher wall is saturated (Kp=K saturated of pitcher wall) it can be shown by rearranging and integrating between the limits of R1, R2 and P1, P2 that:

$$\mathrm{Ln} \frac{R2}{R1} = \frac{2 \pi Kp}{q} \left[P2 - P1 \right] \quad \{11\}$$

Rearranging {11}, the flux q through the pitcher is obtained for a steady state situation :

$$q = \frac{2 \pi Kp}{\ln R2/R1} \left[P2 - P1 \right] \quad \{12\}$$

<u>For the System</u>:

From continuity the flux through the pitcher {12} must equal the flux through the soil {9} so that both equations can be written as:

$$q_{(Pitcher)} = q_{(Soil)}$$

$$\frac{2\pi K_p}{\ln R2/R1}\left[P2 - P1 \right] = \frac{2\pi K_o}{\ln R3/R2} * \frac{1}{C}\left[e^{CP3} - e^{CP2}\right] \quad \{13\}$$

Rearranging equation {13} it can be written as:

(**Left Hand Side** of Eq.) (**Right Hand Side** of Eq.)

$$[P2-P1] * C * \frac{\ln R3/R2}{\ln R2/R1} * \frac{K_p}{K_o} = e^{CP3} - e^{CP2} \quad \{14\}$$

In equation {14} the only unknown is P2, which is the negative pressure head or potential (m) at the outside of the pitcher wall. As it forms the transition zone between the pitcher and the wall it is not possible to measure the potentials e.g. with a tensiometer. All the other parameters are found from measurements or can be assumed or stated.

P1 is the positive pressure or hydrostatic head which is exerted at the inside of the pitcher wall. P3 is the matric potential at a distance R3 from the centre line of the pitcher. It can be a measured value or a designed maximum permissible value to allow in the root zone at that radius.

C is an exponential constant, which describes the unsaturated hydraulic conductivity curve under varying soil moisture tensions, found for a specific soil in relation to the saturated hydraulic conductivity (K_o). Both values can be found though experiments and curve fittings, but since this is difficult and time consuming can also be taken for typical soils from Table No. 6 or from published results e.g. as summarized for 39 soils by AMOOZEGAR-FARD et al.(1984). A third, more practical way which was adopted throughout this project, was to determine the saturated hydraulic conductivity (K_o) through measurements and to us a representative value of C for a particular soil (see also Fig.3).

Kp is the saturated hydraulic conductivity for the pitcher (material) and should be found through experiments. It is assumed that the flow is always saturated. This forms an important part for the understanding of the pitcher behaviour and the water releases under varying potentials and is therefore explained in more detail.

Saturated Flow Through Pitcher Walls :

Flow through the pitcher wall into the adjacent soil can be considered to be the flow though a stratified soil, from a soil of very low hydraulic conductivity (pitcher wall) to a soil of high hydraulic conductivity. BAVER et al. (1972) state that the effect of hydraulic conductivity upon flow is the greatest in such soils and that even when a steep hydraulic gradient exists flow could be nearly zero when large and nearly empty pores with small hydraulic conductivities (which is the fact under dry soil conditions) are dominating. They further state that even when the potential gradient across the wetting front would be of the magnitude of -100 cm in the fine low conducting material to -1000 cm or even -10000 cm in the coarse high conducting sand (soil), the flow could still be nearly zero due to little contact between grains and a small cross-sectional area of liquid flow. Before any relevant flow can occur the potentials in the lower conductivity soil (pitcher wall) must rise to nearly zero before pores can fill and create a higher hydraulic conductivity and hence a larger flow [8]. It may therefore be stated that the flow in the pitcher wall is saturated or close to saturation. This would explain why MONDAL (1974) recommends to "tramp" down the soil after lose materials were mixed into the soil around pitchers.

Graphical Solution for the Determination of P2 :

By knowing the potentials at the outside pitcher wall P2, q could be determined through equation {12}.

P2 can be found by solving equation {14} graphically plotting the LHS (left hand side) and RHS (right hand side) of the equation on the y-axis against different values of P2 on the x-axis. The cross point of the two curves is where LHS and RHS of the equation become equal and hence the appropriate value for P2 can be found on the x-axis. One example for the graphical determination of P2 for the glasshouse situation is given in Fig. 10.

Flow Rate Through Pitcher :

The flow rate (Q) through the pitcher can now be determined by solving equation {12} and finding the flux through the pitcher which then has to be multiplied by the height of the cylindrical pitcher to obtain the flow rate Q in m^3/day. The flow rate is therefore:

$$Q = \frac{2 \pi Kp}{\ln R2/R1} * h * [P2 - P1] \quad \{15\}$$

By the way the integration was done this results in a negative flow, which gives a flow into the pitcher. By changing the sign the positive flow rate for that particular situation is obtained.

4.3 Model Inputs and Use

The model structure with its input an output components is shown in a diagram in Fig. 9.

The model may be used to solve specific problems manually but has its major advantage in the possible use of a computer which speeds up the process of iteration and facilitates the change of variables. In this case a spreadsheet was used to compute the results which showed capabilities of handling the problem on a smaller scale. The development of a computer program would be advisable when more data are to be handled.

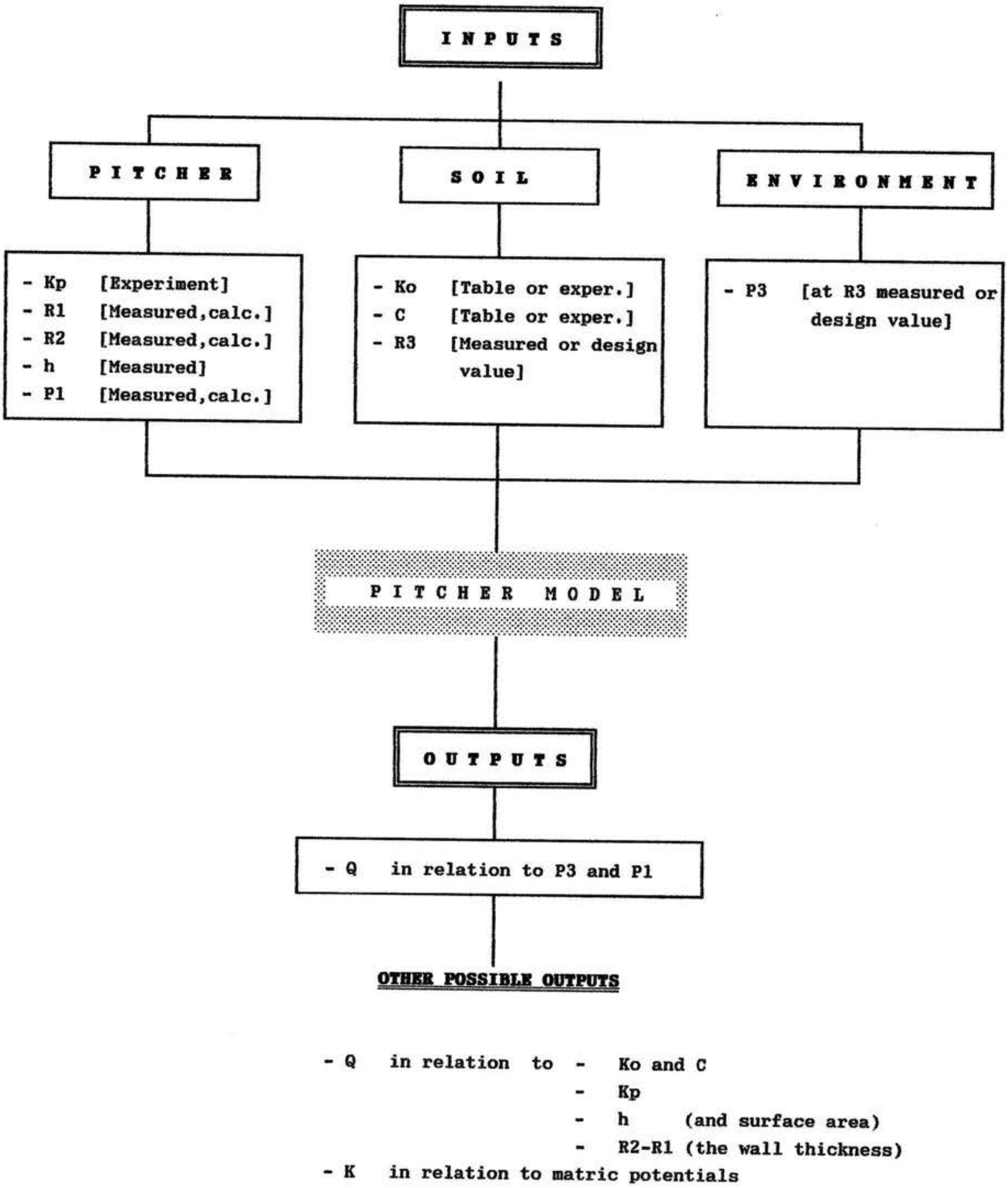
4.4 Results from the Model

4.4.1 Inputs from the Glasshouse Experiment

The model was run on a spreadsheet with the following standard inputs from the glasshouse- and from previous experiments:

Ko	[SOIL saturated K]	=	0.31000	(m/day)
C	[EXPONENT,Table 6]	=	18	(m^{-1})
Kp	[POT saturated K]	=	0.00034	(m/day)
R1	[RADIUS to inside wall]	=	0.0630	(m)
R2	[RADIUS to outside w.]	=	0.0700	(m)
R3	[RADIUS to Soil Point]	=	0.1400	(m)
L	[WALL THICKNESS R2-R1]	=	0.0070	(m)
P1	[POTENTIAL inside wall]	=	0.0900	(m)
P2	[POTENTIAL outside w.]	=	Different	(-m)
P3	[POTENTIAL in Soil]	=	Different	(-m)
R3-R2	[Tensiometer to Wall]	=	0.0700	(m)

Fig. 9: Diagram of the pitcher model structure with its input and output components



The radius from the centre line to the outside wall (R2) was found by averaging the radii of the different pitcher segments. R1 was found by subtracting the average wall thickness from R2 and R3 by adding the tensiometer distance to R2.

P3, the potentials in the soil, have been varied from 0 to - 1 m as no changes in flow was apparent under lower matric potentials.

P2 values, the potentials at the outside wall were found graphically in the way shown in Fig. 10.

4.4.2 Results of the Model in Comparison with the Pitcher Performance

The model flow rates (l/day) for pitcher No. 3 under decreasing matric potentials are given in Fig. 11. Under wet conditions a minimum flow rate of 0.33 l/day was caused by the hydrostatic head exerted on the pitcher wall by the water level in the pitcher. Under decreasing matric potentials the flow increased steeply but already levelled out at - 0.2 m and came to its maximum of about 1 l/day at -0.55 m. This indicated that the soil moisture tension had only an influence in the wetter side when the majority of the pores in the soil were still filled with water.

Under decreasing potentials the system came to its upper equilibrium where the soil tension could still be passed further on to the pitcher wall, through minor pores and channels, but the smaller cross sectional area of flow didn't allow the transmission of larger flow rates.

A comparison between the model prediction and the values obtained in the glasshouse experiment has to be questioned. The matric potentials measured were unreliable through breakdowns and refilling but reliable readings were obtained from the daily seepage rates. Three day averages were included in the graph in Fig. 11 together with the initial single values (on the y-axis) during the period when no matric potentials could be estimated but the potentials were expected to be low due to the very dry soil. Further on the right hand y-axis the flow rate under free air condition is included when the pitcher was placed outside the soil.

One conclusion which might be drawn from this particular experiment is that the model predicted a reasonable range of flows. Even it failed to predict precise flows for given matric potentials it didn't give unrealistic values especially in the upper and lower ranges.

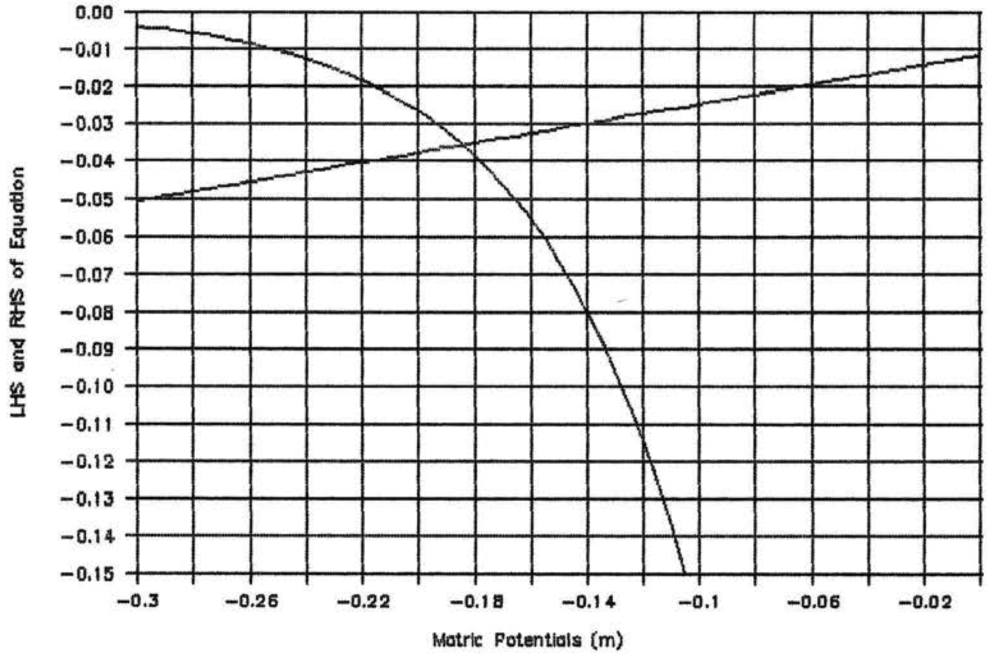


Fig. 10: **Example of the graphical solution of equation {14}; LHS and RHS of equation under matric potentials of - 0.4 m.**

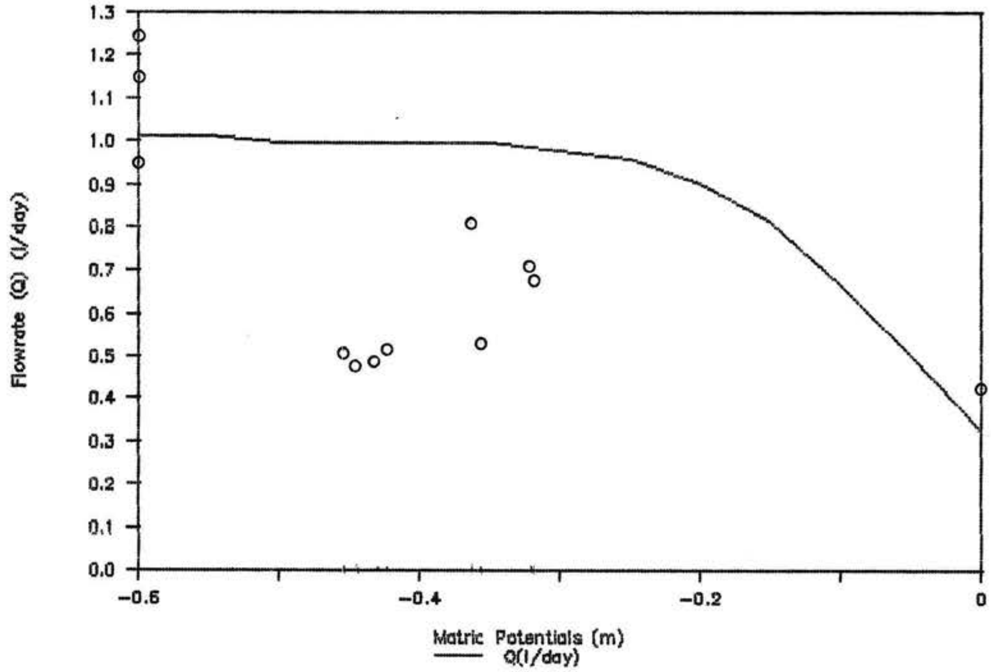


Fig. 11: **Model flow prediction under varying matric potentials in comparison with values found from the experiment**

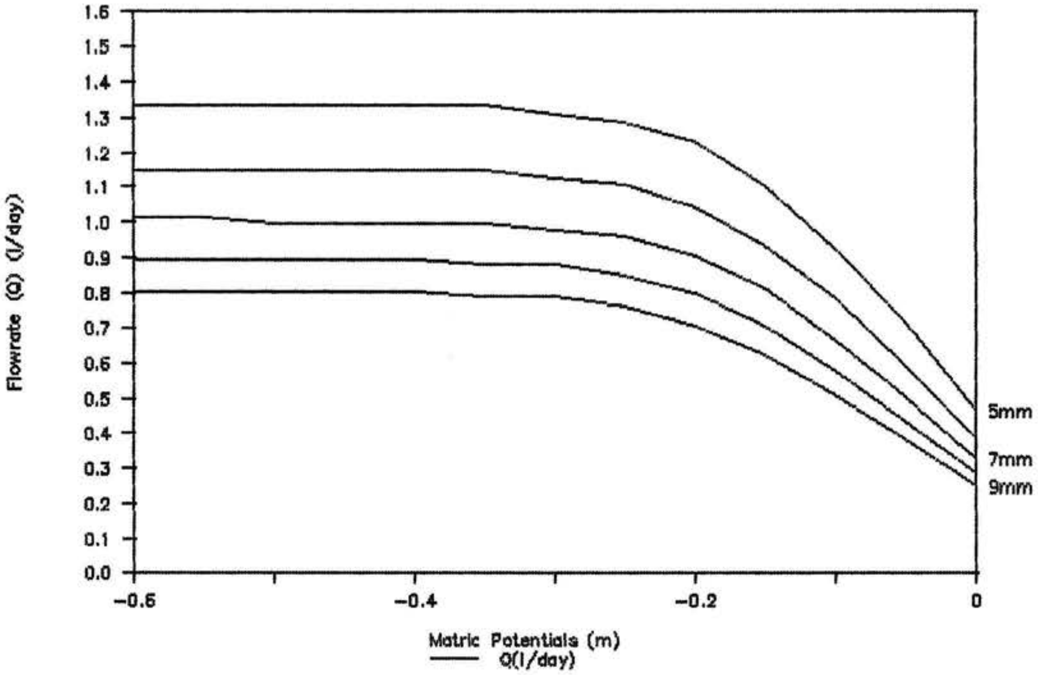


Fig. 12: Model flow prediction for pitchers of different wall thicknesses; standard experimental setting = 7 mm

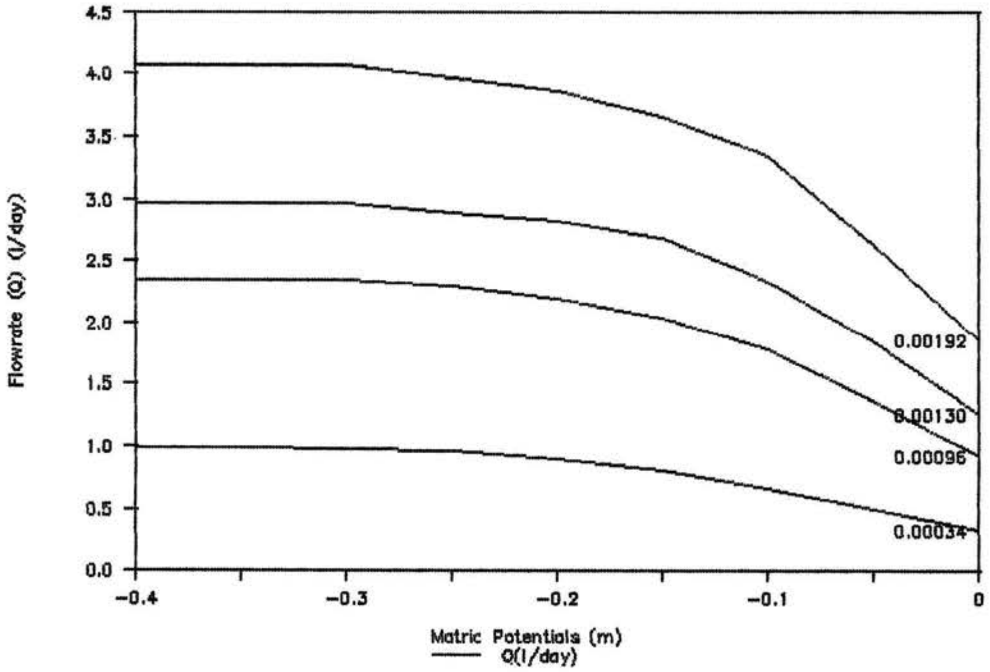


Fig. 13: Model flow prediction for pitchers of different hydraulic conductivities; standard experimental setting = 0.00034 m/day

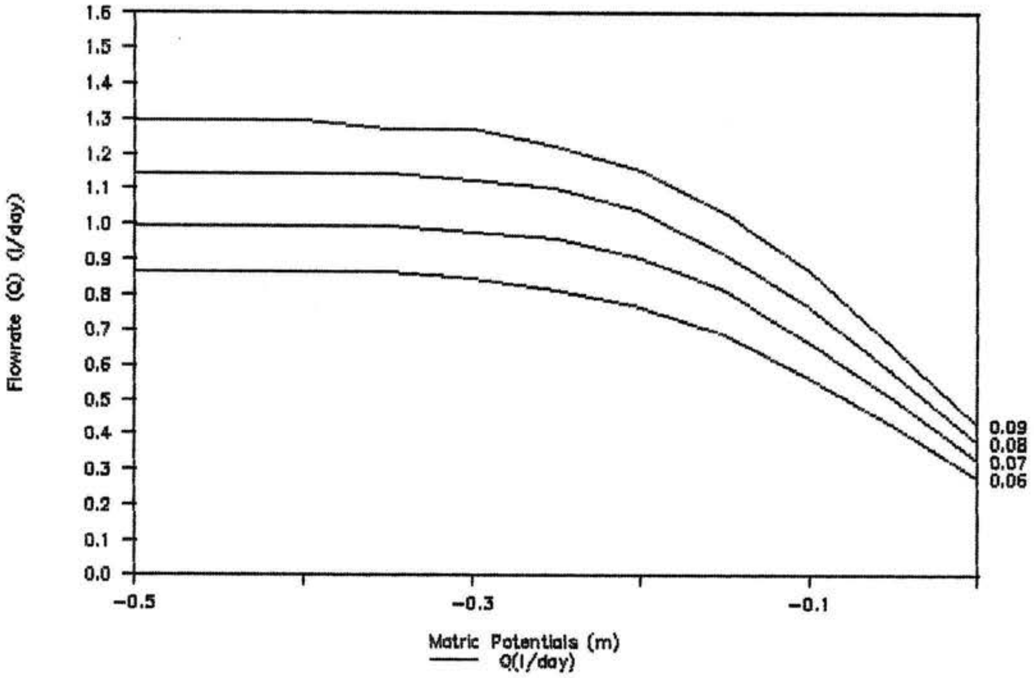


Fig. 14: **Model flow prediction for pitchers of different radii to outside wall (R2); standard experimental setting = 0.07 m**

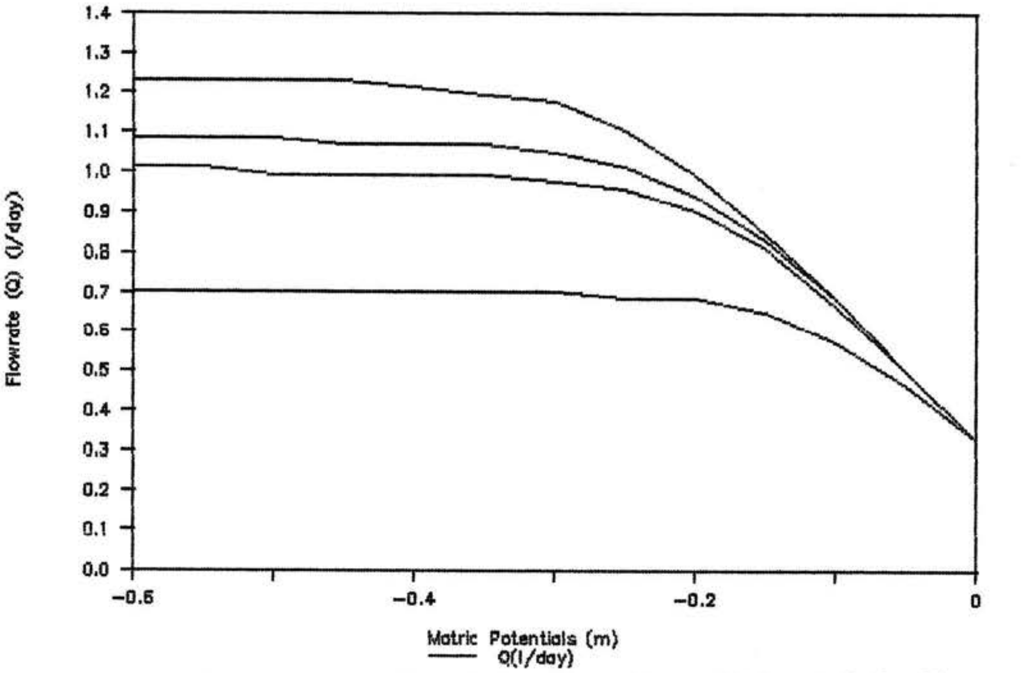


Fig. 15: **Model flow prediction for pitchers in soils of different hydraulic conductivities; standard experimental setting = 0.310 m/day; from bottom to top: 0.049 m/d, 0.310 m/d, 0.480 m/d, 1.151 m/d**

4.4.3 Sensitivity of the Model to Input Changes

The model inputs consisted of variables which were susceptible to errors through measurements and assumptions made. The sensitivity of the model changes in input values was examined for four variables in comparison with the standard curve shown in Fig. 11.

The Wall Thickness :

The standard average wall thickness of the pitcher was calculated to be 7 mm. Irregularly shaped pitchers which were thrown on a wheel are naturally variable to changes in wall thickness. A slight input change in the model by only ± 1 mm may cause a change of 5 % to 20 % in the seepage rates at maximum tensions (Fig. 12).

The Hydraulic Conductivity of the Pitcher Wall :

The saturated hydraulic conductivity of the pitcher was compared with those published by SILVA (1985) and OLGUIN & SANTOS (1977). A rise of K from 0.00034 m/day to 0.00096 would cause an increase in daily flows from 1 l to about 2.3 l. This is illustrated for four different K values in Fig. 13.

The Pitcher Diameter :

Another property of the pitcher is its size which was changed in the radial dimension. Increasing the radius by 1 cm would increase the flow by about 15 % . This is shown for radii of 0.06 m to 0.09 m in Fig. 14.

The Hydraulic Conductivity of the Soil :

During the hydraulic conductivity measurements of the glasshouse soil 3 values were stated (Table No. 7) which are plotted in Fig. 15 (top 3 curves) together with a low K value for a silt loam. The curves, starting at the top, represent flow rates in soils of saturated hydraulic conductivities of 1.15 m/day, 0.48 m/day, 0.31 m/day and 0.049 m/day. Just by using the K value for the undisturbed sample would have given a 20 % higher prediction of the maximum seepage rate.

4.4.4 Input Sensitivity, Experimental Results and Main Sources of Errors

Comparing Fig. 11 with the graphs in Figures 12 to 15 it can generally be stated that small changes in inputs caused remarkable changes in the flow rates out of the pitcher. The different possible sources of errors can be quite easily detected from the graphs. When comparing the graphs it is noticed that changes in inputs cause a general change in the magnitude of the output while the shape of the graphs remain basically the same. The scatter of the observed points in Fig. 11, in comparison with the model results, is therefore more expected to have its origin in the data collection in the glasshouse. The readings which were unreliable due to break downs and refilling, and the location of the tensiometers which were placed too low to be representative are believed to be the main sources of errors comparing with the model input.

5. Experimental Results and Discussion

5.1 The Pitcher and its Properties

During the first experimental procedure the saturated hydraulic conductivity of 13 pitchers was determined to range from 0.0006 cm/day to 0.533 cm/day. In comparison with hydraulic conductivities published (see Table No. 3), being successfully used in experiments only one pitcher (No.3) was found to cover that range. From the remaining, 9 pitchers were too low and only 3 exceeded the maximum published value of 0.1368 cm/day by RENDON (1988), with 0.3685 cm/day to 0.5333 cm/day. The 9 pitchers only reached about 3 % to 44 % of the minimum value published of 0.024 cm/day by OLGUIN and SANTOS (1977).

The main objectives of the pitcher material and its hydraulic conductivity is to form a buffer between water and soil. It is designed to prevent excessive water seepage from the pitcher while still permitting enough water flow to meet crop water requirements.

The saturated hydraulic conductivity forms an important property of the pitcher material. A comparison and evaluation of hydraulic conductivities of pitchers must be made in the context of other properties and factors which are: The wall thickness, the surface area of the pitcher, the permeability of the soil and whether a positive head is applied or the pitcher would work predominantly on the principles of suction.

Applying a hydrostatic pressure, even only of the magnitude of 0.3 m, would increase the seepage rates remarkably but would also diminish the effects of varying suctions on the seepage rates like as found by SILVA et al. (1985). A comparison of different water use efficiencies for corn (Zea mays L.) under 6 different irrigation methods was published by SILVA et al. (1987). It was found that porous capsules under suction had the highest water use efficiencies of 2.7 kg/m^3, followed by capsules under slight hydrostatic pressure of 35 mbar with 2.0 kg/m^3, trickle irrigation with 1.4 kg/m^3 and open furrow, sprinkler and closed furrows with 1.0 kg/m^3, 0.9 kg/m^3 and 0.7 kg/m^3 respectively.

These results of high water use efficiencies suggest that a design should therefore be orientated at the use of pitchers to work predominantly under suction. Out of practical reasons it might be still necessary to apply a very low pressure to ensure the refilling process in a pipe connected system as air entry through joints would prevent the water been drawn towards the pitchers. A hydrostatic head of only 35 mbar was found by SILVA (1987) to be enough. The author even suggests that a lower pressure should be possible to use under level field conditions to ensure the effective use of the suction forces.

The evaluation of the performance of pitcher No. 3, with a hydraulic conductivity of 0.034 cm/day and worked under the principles of suction, may be done by a simplified model calculation.

The daily seepage rates were found to vary between about 1.2 l/day when implemented under very dry soil conditions, and 0.5 l/day when the equilibrium was reached. Assuming an effective soil surface and cropping area of 15 cm around the pitcher or 0.124 m^2, a small vegetable crop with an ET crop of 6.5 mm/day and a water use efficiency of 90 % under no rain conditions. The water requirements were estimated to be 0.890 l/day. Comparing with the observed flow rates this would lie within the supply capacity of the pitcher. By using a crop which would cover a larger area, assuming 25 cm around the pitcher and the same ET_{crop}, about 2 l/day would be necessary to meet the crop water requirement. A different pitcher with a higher flow rate or the use of a hydrostatic head would be necessary.

A second simplified model calculation allows the evaluation of the change in hydraulic conductivity of the pitcher to meet the estimated need of 2 l/day. By using Darcy's equation {1} and rearranging for dh to find the change in head over the pitcher wall for a known flow rate Q (1.2 l/day) and values of K, A and l taken from Table No. 5.

From Darcy rearranged for dh:

$$dh = \frac{Q * dl}{A * K} \qquad \{16\}$$

Where:

Q	=	Flow rate	(m^3/day)
K	=	Hydraulic conductivity or proportionality constant of the porous medium	(m/day)
A	=	Surface area of the pitcher	(m^2)
dh	=	Change in head over the wall	(m)
dl	=	Wall thickness of pitcher	(m)

By using the values for pitcher No. 3 the change in head (dh) over the pitcher wall was estimated to be 0.33 m. Assuming for estimation purposes that dh is independent from the hydraulic conductivity of the pitcher, equation {16} is rearranged for K with the input of Q as the design value of 2 l/day. Using the same pitcher size and wall thickness a saturated hydraulic conductivity of about 0.057 cm/day was estimated to be necessary to meet the maximum requirements of 2 l/day.

Generally it can therefore be said that hydraulic conductivities for pitchers working solely under suction should be higher than 0.034 cm/day assuming the above conditions and taking further into account a larger desirable cropping area around the pitcher. Further it has to be noted that to achieve a wider horizontal spread also higher flow rates would be necessary as shown by JOBLING (1974) in Fig. 1. Higher flow rates further require bigger storage capacities for the pitchers when a daily replenishment is assumed. Up to now, a constant water level and hence a small but important constant head was assumed, regardless of the flow rates from the pitcher. A falling water level causes a decrease in head and conducting surface area. This is irrelevant when an automatic refill is provided otherwise a compensation through increase in pitcher surface area, volume and hydraulic conductivity is required.

5.2 Interaction between the Pitcher and its Environment

Pitcher irrigation is claimed to be an autoregulating system. OLGUIN et al. (1976) and SANTOS (1977) found an autoregulation by the crop water demand which was also observed by SILVA et al. (1987) to be more relevant for capsules with the smallest hydrostatic head during periods of higher crop water demands.

However he couldn't relate the water releases under various treatments of hydrostatic head to the evaporation from the Class A Pan.

During the glasshouse experiment the interaction between the pitcher and its environment was studied. Daily seepage rates from the pitcher were compared with matric potentials at 3 radial distances and the open pan evaporation. Due to breakdowns and the refilling tensiometer readings could not be considered to be reliable. It should be noted that the tensiometers were installed too low to detect any major changes in matric potentials and that a depth of 5 cm to 10 cm would have been more appropriate in this case.

Still a general tendency could be observed that a drop in matric potentials increased the seepage rates from the pitcher shown in Fig. 6.

After the wetting up process when the seepage rates had come to an equilibrium the seepage rates were correlated against the pan evaporation for the time period of 19 days. In contrast to SILVA et al.(1987), it was found that the pan evaporation significantly influenced the seepage rates from the pitcher at the 0.001 level. An increase in evaporation caused an increase in seepage rates. It can therefore be stated that there is an positive interaction between the environment and the seepage rate out of the pitcher. This implies that the evapotranspiration causes a drop in soil moisture which then causes a drop in matric potentials which finally leads to a steeper hydraulic gradient across the pitcher wall and hence to an increase in seepage from the pitcher until the equilibrium is reestablished.

SILVA et al. (1987) examined the evaporation and seepage rates over a period of more than 2 months. It is not clear whether a distinction was made between the wetting up period and the equilibrium stage. In addition, a crop was grown and capsules were used under pressure which diminished the effect of matric potentials. It would have been more appropriate to examine the correlation of the seepage rates against the crop water requirements by using capsules with low or no hydrostatic head. This might be reasons for the differences in results.

Based on the experimental results and the results published in the literature, pitcher irrigation has therefore to be considered being a system with capabilities of autoregulating the water releases according to the soil moisture status under the following condition: The system has to work under the principles of suction or under very low hydrostatic head of about 0.35 m or less.

5.3 The Pitcher Model

A two dimensional pitcher model was developed based on Darcy's law. The flow from a cylindrical-type source though the pitcher wall was assumed to be saturated where the hydraulic conductivity in the soil changed under decreasing matric potentials and was described by an empirical relationship. The model allows the input of pitcher and soil properties, design matric potentials at a distance from the pitcher and positive heads inside of the pitcher.

The conditions of the glasshouse experiments were used as inputs for the model. In comparison with the results from the experiment it was found that the model predicted a reasonable range of values especially for the top (1 l/day) and bottom range (0.35 l/day) for that particular situation. However it was not possible to predict precise flows for given matric potentials of that experiment.

The deviation of the observed points in Fig. 11 from the model results, is expected to have its origin in the data collection of unreliable readings and inappropriate positioning of tensiometers. In addition the inputs from the pitcher were an approximation to the model due to different pitcher shapes.

The pitcher model showed sensitive responses to slight input changes which were examined for wall thicknesses, pitcher sizes (radius) and hydraulic conductivities of pitchers and soil and illustrated in Fig. 12 to 15. It further showed that the effect of matric potentials on seepage rates was only apparent in a narrow span between 0 and about -0.5 m. The major changes occurred at matric potentials between 0 and -0.2 m. This would match with the results from SILVA et al. (1987) who reported that the effect of suction was not clearly apparent anymore when hydrostatic heads of more than 0.35 m were applied. The positive head dominates over the effects of matric potentials.

Generally speaking the pitcher model based on theoretical and empirical analysis showed promising results which followed the line of results published and personal observations made by the author during previous practical work with pitchers. However a final evaluation of the model against results from field experiments has to be done in a separate field experiment with more comparable inputs especially of the pitcher shape and appropriate tensiometer readings and placement.

6. Conclusions

No general recommendations for the design of pitchers for irrigation purposes can be given.

The pitcher with its porous wall is linked into the soil-water-plant-atmosphere continuum forming a lower conducting layer in a stratified soil. The three main interacting components are the pitcher, the soil and the environment which have to be taken into account when designing pitchers for specific site conditions.

The main pitcher properties influencing the performance are the saturated hydraulic conductivity, the surface area, the volume and shape.

Saturated and unsaturated flows in the soil linking the pitcher wall and the environment defined as climate and crop.

After the equilibrium stage had been established, evaporation highly significantly influenced the seepage rates from the pitcher at the 0.001 level. An increase or decrease in evaporation caused an increase or decrease in seepage rates from the pitcher (Fig.7)

The pitcher model developed allowed the simulation of the interacting components of pitcher irrigation with the previously specified inputs. It was based on theoretical and empirical analysis of water fluxes through porous media under saturated and unsaturated flow conditions from a cylindrical type source.

A final evaluation of the model against results from field experiments was not conducted during this project and has to be done in a separate field experiment.

7. Recommendations for Further Research

The theoretical base of a pitcher flow model was established and needs evaluation. The hydraulic conductivity of pitchers was established as being the governing property for the satisfactory functioning of pitchers. However, the achievement of a designed value is difficult and no clear applicable and repeateable recommendations are given.

Both objectives can be combined for one future research project which may lead to useful recommendations for the practical application of pitcher irrigation for different site conditions.

1. Many experiments have been conducted with the objective to create a porous pitcher material with the right porosity. A variety of 'exotic' materials have been mixed with little information about the mixing proportions which would allow the reproduction of pitchers with a certain hydraulic conductivity. Besides many of the materials used are difficult to get hold of. Promising results were reported from BARTH (1989) using sand and clay in different proportions to increase the porosity. Sand and clay are widely available and easy to mix homogeneously. Sand further prevents the pitcher from cracking during drying and firing. It is therefore recommended to produce a series of the same sized cylindrical pitchers with different mixing proportions of a representative sand and clay, orientating at the proportions reported from SILVA et al. (1984) and shown in Table No. 2. The firing temperature should not be less than 850 °C. After finding the hydraulic conductivity values under different mixing proportions, a pitcher with a design K value can be easily reproduced.

2. The pitcher model may be used to evaluate beforehand the effects of different input changes to establish theoretical design criteria for a pitcher suiting the specific site and crop conditions chosen. Using the above pitchers of the same sizes but with different hydraulic conductivities the model can then be evaluated against field data by monitoring seepage rates, climate data and changes in matric potentials.

The main objectives of future research should be the establishment of design criteria and recommendations which allow the directed application of pitcher irrigation to practical field conditions.

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APPENDIX : A

Matric Potentials Around Pitcher No. 3

Matric Potentials 2 cm from Pitcher Wall

DATE	T1 (cm)	T2 (cm)	T3 (cm)	T4 (cm)	AVG of T1-T4 (cm)	STD of T1-T4 (cm)
26.07.90	-26.8	-28.0	-30.5	-25.5	-27.7	1.9
27.07.90	-25.5	-26.8	-26.8	-30.5	-27.4	1.9
28.07.90	-26.8	-28.0	-28.0	-29.3	-28.0	0.9
29.07.90	-24.2	-28.0	-28.0	-30.5	-27.7	2.2
30.07.90	-28.0	-29.3	-30.5	-30.5	-29.6	1.0
31.07.90	-28.0	-28.0	-29.3	-31.8	-29.3	1.5
01.08.90	-31.8	-34.3	-31.8	-35.6	-33.4	1.6
02.08.90		-34.3	-36.8	-38.1	-36.4	1.6
03.08.90		-35.6	-39.4	-40.6	-38.5	2.1
04.08.90	-19.2	-35.6	-39.4	-41.9	-34.0	8.8
05.08.90	-19.2	-35.6	-39.4	-41.9	-34.0	8.8
06.08.90	-17.9	-33.1	-36.8	-36.8	-31.2	7.8
07.08.90	-17.9	-34.3	-38.1	-41.9	-33.1	9.1
08.08.90	-19.2	-35.6	-38.1	-41.9	-33.7	8.7
09.08.90	-19.2	-38.1	-40.6	-44.4	-35.6	9.7
10.08.90	-20.5	-40.6	-41.9	-43.1	-36.5	9.3
11.08.90	-20.5	-39.4	-41.9	-44.4	-36.5	9.4
12.08.90	-28.0	-41.9	-46.9	-46.9	-40.9	7.7
13.08.90	-28.0	-41.9	-46.9	-48.2	-41.3	8.0
14.08.90	-24.2	-39.4	-45.7	-45.7	-38.7	8.8
15.08.90	-23.0	-36.8	-43.1	-41.9	-36.2	8.0
16.08.90	-21.7	-40.6	-43.1	-45.7	-37.8	9.4
17.08.90	-21.7	-41.9	-46.9	-46.9	-39.4	10.4
18.08.90	-23.0	-41.9	-46.9	-46.9	-39.7	9.9
19.08.90	-26.8	-43.1	-45.7	-46.9	-40.6	8.1
20.08.90	-30.5	-48.2	-46.9	-50.7	-44.1	7.9

APPENDIX : B

Matric Potentials Around Pitcher No. 3

	Matric Potentials 7 cm from Pitcher Wall					
DATE	T5 (cm)	T6 (cm)	T7 (cm)	T8 (cm)	AVG of T5-T8 (cm)	STD of T5-T8 (cm)
26.07.90	-26.8	-427.4		-88.2	-180.8	176.2
27.07.90	-31.8		-7.6	-32.8	-24.1	11.7
28.07.90	-57.0	-33.1	-39.1	-26.5	-38.9	11.4
29.07.90	-53.2	-34.3	-35.3	-29.0	-38.0	9.1
30.07.90	-31.8	-41.9	-34.1	-29.0	-34.2	4.8
31.07.90	-33.1	-35.6	-37.8	-30.3	-34.2	2.8
01.08.90	-10.4	-28.0	-40.4	-32.8	-27.9	11.0
02.08.90	-4.1	-40.6	-41.6	-36.6	-30.7	15.5
03.08.90	-2.8	-26.8	-41.6	-37.8	-27.3	15.1
04.08.90	-24.2	-44.4	-45.4	-44.1	-39.5	8.8
05.08.90	-24.2	-28.0	-42.9	-42.9	-34.5	8.5
06.08.90	-25.5	-23.0	-42.9	-41.6	-33.2	9.1
07.08.90	-26.8	-46.9	-42.9	-42.9	-39.9	7.7
08.08.90	-28.0	-49.4	-45.4	-42.9	-41.4	8.1
09.08.90	-26.8	-50.7	-46.7	-45.4	-42.4	9.2
10.08.90	-26.8	-52.0	-47.9	-46.7	-43.3	9.8
11.08.90	-26.8	-52.0	-49.2	-47.9	-44.0	10.0
12.08.90	-29.3	-54.5	-53.0	-49.2	-46.5	10.1
13.08.90	-30.5	-54.5	-50.4	-50.4	-46.5	9.3
14.08.90	-30.5	-52.0	-46.7	-46.7	-44.0	8.0
15.08.90	-28.0	-49.4	-45.4	-45.4	-42.1	8.3
16.08.90	-28.0	-52.0	-47.9	-46.7	-43.6	9.2
17.08.90	-28.0	-53.2	-47.9	-47.9	-44.3	9.6
18.08.90	-29.3	-52.0	-47.9	-46.7	-44.0	8.7
19.08.90	-31.8	-53.2	-50.4	-47.9	-45.8	8.3
20.08.90	-33.1	-57.0	-55.5	-53.0	-49.6	9.7

APPENDIX : C

Matric Potentials Around Pitcher No. 3

	Matric Potentials 12 cm from Pitcher Wall					
DATE	T9 (cm)	T10 (cm)	T11 (cm)	T12 (cm)	AVG of T9-T12 (cm)	STD of T9-T12 (cm)
26.07.90						
27.07.90	-3.8	-51.7			-27.8	23.9
28.07.90	-40.4	-45.4	-42.9	-31.5	-40.0	5.2
29.07.90	-40.4	-47.9	-58.0	-108.4	-63.7	26.6
30.07.90	-37.8	-46.7	-41.6	-40.4	-41.6	3.2
31.07.90	-36.6		-92.0	-54.2	-60.9	23.1
01.08.90				-54.2	-54.2	0.0
02.08.90	-37.8	-31.5	-102.1	-53.0	-56.1	27.7
03.08.90	-2.6	-27.8		-53.0	-27.8	20.6
04.08.90	-3.8	-41.6	-17.7	-54.2	-29.3	19.7
05.08.90	-3.8	-27.8	-27.8	-50.4	-27.4	16.5
06.08.90		-24.0	-45.4	-44.1	-37.8	9.8
07.08.90		-41.6	-44.1	-47.9	-44.6	2.6
08.08.90		-31.5	-44.1	-49.2	-41.6	7.4
09.08.90	-20.2	-27.8	-44.1	-47.9	-35.0	11.4
10.08.90	-30.3	-49.2	-44.1	-51.7	-43.8	8.3
11.08.90	-31.5	-39.1	-42.9	-54.2	-41.9	8.2
12.08.90	-32.8	-31.5	-46.7	-55.5	-41.6	10.0
13.08.90	-34.1	-50.4	-44.1	-58.0	-46.7	8.8
14.08.90	-31.5	-37.8	-39.1	-54.2	-40.7	8.3
15.08.90	-29.0	-32.8	-35.3	-51.7	-37.2	8.7
16.08.90	-31.5	-31.5	-36.6	-53.0	-38.2	8.8
17.08.90	-32.8	-31.5	-36.6	-54.2	-38.8	9.1
18.08.90	-32.8	-30.3	-34.1	-53.0	-37.5	9.0
19.08.90	-8.9	-54.2	-46.7	-54.2	-41.0	18.8
20.08.90	-15.2	-56.7	-51.7	-59.3	-45.7	17.8

APPENDIX : D

Seepage Rates and Pan Evaporation

DATE	SEEPAGE -Pitcher- -Q- (l/day)	EVAPO. A-PAN (mm/day)
24.07	1.252	
25.07	1.153	
26.07	0.959	3.84
27.07	0.864	2.08
28.07	0.863	3.52
29.07	0.786	3.24
30.07	0.662	2.16
31.07	0.720	4.35
01.08	0.749	6.22
02.08	0.692	4.88
03.08	0.702	6.79
04.08	0.649	6.47
05.08	0.568	4.55
06.08	0.510	4.22
07.08	0.488	3.72
08.08	0.496	3.60
09.08	0.535	4.88
10.08	0.510	4.35
11.08	0.502	4.18
12.08	0.534	5.67
13.08	0.490	3.93
14.08	0.477	1.81
15.08	0.484	
16.08	0.518	3.62
17.08	0.497	3.05
18.08	0.478	
19.08	0.443	1.46
20.08	0.510	3.23

REGRESSION OUTPUT
Seepage Rates - Pan Evaporation

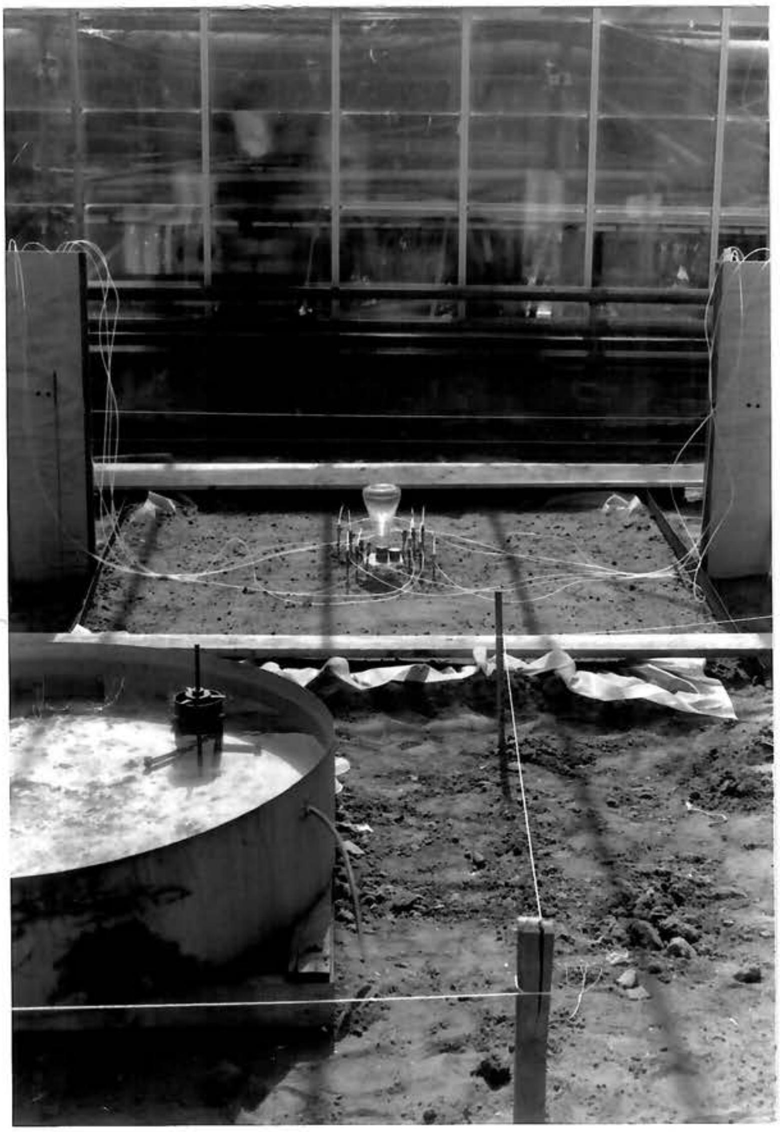
Regression Output:		
Constant		0.3460832
Std Err of Y Est		0.0649999
R Squared		0.5494568
No. of Observations		19
Degrees of Freedom		17
X Coefficient(s)	0.0495728	
Std Err of Coef.	0.0108873	
r		0.7412535

RESULT for values from the 31.07 - 20.8

Without values from the 15 th a. 18 th A

Appendix : E

Illustration of the Project Area



APPENDIX : F

Illustration of the Pitcher with Tensiometers and the Constant Water Level and Flow Rate Monitoring Device