

**IMPACT OF EMITTER CLOGGING ON THE HYDRAULIC  
PERFORMANCE OF DRIP IRRIGATION SYSTEM**

Thesis submitted in part fulfillment of the requirements for the degree of

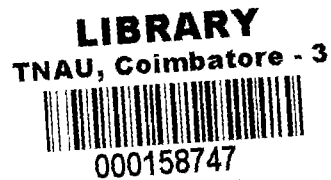
*Doctor of Philosophy in Soil and Water Conservation Engineering*

to the Tamil Nadu Agricultural University, Coimbatore.

By

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COIMBATORE – 641 003**

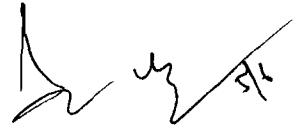
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**CERTIFICATE**

This is to certify that the thesis entitled “**IMPACT OF EMITTER CLOGGING ON THE HYDRAULIC PERFORMANCE OF DRIP IRRIGATION SYSTEM**” submitted in part fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY** in **SOIL AND WATER CONSERVATION ENGINEERING** to the Tamil Nadu Agricultural University, Coimbatore is a record of *bonafide* research work carried out by Mr. **K. SUBRAMANIAN** under my supervision and guidance and that no part of this thesis has been submitted for the award of any other degree, diploma, fellowship or other similar titles or prizes and that the work has not been published in part or full in any scientific or popular journal or magazine.

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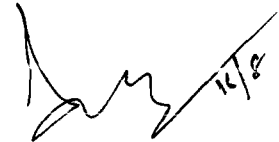


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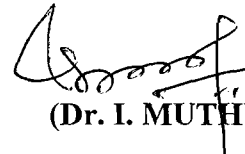
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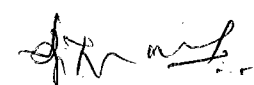
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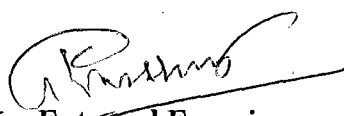
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Coimbatore

  
5/6/2002  
**(K. SUBRAMANIAN)**

*Abstract*

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## ABSTRACT

### IMPACT OF EMITTER CLOGGING ON THE HYDRAULIC PERFORMANCE OF DRIP IRRIGATION SYSTEM

BY

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Degree : **DOCTOR OF PHILOSOPHY in Soil and Water Conservation  
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Over exploitation of surface water resources and unscrupulous pumping of ground water have resulted in menial reserves of water with which agriculture has been becoming a real gamble. Such circumstances have now forced the farming community towards switching over to efficient water saving methods such as drip irrigation for sustaining productivity. However, emitter clogging remains a thorn in rose in most drip irrigation layouts, resulting up to 30 percent flow reduction even if the system is well maintained. The present study was contemplated to analyse the spatial and temporal distributions of emitter clogging along drip flow grids and to assess the impact of emitter clogging on the hydraulic performance of the drip irrigation system.

A three-parameter Weibull model is found to fit the temporal variations of emitter clogging along the drip flow grids while the spatial variations in emitter clogging is best fitted with normal distribution. Clogging is found to be enormous for saline water drip irrigation while it is the least for water with relatively lower salt content. Among the various drippers tested, pressure compensating emitters have exhibited good resistance against clogging as they are provided with in-built self-flushing arrangement. A curvilinear relationship is found to exist between the cumulative clogging percent and the length of the flow path inside the emitter

A computer model namely, DRIPCLOG and its sub model RANGEN were developed to simulate the drip irrigation system inflicted with emitter clogging menace and manufacturing variations. It is found that both individual and combined effect of manufacturing variations and emitter clogging on emission uniformity is significant. It can be concluded that it is safe to operate the drip irrigation system within 3 percent of coefficient of manufacturing variation without sacrificing the emission uniformity. The emission uniformity is found to be highly influenced by the coefficient of variation of clogging rather than the mean clogging.

A new equation for computing expected uniformity from three variations *viz.*, coefficient of manufacturing variation ( $CV_m$ ), emitter clogging variation ( $CV_c$ ) and hydraulic variation ( $CV_h$ ) has been developed. The Christiansen's field emission uniformity and statistical uniformity were determined for various possible clogging patterns. Both uniformity values were found to decrease with increase in coefficient of variation of emitter clogging.

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## ABBREVIATIONS

CV <sub>c</sub>	-	Coefficient of variation of clogging
CV <sub>h</sub>	-	Coefficient of variation of hydraulic pressure
CV <sub>m</sub>	-	Manufacturing coefficient of variation
DRIPCLOG	-	A computer model for evaluation of drip irrigation system inflicted with emitter clogging
dS m <sup>-1</sup>	-	Deci-Siemens per metre
EC	-	Electrical Conductivity
Emitter position		Serial number given to an emitter from the inlet of the lateral
Ha	-	Hectare
K Pa	-	Kilo Pascal
ksc, kg/cm <sup>2</sup>	-	Kilogram per square centimeter
Lateral position		Serial number given to a lateral from the end of the main
lph	-	Liters per hour
M Ha	-	Million hectare
mg /lit	-	Milligram per litre
mg L <sup>-1</sup>	-	Milligram per litre
MHM	-	Million hectare metre
mm	-	Millimetre
RANGEN	-	A computer sub model to DRIPCLOG to generate emitter coefficient (K) and emitter clogging (P) values
SDI	-	Subsurface Drip Irrigation
TDS	-	Total Dissolved Solids
TSS	-	Total Suspended Solids
µm	-	Micro metre

# *Introduction*

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## CHAPTER I

### INTRODUCTION

India has a total geographical area of 329 M ha and is bestowed with bounties of natural resources like minerals, soils, water, flora and fauna. The alarming rate of increase in human population is seriously increasing the demand on earth's limited resource of land, air and water.

Effective utilization coupled with an efficient management of water resources is a *sine quo non* to meet the increasing competition for water between agriculture and non-agriculture sectors. Agriculture sector in India has been and is likely to remain the major user of water. In India, out of a total rainfall of 1170 mm corresponding to a volume of 400 M ha-m, the total utilizable quantum is 114 M ha-m from both surface and ground water resources. With this potential, only 97 M ha is under irrigation against the total cultivated area of 145 M ha.

Tamil Nadu, which is one of the water starving States, receives an annual rainfall of 925mm only, less than the country's average. In Tamil Nadu the irrigated area at the maximum is 3.7 M ha only against the total cultivated area of 6.5 M ha. Therefore it is necessary to economize the use of water in agriculture to bring more area under irrigation, reduce the cost of irrigation per hectare and increase the productivity per unit area and unit quantum of water. This can be achieved only by introducing advanced water saving irrigation methods like drip irrigation with improved water management practices.

Drip irrigation is referred to as a regulated and slow application of water for longer period through evenly spaced emitters at frequent intervals of time near the root zone of the plants. Drip irrigation is gaining popularity and momentum over the past few years as it claims lot of advantages over conventional surface irrigation methods. The supremacy of drip irrigation system lies in saving of water and increasing the water use efficiency. In India, the area under drip irrigation is only 1,70,000 ha. Out of this, Maharashtra is the leading State covering 46, 000 ha under drip irrigation whereas Tamil Nadu ranks third only after Karnataka.

Ideally, a drip irrigation system is expected to supply water uniformly, so that each part of the irrigated area receives the same amount of water. However, in practice, cent percent uniformity is a difficult task to achieve owing to the pressure variations, flow turbulences, frictional losses and more realistic problems of emitter clogging. So the phrase "irrigation uniformity" actually refers to the variation or non-uniformity in the amounts of water applied to locations within the irrigated area. Significant effort in irrigation system design and management is directed towards dealing with problems related to irrigation uniformity.

Irrigation uniformity is controlled by three important factors viz., hydraulic variations, manufacturing variations and emitter clogging. Out of these factors, clogging of drip emitters, the main problem associated with drip irrigation is playing a major role in deciding the irrigation uniformity. Drip emitters usually have very small openings (0.5-1 mm), and they are vulnerable to clogging by physical materials

(such as sand/silt and suspended materials), biological organisms (roots, algae, and bacteria) and chemical precipitates.

The sediments or suspended solids and dissolved salts transported through drip tubing contribute for reduction in the operational pressure chiefly due to the clogging at the emitter points. A comprehensive knowledge on effect of water quality, emitter type and fertigation mechanisms is extremely important from the perspective of reducing clogging in the drip irrigation system. The uniformity of the drip irrigation can be kept at a higher level only if the system is maintained without any emitter clogging.

Nowadays fertigation mechanisms have become an essential component in drip irrigation systems. Fertigation may also cause variations in the performance of the drip irrigation system owing to the deposition of the precipitates of possible reactions of fertilizer chemicals with irrigation water.

Partial or complete clogging drastically affects water application uniformity and hence, crop production. The clogging mechanism appears to be a gradual build up of precipitate in the emitter passage rather than instantaneous obstruction (Hills *et al.*, 1989). Due to clogging problems, drip or trickle irrigation systems are performing at sub optimal application uniformity (Capra and Scicolone, 1998). Though advanced filters are used to trap the suspended solids in the irrigation water, dissolved salts from saline water source are still a major problem for emitter clogging. So it becomes mandatory that the system has to be operated with certain permissible level of emitter clogging.

Generally the emitter clogging resulting up to 30 percent flow reduction is often unavoidable in any drip irrigation field though it is well maintained. So it is required to study the distributions of emitter clogging over a time period between two successive de-clogging operations and its reliability against this clogging. It is also necessary to evaluate the hydraulic performance in terms of pressure profiles and uniformity of water application under such conditions. Hence the present study was formulated to analyse the impact of emitter clogging on the hydraulic performance of the drip irrigation system with the following objectives.

#### **OBJECTIVES**

1. To study the temporal and spatial variations in emitter clogging along drip flow grids
2. To assess the impact of water quality, emitter type and fertigation on clogging
3. To develop and validate a computer model for simulating drip irrigation system under manufacturing and clogging variations
4. To evaluate the hydraulic performance of the drip irrigation system in relation to the emitter clogging patterns

*Review of Literature*

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## CHAPTER II

### REVIEW OF LITERATURE

Hydraulic gradient depicting pressure head variations along laterals, manufacturing variation and emitter clogging are responsible for varying emitter discharge all over the drip layout. An extensive collection of literature pertaining to drip irrigation hydraulics, manufacturing variations, clogging and emission uniformity was made. The review of research in the line of the objectives contemplated is summarized to facilitate devising an appropriate methodology towards accomplishing the objectives under the following sub-topics:

- Drip irrigation status
- Water quality and emitter clogging
- Fertigation and clogging
- Basic hydraulics of drip irrigation
- Advances in hydraulics of drip irrigation
- Statistical distributions for engineering problems
- Manufacturer's variations
- Pressure losses and hydraulic variations
- Hydraulics of spatially varied emitter flow
- Uniformity in trickle irrigation
- De-clogging treatments

## 2.1 Drip irrigation status

Drip irrigation is just a means of providing water within the root zone of crop at the right rate conforming to the consumptive use. In this system, only a fraction of soil surface is wetted, generally varying from 15 to 60 per cent. According to Herman (1982), drip irrigation is one of the innovative methods of irrigation, which enables slow and precise application of water and nutrients to precise locations, avoiding soil erosion and wastage of water by deep percolation, besides keeping the soil moisture at almost zero water tension for extraction by plant root system.

Drip irrigation can be used conveniently for growing vegetable crops with considerable saving in irrigation water (Bengal *et al.*, 1987). According to Nakayama and Bucks (1991), drip irrigation was considered as an emerging technology with its application limited to some special crops. Nowadays, it is used on a wide variety of crops, which were initially considered unprofitable for management under drip irrigation.

In water scarcity areas, drip irrigation is now being used in row crops such as sugarcane, cabbage, vegetables, potato, cassava, sugar beet, mulberry, cotton etc. There can be a considerable saving of irrigation water by adopting drip method since water can be applied almost precisely and directly in the root zone without wetting the entire surface area (Bafna *et al.*, 1993 and Ahlwaalia *et al.*, 1993).

Modern drip irrigation systems have now reached an area of almost two million hectares. Despite this development, its relatively high capital costs have been a major constraint in its broader application especially in developing countries. India, for example has been reported to have a very high potential for drip irrigation, which has been estimated to be 10.5 million hectares. The development of low cost drip irrigation systems has therefore been recognized as a critical need. It was found that all farmers at least doubled their irrigated area and reduced labor by half. In India with water often pumped from deep tube wells the introduction of the low cost drip system showed promising results. (Polak *et al.*, 1997)

## **2.2 Water quality and emitter clogging**

Drip irrigation is also suitable for wastewater reuse because, along with other advantages, it minimizes the risk of wastewater contact with farmers and crops. However, the performance of drip irrigation systems utilizing wastewater is mainly limited by emitter clogging. Emitter clogging is a major problem incurred in the operation of drip irrigation systems, especially when these systems utilize treated wastewater effluent stored in surface reservoirs. Due to clogging problems, most of the drip/trickle irrigation systems examined had sub optimal application uniformity. So many works have been carried out with the aim of determining parameters expressing clogging and studying the relationships between clogging and water quality.

Adin and Sacks (1991) studied the clogging factors and mechanism of blockage within three types of drippers as a basis for developing technical measures to overcome the problem. The relevant effluent constituents are defined and physical and chemical properties of the deposits in hundreds of emitters are examined, using both field and laboratory experiments. The mechanism proposed to explain the sediment build-up begins with the deposition of amorphous slimes, to which other particles adhere. The clogging rate is more affected by particle size than by particle-number density. The chemical composition of the deposits in the dripper changes with the season. Filtration prevents immediate clogging by large particles. Clogging potential may be decreased by modifying the emitter structure and by chemical pretreatment

In an experiment carried out to evaluate the performance of various types of drip irrigation emitters using wastewater, Ravina *et al.* (1992) have found that fine particulate matter agglomerated by microbial by-products and in-line developed biomass were the principal reasons for clogging. There were definable differences between emitters of various types as to their clogging susceptibility. For any particular type, the emitter with smaller discharge was always more sensitive to clogging. The clogging process generally started with emitters located at the far end of the lateral. Partial emitter clogging was more common than complete plugging.

A pilot-scale irrigation scheme was set up to investigate the causes of emitter clogging when waste stabilization pond effluents are used for drip irrigation of crops (Taylor *et al.*, 1995). During field trials over a period of two growing seasons, they have found that those emitters that operated most successfully utilized a long water-

path labyrinth to reduce flow to the required level. Clogging was shown to result from the deposition and entrapment of sand particles within the emitter labyrinth. Organic material, including pond algae, played a secondary role in the clogging process. Emitter design, rather than water quality, was the most important factor determining the degree of clogging. It was concluded that pond micro algae alone do not constitute a major hazard to the operation of drip irrigation equipment and the waste stabilization pond effluents may be safely used for drip irrigation if safeguards are adopted to prevent the contamination of laterals by sand and soil particles.

Experiments were carried out to estimate the effects of reclaimed effluent on clogging and uniformity coefficient of drip emitter (Cicero and Pumo, 1997). It is concluded that the 120-mesh filter was very sensitive to blockage. Granular filters coupled with chlorination were found to improve wastewater quality and prevent both the clogging to emitters and the reduction of water distribution uniformity.

Results from long term studies in Israel to determine the performance of various automatic filters, chlorination, length of drip lines and pumping depth on clogging of trickle irrigation emitters were reported by Schischa *et al.* (1997). Because of clogging occurring in a single emitter longer drip lines offered relative advantages, and gravel and disc filters gave a better protection of check filters. Although chlorination after every 3 days prevented clogging, large amounts of chlorine were harmful to the regulation of elastic membranes. Trickle lines supplied with water from lower pumping depths clogged less than those supplied with water from intermediate

and deeper depths. Irrespective of the amount of chlorination, water pumped from more superficial levels caused the most substantial clogging.

The results of experimental tests on drip emitters for municipal wastewater were reported by Barbagallo and Buttafuoco (1998). Nine different emitters were tested with secondary effluent even after screen filtration. They have found that emitter performance was strongly enhanced by wastewater filtration and not further influenced by chlorination. Pipe flushing at the end of the crop season and increasing water pressure did not fully clear the clogged emitters.

Capra and Scicolone (1998) have demonstrated that screen filters and large-size emitters as a clogging control measures adopted in trickle irrigation systems were not sufficient. Electrical conductivity, suspended solids, total iron, calcium, magnesium and manganese content of irrigation water can be used to classify the potential risk of emitter clogging. Chemical problems due to the precipitation of calcium carbonate are difficult to foresee. The hydrogen sulphide content seems to avoid the precipitation of calcium carbonate.

The flow rates of five types of drip lines (with emitter flow rates of 0.57, 0.91, 1.5, 2.3, and 3.5 lph) of subsurface drip irrigation (SDI) when used with lagoon wastewater were measured by Trooien *et al.* (2000). A disk filter with openings of 55  $\mu\text{m}$  (200 mesh) was used and shock treatments of chlorine and acid were injected periodically. They observed that the two lower flow rate emitter designs decreased in flow rate, indicating that some emitter clogging had occurred. The three-emitter

designs with higher flow rates showed little sign of clogging. Observations showed that the disk filter and automatic back flush controller performed adequately.

The high iron content of the water can cause considerable damage to the irrigation equipment (Alejandro *et al.*, 2001). Oxidation of the iron at the outlets of the drippers causes clogging troubles.

### **2.3 Fertigation and clogging**

Although water quality must be considered when nitrogen fertilizer is applied through a trickle irrigation system, it is less of a problem than other nutrients such as phosphorous. The injection of anhydrous ammonia and aqua ammonia into irrigation will form calcium, magnesium and phosphorous precipitates (Fabry, 1978). This can especially be serious if bicarbonate is also present in irrigation water (Roltson *et al.*, 1979).

Bar-yosef *et al.*, (1989) reported that after four years of tomato and potato plantation under surface and sub surface drip fertigation, the incidence of clogged emitters over an area of 1 ha was more than 2 percent. Chlorination during fertigation cycles is ineffective since whenever nitrogen is present in the water, the biocidal action of chlorine greatly diminishes (Brian, 1999)

### **2.4 Basic Hydraulics of drip irrigation**

Wu and Gitlin (1973) found a simple way of estimating pressure distribution along a drip line and derived the following equation.

$$\frac{dh}{dL} = s_o - s_f$$

where,

$$\frac{dh}{dL} = \text{Change of pressure with respect to length}$$

$S_o$  = Slope of the drip line, and

$S_f$  = Friction slope

Keller and Karmeli (1974) characterized the emitters by the equation

$$q = KH^x$$

where,

$q$  = Emitter discharge (lph)

$K$  = Constant of proportionality which characterizes the emitter

$H$  = Pressure head at which emitter operates (ksc)

$x$  = Exponent which is characterized by the flow regime

The value of  $X$  can be determined by plotting  $H$  versus  $q$  on log-log paper and measuring the slope of the line. They described that when  $x$  is 0, the emitter is fully pressure compensating, when  $x$  is 0.1 to 0.5, the emitter is partially pressure compensating and when  $x$  is more than 0.5, the emitter is non pressure compensating.

Wu (1975) explained the energy gradient lines for different field situations. He suggested that straight energy line can be used to design mainlines for drip irrigation

system. He reported that the optimal slope of the energy gradient line is determined as a curve little bit below the straight energy gradient line.

Wu and Gitlin (1977) developed a simplified submain chart that can be used to simplify and speed up submain design. They concluded that the total discharge was the effective and important factor for submain design.

The Darcy-Weisbach equation was employed for calculating the head losses due to friction in a trickle irrigation system as drip irrigation pipes are assumed to be hydraulically smooth (Watters and Keller, 1978).

The head loss along the drip lateral will be less than that of uniform flow. This reduction over Darcy-Weisbach head loss could be accounted by multiplying the correction factor developed for multi-outlet pipes by Christiansen (1942) and is as follows

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2}$$

Where  $m$  is the exponent of the velocity in the equation used to calculate the friction loss and  $N$  is the number of equally spaced operating outlets in the lateral.

Solomon and Keller (1978) developed expressions for the pressure head in the laterals. Histograms were drawn showing the distribution of pressure in typical drip irrigation systems. Anyoji and Wu (1987) developed statistical approach for lateral design and used total coefficient of variation as the design criteria.

A polynomial expression for the inlet discharge ( $Q_i$ ) and the inlet pressure head ( $H$ ) was developed and used to design drip irrigation system by Kang and Nishiyama (1994), which is as follows

$$Q_i = C_0 + C_1H + C_2H^2 + C_3H^3 + C_4H^4 + \dots C_nH^n$$

Where,  $C_0, C_1, C_2, C_3, C_4 \dots$  and  $C_n$  are coefficient of determination

## 2.5 Advances in hydraulics of drip irrigation

Holzapfel *et al.* (1990) presented a nonlinear optimization model for the design and management of drip irrigation systems. Decision variables are pipe diameter, pipe length, number of emitters in each lateral, number of laterals in a manifold, total number of subunits, number of subunits operating simultaneously, irrigation time per set and emitter discharge. The price effect on the results of the model shows that the cost of the system and its operation are relatively small compared with the benefit obtained. The model shows that the results do not yield the minimum cost of the system when the marginal benefit is greater than the marginal cost

Kang and Nishiyama (1996a) employed the finite-element method to analyze the pressure head and discharge distributions along laterals and submain. The golden section search was applied to find the operating pressure heads of the lateral and submain corresponding to the required average emitter discharge.

Gerrish *et al.* (1996) carried out a research to improve the design of large microirrigation systems using the finite element method and the virtual emitter system

without ignoring minor head losses due to network components. For this, a second-order partial differential equation was derived that describes the flow in a microirrigation system. This equation is solved numerically using Galerkin's formulation of the finite element method. The proposed method requires less computer time and memory usage for analysing a given microirrigation system while preserving the accuracy of the hydraulic analysis by incorporating the contributions of network components.

A similar nonlinear model for the optimum design and operation of drip irrigation systems on flat terrain was presented by Dandy and Hassanli (1996). An improvement over the earlier model, their analysis is based on dividing a field into subunits and evaluating various shift patterns and the corresponding pipe and pump sizes in order to identify a minimum cost solution. They considered an additional decision variable as the shift patterns and the irrigation time for each shift and set of subunits irrigated simultaneously.

## **2.6 Statistical distributions for engineering problems**

There is not much literature available on statistical distributions of drip system failures particularly the reliability of emitter clogging. However, fairly good number of reliability studies on farm machinery has been reported. A study on equipment reliability to estimate incidence of breakdowns, lost time and repair costs for corn and soybean farmers at Indiana and Illinois data have been presented by Hunt (1971).

Nakayama and Bucks (1981) studied the drip irrigation uniformity considering emitter clogging by generating the emitter flow by assuming as a normally distributed one. Bralts and Edwards (1983) used the normal distribution to arrive a statistical uniformity coefficient for evaluating the field drip irrigation system.

Many water resources problems that include irrigation management involve stochastic processes. Stochastic methods have been developed for data generation, forecasting and simulation. (Yen, 1988).

Weibull model has been used to represent the probability distributions of the soil moisture deficit and the critical soil moisture deficit in irrigated lands (Mukherjee and Kottegoda, 1992). Probability distribution functions are used to model the stochastic processes.

As emitter flow and emitter discharge along a lateral line can be considered to have normal distribution, the probability density function and the cumulative probability density of the normal distribution can be applied to derive equations for irrigation application efficiency, storage efficiency, deep seepage, and deficit. A simple drip efficiency, deep seepage, and deficit could be expressed only as a function of the coefficient of variation of emitter flow (Anyoji and Wu, 1994).

## **2.7 Manufacturer's variations**

The concept of manufacturer's variation of emitters was first introduced by Keller and Karmeli (1974) and latter researched by Solomon (1979). The technique

used to find the Manufacturer's variations consisted of measuring the variation of emitter flow under a constant head or pressure.

Typical values of the coefficient manufacturer's variation may range from 0.02 to 0.10, although higher values are sometimes observed. The design of emitter, the materials used in its construction and the care with which it is manufactured determine the amount of variation to be expected from any particular model of emitter (Solomon, 1979).

The manufacturing variation is defined as the ratio of standard deviation to mean emitter flow rate, measured at standard pressure and temperature, with no plugging (Solomon, 1985).

Ozekici and Sneed (1995) compared the manufacturer's rated discharges and coefficient manufacturing variation values with tested values for various online emitters. At suggested operating pressure of 100 kPa only 11 of the 17 emitters had flow rates within 10 percent to those claimed by the manufacturers. This was particularly true for the non-compensating emitters. Measured values of coefficient manufacturer's variation were higher than those specified by the manufacturers. High coefficient manufacturer's variation could result in low emission uniformities. They have concluded that design based on supplied data may deliver too little water to some plants and too much water to others.

## 2.8 Pressure losses and hydraulic variations

An experiment was carried out by Bezdek and Solomon (1978) to develop a continuous functional form, which can represent explicitly the observed relationships between Reynolds number and friction factor for trickle irrigation tubing. Two methods are examined for determining a specific function of the chosen form from empirical data: a numerical analytic technique based on least-squared errors and Newton's method and an interactive computer graphics technique.

Gillespie *et al.* (1979) have pointed out that the kinetic energy is considered to be small and neglected in a drip irrigation line. The pressure variation along a lateral line can be determined by a linear combination of energy drop by friction and energy gain (or loss) by either uniform or non-uniform slopes (Wu and Gitlin, 1979).

Mulaneh and Warrick (1987) have found that the relative error when neglecting velocity head is greater for laminar than for turbulent flow. However, the magnitude of head loss is greater for turbulent regimes. Although the errors caused by neglecting the velocity in most cases are small, the analytical solution remains relatively simple and easy to use.

Madramootoo *et al.* (1988) evaluated the hydraulic performance of five orifice type on-line emitters under laboratory conditions. Tests were performed at five operating pressures ranging from 69 to 138 kPa. Experimental discharge curves fell within  $\pm 10$  per cent of manufacturers' rated curves for all emitters. The emitter

discharge exponents were calculated and used to categorize the emitters as the pressure compensating, non-compensating and partially pressure compensating.

Hathoot *et al.* (1993) considered individual emitters for discharge and pressure estimations along the lateral. The friction head loss between successive emitters is estimated by the *Darcy-Weisbach* formula, taking into account the variation of the Reynolds number. As the net pressure head at each emitter is evaluated, the corresponding emitter discharge is estimated accordingly. They have concluded that Laminar flow prevails in a considerable length at the downstream end of the lateral, whereas an upstream length may be subject to fully turbulent flow.

Kang and Nishiyama (1994) developed a simple method for hydraulic analysis of a microirrigation sub main unit. The lateral discharge equation was used to express the relationship between the inlet discharge and the inlet pressure head of a lateral. This equation allows for considering a sub main as a lateral and a lateral as an emitter. The back step method was applied for calculating pressure distribution along the sub main line. The golden section search was used to find the optimal estimate of pressure head at the end of the sub main. The forward step method was used for determining distributions of the pressure head and the emitter discharge along each later

Kang and Nishiyama (1996b) developed a simplified method for designing microirrigation laterals using the lateral flow rate equation. All hydraulic analysis was performed using back step and forward step methods. When required average emitter discharge rate, required uniformity of water application, and one parameter - either the

lateral length or diameter, are given, the unknown parameter, best sub-main position (paired laterals), and the operating pressure head can be accurately designed using a personal computer.

Al-Amoud (1996) developed some formulae to estimate pressure drop in hoses with connected emitters based on the Darcy-Weisbach and Hazen-Williams equations. Empirical formulae were developed, based on the statistical analysis of the data, for plain pipes and for emitters.

A method was developed for designing microirrigation sub-main units using the lateral flow rate equation, finite element method, and golden section search (Kang and Nishiyama, 1997). Characteristics of water application uniformity affected by lateral parameters (length and diameter) and sub-main parameters (length and diameter) were analysed using computer simulations.

Bagarello *et al.* (1997) carried out an experimental investigation to deduce an evaluating procedure of local losses due to the protrusion of emitter barbs into the flow in drip-irrigation lines. Each pipe-emitter system was characterized by an obstruction index (OI) summarizing the reduction of cross-sectional area of the pipe due to the emitter connection. A power relationship between a characteristic value of the  $\alpha$  coefficient, expressing the local losses amount as a fraction of the kinetic height, and the corresponding OI index was deduced.

Study of the flow field in a emitter is essential to improve emitter performance (Wang *et al.* 2000). The Galerkin penalty finite element method was applied to

simulate flows in the emitter. The flow characteristics and the influence of the Reynolds numbers on flow field in a typical emitter were analysed at different flow rates. A new equation for calculating the coefficient and rate of discharge, developed using the numerical simulation results was presented. This data provide references for continuous emitter development.

Pressure variation in pipelines was evaluated using a modified form of Bernoulli's equation by Reddy *et al.* (2000). Head loss due to friction was evaluated using Darcy's Weisbach equation. Emitter barb losses were also considered while analysing trickle lateral for hydraulics. The design illustration showed that it is better to opt for an economical design with varying pipe sizes for main lines rather than a design with uniform pipe size or higher uniformity. It is possible to save up to 29% on the total annual cost over the criteria where the emission uniformity was the lone parameter in designing the system.

Pedro and Pedro (2001) presented a new approach for solving lateral hydraulic problems in laminar or turbulent flow. The outflow is treated as a *discrete variable event* by means of Taylor polynomials used to calculate flow rates along the lateral (minimal outflow included).

## **2.9 Hydraulics of spatially varied emitter flow**

In application of previous analytical approaches for drip lateral hydraulic computation, it is generally assumed that the emitter outflow along the lateral is constant. This basic assumption may cause significant errors in hydraulic computation.

In the following paragraphs, few works on accurate analytical approach considering variable discharge is presented.

The discharge sensitivities to pressure and temperature of three types of emitters (helical long-path, labyrinth and vortex-type emitters) were determined in the laboratory by Benjamin and Tal (1981). They used the measured discharge sensitivity to calculate the maximal permissible pressure variation in a field for the various emitters. Under field conditions where water is heated as it flows in pipes exposed to solar radiation, emitter discharge along the second half of the pipe is determined by its specific discharge sensitivity to temperature.

Warrick and Mulaneh (1988) and Valiantzas (1998) presented an alternative treatment that includes a spatially variable discharge function as part of the basic solution as against the usual procedures that derive the solution based on uniform discharge, although ramifications of the manufacturer's variability have been modeled based on the derived hydraulic profile.

A differential approach is applied to multiple outlet pipes with constant and continuously variable outflow (Scaloppi and Allen, 1993). Several mathematical relations are derived for computing maximum, minimum, and average pressure heads and their locations of occurrence along a lateral. When compared to pressures and locations of occurrence computed using a discretized, stepwise computation procedure, they have noted that values computed using the developed equations are

generally within 3% for maximum, minimum, and average pressures, and are generally within 5% for the locations of occurrence.

Povoa and Hills (1994) developed a model for relating hydraulic characteristics of micro irrigation system to pump performance and emitter plugging. Data from field trials were used to verify the model. The model then used to determine pressure sensitivity at several system locations for different scenario of partial and full emitter plugging, and of lateral perforations. Partial clogging of 5% of the emitters on a lateral can be readily detected with pressure transducers located at either the lateral or manifold inlets. Similarly, pressure transducers can detect pressure differences due to minor perforations in the laterals. They have concluded that the pressure change sensitivity due to emitter clogging or perforations depends on the hydraulic characteristics of micro irrigation system.

## **2.10 Uniformity in trickle irrigation**

Several methods have been proposed for assessing the uniformity of application in drip irrigation system. The term emission uniformity has generally been used to describe the emitter flow variation for a trickle irrigation unit.

The coefficient of uniformity for sprinkler irrigation system was proposed by Christiansen (1942). This is widely accepted uniformity evaluation technique and is expressed as follows

$$U_c = \left[ 1 - \left( \frac{\bar{\delta}}{\bar{q}} \right) \right] 100$$

where

$\bar{q}$  = Mean sprinkler discharge rate

$\bar{\delta}$  = Mean absolute deviation of sprinkler discharge rates

For a normal distribution, low quarter distribution uniformity,  $DU_{lq}$  was expressed in terms of the coefficient of variation, CV, which is the standard deviation divided by the mean of the emitter flow is as follows (Hart and Reynolds, 1965)

$$DU_{lq} = 100 (1 - 1.27 CV)$$

The design of single chamber drip irrigation lateral lines considering hydraulic variation has been presented by various researchers. Myers and Bucks (1972) and Wu and Gitlin (1975) derived the hydraulic energy gradient line for determining the emitter flow variation and uniformity along a lateral line. Howell and Hiler (1974) used the hydraulic energy gradient principle and developed lateral line design equations based on the specific uniformity criteria.

Basically emission uniformity is the ratio of the average of the lowest  $\frac{1}{4}$ <sup>th</sup> emitter discharge to the average discharge expressed in percent (Keller and Karmeli, 1974). It can be expressed as follows

$$EU = 100 \frac{Q_n}{Q_a}$$

where,

EU = Emission uniformity in per cent

Q<sub>n</sub> = Minimum emitter discharge (average of the lowest ¼ of the emission point discharges) in lph.

Q<sub>a</sub> = Average emission point discharge of a test sample operated at the reference pressure head in lph

Keller and Karmeli (1974) assumed emitter properties as normally distributed and proposed another expression for emission uniformity as follows

$$EU = 100 \left( 1 - 1.27 \frac{CV_E}{\sqrt{N_e}} \right) \frac{q_{\min}}{q_{\text{ave}}}$$

where

q<sub>min</sub> is the minimum emitter flow in the system

q<sub>ave</sub> is the average emitter flow in the system

CV<sub>E</sub> is the manufacturer's coefficient of variation

N<sub>e</sub> is the number of emitters per emission point

Another method for determining the uniformity coefficient is by relating it with relative variation of discharge (Wu and Gitlin, 1975)

$$Rq = \frac{Q_{\max}}{Q_{\min}}$$



where,

$R_q$  =Relative variation of discharge

$Q_{max}$  = Maximum discharge (lph)

$Q_{min}$  = Minimum discharge (lph)

Based on experimental data, an empirical equation,

$$U = \left( \frac{4}{3 + R_q} \right) 100 \text{ has been obtained for uniformity}$$

Expressions are developed and presented for the pressure head available at any point within a trickle irrigation subunit (Solomon and Keller, 1978). It is found that the coefficient of emitter manufacturing variation is to be a significant design consideration. The equations and distributions developed are used to complete tables giving the emission uniformity and efficiency of systems for various combinations of design and equipment characteristics

Simple uniformity or efficiency measures, such as Christiansen's Uniformity coefficient, which do not appropriately weight values for the distribution of infiltrated depths, may not be good measures of irrigation effectiveness. The need for appropriately weighting the distribution has lead to the use of effective term such as the low quarter distribution uniformity (Kruse, 1978) expressed in percentage as

$$DU_{lq} = \frac{\text{Average depth of lowest quarter of area}}{\text{Average depth of total area}} \cdot 100$$

Nakyama and Buck (1981) have suggested the emission uniformity (EU) and absolute uniformity (EU<sub>a</sub>) for evaluating clogged dripper as

$$EU = \left( \frac{q_{35}}{q_m} \right) 100$$

$$EU_a = 50 \left[ \left( \frac{q_{25}}{q_m} \right) + \left( \frac{q_m}{q_{12.5}} \right) \right]$$

Where

$q_{35}$  is average discharge rate for lowest 35% flowing emitters

$q_{25}$  is average discharge rate for lowest 25% flowing emitters

$q_{12.5}$  is average discharge rate for highest 12.5% flowing emitters

$q_m$  is the mean discharge of emitter flow in a field

Bralts *et al.* (1981a) developed an equation to statistically combine the effects of pressure variations and emitter manufacturing variation on the discharge of individual emitters. They used a combination of variance technique to determine the total coefficient of variation of emitter properties and pressure effects. Their development assumed that emitter properties and effective pressure were normally and independently distributed, continuous random variables.

Bralts *et al.* (1981b) studied the drip emitter uniformity considering emitter plugging. They recommended the statistical uniformity coefficient for use in determining the design uniformity of emitter flow along a drip irrigation lateral line when emitter plugging is considered.

$$U_s = (1 - CV_T) 100$$

Where  $CV_T$  is the total variation comprising manufacturing variation and hydraulic variation, which can be expressed as

$$CV_T = \sqrt{CV_E^2 + CV_H^2}$$

Nakayama and Bucks (1981) developed a simulation model for emitter clogging on trickle irrigation systems. Hypothetical emitter populations were generated from specific initial values for the average discharge rate and coefficient of variation of the emitter. Various combinations of clogging were introduced into the model to determine how they affected average discharge rates and uniformity coefficient for single and multiple emitter placements per plant. Uniformity was greatly reduced even when 1 to 5 per cent of the emitters were clogged with two to eight emitters per plant.

Uniform water application along a drip irrigation line can be achieved by using different size of emitters, length or size microtube, and spacing between emitters. (Wu and Gitlin, 1983). A simple procedure for evaluating the field uniformity of water application using the time required to fill a container of known volume was described by Fischer (1983).

The factors that influence the uniformity of application from trickle irrigation system include emitter factors and hydraulic system factors (Solomon, 1985).

Clemmens (1987) developed a simulation model for estimating trickle irrigation uniformity by considering emitter and hydraulic properties as independent factors. They have revealed that the variation in the estimated combined uniformity is greater when it is caused by an emitter variation than when it is caused by hydraulic variation.

A computer model simulation was conducted to determine the spatial uniformity expressed as uniformity coefficient along a lateral line for various hydraulic designs, manufacturing variation, emitter spacing, plugging percentages and plugging patterns (Wu *et al.*, 1988). The simulation results showed that plugging is also the most significant factor affecting the spatial uniformity.

Hills *et al.* (1989) studied the effect of chemical clogging on drip-tape irrigation uniformity. They found that the water quality is a critical factor in chemical clogging and thereby deciding irrigation uniformity.

Capra and Scicolone (1998) have mentioned that a sample of 16 emitters is sufficient to test uniformity distribution. In drip systems, to be representative of the whole population of emitters, the sample of emitters must be chosen in different positions on the lateral with respect to the water inlet.

In a lab experiment conducted by Gontia *et al.* (1998) with 0,5,10,20,30,40 and 50 percent of complete clogging of emitters randomly along the lateral, they have revealed that even 5 to 20 percent clogging of emitters greatly reduced the uniformity.

In case of clogged emitters absolute uniformity is the better parameter to evaluate the hydraulics of the system.

### 2.11 De-clogging treatments

Four concentrations of hydrochloric acid ( $p^H$  of 2, 4, 6, and 6.5) and 10-20 ppm chlorine in the form of sodium hypochlorite were tested for their effectiveness in preventing clogging of drip irrigation (Goyal *et al.*, 1990). Weekly, fortnightly, monthly and continuous treatments were compared on an artificially clogged and a new drip set at Akola. The new set required treatment after 24 weeks in operation. Monthly low concentrated hydrochloric acid treatments ( $p^H$  of 6) were effective.

Trials were conducted on drip irrigation of strawberry fields (Meyer *et al.*, 1991). In 2 plots, maleic anhydride polymer was injected into the irrigation water at 2 mg/lit (2 ppm) and continuous chlorine at 1 mg/lit, whilst 2 other plots used only continuous chlorine injection. Results indicated a trend towards lower flow rates on the untreated (chlorine only) plots, whilst polymer-treated water flow rates declined only slightly and continued to supply the plants' water requirement.

The clogging of drippers and emitters in trickle irrigation can be reduced if effluents are treated with oxidants (Rav-Acha *et al.*, 1995). The effects of  $Cl_2$  and  $ClO_2$  on synthetic effluents were studied. The demand of these effluents for  $Cl_2$  was 5-8 mg/lit, and for  $ClO_2$  3-4 mg/litre. Two mg/lit of either oxidant caused rapid bacteria inactivation. However, for algae, conc. up to 20 mg/lit of either oxidant did not affect cell numbers, although algal viability markedly decreased. The presence of clogging

agents 'immune' to low  $\text{Cl}_2$  conc., produced in the reservoir, made 5-10 mg  $\text{Cl}_2$ /lit not very effective in a pilot system. Batch treatment combined with settling was much more efficient, since  $\text{Cl}_2$  reacted not only as a disinfectant, but also as a coagulant due to the oxidation of humic constituents.

Drip irrigation of 16 ha of greenhouses, shade houses and field grown containers was accomplished using water containing up to 6 mg Fe/lit (Bar, 1995). The system designed and installed to control the iron problems consisted of the following components: (1) a gas chlorinator to allow consistent injection of chlorine in its most available and efficient form; (2) hydrocyclone containing filtering discs to ensure complete and uniform mixture of the gas in the water within a limited space; (3) sand media filters to settle the oxidized iron and filter it from the water; and (4) back-up disc filters to control filtration failures and complete iron separation.

Ravina *et al.* (1997) have found that reliable long-term operation of most emitter types was achieved with filtration at 80 mesh (180  $\mu\text{m}$  opening) combined with daily chlorination and bimonthly lateral flushing. Regular lateral discharge monitoring was a convenient way to detect the initiation of the clogging process. Chlorination was most efficient when applied before the emitters became extensively clogged.

Three organic acid compounds were evaluated for preventing precipitation of salts and/or removing salts in drip irrigation systems and soils (Yuan *et al.*, 1998). The first organic acid was composed of polymaleic acid, maleic acid, surfactant blend, and

inert ingredients. The second was an anionic polymer with maleic acid as the organic acid. The third included soap and was a 1:1 stoichiometric equivalent of an organic carboxylic acid and an amine base. The first and third organic acid significantly reduced drip emitter clogging compared to a water-only treatment. The third organic acid was significantly better than the first for reducing clogging.

Muriatic Acid (HCl) was injected into the system through the fertigation system, to remove incrustations caused by the iron content of the water and restore the original volume of the drippers (Alejandro *et al.*, 2001).

The crisp review of work done and results as above helped in gaining sufficient insight to devise appropriate methodology for the study contemplated.

## *Materials and Methods*

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## **CHAPTER III**

### **MATERIALS AND METHODS**

Hydraulically, the flow through the network of micro irrigation pipes and outlets is considered as a turbulent flow through smooth pipes. However, when problem waters are used for irrigation or the water contains salt and other impurities, the problem of emitter clogging is inherent and assumes a greater role in causing non-uniform pressure and discharge distribution all over the layout. Hence, it is necessary to assess the impact of emitter clogging on the hydraulic performance of drip irrigation system. A compendium of research methodology already done on this aspect was reviewed and the methodology for the present study arrived at is as follows.

#### **3.1 Temporal and spatial analysis of trickle emitter clogging**

##### **3.1.1 Location of the study**

The study was conducted in a farmer's field at Vadavalli in Coimbatore district (Appendix – I). The drip irrigation system was installed in Arecanut crop. The field lies at 76° 58' E Longitudes and 11° N Latitude.

##### **3.1.2 Experimental details**

The entire drip system of selected field consisted of four sub-main units each consisting of 40 laterals. Each lateral was provided with 21 drippers with an equal spacing of 2.2 meters. The water supply for the system was drawn from a bore well located in the same field. A filtration unit was used to remove the fine particles from

the irrigation water. The EC of the water was found  $2.7 \text{ d S m}^{-1}$ , which is a major cause for emitter clogging. A pressure gauge was fitted on the sub-main line to monitor the operating pressure. For the clogging analysis, only 36 emitters from a single sub-main unit were selected as shown in Fig. 3.1. These emitters were newly placed just before the commencement of the experiment and the farmer was requested not to disturb or clean these emitters during the study period. The discharge rate of the selected emitters at the emission points was measured for a period of five months starting from 1<sup>st</sup> April 2001 at an interval of one week (Appendix – II).

### 3.1.3 Temporal Analysis

The emitter clogging over a time due to saline nature of water was perceived as a random variable. This randomness comes to the emitter clogging in the field because of the random occurrence of the clogging inducing factors *viz.*, manufacturing variations, dripper position on the field and exposure to sun. The random distribution of the emitter clogging can easily be fitted with the Weibull distribution, which is the most common probability distribution function (PDF) used for forecasting the reliability of any machine component. Suppose, we want to see the reliability of drip emitter against a clogging percentage of  $x$ , then the frequency distribution of emitters with  $x$  per cent clogging over a time has to be modeled with Weibull distribution. Appendix - III presents the Weibull distribution theory.

A computer program was developed using the Weibull distribution theory to estimate the Weibull parameters with the help of a low-level computer language 'C'.

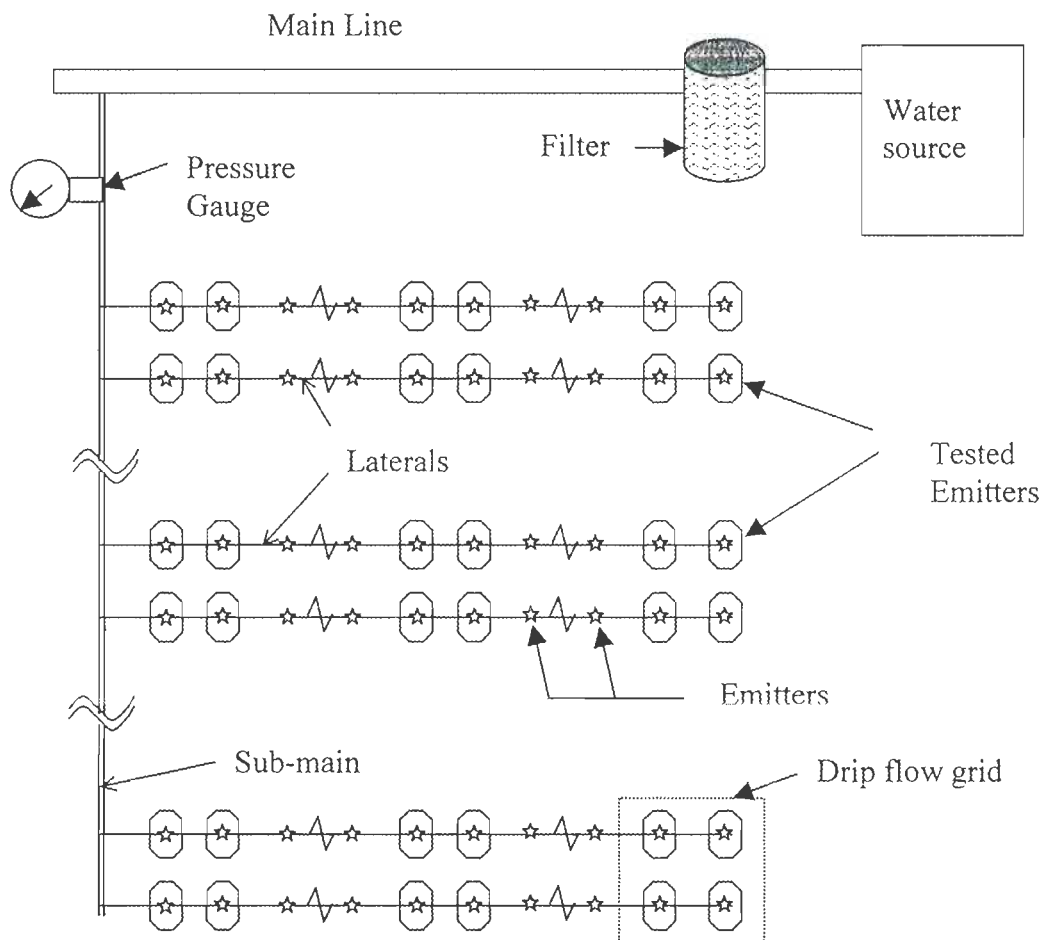


Fig. 3.1 Schematic of emitters tested along drip flow grids

The program utilizes the least square algorithm for estimating the parameters. Fig. 3.2 depicts the flow chart for the computer program. The corresponding C language code is given in Appendix – IV.

### 3.1.4 Spatial Distribution

The emitter clogging at any time is not uniform in the field. The emitter clogging can be considered to have a normal distribution. When a population is normally distributed with a mean and standard deviation expressed as  $\mu$  and  $\sigma$ , respectively, the probability density function of the population can be expressed as

$$f(p) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{p-\mu}{\sigma}\right)^2}$$

Where  $p$  is percent clogging in the field. Here, as the model parameters are mean and standard deviation of the population, they can be directly estimated from the field data.

## 3.2 Emitter type and water quality on clogging rates

### 3.2.1 Field Selection

A careful survey was made to identify the suitable field with drip irrigation system for carrying out the experiment. While selecting the fields, the following criteria were taken into consideration

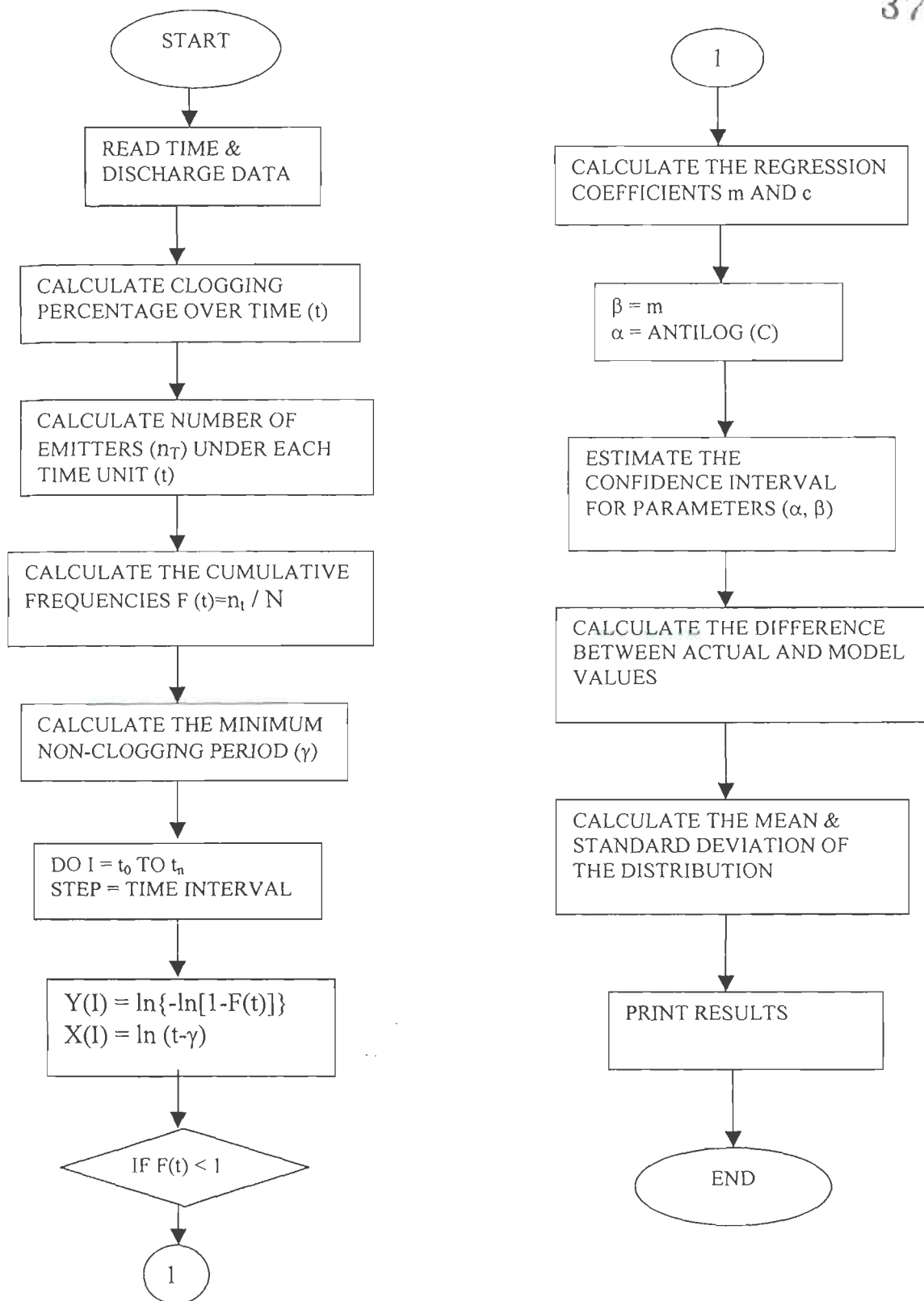


Fig. 3.2 Flowchart for estimation of Weibull parameters ( $\alpha$ ,  $\beta$  and  $\gamma$ )

**Crop:** Drip fields with same crop were selected in order to have the identical drip system parameters like emitter spacing, lateral spacing, emitter size, etc. As all the fields are around Coimbatore, the crop water requirement and operating hours are also equal for all the fields.

**Water:** Fields with different irrigation water qualities were selected to study the effect of water quality on emitter clogging. For this purpose, Electrical Conductivity (EC) was considered as a single factor for assessing the salinity of irrigation water.

Based on the above requirements, only four grape fields around Coimbatore were selected for this study (Appendix–V& VI). The details of the irrigation source, drip system parameters in all the selected fields are given in Tables 3.1.

### **3.2.2 Emitter selection**

The selection of the emitter was based on the geometry of the dripper and its sensitivity to operating pressure. Four distinguished emitters with flow rate of 8 lph were selected. The emitter flow equations and performance characteristics of each emitter were arrived by conducting pressure – discharge experiment in a laboratory setup. The geometry of the selected emitters is given in Table 3.2. Appendix-IX presents the photographic view of the selected emitters.

Table 3.1 Drip system parameters in the experimental fields

Field No	Total Area (Acre)	Lateral size (mm)	Lateral spacing, (m)	Dripper spacing, (m)	Operating pressure (Kg/cm <sup>2</sup> )	Irrigation Frequency	Irrigation Duration (hrs)
F1	10	12	2.5	0.75	1-1.25	Daily	4-5
F2	3	12	2.5	0.75	1-1.3	Daily	4-5
F3	5	12	2.5	0.75	1-1.1	Daily	4-5
F4	1	12	2.5	0.75	1-1.3	Daily	4-5

Table 3.2 Emitter geometry for the selected emitters

Emitter Name	Emitter coefficients		Sensitivity to pressure	Type of flow path	Length of flow path, cm	Approx Diameter, mm	Manufacturer discharge, lph
	K	X					
A	7.87	0.015	Very less	Pressure compensating	—	—	8
B	3.1	0.43	Less	Helical long flow path	3.7	1	8
C	2.16	0.56	Medium	Helical short flow path	6.2	0.8	8
D	1.06	0.87	High	Screw flow path	8.5	1	8

### 3.2.3 Experimental procedure

The experiment was conducted during the summer months of March 2001 to September 2001. The irrigation system main lines, sub mains, and laterals had been installed and operated for 1-2 years prior to conducting the experiment. In all the fields, only four laterals were selected for the study. The lateral selection was made as close as possible to the pumping source to have equal operating pressure in all the fields. The operating pressure during the irrigation had been noted in all the fields from the pressure gauge, which was in the range of 1-1.3 kg/cm<sup>2</sup> in all the fields. In each selected lateral, three numbers of similar emitters were inserted for replication by replacing the existing drippers.

Fig. 3.3 illustrates the schematic sketch of laterals and emitters tested in the fields. The farmers were requested not to disturb these emitters throughout the study period. A filtrations unit was fitted invariably in all the fields to trap the fine clay particles and other sediments. To analyse the irrigation water quality, water samples were collected after the filtration unit. Immediately after the insertion of testing emitters to the laterals, the initial flow was measured. Then, the flow rate of all the emitters fitted in all the trials were periodically (once in a month) measured for the whole study period of 7 months in order to estimate the clogging in the testing emitters.

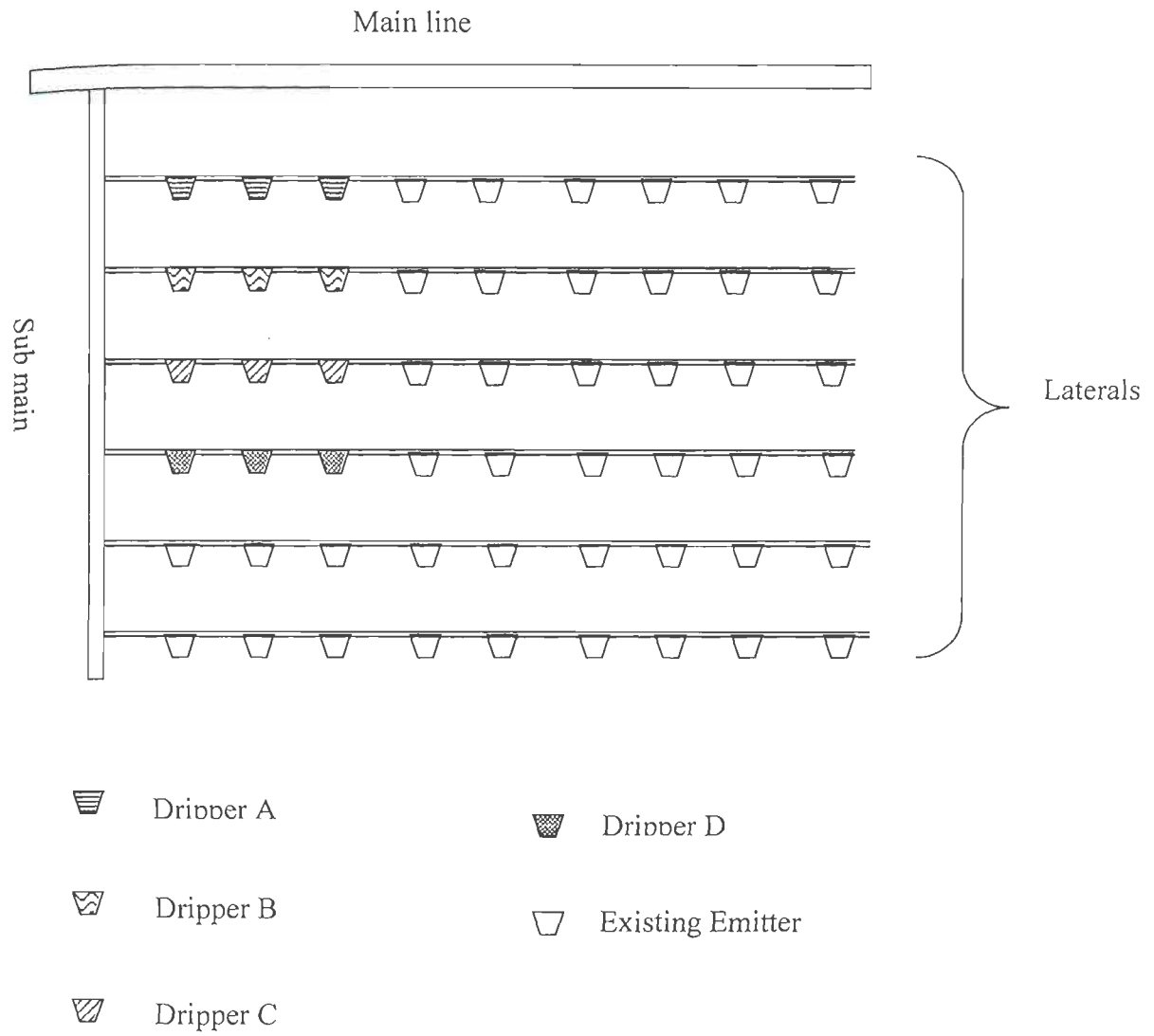


Fig. 3.3 Schematic of emitters connected to an existing drip field for carrying out clogging rate experiments

### 3.2.4 Emitter clogging rate

The relation between Emitter clogging and elapsed time for the selected emitters studied under four water quality categories were arrived using a statistical package called CURVE EXPERT. They have been best fitted with the modified exponential function as given below

$$P = a(b - e^{-ct}) \quad \dots (3.1)$$

where,

$P$  = total clogging in a dripper, %

$t$  = elapsed time, weeks

$a$ ,  $b$  and  $c$  are the regression coefficients.

$e$  = base of the system of natural logarithms, approximately 2.71828

The emitter-clogging rate (CR) can be derived by differentiating the equation (3.1)

$$CR = \frac{dp}{dt} = ace^{-ct} \quad \dots (3.2)$$

By rewriting the Equation 3.1, the term,  $e^{-ct}$  can be expressed as

$$e^{-ct} = b - \frac{P}{a} \quad \dots (3.3)$$

Now, relation between clogging rate (CR) and clogging (P) can be arrived by replacing the time component from equation 3.2 from equation 3.3.

$$CR = abc - Pc \quad \dots (3.4)$$

Using the above equation, clogging rate for different clogging conditions were calculated with the estimated regression coefficients a, b and c. The data are presented in the form of graph.

### 3.3 Fertigation on clogging

Two similar farmers fields were selected at Thondamuthur in Coimbatore district. The fields were installed with drip irrigation system for banana. Among these fields, one is installed with fertigation mechanism (Fertilizer tank). The water quality is found to be moderately saline ( $EC = 1.7 \text{ dSm}^{-1}$ ). In the fertigation field, water-soluble NPK fertilizer is filled inside the fertilizer tank whenever it is needed. The dissolved fertilizer was moving along with irrigation water to feed the crop. The concentration was not maintained strictly. A study was conducted to see the impact of this farmer's method of fertigation on emitter clogging and is compared with non-fertigation drip emitter clogging.

### 3.4 Development of a hydraulic model for drip irrigation incorporating emitter clogging and manufacturing coefficient of variation

A hydraulic model for a drip irrigation system considering manufacturing variation and emitter clogging has been developed to study the impact of manufacturing variation and emitter clogging on the hydraulic performance of the

drip irrigation system. Fig. 3.4 describes the variables of drip irrigation laterals considered for the model development.

Bernoulli equation for the fluid flow in a closed pipe is modified to suit the irrigation water distribution in a drip irrigation lateral tube. The general form of the Bernoulli equation is given by

$$\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{w} + \frac{v_2^2}{2g} + z_2 + h_L \quad \dots(3.5)$$

Where

$\frac{p}{w}$  = Pressure head or static head, m

$p$  = pressure, kg(f)/m<sup>2</sup> and  $w$  = Specific weight of water, kg(f)/m<sup>3</sup>

$\frac{v^2}{2g}$  = Velocity head or kinetic head, m

$v$  = Velocity of flow, m/s and  $g$  = Acceleration due to gravity, m/s<sup>2</sup>

$Z$  = Potential head or datum head

$h_L$  = Loss of energy between points 1 and 2.

The velocity head at any point in the drip lateral can be expressed in terms of lateral discharge flowing at that point as given below

$$\frac{v^2}{2g} = \frac{Q^2}{2gA^2} \quad \dots (3.6)$$

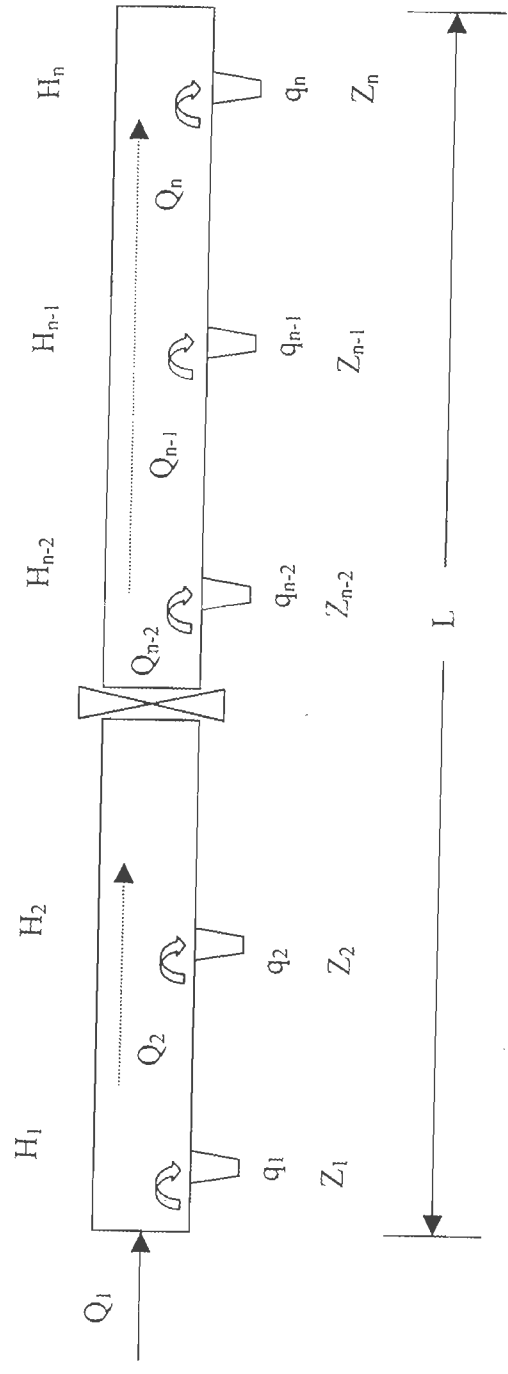


Fig. 3.4 Drip lateral with n number of nodal points used in the proposed model

where,

- L = Length of the lateral
- q = Emitter flow
- Q = Lateral flow at any point
- Z = Elevation
- H = Pressure head

where

$Q$  = Flow through pipe,  $m^3/s$

$A$  = Cross sectional area of pipe,  $m^2$

For a drip irrigation lateral segment between any two emitters  $n$  and  $(n-1)$ , the Bernoulli equation can be written as

$$H_{n-1} = H_n + \frac{(Q_n^2 - Q_{n-1}^2)}{2gA^2} + (Z_n - Z_{n-1}) + h_L \quad \dots (3.7)$$

For a drip pipe, the Darcy-Weisbach equation can be used to calculate the frictional losses between emitters as follows

$$H_L = \frac{8fLQ^2}{\pi^2 gD^5} \quad \dots (3.8)$$

Where  $f$  is the friction factor, which can be calculated using Blasius formula.

It is modified as follows to suit the drip laterals

$$f = 0.42 \left( \frac{\mu D}{\rho Q} \right)^{0.25}$$

where

$\mu$  = Dynamic viscosity of water,  $kg (f)\cdot s/m^2$

$\rho$  = Density of water,  $kg (f)/m^3$

$Q$  = flow rate inside the lateral,  $m^3/s$

$D$  = diameter of the lateral, m

The flow at any point in the lateral is the sum of all the emitters' discharge that follows assumed point till the lateral end.

$$Q_n = \sum_{i=1}^n q_i \quad \dots (3.9)$$

The relationship between the emitter discharge and the pressure head is given by

$$q = kH^x \quad \dots (3.10)$$

Where,

$q$  = Flow rate in l/h

$k$  = Discharge coefficient

$H$  = Pressure in m

$x$  = Emitter exponent that classifies the flow regime

Due to the manufacturing variations, any two emitter of same type cannot deliver a same flow rate under same pressure and temperature. These variations in the emitter discharges can be incorporated in the emitter discharge equation as follows.

$$q = (\sigma_k R_N + \bar{k}) H^x \quad \dots (3.11)$$

where

$\sigma_k$  = Standard deviation of the discharge coefficients

$\bar{k}$  = Mean of the discharge coefficients.

$R_N$  = Standard normal deviate

Povoa and Hills (1994) used the following relation to incorporate the effect of emitter clogging in the emitter discharge equation.

$$q = (1 - p)kH^x \quad \dots (3.12)$$

Where  $p$  is the fraction of emitter clogging. The distribution of the percentage clogging ( $p$ ) of the emitters at any specified time over the space can be fit well into the normal distribution. So the random variable  $p$  can be generated using the relation

$$(1 - p) = (\sigma_{(1-p)} R_N + \overline{(1-p)}) \quad \dots (3.13)$$

The most generalized form of the emitter discharge equation, which includes correction terms for both manufacturing variations and emitter clogging, can be written as follows

$$q = (\sigma_{(1-p)} R_N + \overline{(1-p)}) (\sigma_k R_N + \bar{k}) H^x \quad \dots (3.14)$$

Lateral discharge at any point can be modified from equation (3.9) by substituting equation (3.14) for emitter discharge

$$Q_n = \sum_{i=1}^n \left( \sigma_{(1-p)} (R_N)_i + (\overline{1-p}) \right) \left( \sigma_k (R_N)_i + \bar{k} \right) H_i^x \quad \dots (3.15)$$

The change in the velocity head between  $n^{\text{th}}$  and  $(n-1)^{\text{th}}$  emitter can be given by

$$\frac{(Q_n^2 - Q_{n-1}^2)}{2gA^2} = \frac{Q_n^2 - \left[ \left( \sigma_{(1-p)} (R_N)_{n-1} + (\overline{1-p}) \right) \left( \sigma_k (R_N)_{n-1} + \bar{k} \right) H_{n-1}^x + Q_n \right]^2}{2gA^2} \quad \dots (3.16)$$

By rearranging the terms in equation 3.16, a polynomial equation is obtained as follows

$$f(H_{n-1}) = H_{n-1} - H_n + \frac{Q_n^2 - \left[ \left( \sigma_{(1-p)} (R_N)_{n-1} + (\overline{1-p}) \right) \left( \sigma_k (R_N)_{n-1} + \bar{k} \right) H_{n-1}^x + Q_n \right]^2}{2gA^2} + (Z_n - Z_{n-1}) + H_L = 0$$

The only unknown in the above equation is  $H_{n-1}$ , which can be solved using an iterative procedure *Newton-Secant* method.

### 3.4.1 Newton – Secant method

Newton- Secant method is a numerical method used to solve the polynomial equations of type  $f(x)=0$ . Secant method uses two initial estimates but does not require that they must bracket the root. For example, the secant method can use  $x_1$  and  $x_2$  as initial values, and finds the third value  $x_3$  as below

$$x_3 = \frac{f(x_2)x_1 - f(x_1)x_2}{f(x_2) - f(x_1)}$$

The difference between  $x_3$  and  $x_2$  are checked for the minimum. If it is not satisfied, then  $x_2$  is assigned as  $x_1$  and  $x_3$  is assigned as  $x_2$ , and the process is repeated till we get a minimum difference.

For the derived polynomial equation,  $f(H_{n-1})=0$ , the above procedure is applied to find the solution for the pressure head  $H_{n-1}$  by assuming  $H_n$  and  $(H_n + 2)$  as initial estimates.

### 3.4.2 Development of computer models

The developed hydraulic equations were used to develop the computer models using C language to simulate the drip irrigation system with emitter clogging. A separate programme named as RANGEN was developed to simulate the emitter coefficient values (K) and clogging values (P). This programme utilizes the Monte Carlo simulation technique to generate these values. The flowchart of RANGEN is illustrated in Fig. 3.5. The C code for this flowchart is given in Appendix-X.

The drip hydraulics is programmed as a main model named as DRIPCLOG. This program utilizes a backward step algorithm for computing the pressure heads at the different emitter nodes. Fig. 3.6 illustrates the flow chart for this algorithm. The corresponding C language code is given in Appendix-XI. This algorithm utilizes the output files from the sub model RANGEN and runtime input by user about the system parameters.

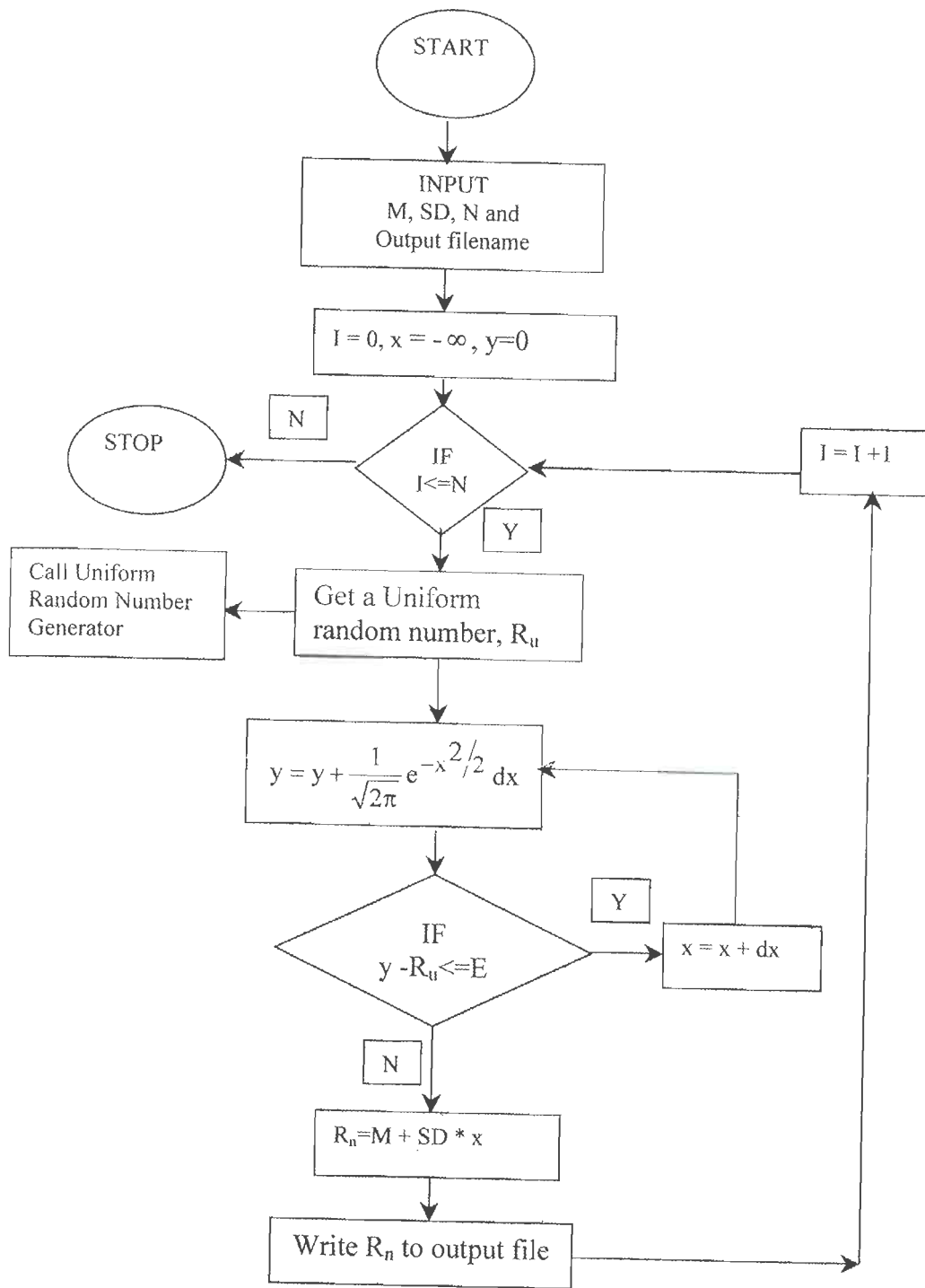


Fig. 3.5 Flowchart of the sub model **RANGEN** for generating K and P values to the main model DRIPCLOG



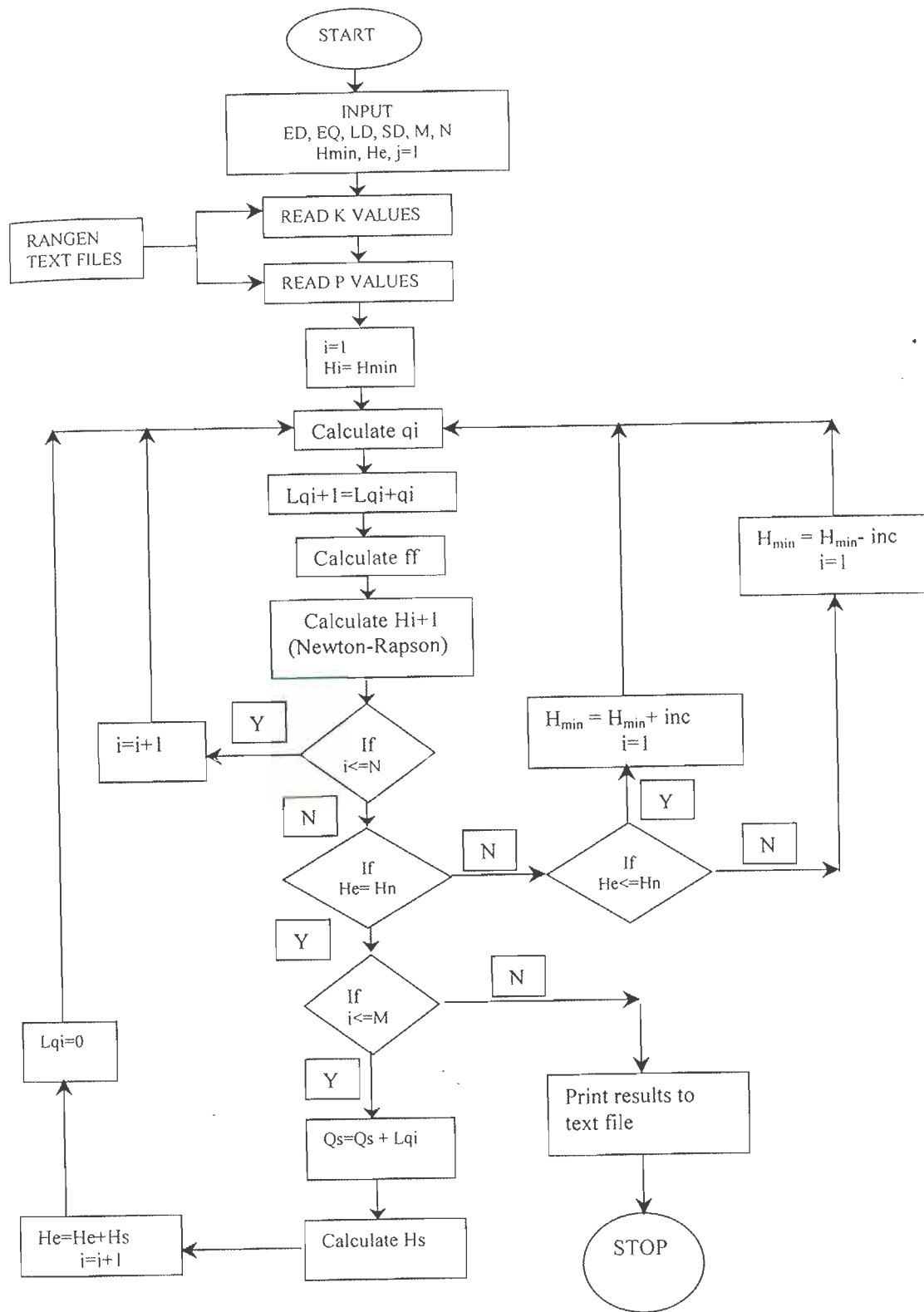


Fig. 3.6 Flowchart of the hydraulic model **DRIPCLOG**

### Nomenclature used in Flowchart of RANGEN

M	Mean of the K/P
N	Total Number of P/K required
SD	Standard normal deviate
x	Normalized Random variable
y	Cumulative frequency of x
$R_n$	Random variable, which is assigned to K/P
E	Permissible Error

### Nomenclature used in Flowchart of DRIPCLOG

ED	Emitter size
LD	Lateral diameter
SD	Submain diameter
M	Number of drippers per lateral
N	Number of laterals per submain
$H_{min}$	Required minimum pressure at the remote dripper
$H_e$	Expected pressure head at the inlet of any lateral
K	Emitter constant
P	Emitter clogging
$H_i$	Pressure head at $i^{th}$ emitter
$q_i$	Discharge from $i^{th}$ emitter
$L_{q_i}$	Flow in $i^{th}$ lateral
ff	Frictional factor used in Darcy-Weisbach equation
$Q_s$	Submain flow
$H_s$	Head loss in submain between two laterals
inc	Increment in pressure head between iterations
i	Position locator for emitter
j	Position locator for lateral

Simulation starts by assuming a Initial pressure head to the last emitter in the last lateral. Then the pressure heads at all the emitter in the laterals are calculated backwards. The inlet pressure head of the lateral is checked for the required value. This loop is continued till the required value of pressure head at the inlet is met out by reassigning the initial pressure head value. Then the inlet pressure head required for the next inlet is calculated by adding the head loss in the submain to the inlet pressure head of the previous lateral. The whole procedure is repeated for all the laterals in the submain/main.

### **3.5 Design of a lab scale drip irrigation layout**

A lab scale drip irrigation system was installed for validating the computer model DRIPCLOG. The layout is shown in Fig. 3.7(a). The sub main and laterals were laid on a stand constructed with MS rod in order to place the collection cups beneath the emitters. The two ends of a five-meter PVC sub main were supported by the bricks. A six numbers of ten-metre MS rods were tied up between two poles driven at the extreme ends of the laterals. The laterals were tightly tied with the standing MS rods raised to a height of 15 cm.

The sub main is 50 mm PVC pipe connected to a 3 HP pump, which draws the water from a pure water sump. A gate valve is fixed on the delivery side in order to regulate the flow and pressure in the system. A pressure gauge is connected in the sub main at the start of the first lateral.

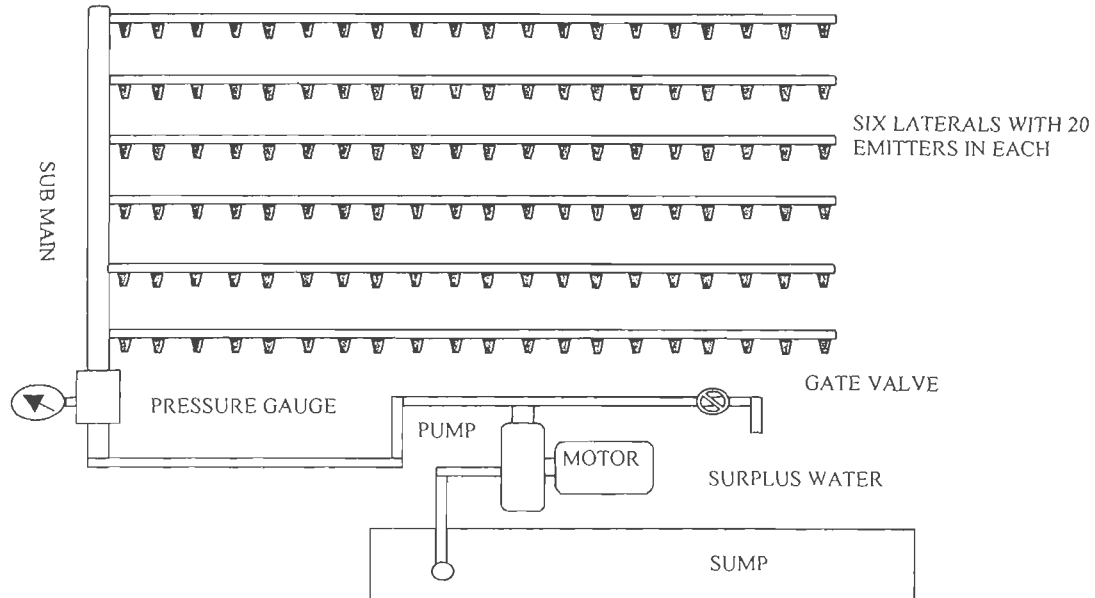


Fig. 3.7 (a) Experimental layout of drip irrigation system

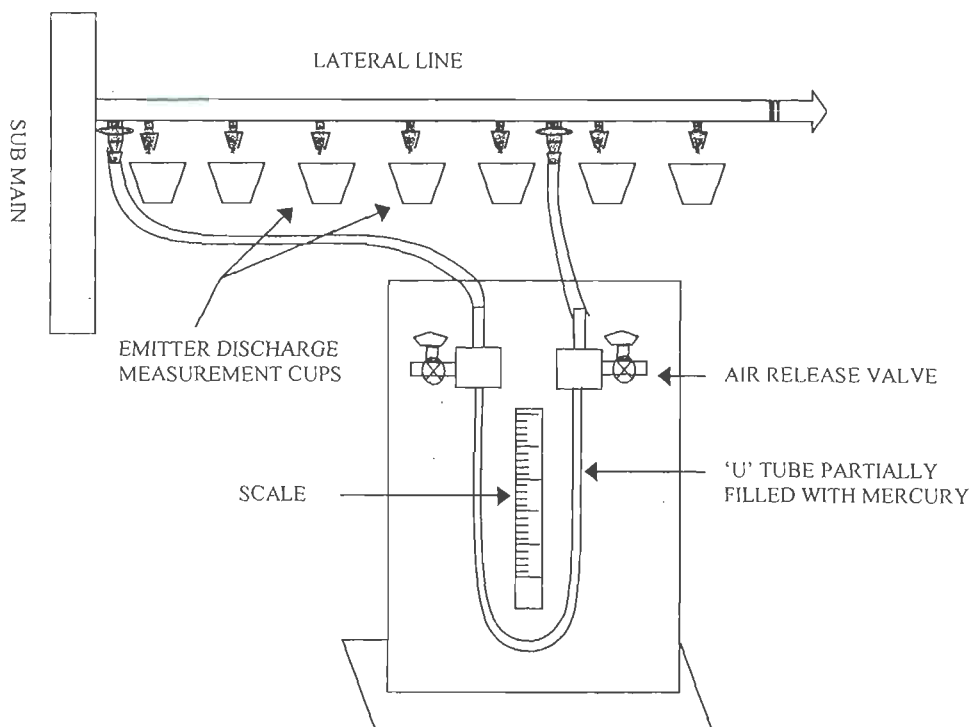


Fig. 3.7 (b) Measurement of differential pressure along the drip lateral using 'U' tube manometer

The laterals are 12 mm PVC tubes connected straight and perpendicular to the sub main. The ends of the each lateral were provided with a tap to get a manometer connected. Twenty emitters were inserted in each lateral at a spacing of 50 cm. The laterals were provided with taps at a regular interval of 2.5 metres in order to get the connection to the manometer. The differential pressures over the sub main and lateral were obtained using this 'U' tube mercury manometer. Fig. 3.7 (b) represents the measurement of the head loss using the 'U' tube mercury manometer. The photographic view of the laboratory scale drip irrigation layout and segmental hydraulic gradient assessment using 'U' tube manometer is given in Appendix-XII.

The operating pressure at the inlet is controlled using a gate valve connected near the supply end of the pipe. For a set pressure, the pressure variations along the each lateral and corresponding emitter discharges were recorded to validate the computer model.

## *Results and Discussion*

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## CHAPTER IV

### RESULTS AND DISCUSSION

Emitter clogging has become a serious problem in a pressure based micro-irrigation systems when poor quality water (saline or waste water) is used. For all practical purposes, the flow through a network of micro-irrigation system, drip irrigation, is considered as a turbulent flow through smooth pipes. The hydraulic gradients caused due to frictional losses during flow under different pressure heads are further amplified and disturbed due to emitter clogging problems. The spatial and temporal variation need to be studied with reference to the type of layout, operating pressures and qualities of water used. This chapter deals with the results obtained from various studies on emitter clogging in the field and its impact on hydraulic performance of the drip irrigation system.

#### **4.1 Temporal distribution of emitter clogging**

Discharge data of selected emitters in a drip irrigation over time were used as a primary input for analysing the temporal variations in emitter clogging. From the discharge data, the number of emitters delivering flow rate less than a stipulated discharge rate are calculated. Figs. 4.1 (a)-(d) show the histogram representing the number of the clogged emitters over different times between failures for 5, 10, 15 and 20 per cent of emitter clogging respectively. The cumulative frequencies were calculated from the discrete values and are used by the computer program to fit them in a suitable Weibull model.

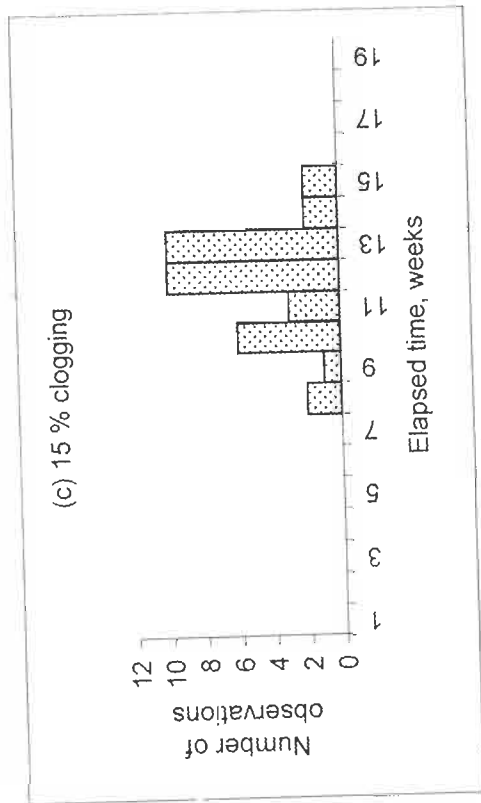
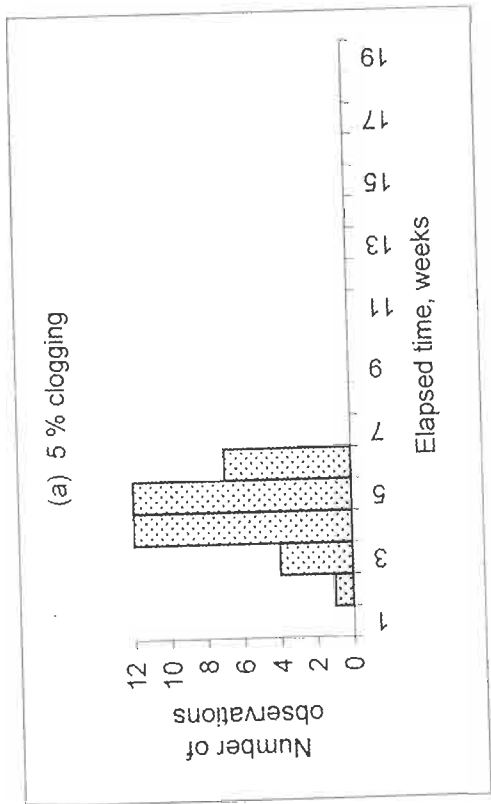
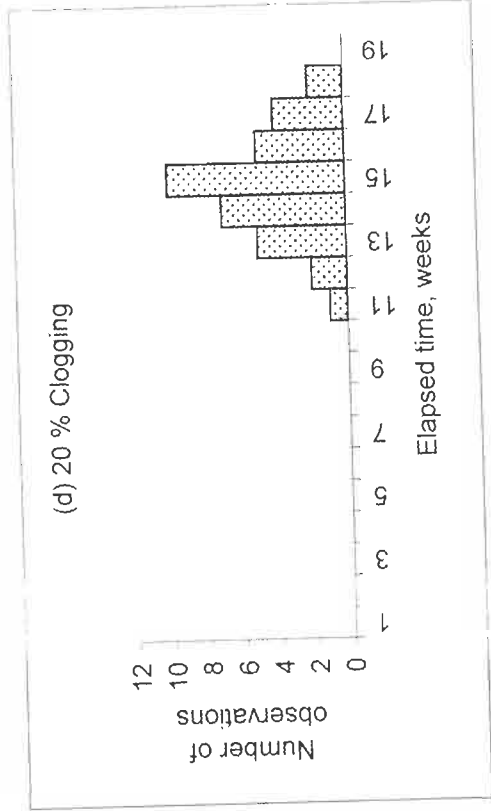
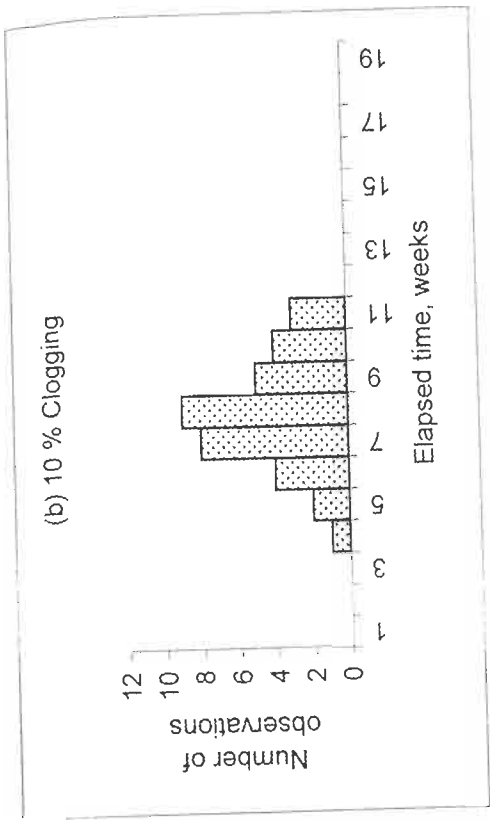


Fig. 4.1 Histogram of number of observations exceeding the selected clogging level in each week

#### 4.1.1 Estimation of Weibull parameters

The program was run separately for 5, 10, 15 and 20 per cent levels of emitter clogging for obtaining the Weibull model parameters. The values of the Weibull parameters ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) calculated by the computer program using regression analysis are given in Table 4.1. The same program was used to calculate the theoretical cumulative frequencies at different times between failures and the difference between actual and theoretical values. Fig. 4.2 shows both actual and theoretical cumulative distribution of emitters at four different clogging levels. The deviations of theoretical cumulative frequency values from the actual frequency values are shown graphically in Fig. 4.3. Maximum deviations observed for the four models are 0.131, 0.068, 0.096 and 0.043 respectively.

Table 4.2 presents the mean time to reach the clogging levels of 5, 10, 15 and 20 per cent and the 95-percentage confidence interval for these mean values. It is evident from the values that the time per percentage clogging is reducing with respect to clogging levels. This may be due to the reason that clogged emitters are more vulnerable to further clogging.

The validation of the Weibull model for fitting the temporal distribution of emitter clogging was carried out with the help of the Chi-square ( $\chi^2$ ) test. The calculated  $\chi^2$  values (0.0076, 0.0036, 0.0037 and 0.0076 respectively) for the four models are less than the tabulated value (1.40). From the test it is found that there is a

Table 4.1 Estimated Weibull parameter values for different emitter clogging

S. No	Clogging %	$\gamma$	$\alpha$	$\beta$
1	5	1	5790.6	6.014
2	10	3	2904.89	4.47
3	15	7	586.63	3.6
4	20	10	750.44	3.78

Table 4.2 Mean time for clogging with 95 % confidence of interval

S. No	Clogging %	Mean Time (Week)	Standard Deviation	95 % Confidence Interval	
				Lower Limit	Upper Limit
1	5	4.914	0.786	4.090	5.738
2	10	8.434	1.355	7.394	9.474
3	15	12.289	1.643	11.019	13.559
4	20	15.211	1.520	14.041	16.381

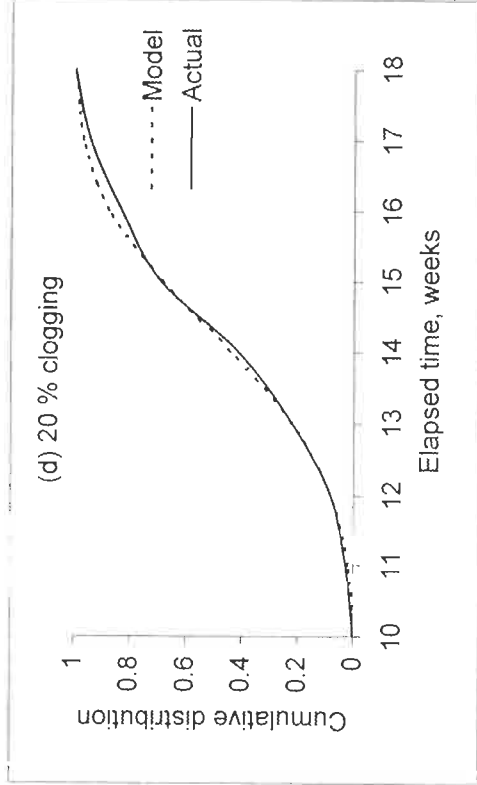
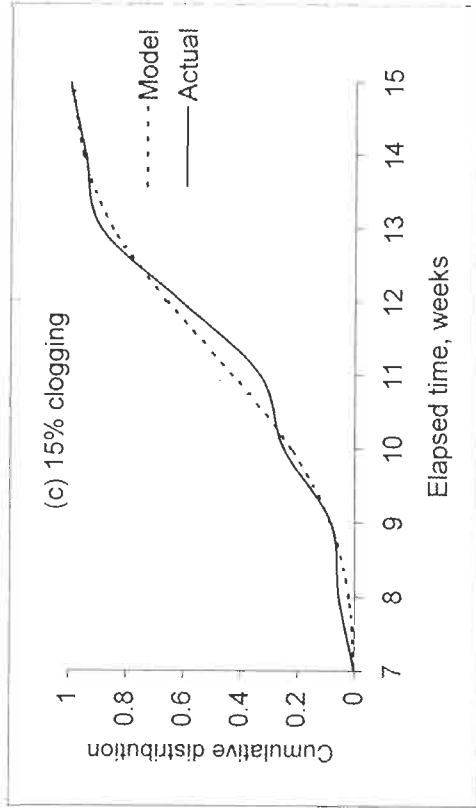
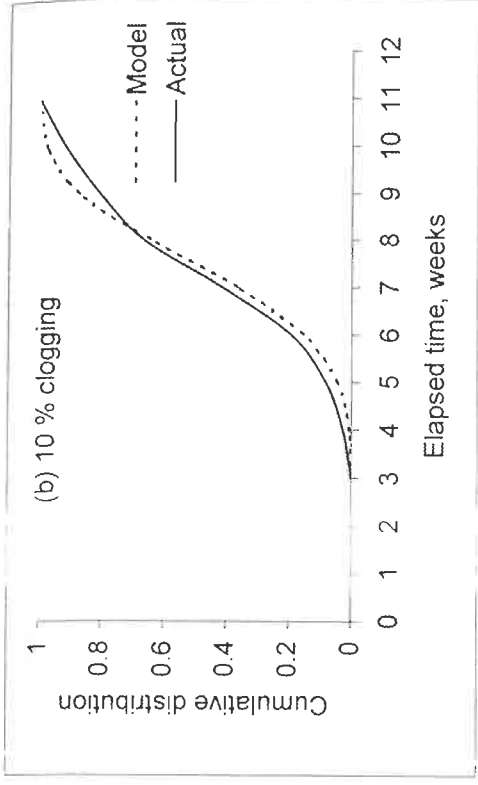
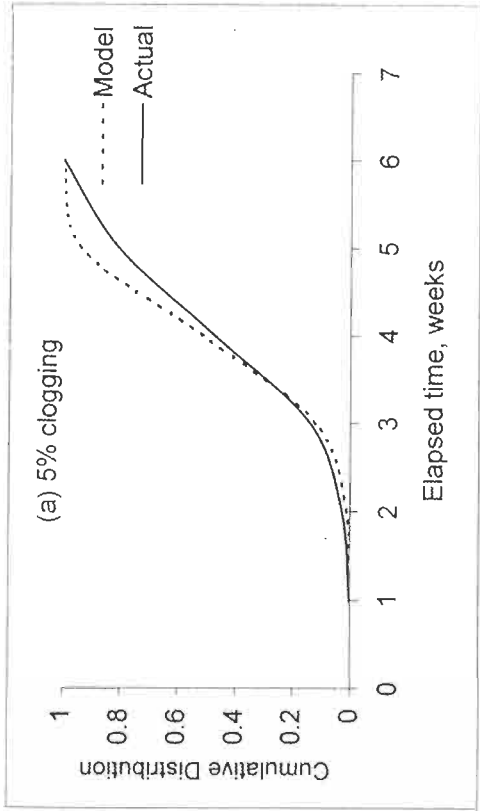


Fig. 4.2 Weibull distribution model for emitter clogging at different levels

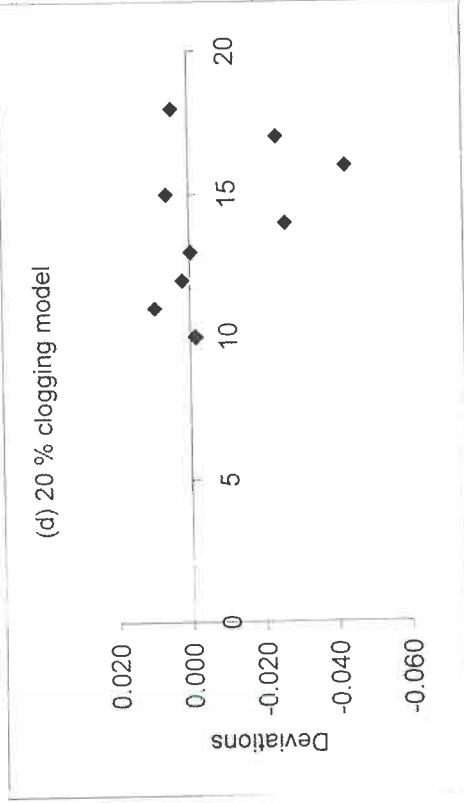
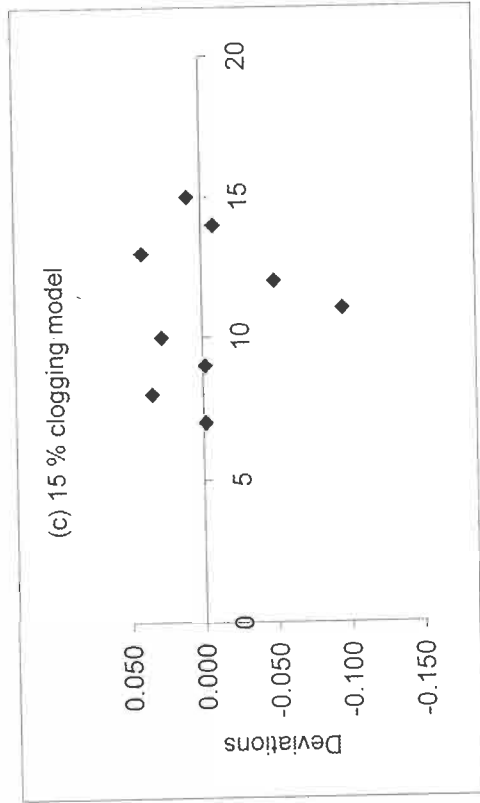
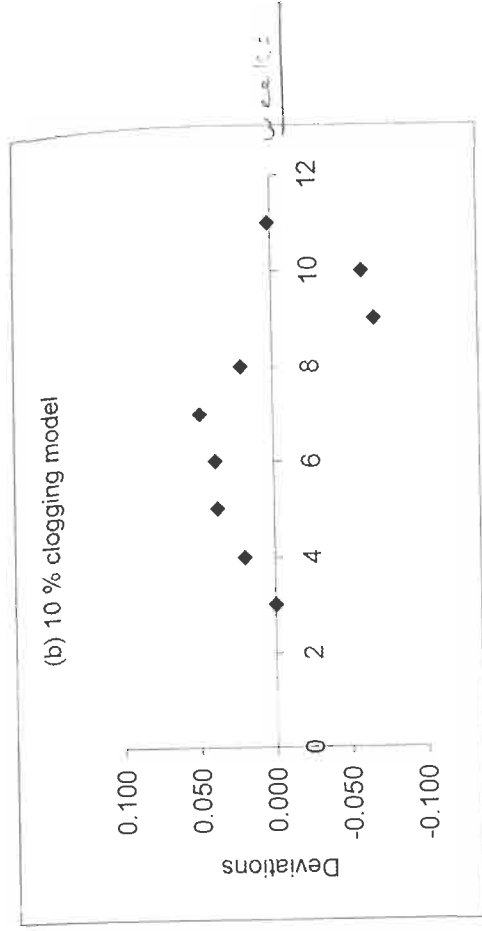
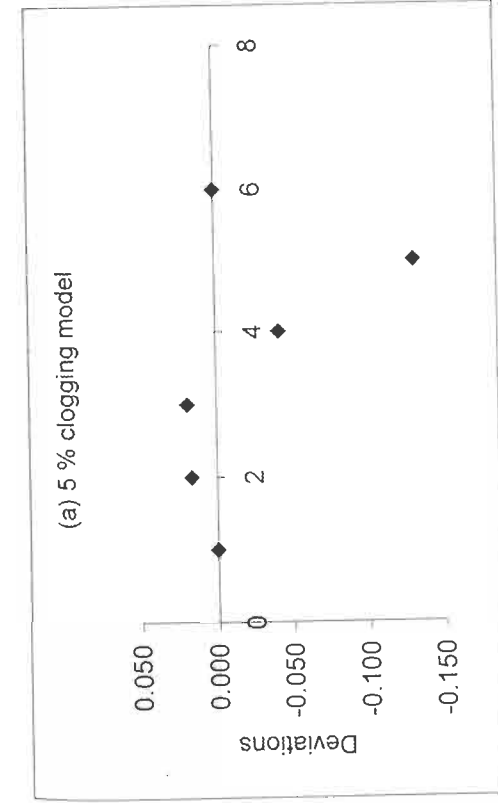


Fig. 4.3 Error chart for different clogging distribution models fitted with Weibull distribution

remote evidence (1 % level) to neglect the Weibull model for fitting the temporal variations of emitter clogging over time.

#### **4.1.2 Simulation of emitter clogging**

Monte-Carlo technique was used to simulate the time of clogging for emitters to an assumed level, using the predicted Weibull parameter values as the input to the model. The simulation was carried out using a developed computer program for this purpose. The values generated for different levels of emitter clogging are given in Table 4.3.

For examining the simulation results, only 20 numbers representing time of clogging were generated for each clogging percentage. Mean of the simulated clogging time data are well within the 95 per cent confidence interval of theoretical mean. This proves the applicability of the model for generating the synthetic data on emitter clogging for any hydraulic performance evaluation model. The mean clogging time is increasing in a declining manner with respect to percentage clogging, as the clogging rate is becoming faster once some percentage of emitter path is clogged. The expected number of times the de-clogging treatments have to be carried out can be calculated from the mean values. For example, the number of times de-clogging will be required to keep the emitters within 5 per cent level of clogging is 11 per year. Similarly the treatments required for 10, 15 and 20 per cent levels of clogging are 7, 5 and 4 times per year respectively.

Table 4.3 Simulated times for emitters to get clogged to different levels using Monte-Carlo technique

S. No.	Time to clog, weeks			
	5%	10%	15%	20%
1	5.20	8.05	13.54	14.87
2	4.23	8.16	13.95	14.29
3	6.44	8.34	12.82	15.71
4	5.67	5.13	13.28	16.65
5	4.97	9.32	12.43	14.99
6	5.30	6.51	12.82	12.05
7	4.00	11.08	9.71	13.34
8	5.60	9.93	11.56	14.24
9	5.97	9.58	14.50	14.04
10	5.12	9.32	12.52	16.48
11	4.08	8.59	10.14	15.03
12	3.73	6.60	11.79	15.63
13	5.93	8.27	10.99	14.09
14	5.03	10.32	11.46	13.42
15	3.21	8.70	12.14	14.61
16	5.62	8.59	12.26	17.70
17	6.44	7.77	11.21	12.29
18	5.82	8.16	12.65	16.48
19	3.48	11.38	11.51	15.67
20	4.08	9.06	15.13	13.09
Mean time	<b>5.00</b>	<b>8.64</b>	<b>12.32</b>	<b>14.73</b>

## 4.2 Spatial distribution of emitter clogging

Emitter clogging is not uniform over the space. Clogging of any emitter depends on various factors like, hydraulic pressure available at the dripping point, manufacturer's defect, etc. The same discharge data, which were selected for temporal variations study, were used to analyze the spatial distribution.

The spatial variation was fitted with normal distribution at four stages of clogging i.e. at the average time for the emitters to get clogged to 5, 10, 15 and 20 per cent, estimated using fitted Weibull distribution, which attained 5, 9, 13, and 16 weeks respectively after the installation of the new drippers. The standard deviation for the above four cases were calculated as 1.65, 2.28, 2.34 and 2.31 respectively.

The number of emitters clogged within each interval of clogging percentage is counted to obtain an actual frequency of emitters under clogging for the above-mentioned stages. The mean and standard deviation values of clogging for these stages are used to fit this frequency with theoretical normal distribution.

Fig. 4.4 shows both actual frequency of emitters under clogging represented by the bar diagram and the theoretical frequency represented by the smooth bell shaped curve for all the four stages. It is seen from the figures that the spatial distribution follows the normal distribution. The goodness of fit was further checked with the  $\chi^2$  test. The calculated  $\chi^2$  values for all the four cases (0.041, 0.043, 0.035 and 0.015) are well within the tabulated  $\chi^2$  value (1.37), which confirms the validity of the chosen distribution.

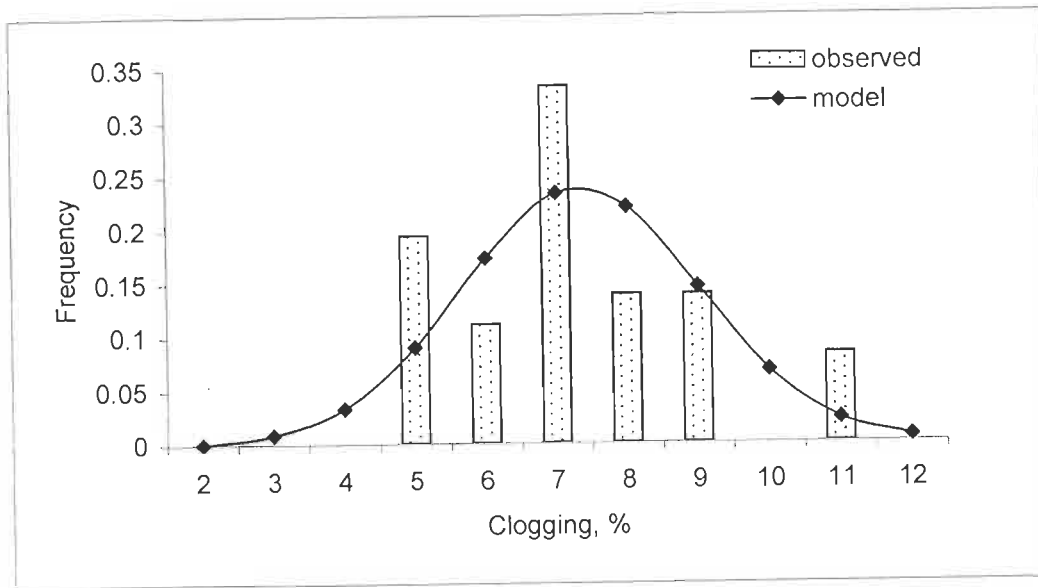


Fig. 4.4(a) Spatial distribution of emitter clogging after 5 weeks of operation

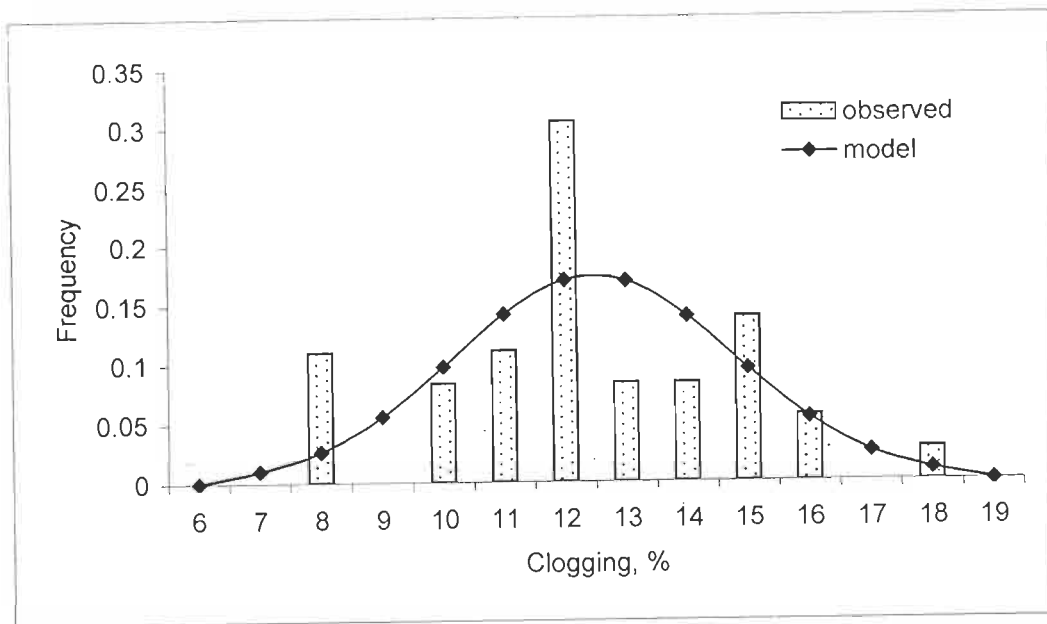


Fig. 4.4(b) Spatial distribution of emitter clogging after 9 weeks of operation

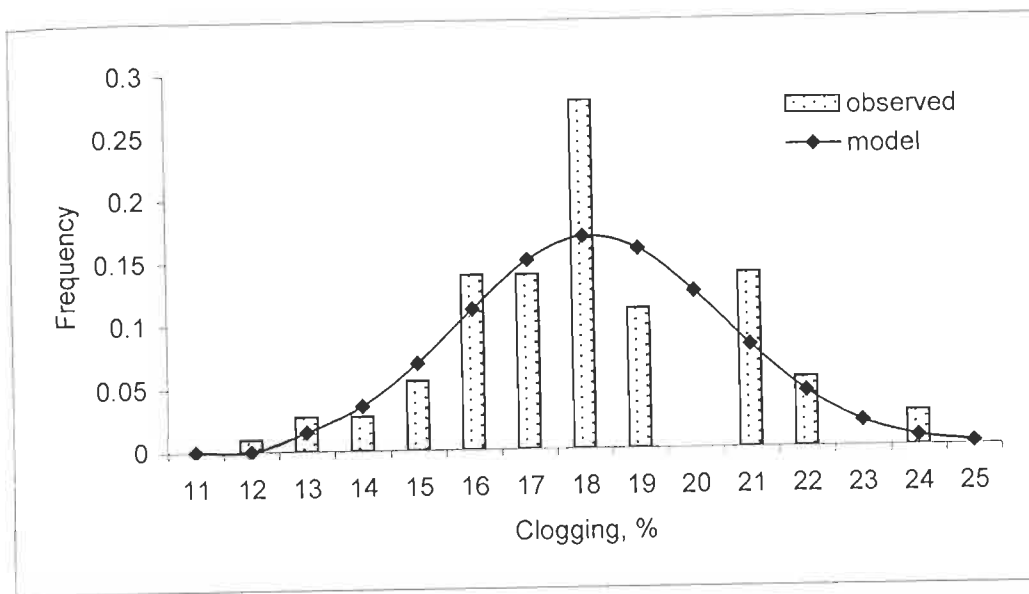


Fig. 4.4(c) Spatial distribution of emitter clogging after 13 weeks of operation

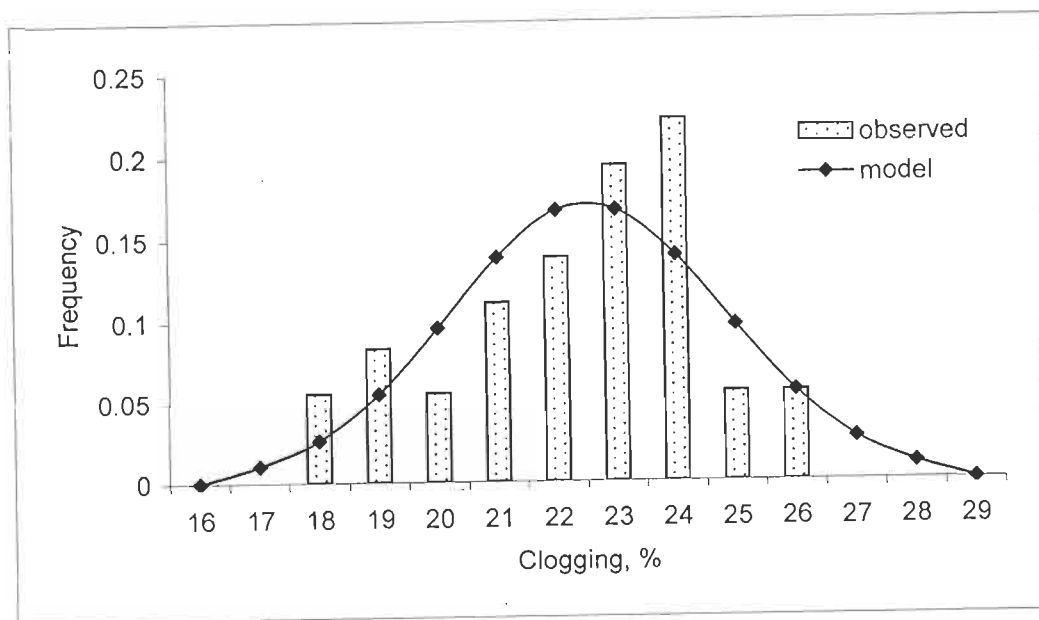


Fig. 4.4(d) Spatial distribution of emitter clogging after 16 weeks of operation

### **4.3 Effect of emitter type and water quality on clogging rates**

Water quality and emitter types are the critical factors in determining the emitter clogging in a drip irrigation system. The irrigation water quality in the selected fields and emitter characteristics and their impact on clogging are presented as follows.

#### **4.3.1 Emitter characteristics**

The performance curves and discharge equations of the four selected drippers for carrying out the field clogging experiments are shown in the Fig. 4.5. The drippers have been named as Dripper-A, Dripper-B, Dripper-C and Dripper-D by arranging the power coefficient ( $X$ ) of pressure head of the emitter discharge equation in an ascending order. These coefficient values for drippers A, B, C and D are 0.015, 0.43, 0.56 and 0.87 respectively. From the  $X$  values as well as graph, it is seen that Dripper-A is least sensitive to pressure and hence it is termed as pressure compensating dripper. Dripper-D is most sensitive to operating pressure among the selected drippers, as its  $X$  value is higher.

#### **4.3.2 Water quality in the tested fields**

The irrigation water quality parameters of the selected fields are given in the Appendix VIII. The fields are named as F1, F2, F3 and F4 based on the salinity levels of the irrigation water. The EC values for the water from four fields F1, F2, F3 and F4 are 0.9, 1.2, 2.4 and 3.0  $\text{dS m}^{-1}$  respectively. Though, EC itself is a good indicative

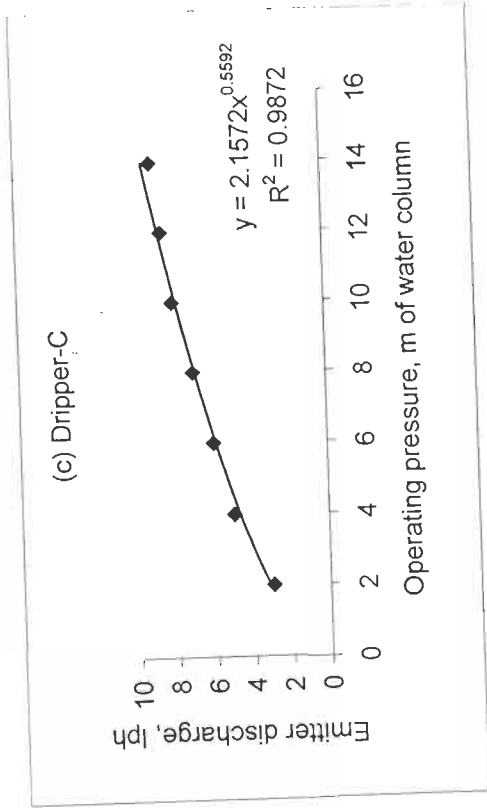
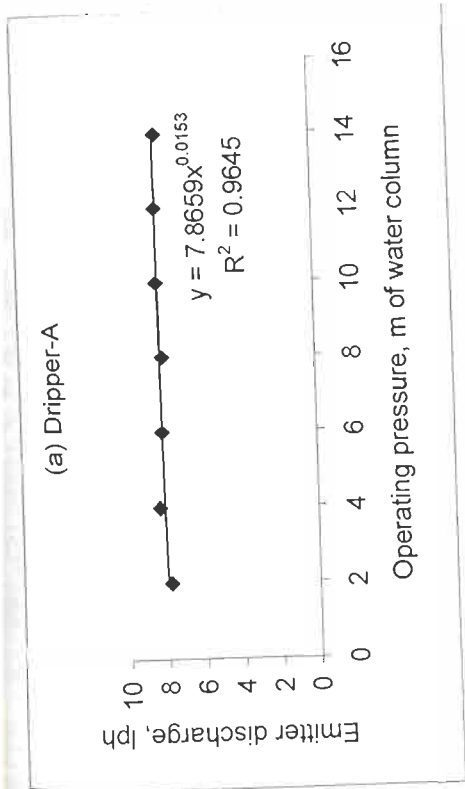
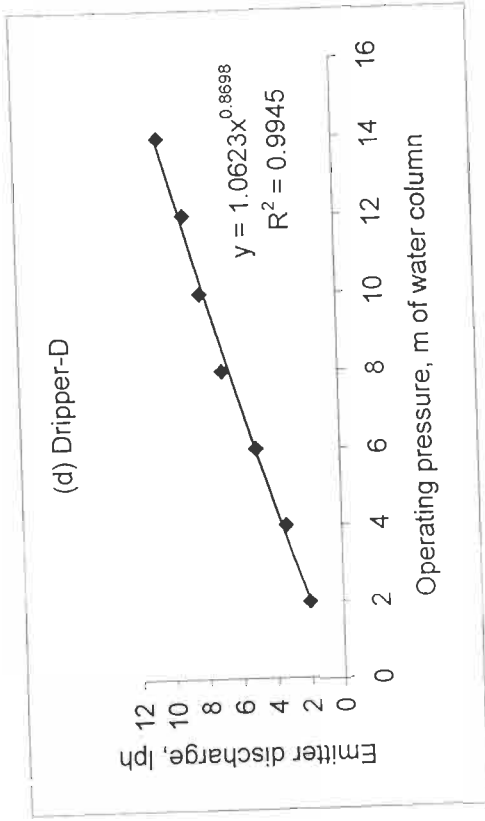
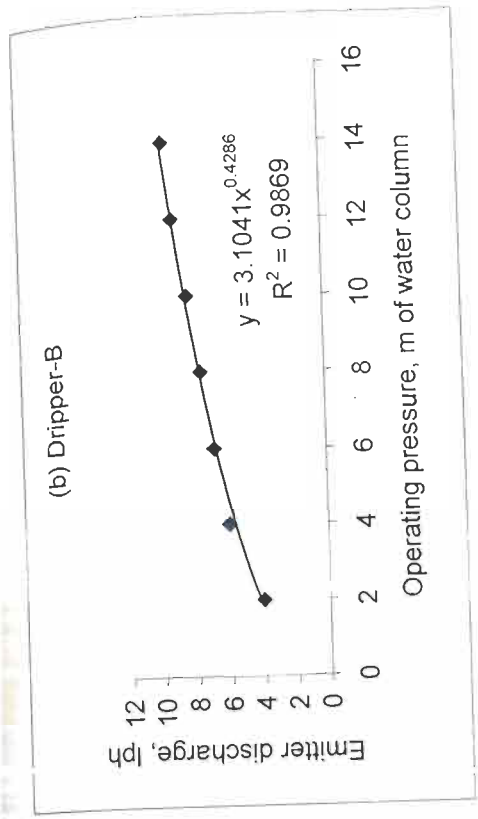


Fig. 4.5 Performance curve for the selected makes of drippers

value for salinity level, important anions like calcium, sodium and potassium and cations like bicarbonates and chlorides are also estimated to have a clear idea about the nature of irrigation water. It is also seen that TDS and the EC are having good correlation. TSS is below  $70 \text{ mg L}^{-1}$  in all the irrigation waters as the waters were collected after the filtering unit of the drip irrigation system.

#### **4.3.3 Effect of water quality and dripper type on clogging**

Clogging in the selected emitters (Dripper A, B, C and D) over the duration of study is given in Figs. 4.6(a), 4.7(a), 4.8(a) and 4.9(a) for the four water qualities. Each datum point on this graph represents the percentage clogging, which is the percentage reduction in emitter flow to the initial condition under identical operating conditions. The figures indicate, not only the occurrence of some clogging in all the trials carried out, but also the existence of a significant difference between the trials. The clogging was enormous for the high salt content irrigation water ( $\text{EC}=3.0 \text{ dS m}^{-1}$ ) while it was the least for the water ( $\text{EC}=0.9 \text{ dS m}^{-1}$ ) with lower salt content.

For all the four water qualities, Dripper-A performed better with lower clogging percentage during the study while the clogging percentage was observed maximum in Dripper-B. This clearly indicates that pressure compensating emitter has exhibited good resistance for clogging due to self-flushing arrangement within them.

Dripper-C performed better followed by Dripper-A. This may be due to the reason that the length of the helical path of this dripper is less when compared to the other two drippers (Dripper-B and Dripper-D). Between Dripper-B and Dripper-D,

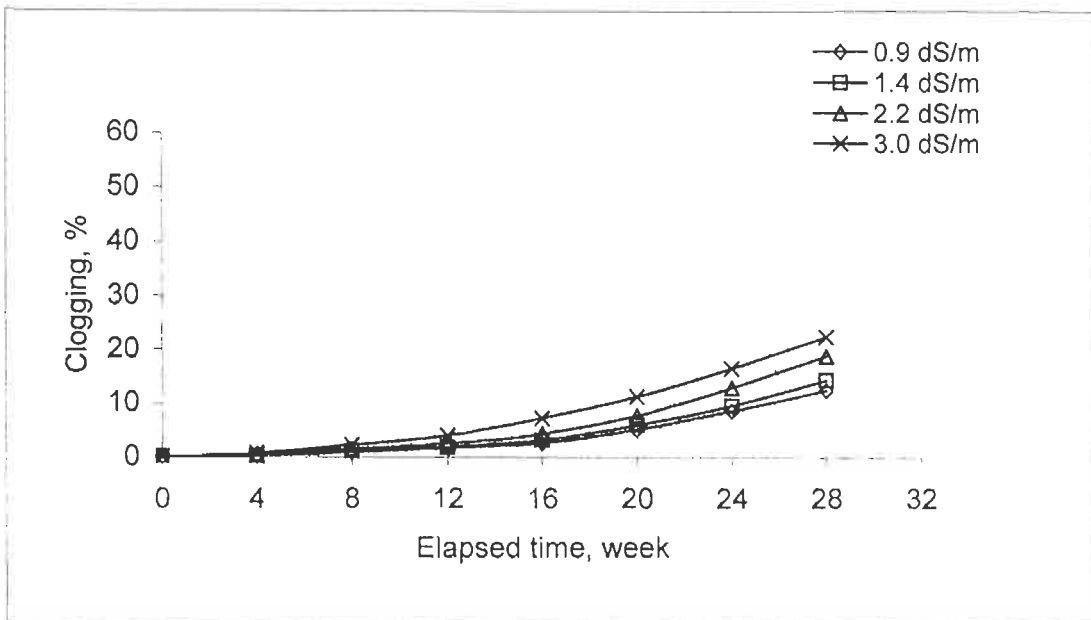


Fig. 4.6 (a) Clogging of Dripper-A under different quality of irrigation water

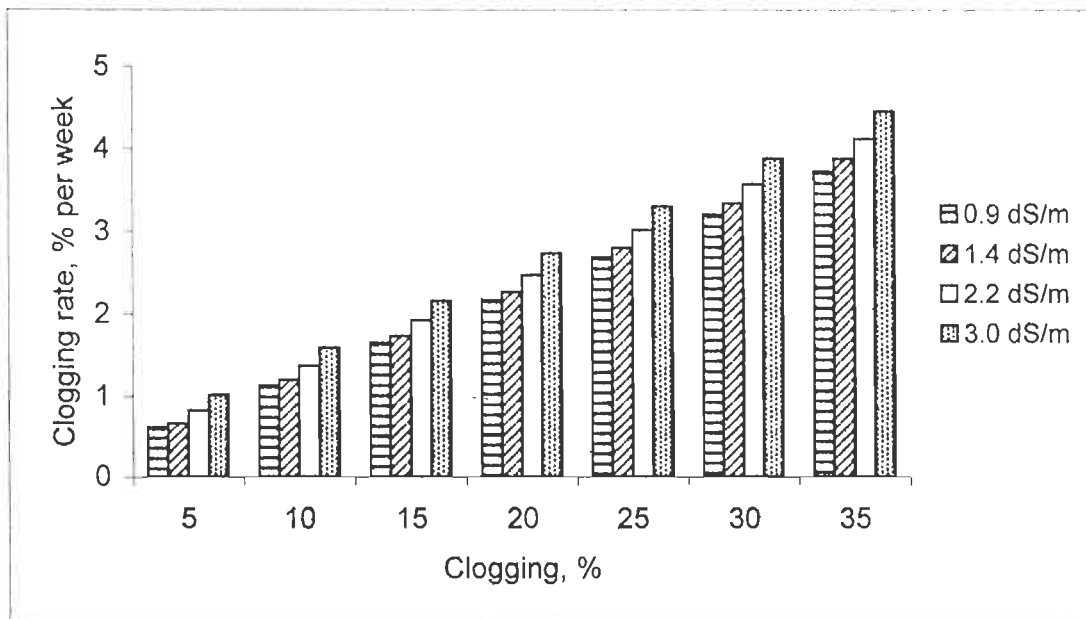


Fig. 4.6 (b) Clogging rate at different clogging stages for four different irrigation water quality in Dripper-A

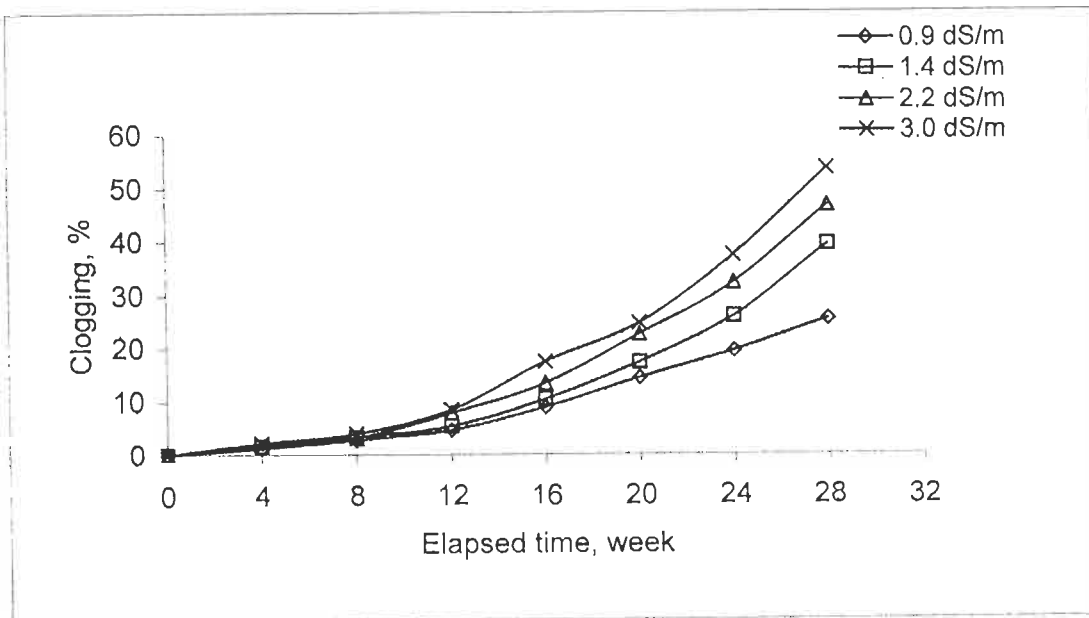


Fig. 4.7(a) Clogging of Dripper-B under different quality of irrigation water

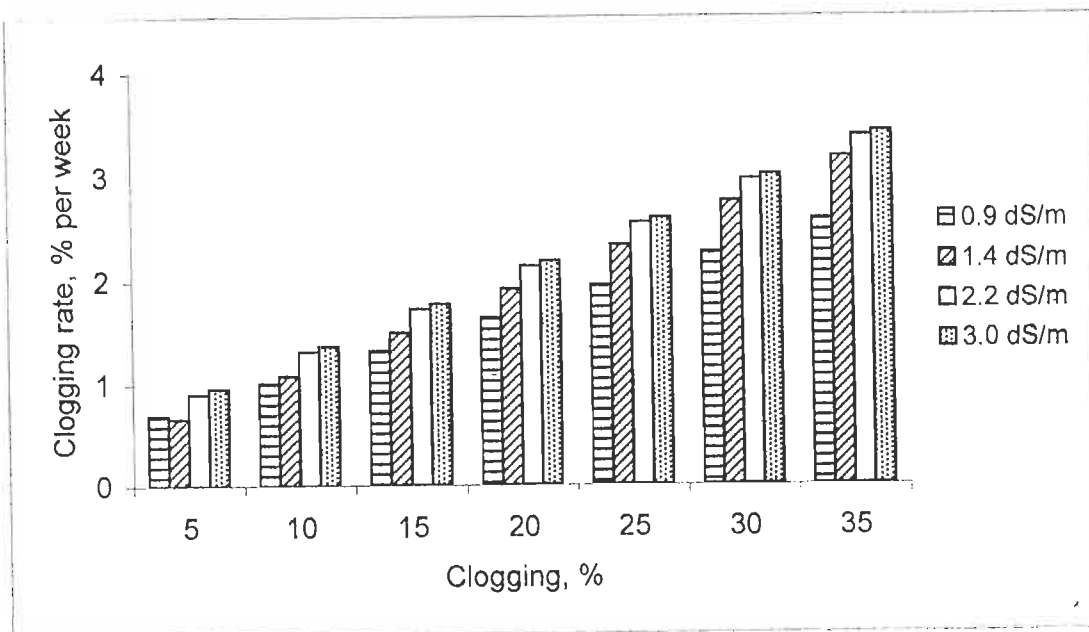


Fig. 4.7(b) Clogging rate at different clogging stages for four different irrigation water quality in Dripper-B

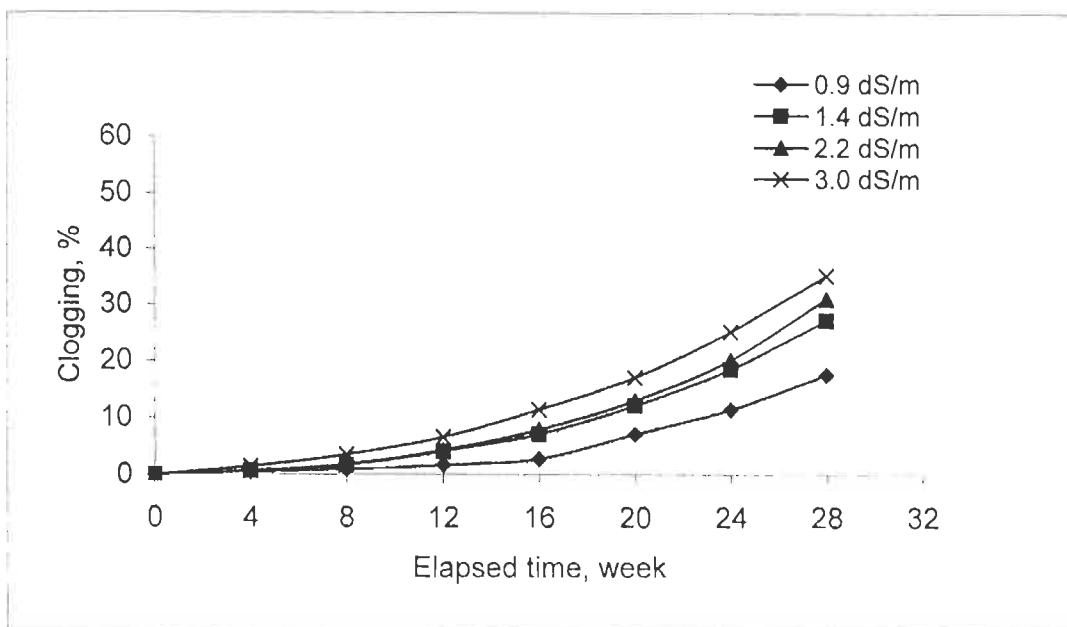


Fig. 4.8 (a) Clogging of Dripper-C under different quality of irrigation water

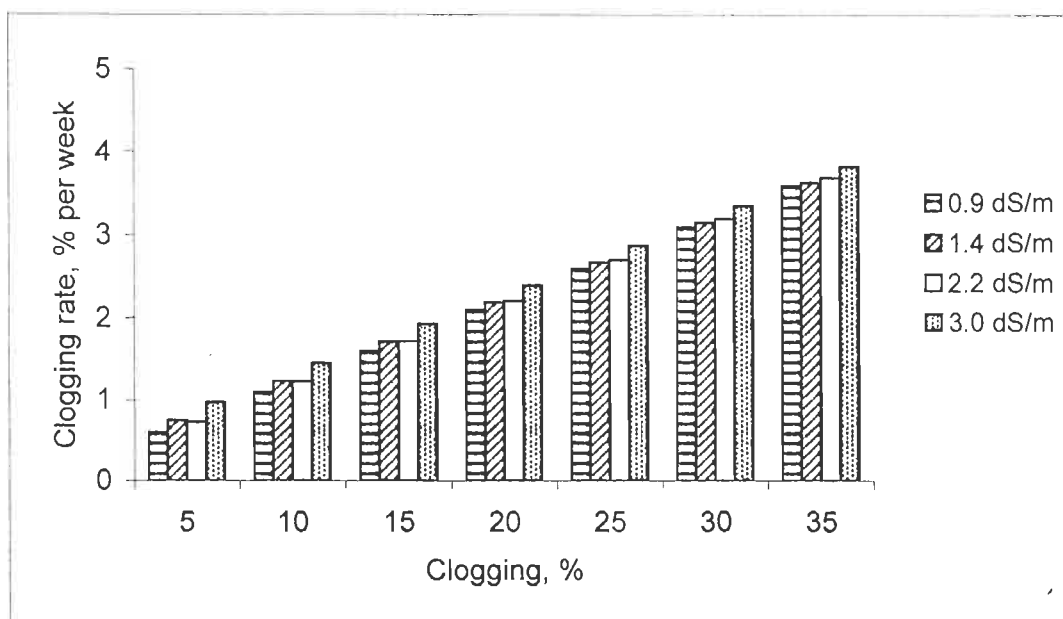


Fig. 4.8 (b) Clogging rate at different clogging stages for four different irrigation water quality in Dripper-C

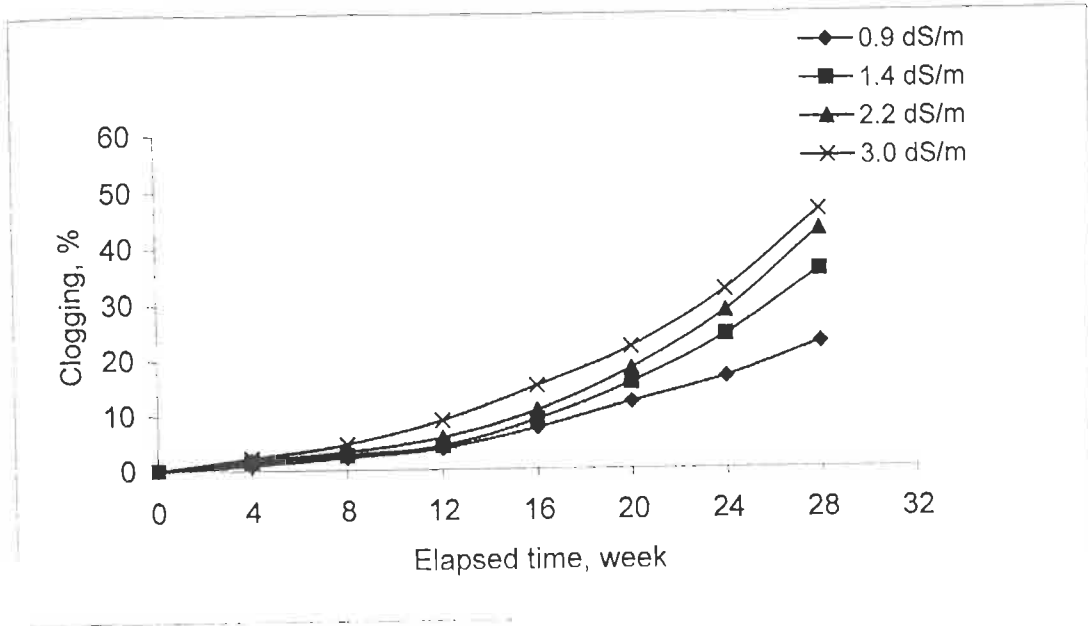


Fig. 4.9 (a) Clogging of Dripper-D under different quality of irrigation water

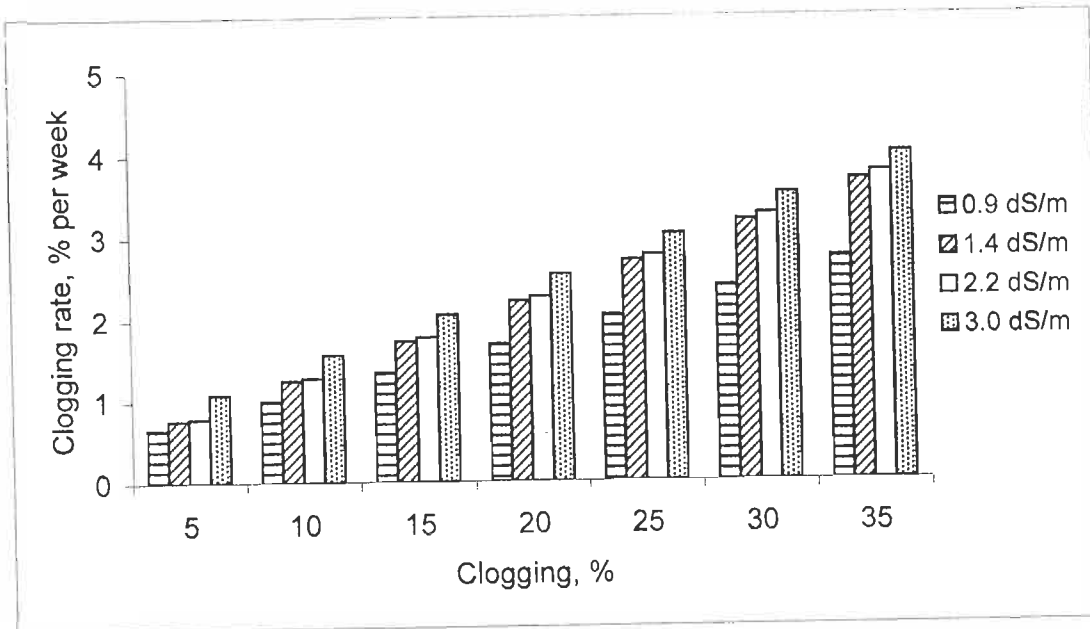


Fig. 4.9 (b) Clogging rate at different clogging stages for four different irrigation, water quality in Dripper-D

clogging is less in Dripper-D as the length of the flow path in this dripper falls in-between Dripper-C and Dripper-B.

#### **4.3.4 Relationship between emitter clogging and elapsed time**

The relationship between emitter clogging and elapsed time are not linear in all cases tried. Among the various models tried to fit this relationship, modified exponential equation was selected based on its high  $R^2$  value. The fitted equations for selected drippers for four different water qualities are tabulated in Table. 4.4. This result is in agreement with the findings of Hills *et al.* (1989), who has observed in a study utilizing secondary sewage effluent in a single chamber tube with 0.4 mm orifice emitter spaced at 460 mm that the reduction in emitter flow rate was a curvilinear function with time. The geometric arrangement of a blockage also influences the clogging.

#### **4.3.5 Relationship between clogging rate and clogging stages**

Clogging rate of the selected emitters (Dripper A, B, C and D) at different clogging conditions are given in Figs. 4.6(b), 4.7(b), 4.8(b) and 4.9(b) for the four water qualities. As shown in figures, it is evident that the clogging rate increases with percentage clogging in all the trials. Within a dripper also, the increase in the clogging rate varies with water qualities.

In the case of Dripper-A, the clogging rate is in the range of 0.6 to 1.0 per cent per week for all the water qualities of F1, F2, F3 and F4 at 5 per cent clogging condition. It went on to reach 3.7 to 4.5 per cent per week at 35 per cent clogging.

Table 4.4 Relationship between emitter clogging (P in per cent) and elapsed time (t in weeks)

S. No.	Dripper type	Water quality	Equation	R <sup>2</sup>
1	A	F1	$P = -0.73 (1.23 \cdot e^{0.1t})$	0.99
2		F2	$P = -0.84 (1.19 \cdot e^{0.1t})$	0.99
3		F3	$P = -1.15 (1.13 \cdot e^{0.1t})$	0.99
4		F4	$P = -3.39 (1.11 \cdot e^{0.07t})$	0.99
5	B	F1	$P = -3.88 (1.33 \cdot e^{0.07t})$	0.99
6		F2	$P = -2.52 (1.11 \cdot e^{0.01t})$	0.99
7		F3	$P = -2.76 (1.04 \cdot e^{0.01t})$	0.99
8		F4	$P = -5.93 (1.02 \cdot e^{0.08t})$	0.99
9	C	F1	$P = -0.75 (1.29 \cdot e^{0.12t})$	0.99
10		F2	$P = -2.39 (1.18 \cdot e^{0.09t})$	0.99
11		F3	$P = -2.13 (1.16 \cdot e^{0.10t})$	0.99
12		F4	$P = -4.97 (1.06 \cdot e^{0.08t})$	0.99
13	D	F1	$P = -5.41 (1.10 \cdot e^{0.06t})$	0.99
14		F2	$P = -2.80 (1.03 \cdot e^{0.10t})$	0.99
15		F3	$P = -5.21 (1.14 \cdot e^{0.08t})$	0.99
16		F4	$P = -6.04 (1.10 \cdot e^{0.08t})$	0.99

In the case of Dripper-B also, the clogging rates for four water qualities are not uniform at all the stages of clogging examined. Clogging rate was about 0.69 to 0.96 per cent per week at 5 per cent clogging condition for all the water qualities. The range is further widened at 35 per cent clogging as 2.6 to 3.4 per cent per week.

Dripper-C is also getting clogged at a faster rate as the clogging percentage increases for all the four water qualities. The clogging rates at the 5 per cent clogging are ranging from 0.6 to 0.97 per cent per week and the same at 35 per cent clogging are varying from 3.6 to 3.8 per cent per week. In the case of Dripper-D, the values of clogging rates at the 5 per cent are in the range of 0.65 to 1.0 per cent per week and the same at 35 per cent clogging are 2.7 to 4.0 per cent per week.

As seen from the above results, it is concluded that the rate of clogging is increasing invariably with percentage clogging in all the trials. However, there is variation in clogging rate for the same dripper tested under different water quality. Irrigation water with high salinity level induces clogging faster and results in increased clogging rate. However, the difference in clogging rate is in the order of 0.1 to 0.6 per cent per week among all the trials.

#### **4.3.6 Effect of emitter flow path length on emitter clogging**

Figs. 4.10 (a) and (b) show the curvilinear relationship between the total clogging percentage and the length of the flow path inside the emitter for 12 weeks and 28 weeks after the starting of experiment respectively. An inverse relationship was evident between these two parameters. The emitter with a lengthier flow path

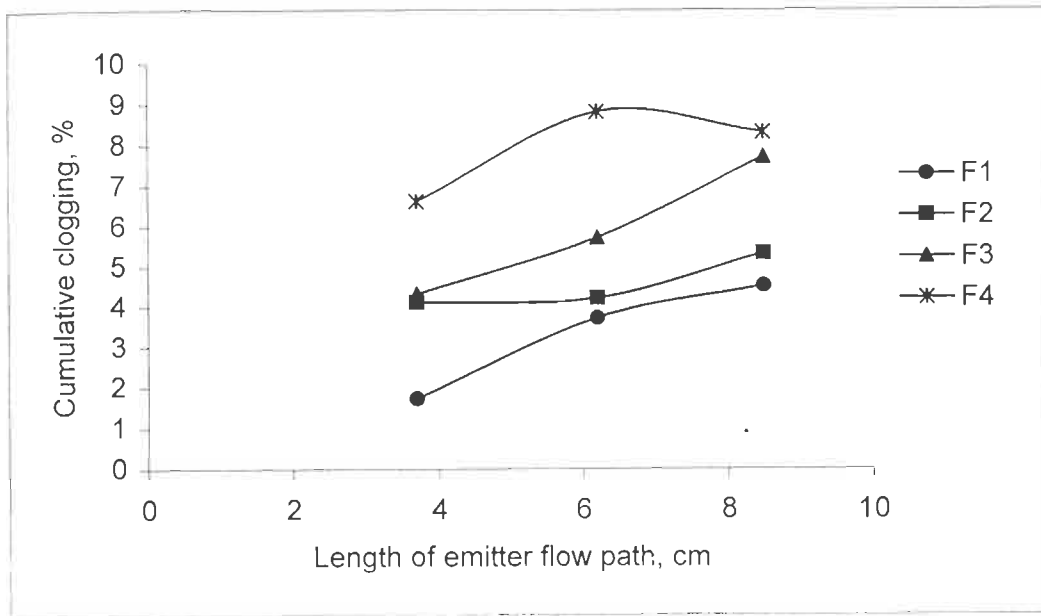


Fig. 4.10 (a) Effect of emitter flow path length on emitter clogging after 12 weeks

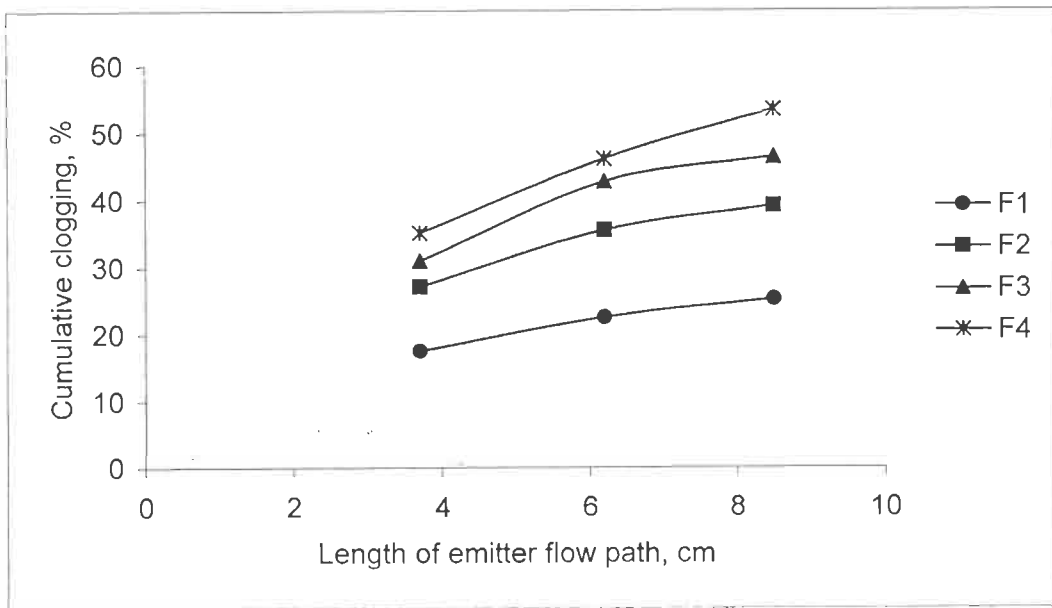


Fig. 10(b) Effect of emitter flow path length on emitter clogging after 28 weeks

may be more prone to clogging, as the water has to travel a longer distance with lesser velocity. Moreover, the stagnation of water inside the emitter will be more in this case even after the irrigation is stopped. This water results in deposition of salts on the flow path.

#### **4.3.7 Effect of fertigation on clogging**

The effect of using water-soluble fertilizers through drip irrigation on the system performance is an important concern. A sample study was conducted to have a broad idea about the clogging and flow variations due to introduction of fertigation mechanism. Fig. 4.11(a) shows the comparison between the emitter flow with fertigation and without fertigation by maintaining the same operating pressures after the fertigation unit. It is clear that the fertigation does not have any influence over the emitter discharge at any point of time. However, there will be a considerable pressure head loss inside this fertigation equipment. The head loss is different for different fertigation mechanism. It is noted from the manufacturer's guide that the head loss for fertilizer tank is around 0.5-1.0 m. The head loss in venturi fertigation unit stands in the range of 1.0-2.0 m.

The rate of clogging due to fertigation with NPK water-soluble fertilizers was compared with that of fertigation free emitters (Fig. 4.11(b)). The clogging is observed to be more in the case of emitters with fertigation. Insoluble particles of fertilizers and the reaction of chemicals in the water result in more clogging in drip

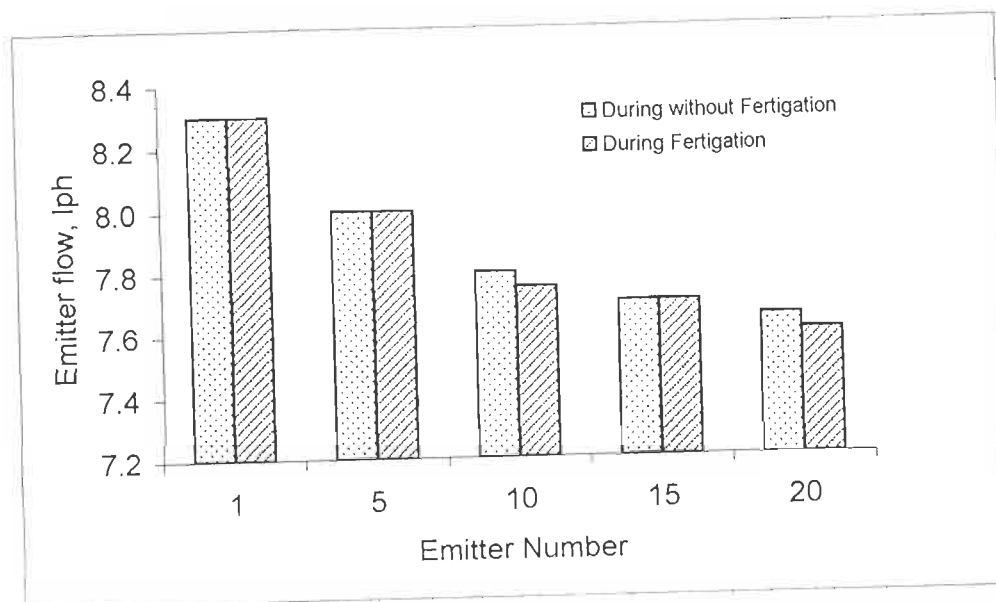


Fig. 4.11 (a) Effect of fertigation on emitter flow for same operating pressure at any point of time

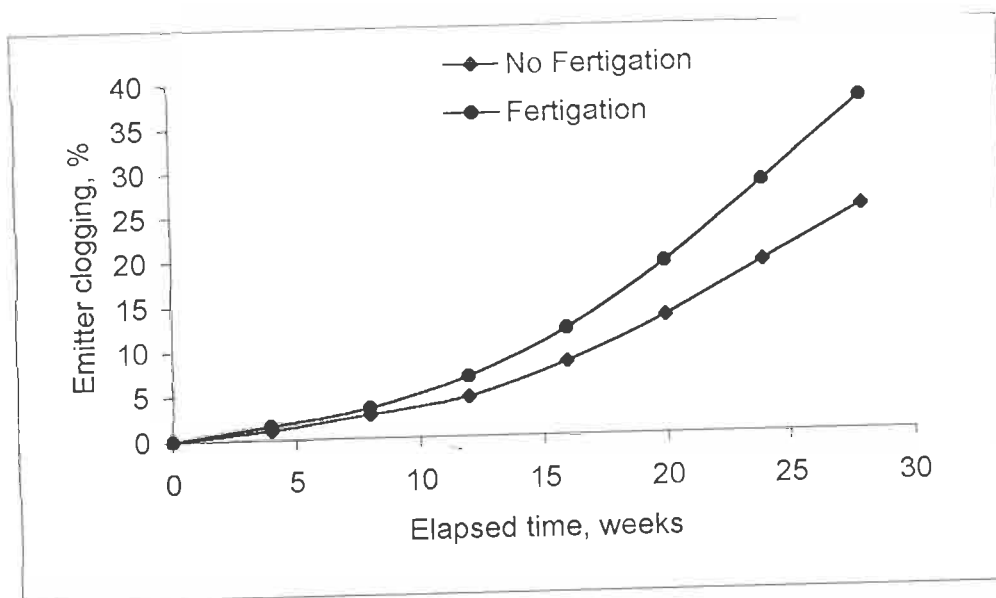


Fig. 4.11 (b) Effect of fertigation on clogging

emitters with fertigation. Intensive studies on this clogging process due to emitter clogging have been studied by many researchers (Fabry, 1978 and Rolston *et al.*, 1979). The injection of fertilizers into irrigation water will bring about an increase in  $p^H$  that may be conducive to the precipitation of calcium, magnesium, and phosphorous which are insoluble (Rolston *et al.*, 1979).

#### **4.4 Simulation and validation of DRIPCLOG and RANGEN**

The computer programs (DRIPCLOG and RANGEN) developed using 'C' language for the methodology described in the earlier chapter, were run for the results. As a first step the validity of the developed models were evaluated by comparing the sample simulation results with the experimental results.

##### **4.4.1 Simulation of the models**

The simulation of the hydraulic model is consisting of two phases. In the first phase, the emitter coefficients (K) and clogging percentages (P) are generated using the developed computer sub model RANGEN and are stored in the text files. These files are the input for the main model DRIPCLOG. Secondly, the main model is run for the drip system parameters supplied during runtime and the values stored in the text files generated from the sub model RANGEN. DRIPCLOG is calculating the hydraulic pressure available at each emitter and discharge of all the emitters in the lateral line. The results from this model is stored in a text file named by the user and can be retrieved back to analyse further.

The distribution of the emitter coefficients (K) for a typical case (Appendix – XIII) is shown in Fig. 4.12. Here, the K value is assumed as 2.16 and a coefficient of variation of 3 per cent. The dotted line in the figure shows the values for the emitter constant K for the 100 emitters positioned in a single lateral. The values are distributed equally on both the sides of the dotted line, which represent the constant value of emitter coefficient (K) of 2.16.

The distribution of the emitter clogging (P) for a typical situation (Appendix – XIV) is shown in Fig. 4.13. The average clogging percentage and the coefficient of variation of it are assumed as 10 and 3 per cent respectively. The line in the graph shows the values for the emitter clogging P in percentage for the 100 emitters positioned in a single lateral. The values are distributed equally on both the sides of the dotted line, which represent the average value of emitter clogging (10%) for the 100 emitters.

DRIPCLOG simulated pressure head and emitter flow values for 100 emitters with the above generated K and P values, are given in Appendix – XV. Fig 4.14 represents the effective hydraulic pressure ( $h^x$ ) variation along the lateral for a typical system and design parameters of a drip irrigation lateral. The effective hydraulic pressure variation is calculated by assuming zero coefficient of manufacturing variations and no emitter clogging for all the 100 emitters placed in a lateral. The effective pressure heads available at the head end and tail end of the lateral are 4.02 and 3.32 meter of water column respectively for the X value of 0.56. The coefficient of variation of hydraulic pressure for the assumed drip lateral system is 5.85 per cent.

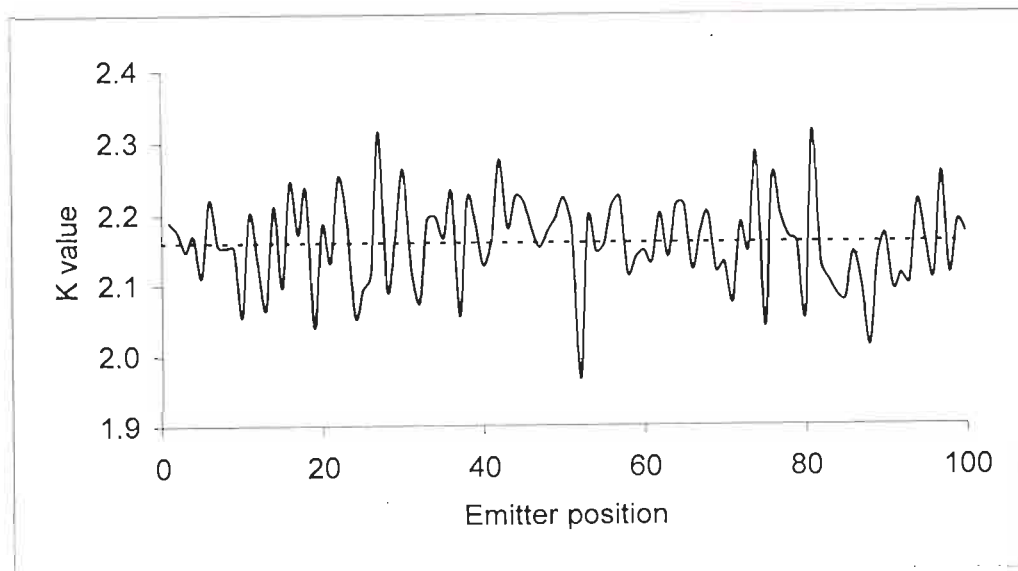


Fig. 4.12 Distribution of emitter constant (K) for an emitter coefficient of variation ( $CV_m$ ) of 3%

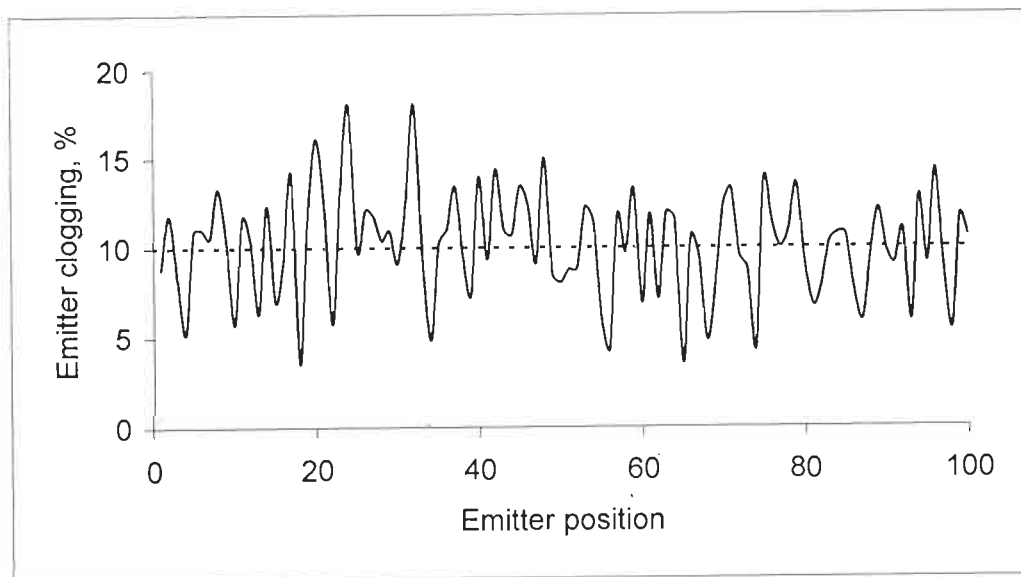


Fig. 4.13 Distribution of 10% emitter clogging (P) with a coefficient of variation ( $CV_c$ ) of 3%

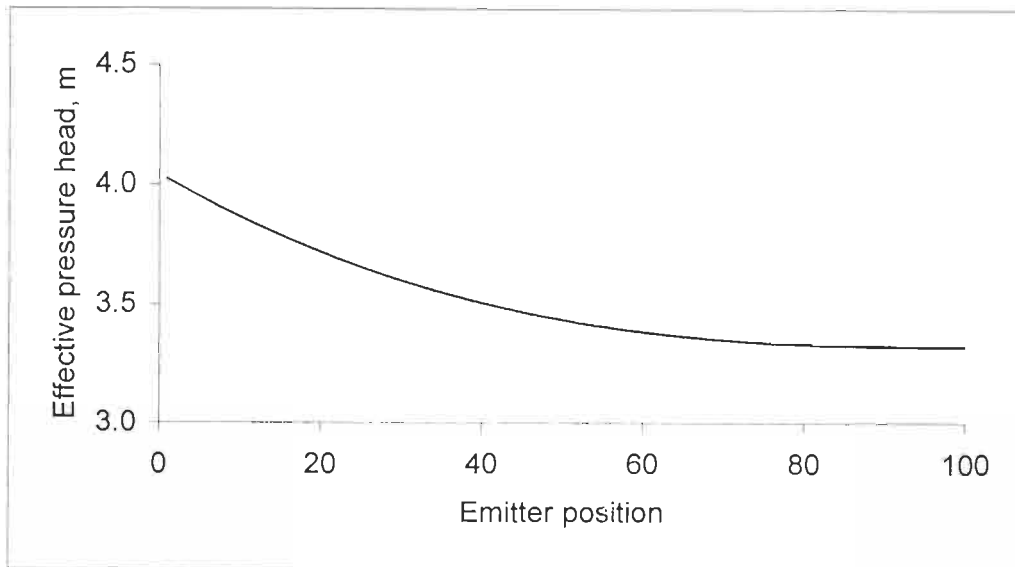


Fig.4.14 Distribution of effective hydraulic pressure ( $h^x$ ) for a coefficient of variation ( $CV_h$ ) of 5.85%

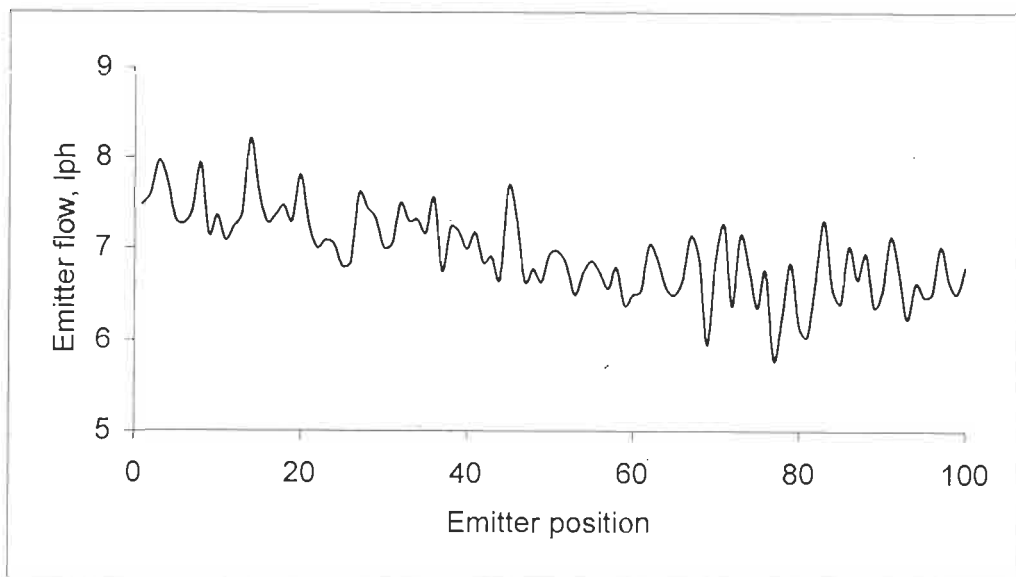


Fig. 4.15 Simulated emitter flow for a hypothetical drip irrigation system ( $CV_m = 3\%$ ,  $P = 10\%$ ,  $CV_c = 3\%$  and  $CV_h = 5.85\%$ )

Fig. 4.15 depicts the emitter discharge for all the 100 emitters in the lateral as obtained from the main model DRIPCLOG. This emitter discharge is resulting from three variations viz. manufacturer's coefficient of variation of 3 per cent, emitter clogging of 10 per cent with coefficient of variation of 3 per cent and effective hydraulic pressure variation of 5.85 per cent presented separately in the Figs. 4.12, 4.13 and 4.14 respectively.

#### 4.4.2 Validation of the model

The developed models RANGEN and DRIPCLOG were validated with the actual values. For validating the sub model RANGEN, the values generated for drip clogging and emitter coefficients by this sub model were evaluated for its indented normal distribution pattern. Fig. 4.16 shows the comparison of frequency of generated emitter coefficients and that of theoretical normal distribution. The points on the graph represent the frequency of generated emitter coefficients, which follow very closely to the theoretical curve. The validation was carried out using chi-square ( $\chi^2$ ) test. The calculated  $\chi^2$  value (10.0) is less than the tabulated  $\chi^2$  value (10.1) at 5% level, which confirms the validity of the sub-model. A further confirmation of this sub model was made with the generated clogging values. The frequency of this generated emitter clogging data was compared for its theoretical normal distribution.

The points on the Fig. 4.17 represent the frequency of generated emitter clogging and the line represents the theoretical frequency. The calculated  $\chi^2$  value

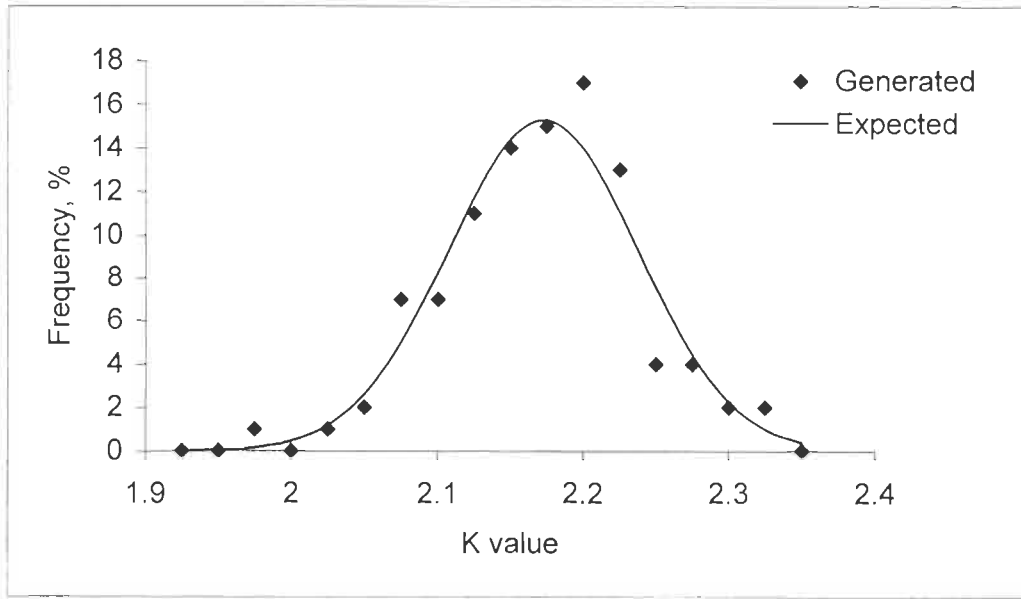


Fig. 4.16 Comparison of frequency of generated K value with its expected value

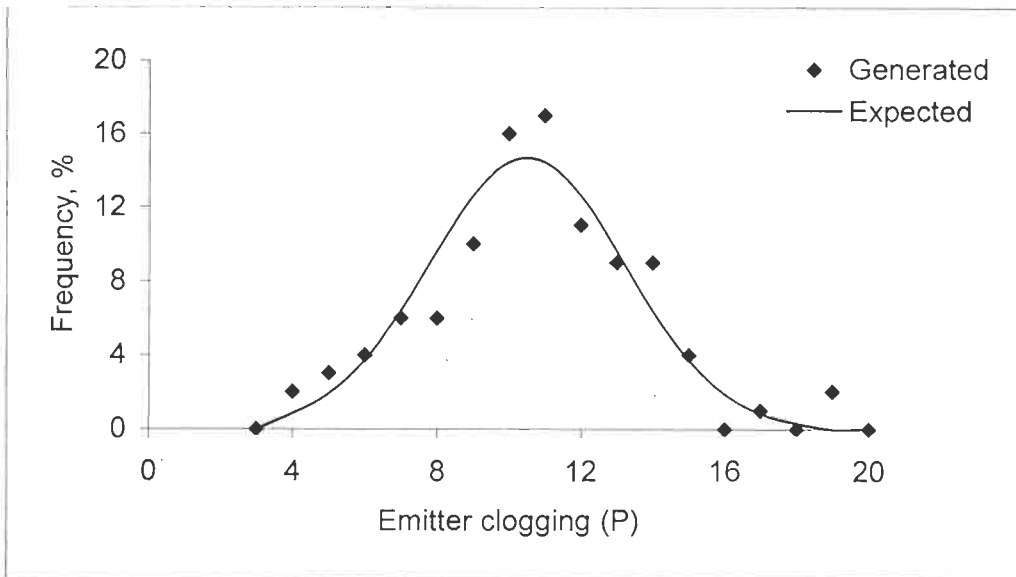


Fig. 4.17 Comparison of frequency of generated P value with its expected value

(8.0) for this data set is also less than the tabulated  $\chi^2$  value (9.4) at 5% level, which further confirms the validity of the sub model.

The validation of the main model DRIPCLOG was made by comparing the pressure distribution and emitter discharges. The hydraulic pressures at five points along a 10m lateral in the lab scale drip irrigation system were measured by maintaining the inlet pressure head of 10 m of water column. Similar system parameter was fed to the model while running and the pressure heads at the same points as measured in the lab model lateral were stored in a text file. This model values were then compared with the measured pressure head values. Fig.4.18 shows the measured and simulated pressure head values. The calculated  $\chi^2$  value (0.00005) for this data set is less than the tabulated  $\chi^2$  value (1.15) at 5% level, which confirms the validity of the main model DRIPCLOG.

The main model DRIPCLOG was also evaluated for its discharge simulation. For the same input parameters as mentioned in the previous paragraph, the model output of emitter discharge values were compared with observed values. Fig. 4.19 shows the observed and simulated emitter discharge values for the selected five emitters along the lateral. From the statistical test, the  $\chi^2$  value (0.00003) for this observed and simulated emitter discharge data set is less than the tabulated  $\chi^2$  value (1.15) at 5% level, which further confirms the validity of the main model DRIPCLOG.

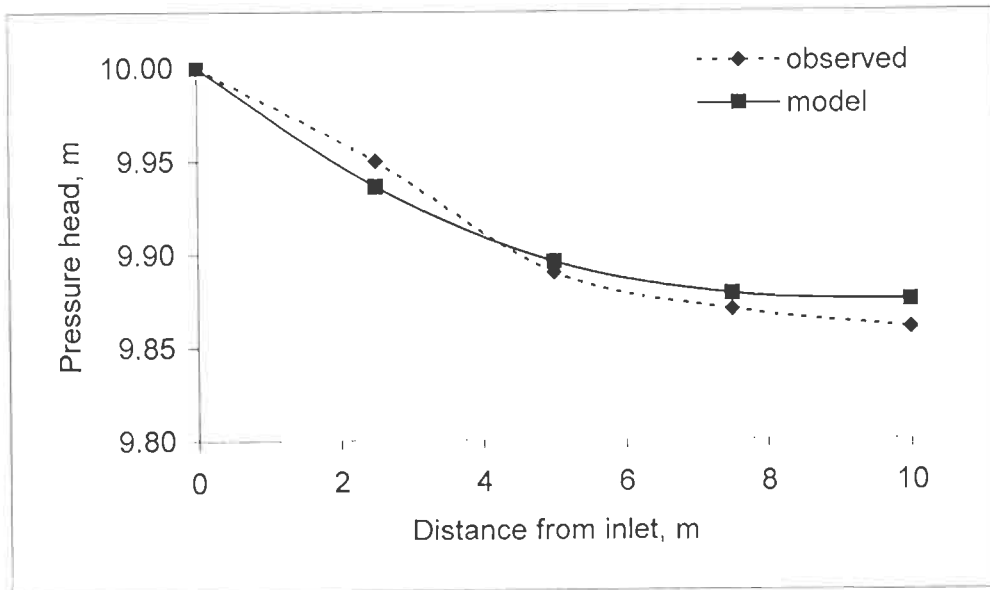


Fig. 4.18 Comparison of observed and simulated pressure profiles

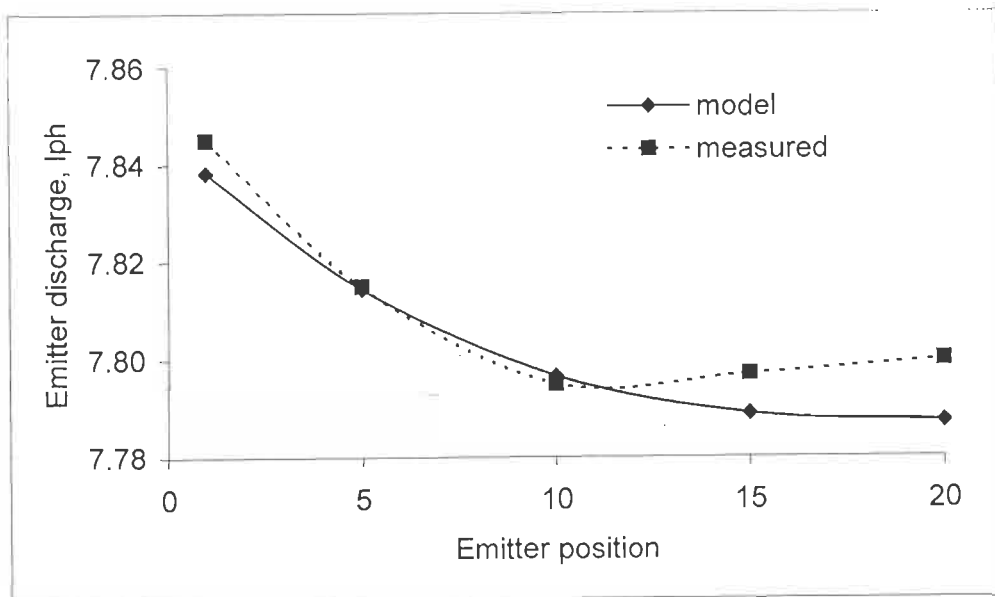


Fig. 4.19 Comparison of observed and simulated emitter discharges

#### **4.5 Effect of manufacturing variations and emitter clogging on emission uniformity**

Emitter flow variation is chiefly controlled by the three important factors namely hydraulic variation, manufacturing variations and emitter clogging. Hydraulic variation and manufacturing variations are inevitable and are constant for any drip irrigation system, whereas the clogging variation is a function of water quality and emitter type. So a detailed study on effect of emitter clogging in combination with manufacturing variations was made using computer simulation and is discussed below.

##### **4.5.1 Effect of manufacturing variations on emission uniformity**

In order to find the magnitude of the effect that manufacturing variations can have on trickle irrigation uniformity, flow distributions for four coefficients of manufacturing variations ( $CV_m$ ) were simulated using the models RANGEN and DRIPCLOG. The flow distributions for 0, 3, 6 and 9 percent of coefficient of manufacturing variations are shown in the Figs. 4.20(a)–(d). The emitter coefficients used are,  $K=2.16$  and  $X = 0.56$ . The inlet pressure is considered as 12 m of water column for the entire simulation. The minimum and maximum flow in lph obtained for the  $CV_m$  of 0, 3, 6, and 9 per cent are 7.18-8.69, 6.82-8.65, 6.63-9.73, and 5.70-10.01 respectively.

The emission uniformities for all the four hypothetical conditions were estimated and are shown in Fig. 4.20(e). The uniformity for zero coefficient of

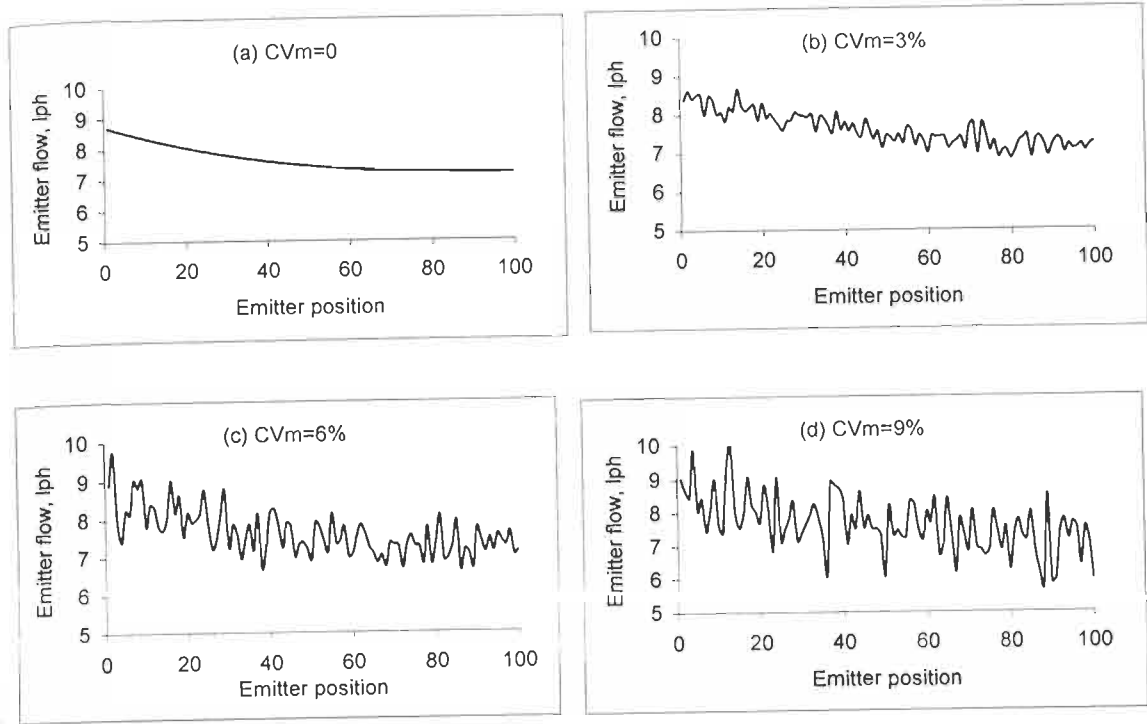


Fig. 4.20 Effect of coefficient of manufacturing variation ( $CV_m$ ) on emitter flow

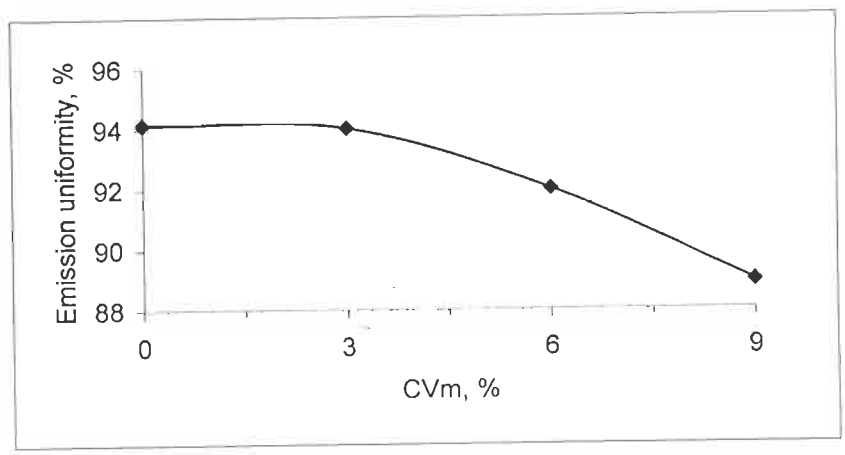


Fig. 4.20 (e) Effect of coefficient of manufacturing variation ( $CV_m$ ) on emission uniformity

manufacturing variation is 94.14 per cent. This reduction is purely due to the hydraulic variation. The uniformity is not reduced much for the  $CV_m$  of 3 per cent whereas the reduction is very fast for 6 and 9 per cent  $CV_m$  values. Hence it is safe to operate the drip irrigation system within the 3 per cent of coefficient of manufacturing variation without sacrificing the emission uniformity.

#### 4.5.2 Effect of emitter clogging on emission uniformity

Nine hypothetical situations of clogging without any coefficient of manufacturing variation were simulated with the developed models. The hypothetical situations were clogging of 10, 20, and 30 per cent with coefficient of manufacturing variation of 3, 6 and 9 per cent in each clogging level. In all the cases, the degree of emission uniformity is highly influenced by the clogging variations.

The effects of 10 per cent clogging at different levels of coefficient of variations on emitter flow are presented in the Figs. 4.21(a)-(c). The minimum and maximum flow in lph obtained for the  $CV_c$  of 3, 6, and 9 per cent are 6.08-8.15, 6.00-8.39 and 4.90-8.83 respectively. The emission uniformities at 10 per cent clogging were estimated for all  $CV_c$  and are shown in Fig. 4.21(d). The uniformity decreases with increase in  $CV_c$  in an increasing trend.

The effects of 20 per cent clogging at different levels of coefficient of variations on emitter flow are presented in the Figs. 4.22(a)-(c). The minimum and maximum flow in lph obtained for the  $CV_c$  of 3, 6, and 9 per cent are 5.67-7.03, 5.00-7.80 and 4.48-8.42 respectively. The Emission uniformities at 20 per cent clogging

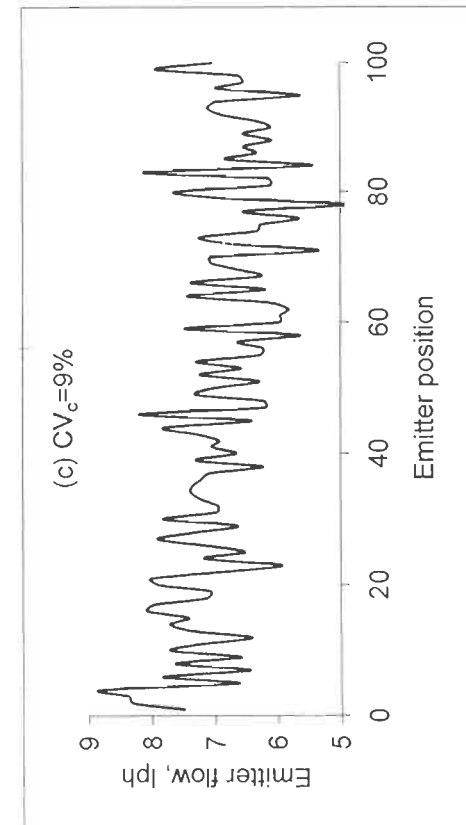
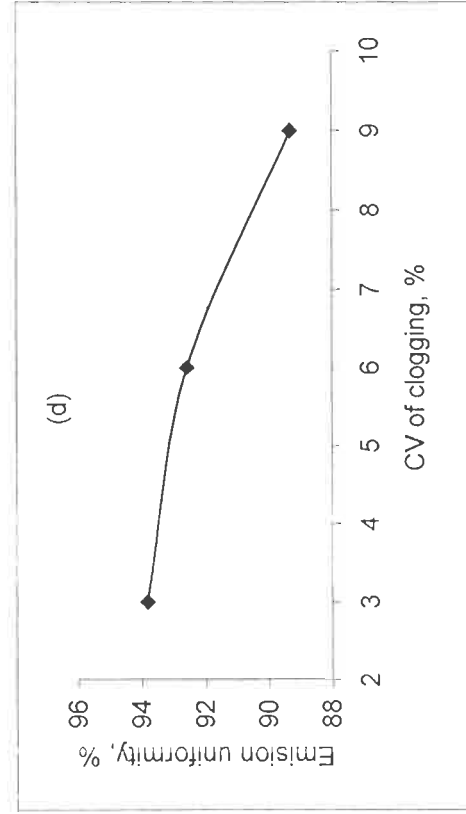
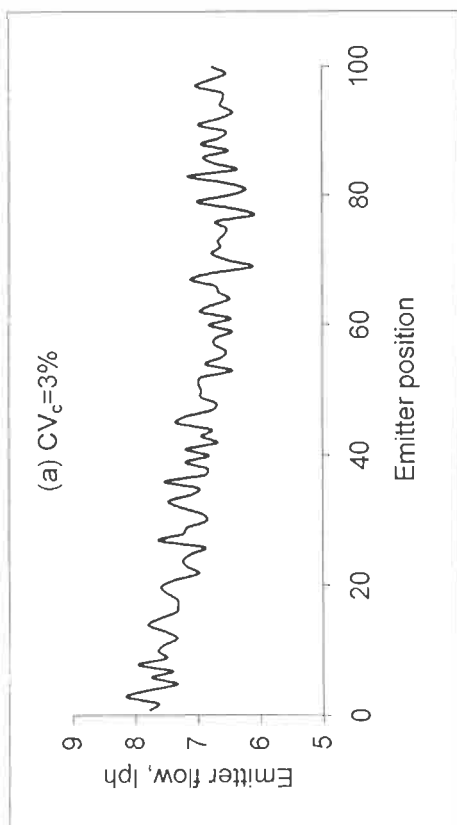
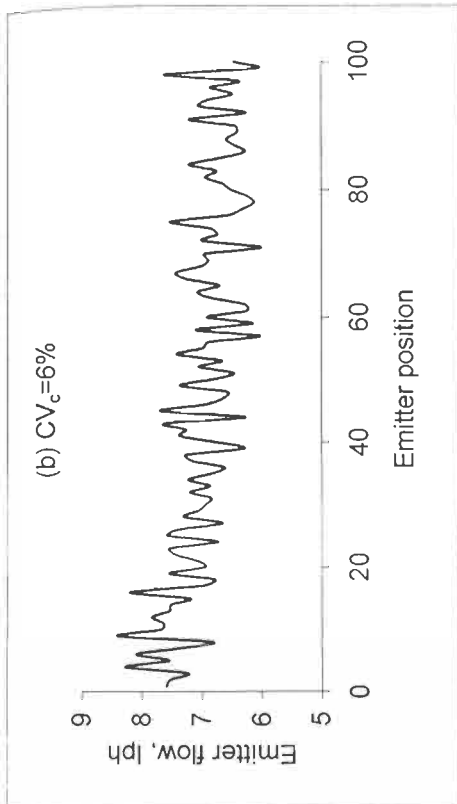


Fig. 4.21 Effect of 10 per cent clogging with different coefficient of variation ( $CV_c$ ) on emitter flow and emission uniformity

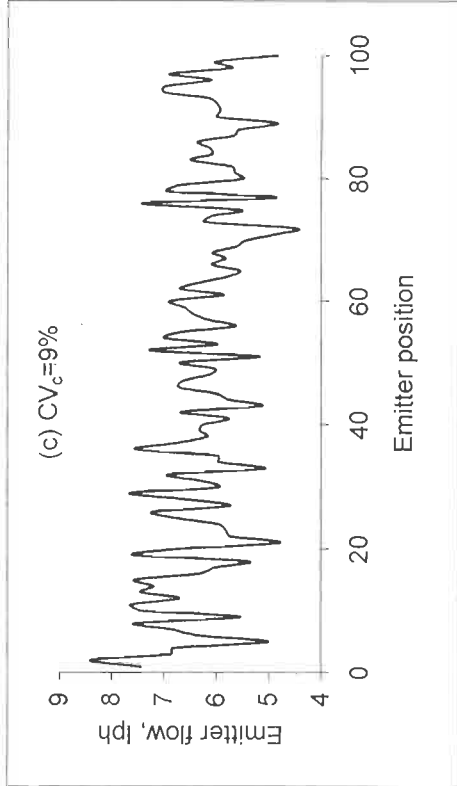
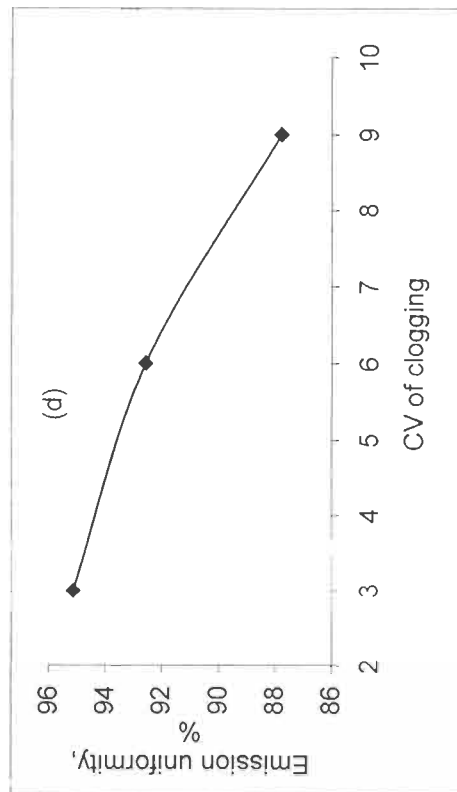
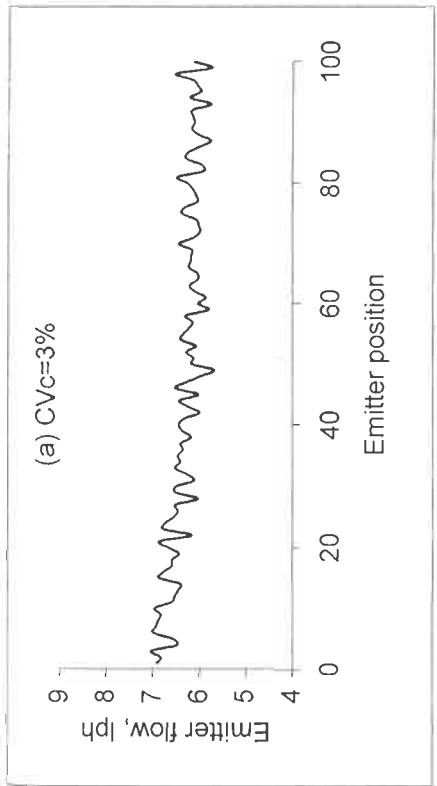
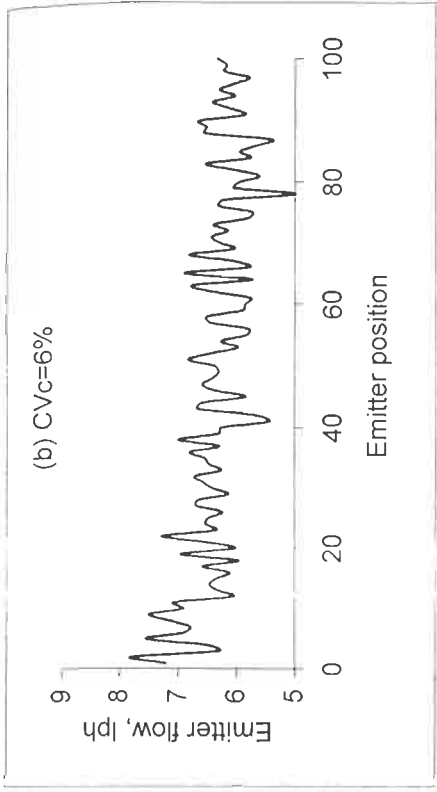


Fig. 4.22 Effect of 20 per cent clogging with different coefficient of variation ( $CV_c$ ) on emitter flow and emission uniformity

were estimated for all  $CV_c$  and are shown in Fig. 4.22(d). The uniformity decreases with increase in  $CV_c$  in an increasing trend as in the case of 10 per cent clogging.

The effects of 30 per cent clogging at different levels of coefficient of variations on emitter flow are shown in the Figs. 4.23(a)-(c). The minimum and maximum flow in lph obtained for the  $CV_c$  of 3, 6, and 9 per cent at this clogging level are 5.01-6.30, 4.89-6.59 and 4.40-7.10 respectively. The emission uniformities at 30 per cent clogging were estimated for all  $CV_c$  and are shown in Fig. 4.23(d). Here also, the emission uniformity decreases with increase in  $CV_c$  in an increasing trend similar to 10 and 20 per cent clogging.

#### **4.5.3 Combined effect of manufacturing variations and emitter clogging on emission uniformity**

In order to make out the interaction effects of manufacturing variations and emitter clogging on emission uniformity, various combinations of these two parameters were contemplated. Three sets of emitter K values representing the  $CV_m$  of 3, 6 and 9 per cent and nine sets of emitter clogging values representing 10, 20 and 30 per cent with coefficient of variations of 3, 6 and 9 per cent in each clogging level were generated using the model RANGEN. The emitter flow in a lateral consisting of 100 emitters for all the contemplated situations were simulated with the model DRIPCLOG using the generated emitter coefficients (K) and clogging (P) values. From the emitter flow values, emission uniformities were computed for all the cases.

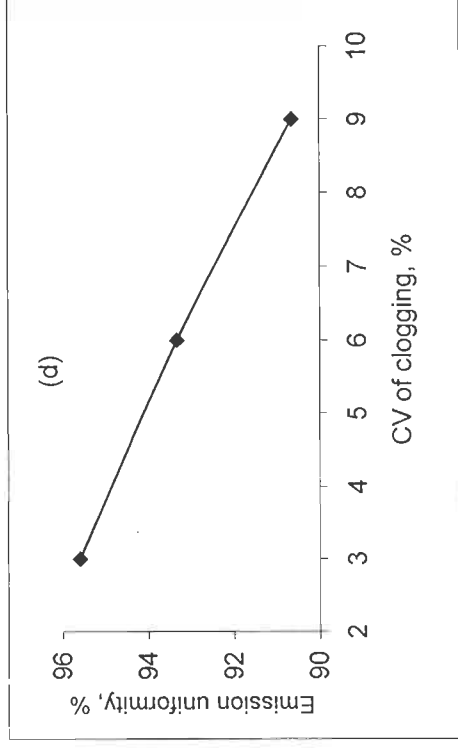
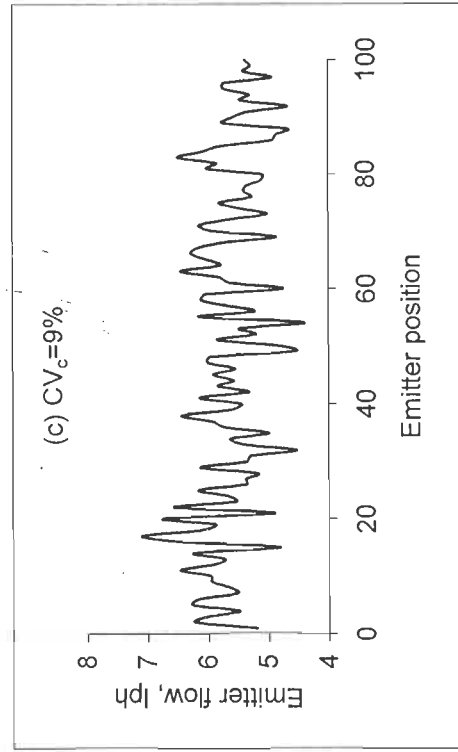
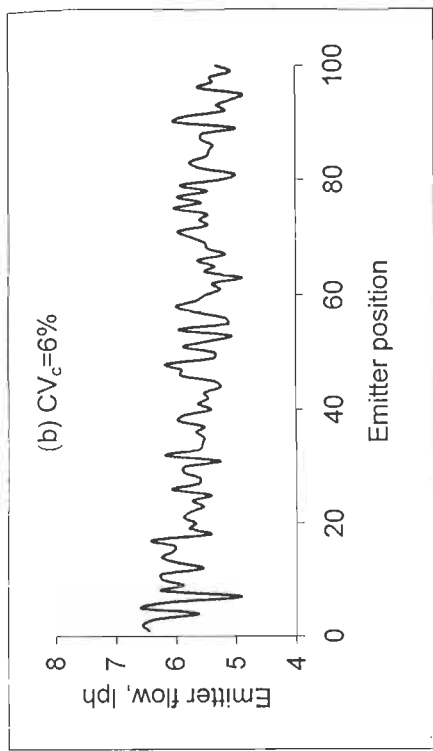
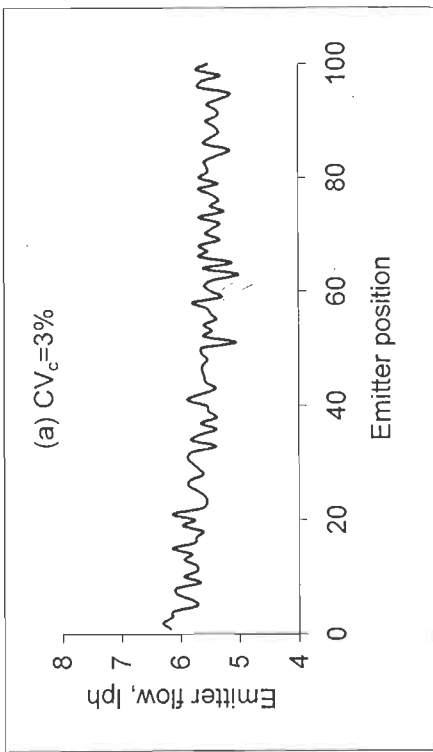


Fig. 4.23 Effect of 30 per cent clogging with different coefficient of variation ( $CV_c$ ) on emitter flow and emission uniformity

Fig. 4.24(a) shows the interaction effect of 3 per cent  $CV_m$  with various clogging conditions. In all the clogging levels, the uniformity reduces with increase in  $CV_c$ . It is interesting to note that the uniformity values are enhanced for higher clogging levels for the same  $CV_c$ , though the average emitter flow is reduced. The comparison of Uniformity values for same  $CV_c$  between different emitter clogging levels (10, 20 and 30 per cent) is not informative, as they are not following any definite trend.

Figs. 4.24 (b) and 4.24 (c) show the interaction effects of 6 and 9 per cent  $CV_m$  with various clogging conditions respectively. Here also, a similar trend for the uniformity values plotted against the different  $CV_c$  at different levels of clogging was observed. However, the emission uniformity is getting reduced with increase in coefficient of manufacturing variation in all the combinations.

#### **4.6 Comparison of different uniformity estimation methods for various manufacturing variations and emitter clogging conditions**

The emitter flow simulated for the 100 emitters in each combinations of manufacturing variations and emitter clogging as discussed earlier was used to compute the uniformities using various proposed equations by different authors.

A new equation for computing expected uniformity from three variations *viz.*, coefficient of manufacturing variation ( $CV_m$ ), clogging variation ( $CV_c$ ) and Hydraulic variation ( $CV_h$ ) has been developed. To calculate the total variance, dependability among these three factors was first analysed. It was found that  $CV_h$

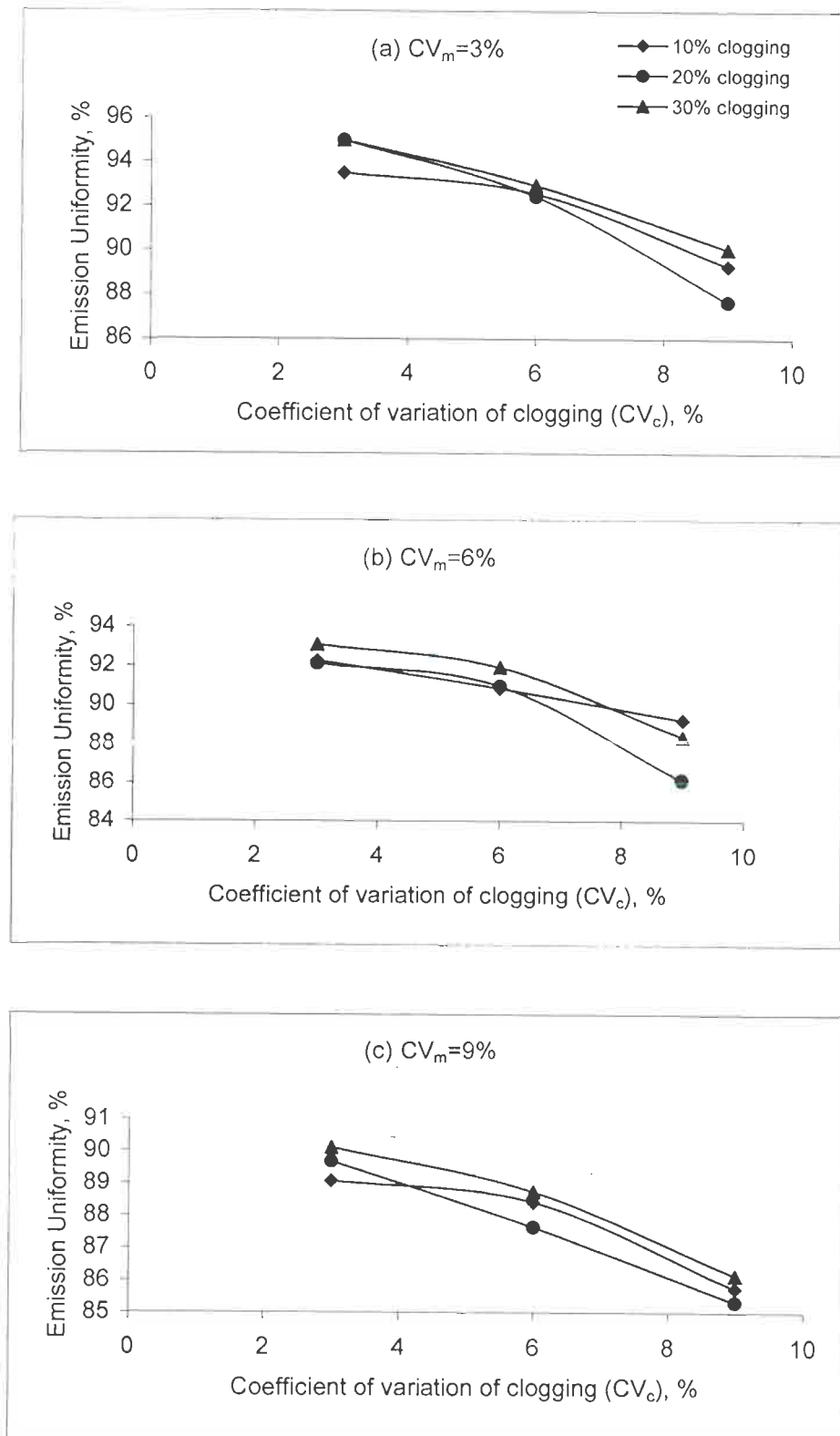


Fig. 4.24 Effect of manufacturing variations and emitter clogging on emission uniformity

does not depend on the  $CV_m$ . This result is in accordance with the earlier study made by Clemmens (1987). However, the percentage clogging has a strong influence over hydraulic variation ( $CV_h$ ). Fig. 4.25 shows the effect of clogging on the coefficient of hydraulic variation. In order to generalize the relation, a non-dimensional ratio of adjusted coefficient of hydraulic variation to the coefficient of hydraulic variation when there is no clogging ( $CV_h^*/CV_h$ ) was considered. Adjusted coefficient of hydraulic variation  $CV_h^*$  can be used to nullify the dependability effect due to clogging. A linear regression equation between  $CV_h^*/CV_h$  and emitter clogging (P) was fitted using least square technique and is as follows

$$CV_h^*/CV_h = 1 - 1.13 P \quad \text{--- (4.1)}$$

Total variance of three independent variables x, y and z (Mood *et al.*, 1974) can be written as

$$CV_t^2 = CV_x^2 + CV_y^2 + CV_z^2 \quad \text{--- (4.2)}$$

Hence, the total variance for our case can be estimated as follows

$$CV_t^2 = CV_m^2 + CV_c^2 + CV_h^{*2} \quad \text{--- (4.3)}$$

The above equation for total variance can be modified by substituting the equation 4.1 for  $CV_h^*$  as

$$CV_t^2 = CV_m^2 + CV_c^2 + CV_h^2 (1 - 1.13 P)^2 \quad \text{--- (4.4)}$$

Statistical uniformity relation (Bralts *et al* 1981 a) can be written as

$$U_s = (1 - CV_t) 100 \quad \text{--- (4.5)}$$

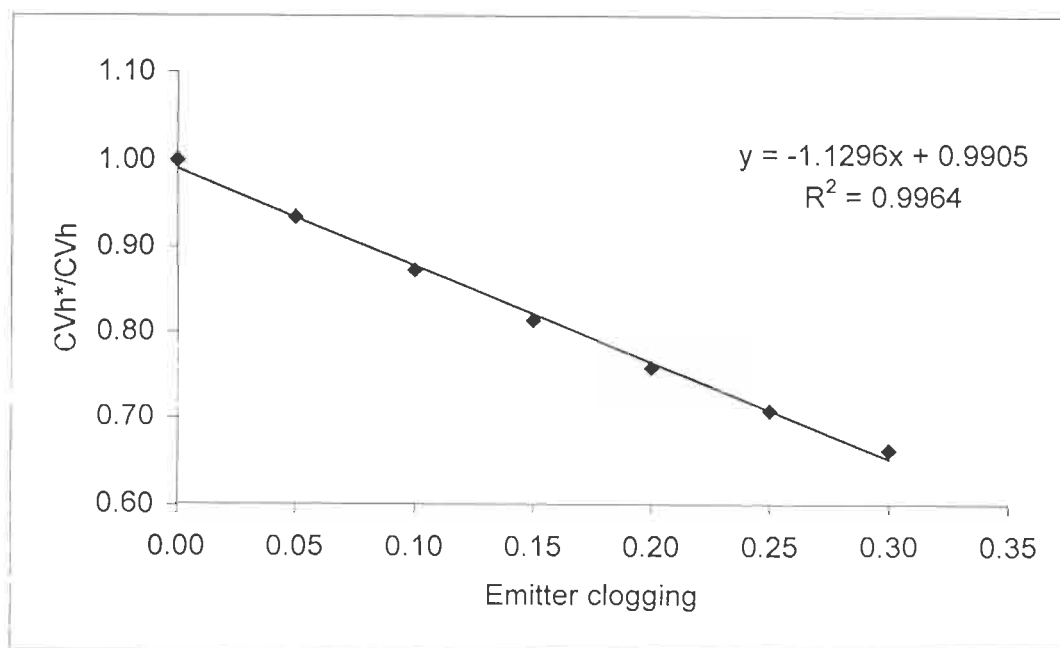


Fig. 4.25 Effect of clogging on the coefficient of hydraulic variation

By substituting the expression for  $CV_t$  from equation 4.4 in equation 4.5, the relationship for expected uniformity ( $U_e$ ) can be written as

$$U_e = \left[ 1 - \sqrt{CV_m^2 + CV_c^2 + CV_h^2(1 - 1.13P)^2} \right] 100 \quad \text{---(4.6) } \checkmark$$

Table 4.5 presents the emission uniformities for various manufacturing variations and emitter clogging conditions. Column 4 gives the expected uniformity ( $U_e$ ) values computed using the above-derived relation.

Column 5 represents the statistical uniformity calculated from total variance ( $CV_t$ ) estimated from the mean and standard deviation of the simulated emitter flow values using the equation given by Bralts et al (1981 a)

Column 6 represents the low quarter uniformity ( $U_{lq}$ ). It is estimated as percentage of mean discharge of lowest flowing 25 percent emitters to the total mean. The simulated discharges of 100 emitters are arranged in a ascending order and the first 25 emitter's discharge was averaged and this value was divided by the total average to get the low quarter uniformity ( $U_{lq}$ ).

Column 7 represents the absolute uniformity proposed by Nakyama and Buck (1981), which take care of both lowest flowing and highest flowing emitters. Column 8 represents the uniformity proposed by Christiansen (1942). Column 9 presents the uniformity calculated from only two discharge values (minimum and maximum discharge) (Wu and Gitlin, 1975).

Table 4.5 Comparison of different uniformity estimation methods for various manufacturing variations and emitter clogging conditions

CV <sub>m</sub> (1)	P (2)	CV <sub>c</sub> (3)	Emission Uniformity						
			U <sub>e</sub> (4)	U <sub>s</sub> (5)	U <sub>lq</sub> (6)	U <sub>a</sub> (7)	U <sub>c</sub> (8)	U <sub>rq</sub> (9)	
0	0		94.14	94.14	94.68	92.20	95.09	90.97	
	10	3	94.00	93.82	92.95	91.59	94.96	92.17	
		6	92.06	92.58	90.80	89.96	94.07	90.92	
		9	89.61	89.33	86.69	85.93	91.35	83.28	
	20	3	94.56	95.14	94.36	93.07	96.05	94.34	
		6	92.48	92.56	90.98	89.75	94.37	87.73	
		9	89.92	87.77	85.09	84.00	90.18	81.96	
	30	3	95.10	95.60	94.68	93.65	96.71	93.96	
		6	92.86	93.33	92.06	90.83	94.67	92.04	
		9	90.20	90.65	87.86	87.63	92.49	86.72	
	3	0		93.42	94.02	93.04	91.73	94.99	93.72
		10	3	93.29	93.49	92.01	91.15	94.76	90.53
6			91.52	92.56	90.29	90.02	93.87	90.98	
9			89.18	89.27	86.74	85.67	91.41	82.76	
20		3	93.79	94.97	93.60	93.13	95.97	93.49	
		6	91.90	92.43	90.97	89.94	94.04	87.13	
		9	89.49	87.65	84.47	84.03	90.08	80.92	
30		3	94.26	94.97	93.59	93.01	95.95	93.64	
		6	92.25	92.93	91.33	90.22	94.44	91.59	
		9	89.75	93.49	87.57	86.65	92.30	85.93	

CV <sub>m</sub> (1)	P (2)	CV <sub>c</sub> (3)	Emission Uniformity						
			U <sub>c</sub> (4)	U <sub>s</sub> (5)	U <sub>lq</sub> (6)	U <sub>a</sub> (7)	U <sub>c</sub> (8)	U <sub>rq</sub> (9)	
6	0		91.62	92.01	91.24	89.12	93.64	89.52	
	10	3	91.52	92.26	91.02	89.35	93.87	88.94	
		6	90.05	90.84	89.12	87.74	92.92	87.56	
		9	88.00	89.24	86.43	85.87	91.43	83.87	
	20	3	91.90	92.11	90.87	89.16	93.68	90.56	
		6	90.38	90.97	90.12	87.96	93.16	85.47	
		9	88.27	86.14	83.51	82.35	89.52	75.68	
	30	3	92.25	93.08	92.00	90.50	94.67	88.93	
		6	90.67	91.92	90.63	88.77	93.89	87.31	
		9	88.51	88.38	85.29	84.44	90.64	85.49	
	9	0		89.26	88.94	86.34	85.36	91.49	84.11
		10	3	89.18	89.08	86.45	85.72	91.07	84.96
6			88.00	88.43	85.96	85.02	91.17	82.95	
9			86.25	85.76	81.90	81.29	89.00	77.35	
20		3	89.49	89.69	86.92	86.33	92.04	86.31	
		6	88.27	87.66	84.50	83.89	89.97	84.35	
		9	86.49	85.33	81.54	81.07	88.37	76.34	
30		3	89.75	90.12	87.45	86.97	92.58	85.19	
		6	88.51	88.75	85.29	85.23	90.94	85.52	
		9	86.70	86.16	81.44	82.03	88.93	77.82	
Average deviation from expected Uniformity, U <sub>e</sub>			-0.22	1.93	2.91	-2.05	3.896		
Average absolute deviation from expected Uniformity, U <sub>e</sub>			0.71	1.91	2.91	2.04	3.911		

The tabulated values of uniformity were compared with the corresponding expected uniformity ( $U_e$ ) values. Average values of absolute deviations and algebraic deviations were calculated and are presented in the bottom of the table under each column. It could be seen that statistical uniformity stands very close to the expected values. The reason for this is that statistical uniformity takes into account of total variance of the emitter flow. The average values of absolute deviations and algebraic deviations are only 0.71 and 0.22 per cent. Next to statistical uniformity, low-quarter uniformity performs better and the deviations are 1.93 (algebraic) and 1.91 (absolute). The deviations of Christiansen's uniformity from expected uniformity (-2.05, 2.04) is very close to that of low-quarter uniformity.

The deviations observed with the absolute uniformity ( $U_a$ ) and discharge ratio uniformity are more when compared to the Christiansen's and low-quarter uniformity. Among absolute uniformity ( $U_a$ ) and discharge ratio uniformity, absolute uniformity performs better. This is due to the fact that the discharge ratio uniformity is a very crude and approximate method, which can't accommodate any variations in the emitter flow as it considers only maximum and minimum discharge values.

#### **4.7 Pressure profiles**

The pressure gradient lines are exponential curves rather than the straight lines as the flow in the lateral line is spatially varied with decreasing discharge. These pressure profiles are influenced by the flow variations in the emitter.

#### 4.7.1 Effect of clogging on pressure profiles

In order to study the impact of emitter clogging levels on the hydraulic pressure along the lateral, pressure profiles at different clogging levels (10, 20 and 30 per cent) were plotted (Fig. 4.26). It is interesting to note that pressure loss is less for the lateral having highly clogged emitters (30 per cent) than for the lateral without or less clogged emitters. This is due to the fact that the total flow through a lateral line with clogged emitters is less than that through a lateral line with out any clogged emitters.

#### 4.7.2 Effect of $CV_m$ and $CV_c$ on Pressure profiles

The coefficient of manufacturing variations ( $CV_m$ ) and coefficient of variations of emitter clogging ( $CV_c$ ) do not have any significant effect on the pressure profiles. The reason for this is that the total flow volume is not getting affected by the coefficient of variation which is the sole factor for pressure head loss.

#### 4.7.3 Dimensionless pressure head loss

Two dimensionless numbers namely, ratio of head loss at any point  $x$  from the head end to the total head loss ( $R_h = \Delta H_x / \Delta H$ ) and length ratio ( $R_l = x/L$ ), where,  $L$  is the total length of a lateral, were worked out for different distance ( $x$ ) values. Fig.4.28 represents the dimensionless head loss curves for different clogging conditions. Though the pressure gradients are different in shape and magnitude, the

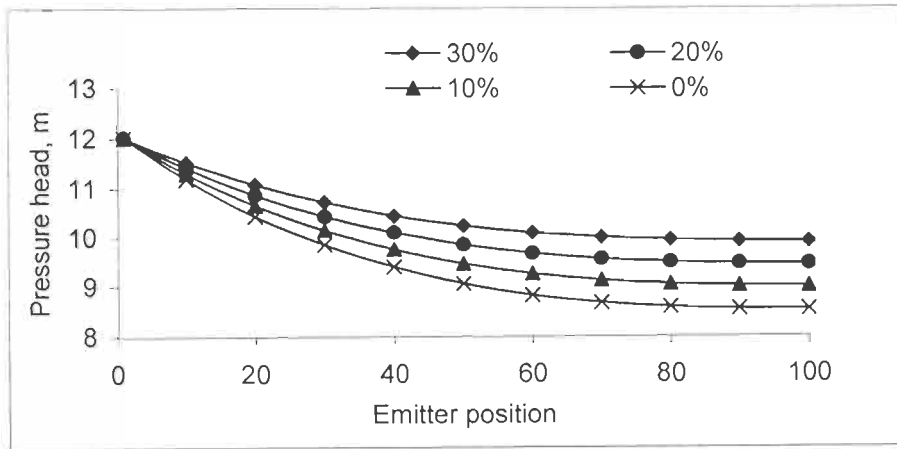


Fig. 4.26 Effect of clogging on pressure profile

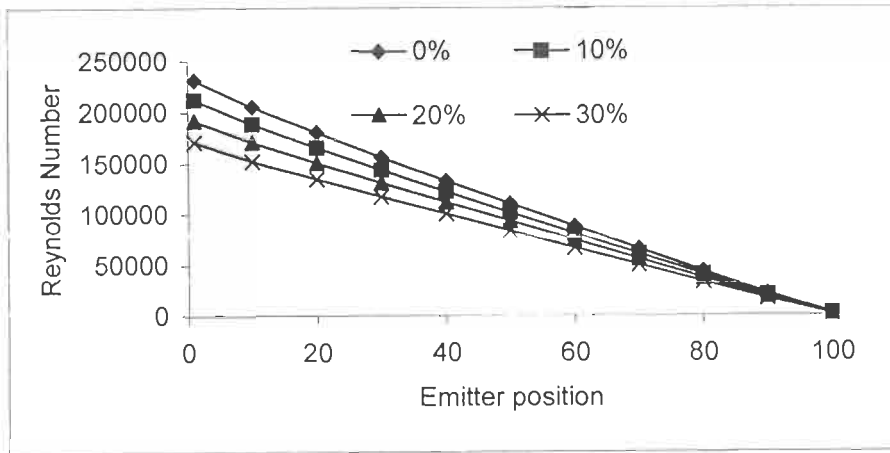


Fig. 4.27 (a) Reynolds Number variation along a lateral

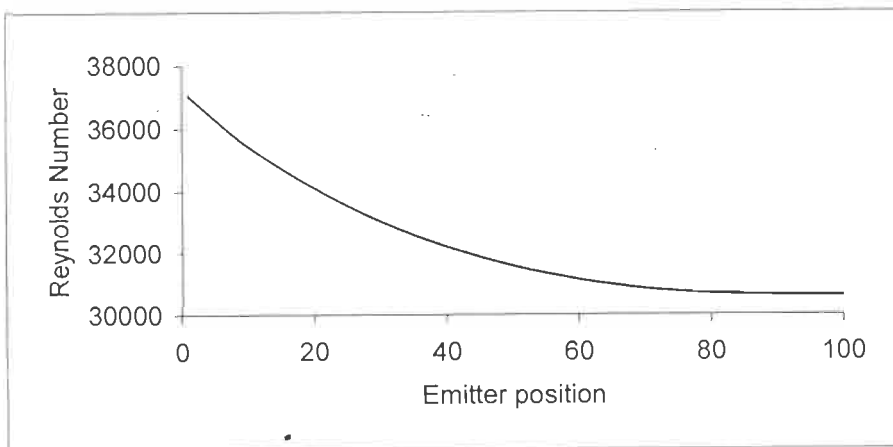


Fig. 4.27 (b) Reynolds Number variation inside the emitter flow path along a lateral

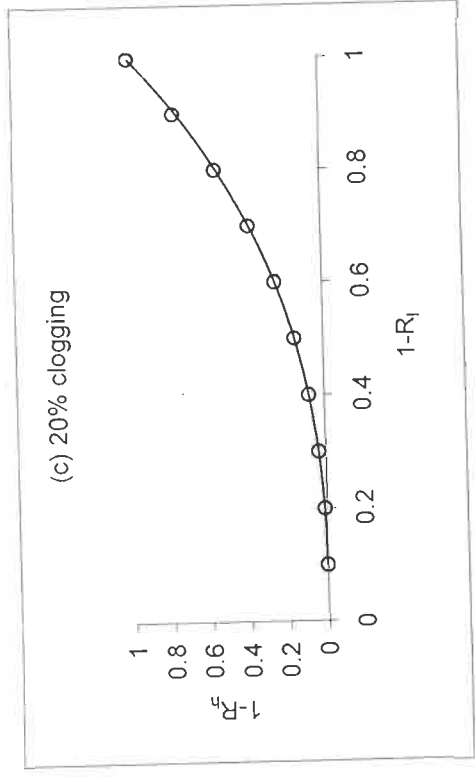
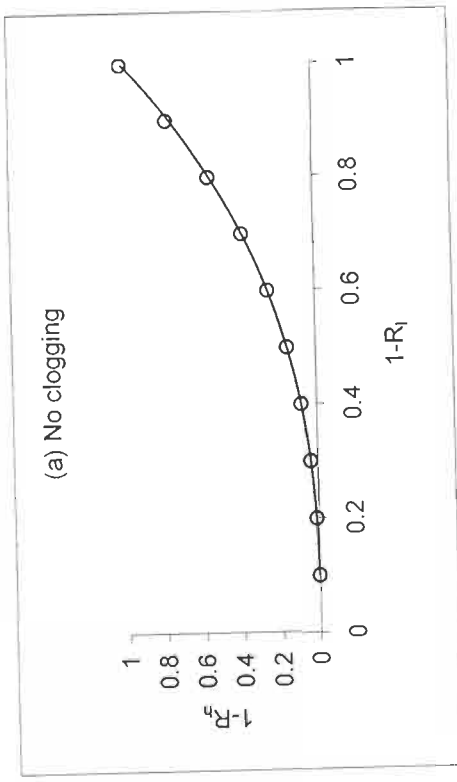
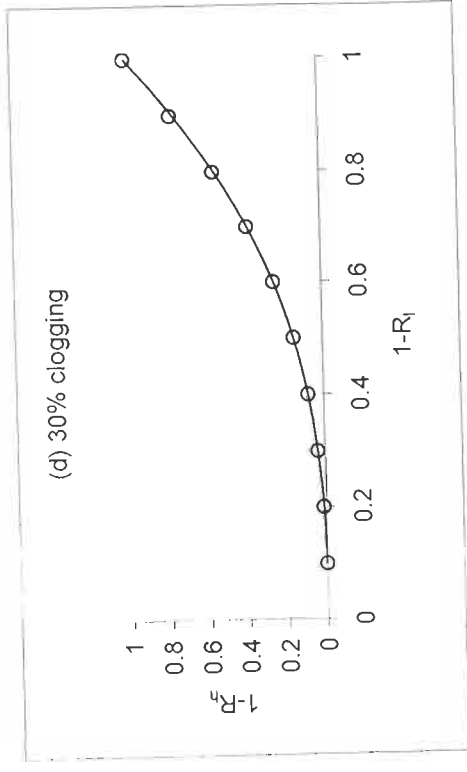
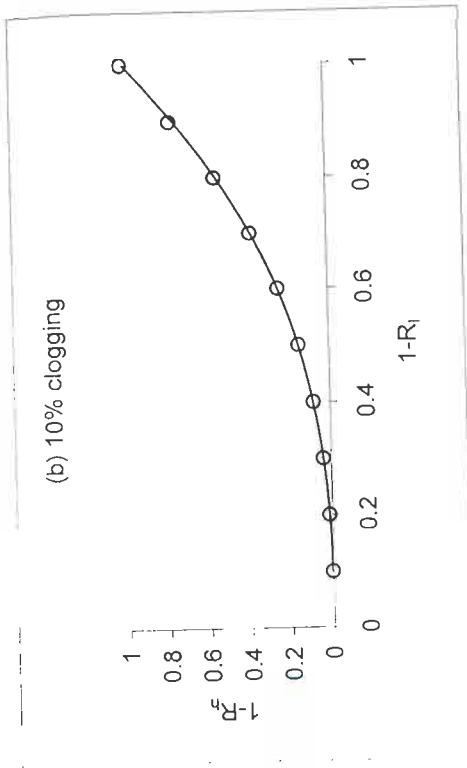


Fig. 4.28 Dimensionless pressure head loss gradients at different clogging conditions

dimensionless head loss curves are exactly similar for all cases of clogging levels.

These curves are fitted to the standard form as given below

$$\frac{\Delta H_x}{\Delta H} = 1 - \left(1 - \frac{x}{L}\right)^{m+1} \quad \text{where, } m = 1.7$$

#### 4.7.4 Reynolds number (Re) along the drip lateral

In order to evaluate the flow characteristics along a lateral, Reynolds Number (Re), which is directly related to the friction losses was calculated at different emission points. Fig. 4.27 (a) shows the straight-line relationship between Reynolds Number and lateral length at different clogging conditions (0, 10, 20 and 30 per cent). The Reynolds Number gradient is less for a lateral, which is having more percentage of emitter clogging when compared to a lateral, which is having less percentage of emitter clogging. This is due to the fact that the total flow in the lateral with more clogged emitters is less than that in a lateral with less clogged emitters. In all the cases, the Re value is more than 2000 up to tail end except for a few emitter length at the tail end, which indicates that the flow is completely turbulent all along the lateral. This is in agreement with the findings of Hathoot *et al.* (1993)

Fig. 4.27 (b) represents the Reynolds number value for the flow inside a typical emitter with a flow path of 1mm and a flow rate of 8 lph. The minimum value of 30605 and a maximum value of 37046 are obtained at tail end and head end of a lateral respectively. It is evident from the Reynolds number value that the flow inside the emitter path is extremely turbulent.

#### 4.8 Simulation of field scale drip irrigation system

A submain unit of drip irrigation system consisting of 50 laterals and 100 emitters in each lateral was considered to study the field scale drip irrigation system inflicted with emitter clogging for its hydraulic performances. The drippers are numbered from an inlet of the lateral, while the laterals are numbered from the end of the submain. So (50,1) is the closest emitter while (1,100) is the farthest emitter in the assumed system. In order to simulate emitter flow for such a drip unit, as a first step, emitter coefficient (K) values, clogging values (P) were simulated for all the 5000 emitters using the model RANGEN and are stored in separate text files.

Fig. 4.29 represents the simulated K value distribution for the assumed drip system, which has the mean and coefficient of variation of 2.16 and 3 per cent respectively. It is seen from the figure that the values are randomly distributed over the space. Fig. 4.30 represents the simulated clogging value (P) distribution for the same drip system, which has the average emitter clogging of 10 per cent and a coefficient of variation of 3 per cent.

Fig 4.31 represents the effective hydraulic pressure ( $h^x$ ) variation distributed over the space for the hypothetical drip system with assumed design parameters like emitter spacing, lateral size, lateral spacing, sub main size, etc. The effective hydraulic pressure variation is calculated by assuming zero coefficient of manufacturing variations and no emitter clogging for all the 5000 emitters placed. The effective pressure heads available at the head end and tail end of the system are

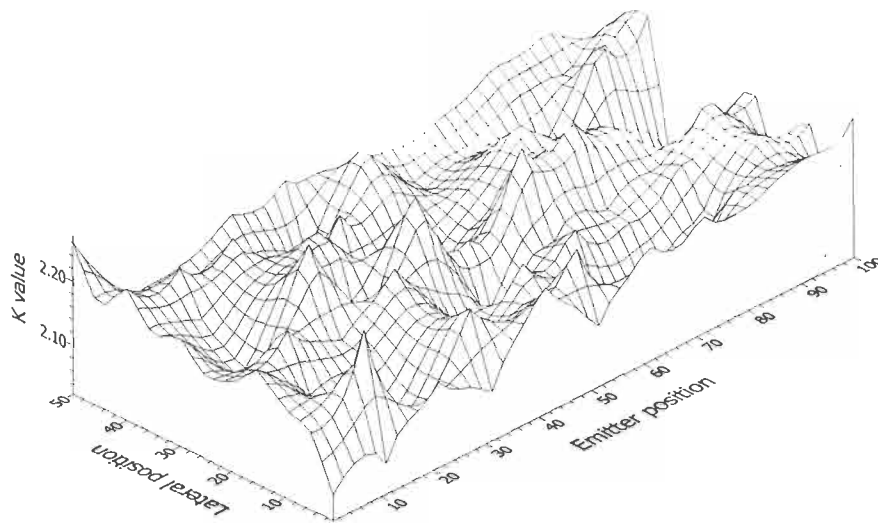


Fig. 4.29 Simulated emitter coefficient (K value) distributions along drip flow grid

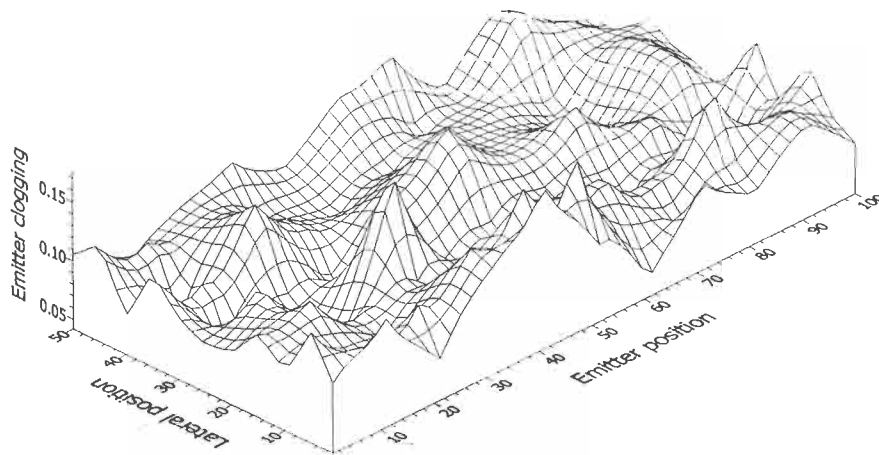


Fig. 4.30 Simulated clogging (P value) distributions along the drip flow grid

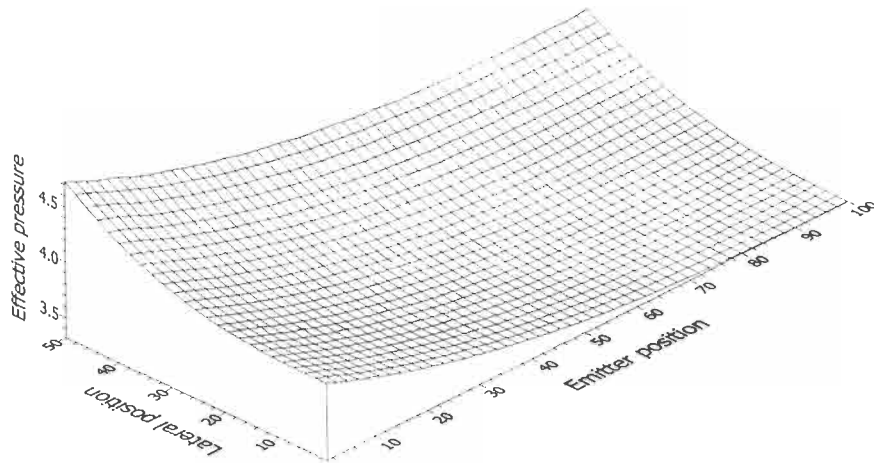


Fig. 4.31 Simulated pressure ( $h^x$ ) profiles along the drip flow grids *with no clogging*

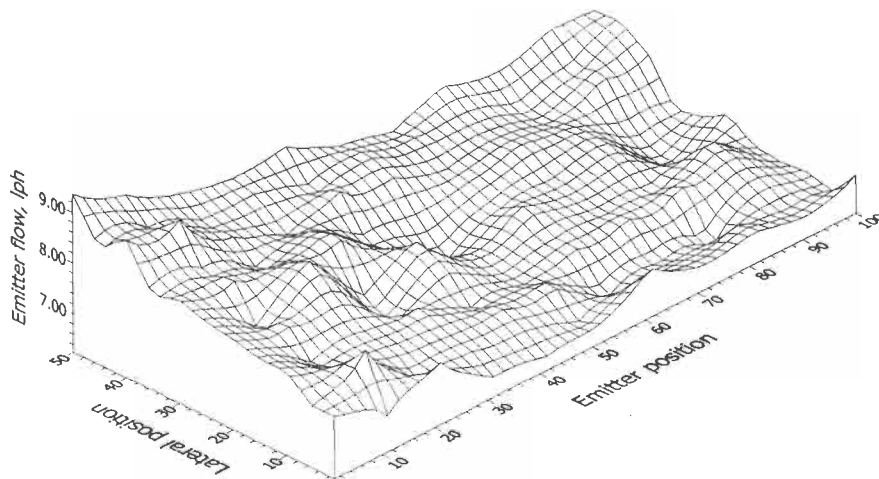


Fig. 4.32 Simulated emitter flow along the drip flow grids *with clogging*

4.73 and 3.32 meter of water column respectively for the emitter coefficients X value of 0.56. The coefficient of variation for the assumed drip lateral system is 8.5 per cent.

Fig. 4.32 depicts the emitter discharge for all the emitters of all the 50 laterals as obtained from the main model DRIPCLOG (Appendix–XVI). This emitter discharge is resulting from three variations viz., manufacturer's coefficient of variation of 3 per cent, emitter clogging of 10 per cent with coefficient of variation of 3 per cent and effective hydraulic pressure variation of 8.5 per cent presented separately in the above explained Figs. 4.29, 4.30 and 4.31 respectively.

#### **4.8.1 Effect of clogging on field uniformity**

The uniformity of emitter flow for a field scale drip system is the single most parameter determining the performance of the drip irrigation system. In order to study the impact of clogging on field scale uniformity, various hypothetical clogging conditions were assumed. The various assumed conditions are 10, 20 and 30 per cent clogging with coefficient of variations of 3, 6, and 9 per cent. In all the cases, the coefficient of manufacturing variation was assumed to be 3 per cent. In addition to this, two more cases were also considered for the comparison purpose. One is an identical condition that operates without any manufacturing coefficient of variation and clogging. The second one is a typical situation, which can occur with the newly installed system, which operates with a manufacturing coefficient of variation (3%)

and without any clogging. Simulations were carried out for the assumed conditions to obtain the emitter flow pattern for the entire emitters.

Fig. 4.33 show the three-dimensional emitter flow distribution for the identical conditions of without any  $CV_m$  or clogging. The flow surface is very smooth indicating gradual drop of emitter flow diagonally over the field from the source point (50, 1) to the remote point (1, 100). The Christiansen's field emission uniformity and statistical uniformity were determined for this flow pattern and are found to be 91.5 and 93 per cent respectively.

Fig. 4.34 represents three-dimensional emitter flow distribution for the drip system with a  $CV_m$  of 3 per cent and without any clogging. The surface is slightly rough because of the manufacturing coefficient of variation. The Christiansen's field emission uniformity and statistical uniformity are found to be 90.75 and 92.5 per cent respectively. These values are little less than the above said condition.

Figs. 4.35 (a) - (c) show the three-dimensional view of emitter flow pattern for the clogging of 10 per cent with coefficient of variations of 3, 6, and 9 per cent respectively. Though emitter flow are very haphazard, a common trend of decreasing emitter flow is seen diagonally across the head end to the tail end of the unit. The maximum and minimum values for emitter flow with 3, 6, and 9 per cent of  $CV_c$  were obtained as 9.4-6.0, 10.1-5.8 and 10.7-5.4 respectively. Fig. 4.36(a) is the iso-discharge map for the emitters free from clogging and manufacturing variations. Figs. 4.36 (b)-(d) are the iso-discharge maps for the emitters with the clogging of 10

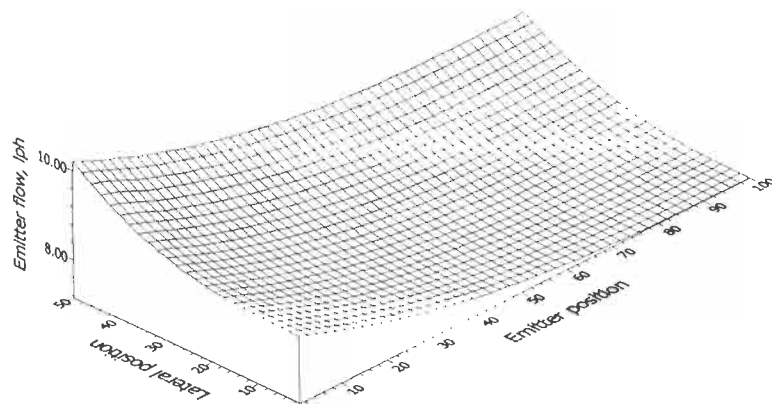


Fig. 4.33 Emitter flow distributions for a drip field without any manufacturing coefficient of variation and clogging

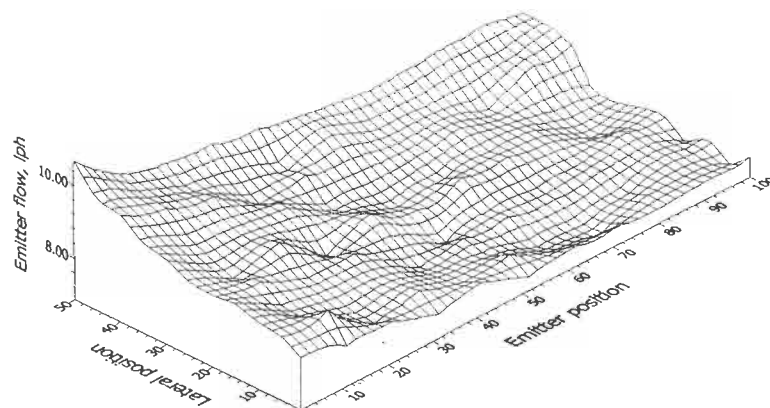
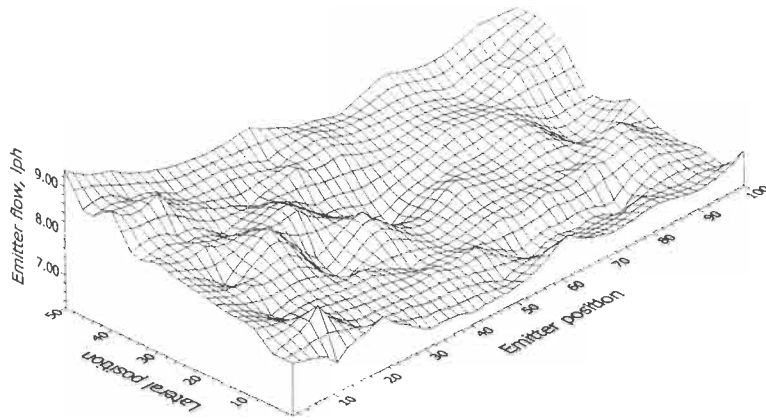
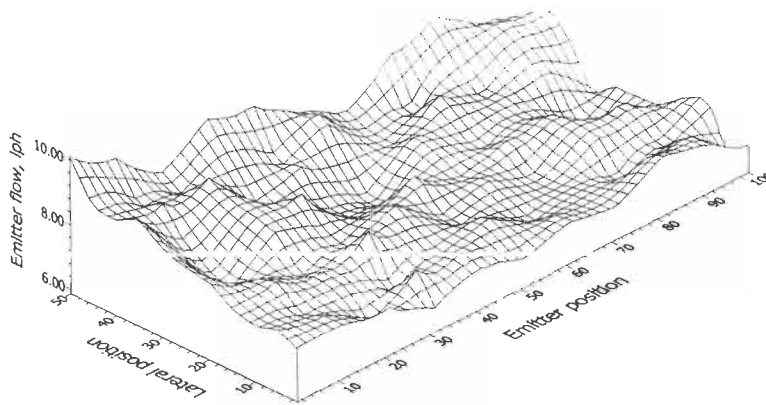


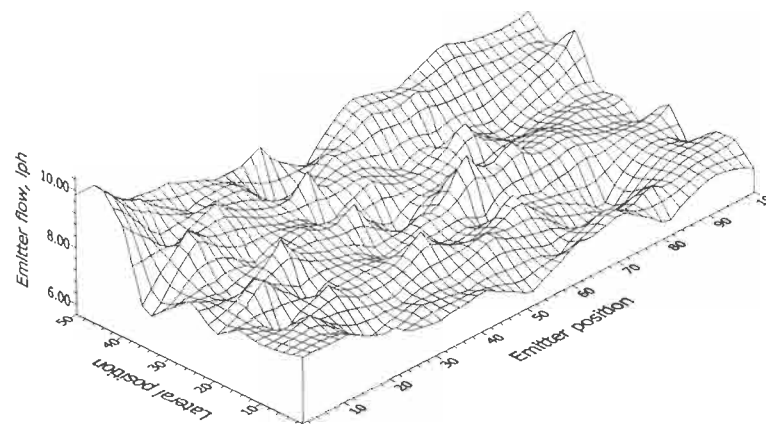
Fig. 4.34 Emitter flow distributions for a drip field with a manufacturing coefficient of variation of 3 per cent and without any clogging



(a)  $CV_c = 3\%$

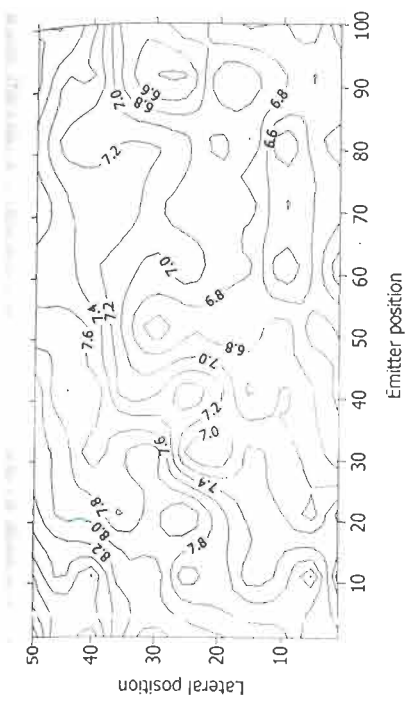


(b)  $CV_c = 6\%$

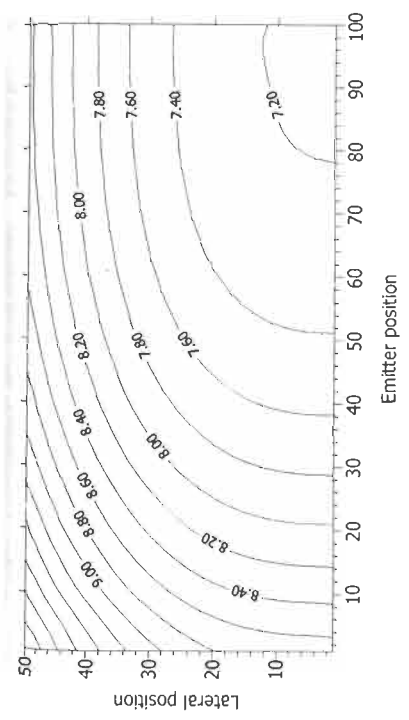


(c)  $CV_c = 9\%$

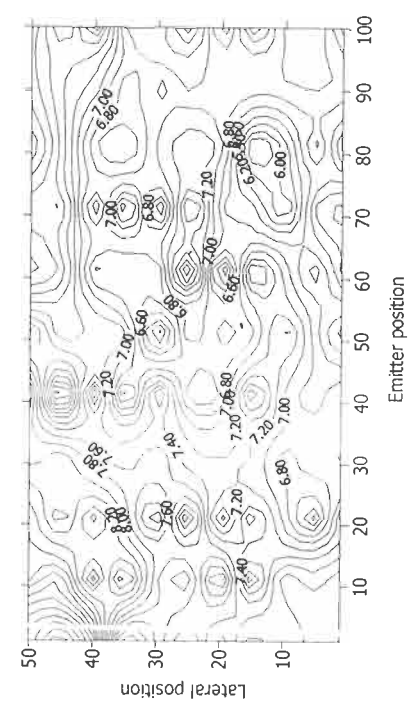
Fig. 4.35 Emitter flow distributions for 10 per cent clogged emitters with different coefficient of variation



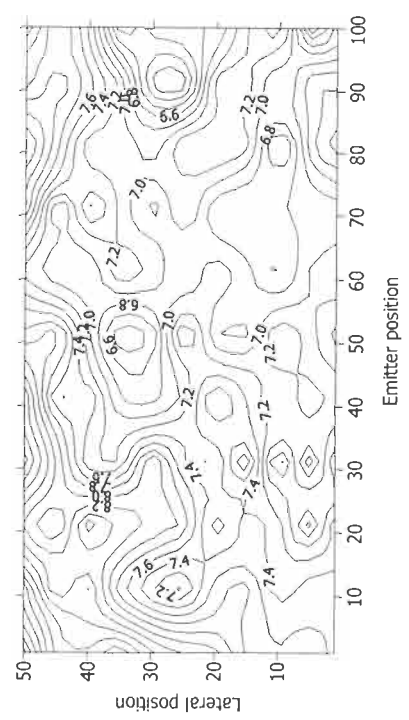
(a) No clogging



(b)  $CV_c = 3\%$



(c)  $CV_c = 6\%$



(d)  $CV_c = 9\%$

Fig. 4.36 Iso-discharge map for 10 per cent clogged emitters with different coefficient of variation ( $CV_c$ )

per cent with the coefficient of variations of 3, 6, and 9 per cent respectively. The iso-discharge lines are getting concentrated as the  $CV_c$  increases.

Fig. 4.41(a) represents the Christiansen's field emission uniformity and statistical uniformity for various coefficients of variations at 10 per cent clogging. Both uniformity values are decreasing with coefficient of variations. It is also seen that the uniformity is lesser than the single lateral uniformity for the same conditions.

Figs. 4.37(a) - (c) and Fig. 4.39(a) - (c) show the three-dimensional view of emitter flow pattern for the clogging of 20 per cent and 30 per cent with coefficient of variations of 3, 6, and 9 per cent in each case. Though these figures also look similar to the 10 per cent clogging flow pattern, the emitter flow is reduced in 20 per cent clogging and still reduced in 30 per cent clogging. Figs.4.38 (b)-(d) are the iso-discharge maps for the emitters with the clogging of 20 per cent with the coefficient of variations of 3, 6, and 9 per cent respectively. Figs.4.40 (b)-(d) are the iso-discharge maps for the emitters with the clogging of 30 per cent with the coefficient of variation of 3, 6, and 9 per cent respectively. In all the cases, the iso-discharge lines are getting concentrated as the  $CV_c$  increases.

The maximum and minimum values for emitter flow at 20 per cent clogging with 3, 6, and 9 per cent of  $CV_c$  were obtained as 7.9-5.6, 8.3-5.0 and 8.6-5.0 respectively. The maximum and minimum values for emitter flow at 30 per cent clogging with 3, 6, and 9 per cent of  $CV_c$  were obtained as 7.2-5.0, 7.2-4.5 and 7.7-4.3 respectively.

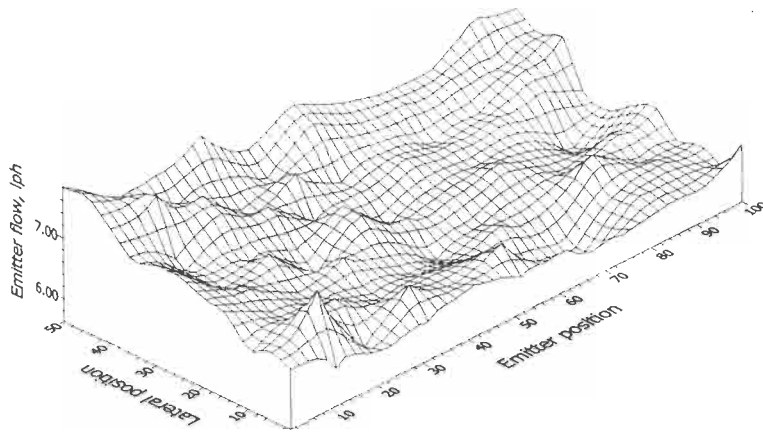
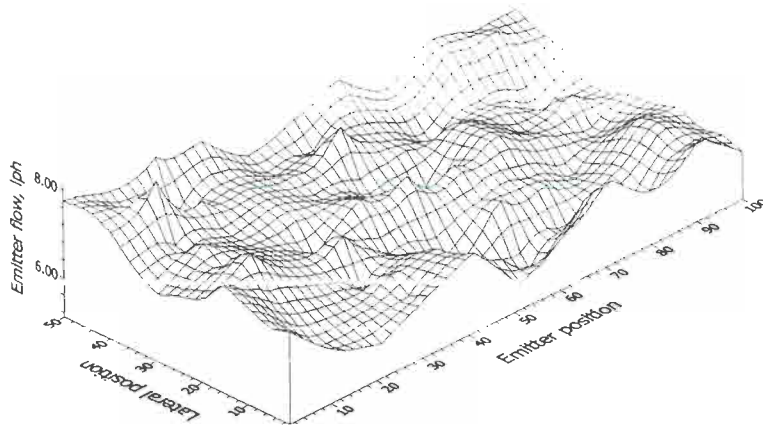
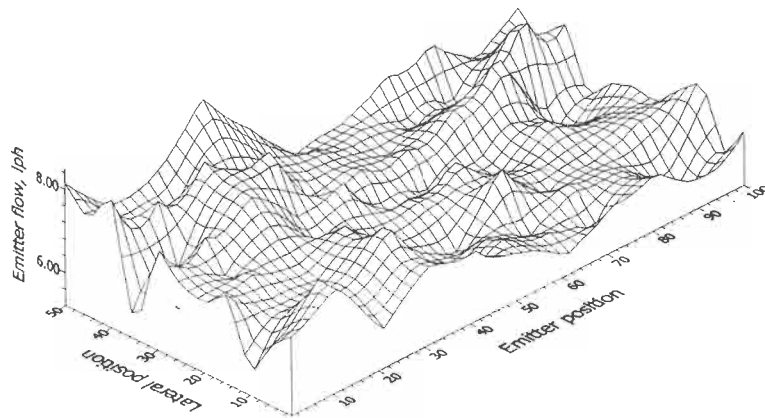
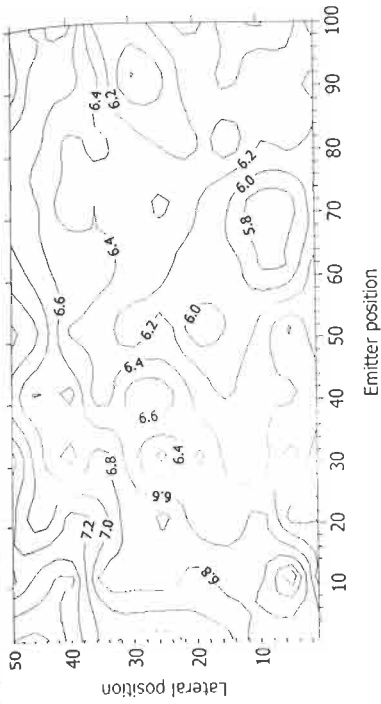
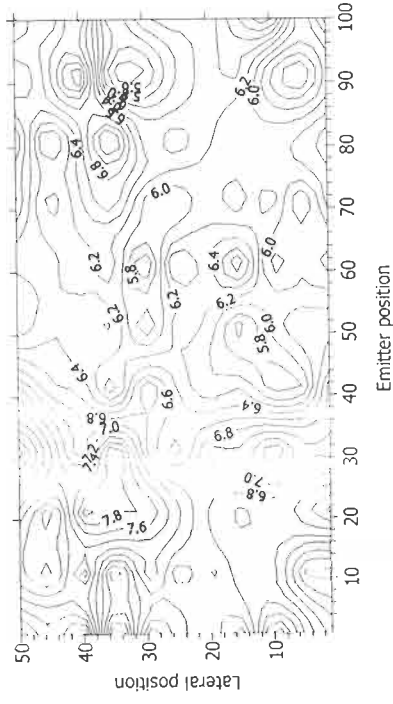
(a)  $CV_c = 3\%$ (b)  $CV_c = 6\%$ (c)  $CV_c = 9\%$ 

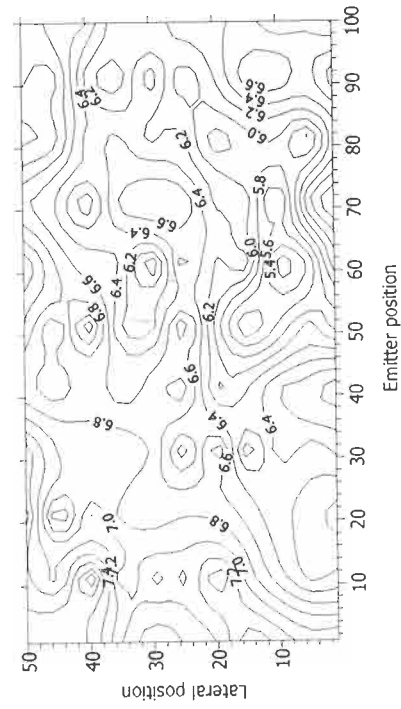
Fig. 4.37 Emitter flow distributions for 20 per cent clogged emitters with different coefficient of variation



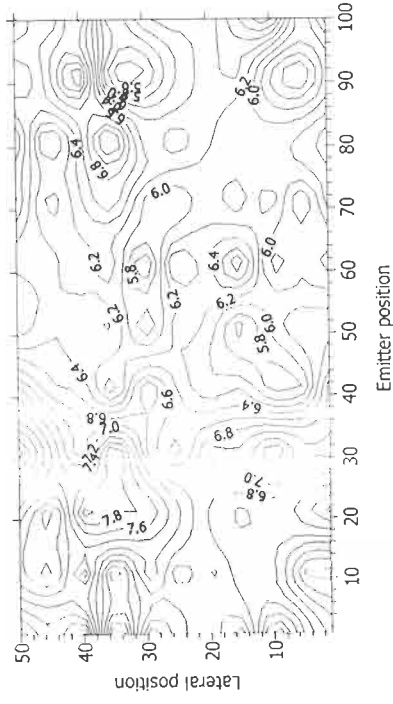
(a) No clogging



(b)  $CV_c = 3\%$

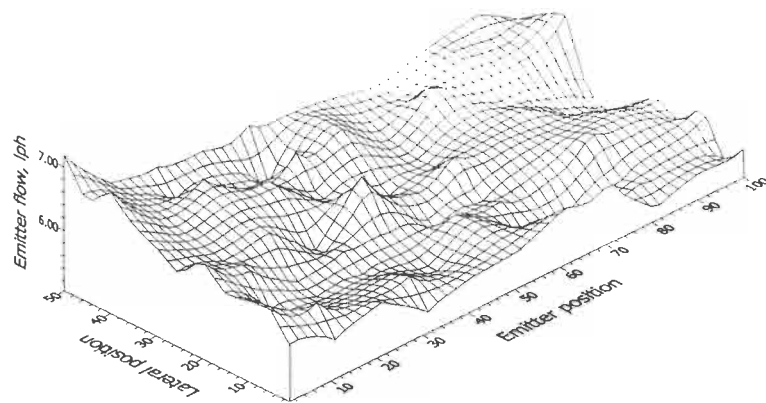


(c)  $CV_c = 6\%$

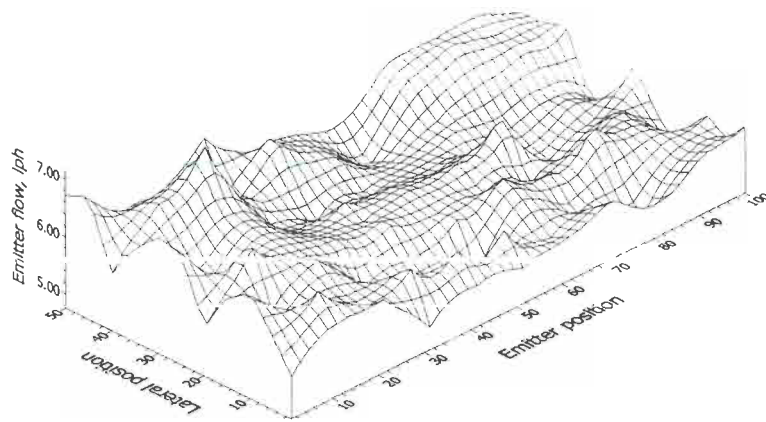


(d)  $CV_c = 9\%$

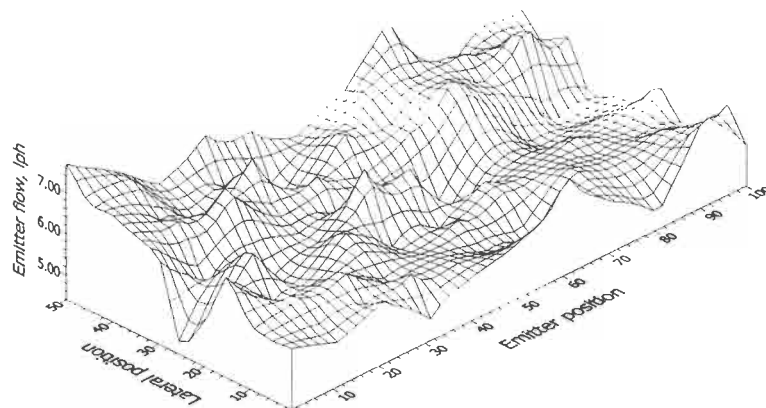
Fig. 4.38 Iso-discharge map for 20 per cent clogged emitters with different coefficient of variation ( $CV_c$ )



(a)  $CV_c = 3\%$

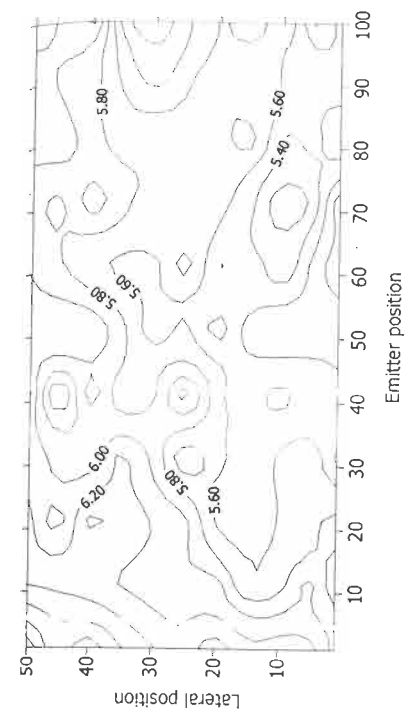


(b)  $CV_c = 6\%$

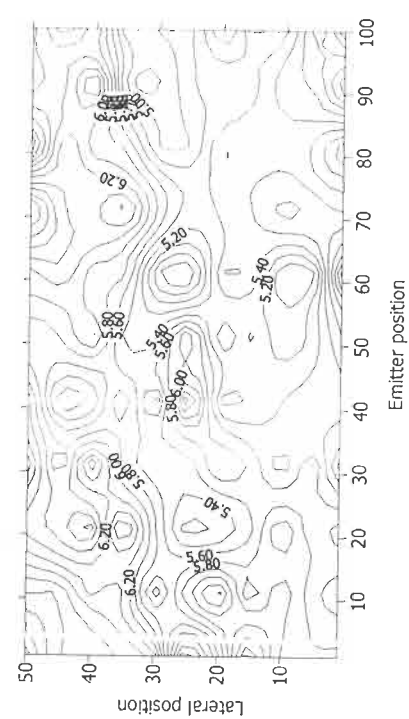


(c)  $CV_c = 9\%$

Fig. 4.39 Emitter flow distributions for 30 per cent clogged emitters with different coefficient of variation



(b)  $CV_c = 3\%$



(c)  $CV_c = 6\%$

Fig. 4.40 Iso-discharge map for 30 per cent clogged emitters with different coefficient of variation ( $CV_c$ )

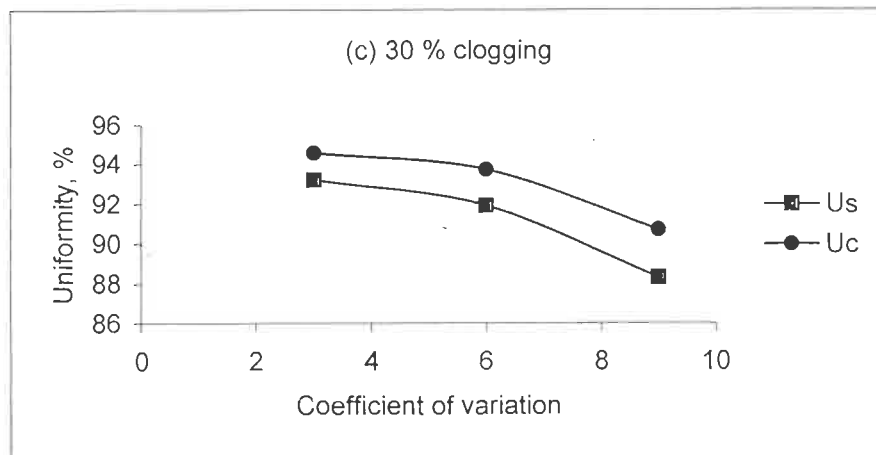
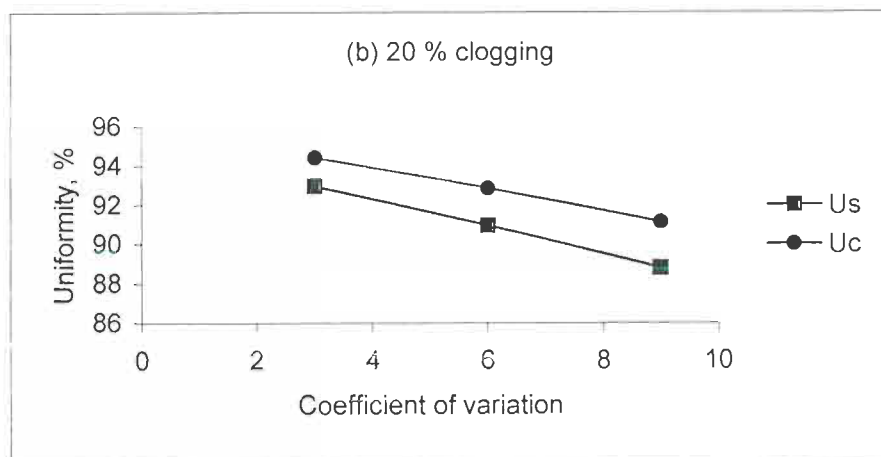
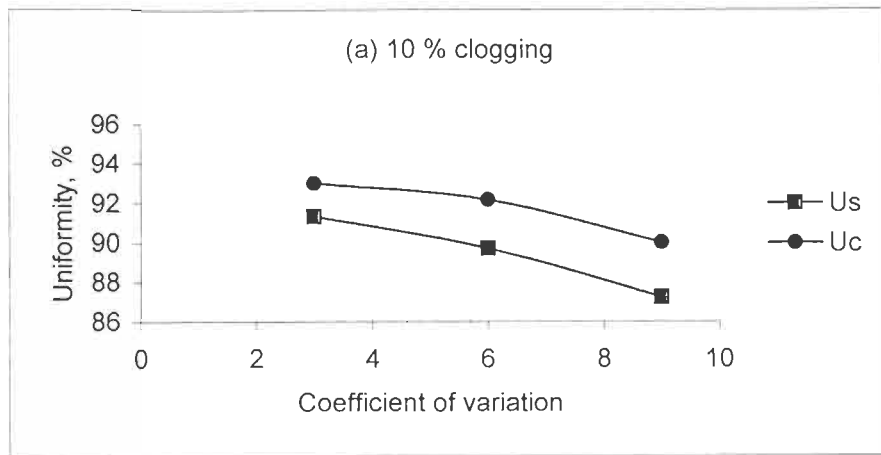


Fig. 4.41 Effect of clogging on Statistical ( $U_s$ ) and Christiansen's ( $U_c$ ) uniformities at field scale level

Figs. 4.41(b) and (c) show the Christiansen's field emission uniformity and statistical uniformity for various coefficient of variations at 20 and 30 per cent clogging. The uniformity values are decreasing with coefficients of variations in both the cases as seen in the earlier case.

#### **4.8.2 Effect of clogging on pressure profiles**

In order to study the impact of emitter clogging levels on the hydraulic pressure along the different laterals of drip field, pressure profiles at different clogging levels (0, 10, 20 and 30 per cent) were plotted (Figs. 4.42 (a)-(d)). In all the cases, the space between pressure profile lines is more for head end laterals and it is decreasing towards the tail end laterals. This is due to the fact that the head loss is more in sub main at head ends as it carries lot of water.

The required operating pressure for the first lateral is decreasing with clogging to maintain the same pressure of 12 m of water column at the last lateral. This is due to the fact that the total flow through a submain line, whose laterals are fitted with clogged emitters, is less than the flow through a submain line whose laterals are without any clogged emitters.

#### **4.8.3 Dimensionless pressure head loss**

Two dimensionless numbers namely, ratio of head loss at any point  $x$  from the head end of the submain to the total head loss in the submain ( $R_H = \Delta H_x / \Delta H$ ) and the length ratio ( $R_L = x/L$ ), where,  $L$  is the total length of a submain, were worked out for

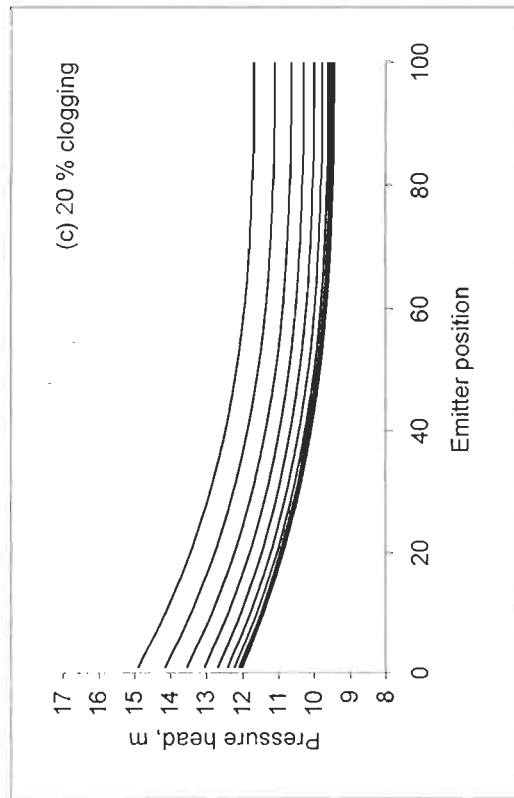
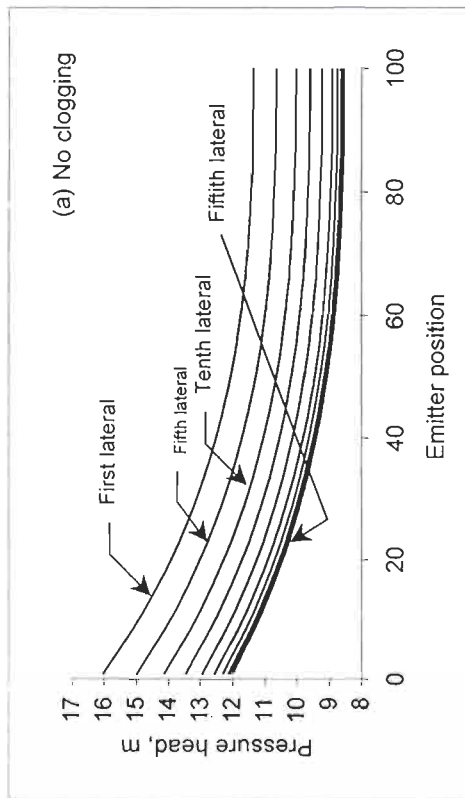
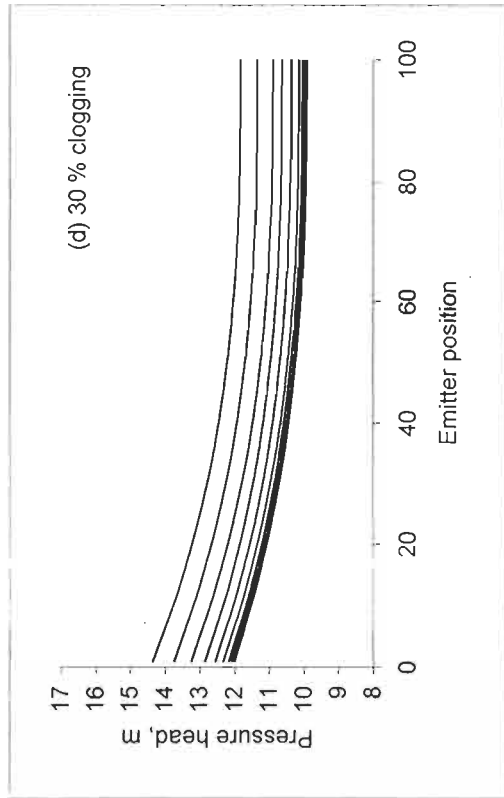
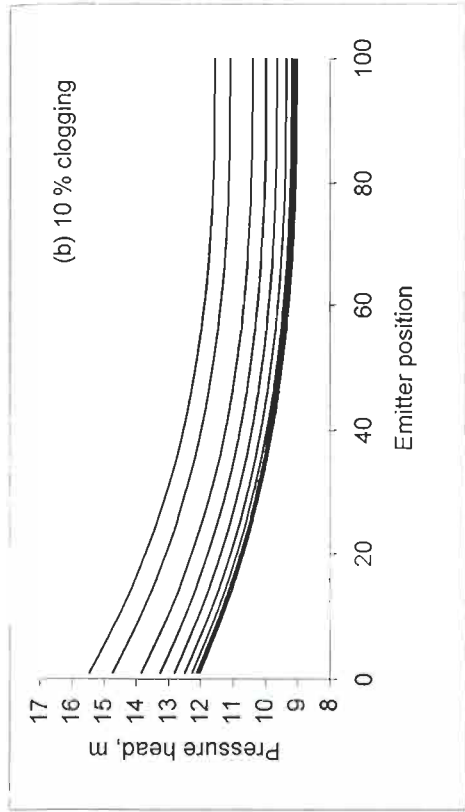


Fig. 4.42 Pressure profiles along the laterals for various clogging conditions

different distance ( $x$ ) values. Figs. 4.43 (a) and (b) represent the dimensionless head loss curves for 0 and 30 percent clogging conditions. The dimensionless head loss curves are exactly similar for all cases of clogging levels as in the case of laterals. These curves are fitted to the standard form as follows

$$\frac{\Delta H_x}{\Delta H} = 1 - \left(1 - \frac{x}{L}\right)^{m+1} \quad \text{where, } m = 1.9$$

Most of the fields are with 3-10 percent of manufacturing coefficient of variations and 0-30 percent of clogging, though de-clogging is done periodically. From the study it is seen that even this clogging, can alter the hydraulic performance of the whole drip irrigation system. The hydraulic performance of a drip irrigation layout is often visciated by emitter clogging due to one or more reasons. Clogging reflects on discharge reduction and can be depicted by the distortions caused on the smooth hydraulic gradient besides the varying frictional head losses.

Increasing the inlet operating pressure heads may minimize emitter clogging but may simultaneously increase the cost of operation. Usage of good quality water is the only solution but the local conditions of irrigation may not favour this. An optimal combination of operating pressure at the starting point and dilution of problem water with harvested rainwater may solve this problem if clogging is to be prevented.

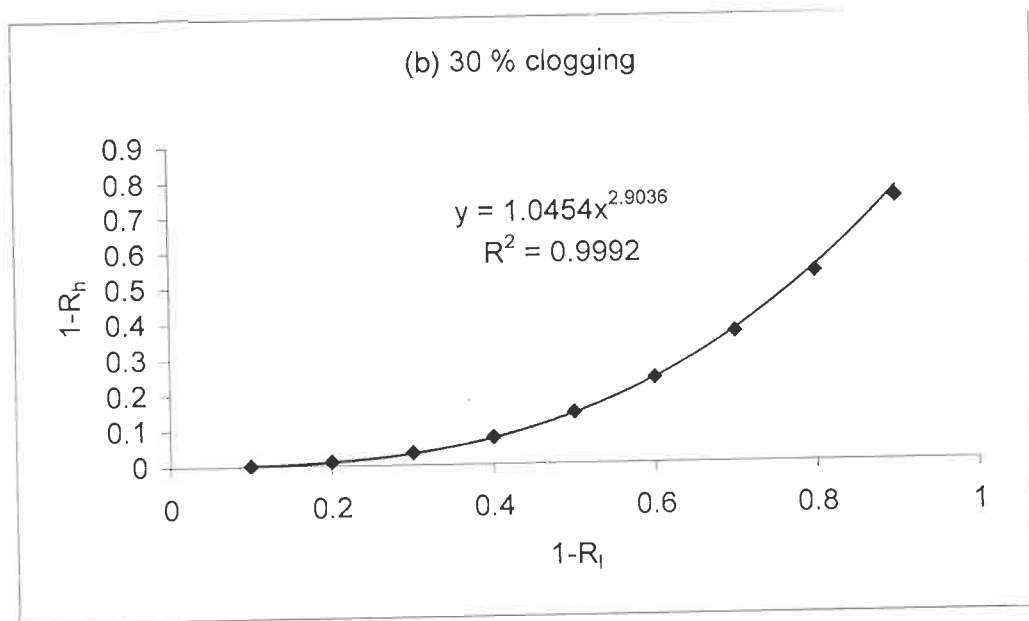
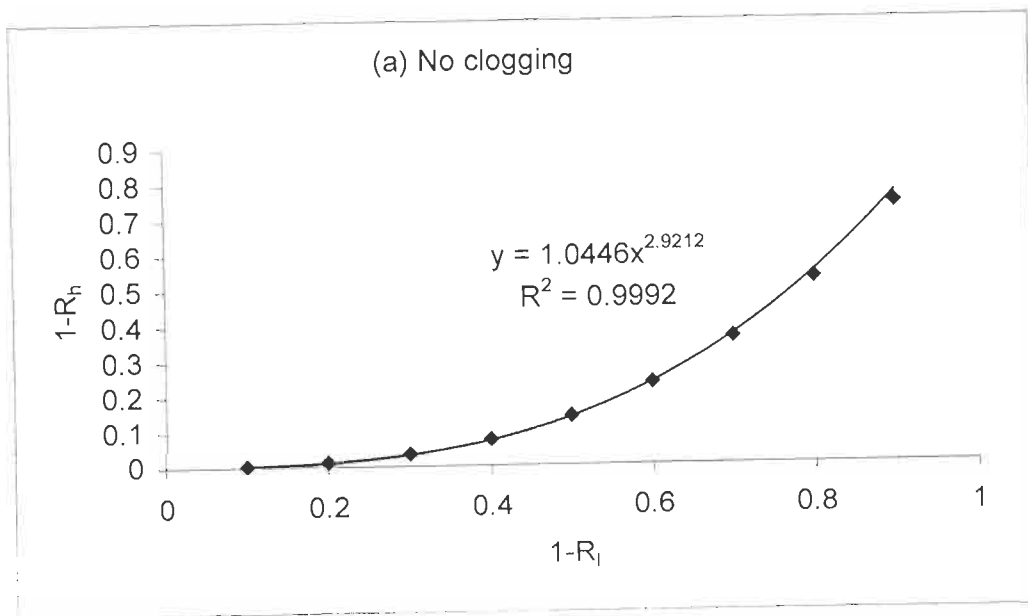


Fig. 4.43 Dimensionless pressure head loss gradients in submain

## *Summary and Conclusions*

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## CHAPTER V

### SUMMARY AND CONCLUSIONS

Emitter clogging remains a thorn in rose in most of the drip irrigation layouts. Generally the emitter clogging of 5 to 30 per cent is often unavoidable in any drip irrigation field layout even if it is well maintained. Hence, it is necessary to study the spatial and temporal distributions of emitter clogging between two successive de-clogging operations. It is also necessary to evaluate the hydraulic performance in terms of changes in hydraulic gradient as depicted by pressure profiles and uniformity of water application under such conditions. The present study was contemplated to analyse the impact of emitter clogging on the hydraulic performance of the drip irrigation system.

- Trickle emitter discharge data were analysed for clogging and their temporal variations. It was found that their clogging is subjected to temporal variations, which can be considered as a random process. A method has been proposed to fit this temporal variation of emitter clogging with a three-parameter Weibull model. The developed model is more useful in estimating the average non-clogging time period and standard deviations of clogging for 5, 10, 15 and 20 percent emitter clogging in terms of flow reduction.
- Monte-Carlo technique was found to be useful in generating the clogging time for the emitters with the developed Weibull model. The mean of generated values (clogging time) for 5, 10, 15 and 20 percent clogging fell within the 95% confidence limits of the theoretical mean. The proposed method is very

simple and can be easily applied to any field conditions of trickle irrigation system for determining their mean clogging time and the number of treatments needed to keep them free from clogging.

- It was found that emitter clogging is not uniform over the space. The spatial variation was successfully fitted with normal distribution at four stages of clogging (5, 10, 15 and 20 %).
- The clogging was enormous for saline irrigation water ( $EC=3.0$  dS/m) while it was least for water with the lower salt content ( $EC=0.9$  dS/m). For all the four water qualities tested, Dripper-A (Pressure compensating type) performed better with lower clogging percent during the study, while the maximum clogging percent was observed in the Dripper-B (Long path helical type). This clearly indicates that pressure compensating emitters have exhibited good resistance for clogging as they have got self-flushing arrangement within them.
- It was also found that a curvilinear relationship exists between the total clogging percent and the length of the flow path inside the emitter. The reason for the inverse relationship between these two parameters is due to the fact that the emitter with lengthier flow path may be more prone to clogging, as the water has to travel a long distance with low velocity.
- The clogging was observed more in the case of emitters used for fertigation along with irrigation.

- A computer model namely DRIPCLOG and its sub model RANGEN were developed to simulate the drip irrigation system inflicted with emitter clogging and manufacturing variations. The models were based on the solution of fundamental hydraulic relationships to predict pressure and flow rates within laterals and submain. The model DRIPCLOG was validated with observed data from the lab scale drip irrigation system. The RANGEN model was validated by comparing with the intended normal distribution and was found to be satisfactory.
- Effect of manufacturing variations on emission uniformity was found to be significant. The uniformity is not affected up to 3 percent  $CV_m$  whereas the reduction is more at 6 percent and 9 percent  $CV_m$  values. Hence it is safe to operate the drip irrigation system within the 3 percent of coefficient of manufacturing variation without sacrificing the emission uniformity.
- The effect of emitter clogging on emission uniformity shows that the degree of emission uniformity is highly influenced by the coefficient of variations of clogging rather than the mean clogging. The emission uniformity at 10, 20 and 30 per cent clogging levels decreases with increase in  $CV_c$ , but in an increasing trend.
- Combined effect of manufacturing variations and emitter clogging on emitter flow resulted in reduction of emission uniformity with increase in these two factors. It is interesting to note that the uniformity values are enhanced for

higher clogging levels for the same  $CV_c$ , though the average emitter flow is reduced.

- A new equation for computing expected uniformity ( $U_e$ ) from three variations viz., coefficient of manufacturing variations ( $CV_m$ ), emitter clogging fraction ( $P$ ) with variations ( $CV_c$ ) and hydraulic variations ( $CV_h$ ) has been developed as follows

$$U_e = \left[ 1 - \sqrt{CV_m^2 + CV_c^2 + CV_h^2(1-1.13P)^2} \right] 100$$

- The dimensionless head loss curves for laterals are exactly similar for all cases of clogging levels, though the pressure gradients are different in shape and magnitude. These curves are fitted to the standard form as given below

$$\frac{\Delta H_x}{\Delta H} = 1 - \left( 1 - \frac{x}{L} \right)^{m+1} \quad \text{Where, } m = 1.7$$

$\Delta H_x$  is the head loss at any distance  $x$  from lateral inlet and  $\Delta H$  is the total head loss for the entire length ( $L$ ) of the lateral

- A submain unit of drip irrigation system consisting of 50 laterals and 100 emitters in each lateral was considered to study the field scale drip irrigation system inflicted with emitter clogging for its hydraulic performances. The Christiansen's field emission uniformity and statistical uniformity were determined for various possible clogging pattern. Both uniformity values are decreasing with increase in coefficient of variations. It was also found that the

field uniformity is lesser than the single lateral uniformity for the same conditions.

- It was found that the space between pressure profile lines is more for head end laterals and it is decreasing towards the tail end laterals. It was also noticed that the required operating pressure for the first lateral is decreasing with clogging levels to maintain the same operating pressure at the last lateral.

#### **Limitations and suggestions for future study**

- Simulation was carried out for particular system parameters only, which results in a single hydraulic variation. The effect of hydraulic variations combined with emitter clogging on uniformity can be studied in detail.
- The effect of field slope on uniformity was not studied as it can be considered as a component of hydraulic variation. The independent effect of slope on hydraulic performance of drip irrigation system has to be studied.
- Emitter clogging was assumed to be normally distributed over the space. This assumption may not be true always. So, different clogging patterns like, more clogging at the head end or tail end or middle or any combination can be assumed and its effect on hydraulic gradient and uniformity has to be studied.

Prevention is better than cure. So, an optimal combination of operating pressure at the starting point and dilution of problem water with harvested rainwater may solve clogging problem and enhance the performance of drip irrigation system.

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\* Originals not seen

## *Appendices*

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## APPENDIX I



**Emitter clogging studies in an arecanut field**



**A close up view of a clogged emitter in the arecanut field**

## APPENDIX - II

Emitter discharge data in lph for analysing temporal and spatial distributions of clogging

	Elapsed time, Week																		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	4.05	3.99	3.94	3.89	3.87	3.78	3.72	3.63	3.57	3.52	3.47	3.38	3.33	3.31	3.23	3.18	3.15	3.07	3.01
2	4.00	3.96	3.91	3.85	3.78	3.72	3.66	3.63	3.59	3.52	3.46	3.42	3.36	3.30	3.27	3.19	3.15	3.06	2.99
3	3.77	3.70	3.68	3.63	3.55	3.51	3.46	3.42	3.37	3.35	3.32	3.29	3.21	3.14	3.06	3.01	2.93	2.88	2.81
4	3.35	3.30	3.25	3.22	3.21	3.12	3.07	2.99	2.94	2.90	2.84	2.80	2.76	2.72	2.66	2.62	2.58	2.51	2.47
5	3.79	3.73	3.70	3.66	3.61	3.52	3.48	3.44	3.40	3.35	3.31	3.29	3.25	3.13	3.10	3.01	2.96	2.93	2.87
6	3.80	3.74	3.69	3.66	3.64	3.54	3.50	3.42	3.36	3.31	3.26	3.20	3.15	3.11	3.04	2.96	2.90	2.87	2.79
7	3.80	3.74	3.72	3.69	3.66	3.62	3.59	3.57	3.50	3.48	3.44	3.40	3.35	3.30	3.26	3.19	3.13	3.10	3.02
8	3.85	3.78	3.73	3.69	3.66	3.59	3.53	3.45	3.41	3.38	3.37	3.33	3.25	3.16	3.08	3.03	2.96	2.91	2.84
9	3.82	3.77	3.71	3.69	3.63	3.58	3.52	3.46	3.42	3.37	3.34	3.29	3.22	3.12	3.06	2.98	2.92	2.91	2.87
10	3.83	3.75	3.66	3.57	3.52	3.44	3.37	3.32	3.25	3.22	3.16	3.10	3.06	3.01	2.95	2.91	2.85	2.80	2.71
11	3.84	3.77	3.73	3.68	3.62	3.58	3.53	3.49	3.45	3.41	3.34	3.29	3.24	3.18	3.13	3.07	2.99	2.94	2.89
12	3.77	3.68	3.55	3.49	3.38	3.36	3.32	3.29	3.26	3.18	3.09	3.00	2.95	2.88	2.83	2.78	2.70	2.66	2.63
13	3.85	3.78	3.74	3.70	3.61	3.56	3.53	3.46	3.43	3.39	3.37	3.31	3.25	3.18	3.08	3.03	2.98	2.92	2.86
14	3.72	3.66	3.62	3.59	3.52	3.46	3.42	3.37	3.33	3.30	3.24	3.20	3.15	3.09	3.01	2.97	2.89	2.85	2.79
15	3.77	3.71	3.68	3.63	3.55	3.50	3.46	3.38	3.35	3.32	3.28	3.23	3.17	3.08	3.00	2.96	2.90	2.87	2.82
16	3.88	3.83	3.80	3.74	3.70	3.61	3.55	3.53	3.48	3.45	3.40	3.34	3.29	3.20	3.14	3.08	3.02	2.97	2.92
17	3.78	3.71	3.66	3.59	3.55	3.47	3.40	3.35	3.31	3.22	3.18	3.14	3.09	3.01	2.98	2.92	2.89	2.85	2.80
18	3.75	3.69	3.62	3.56	3.52	3.42	3.35	3.29	3.23	3.19	3.13	3.08	3.07	2.97	2.91	2.83	2.79	2.78	2.77
19	3.92	3.87	3.85	3.82	3.79	3.74	3.70	3.67	3.61	3.60	3.56	3.52	3.47	3.41	3.38	3.30	3.23	3.20	3.12
20	3.82	3.76	3.72	3.67	3.61	3.56	3.50	3.45	3.42	3.37	3.33	3.27	3.17	3.13	3.10	3.04	2.99	2.96	2.90
21	3.85	3.79	3.75	3.72	3.63	3.58	3.53	3.50	3.47	3.39	3.35	3.27	3.23	3.18	3.16	3.07	3.00	2.93	2.91
22	3.86	3.78	3.71	3.59	3.53	3.46	3.40	3.34	3.27	3.20	3.17	3.15	3.08	3.02	2.99	2.95	2.92	2.86	2.82
23	3.76	3.71	3.68	3.65	3.61	3.58	3.53	3.50	3.45	3.42	3.38	3.31	3.25	3.20	3.11	3.08	3.03	2.97	2.93
24	3.76	3.69	3.62	3.58	3.50	3.44	3.38	3.31	3.25	3.20	3.13	3.11	3.08	3.00	2.93	2.87	2.82	2.77	2.73
25	3.96	3.91	3.87	3.84	3.80	3.76	3.71	3.64	3.61	3.56	3.50	3.44	3.40	3.33	3.26	3.23	3.16	3.08	3.03
26	3.85	3.79	3.75	3.74	3.71	3.66	3.63	3.59	3.52	3.50	3.46	3.40	3.35	3.26	3.23	3.16	3.12	3.08	3.01
27	3.86	3.80	3.78	3.75	3.71	3.67	3.64	3.59	3.54	3.50	3.45	3.40	3.34	3.26	3.21	3.18	3.14	3.08	3.01
28	3.96	3.90	3.86	3.84	3.80	3.75	3.69	3.63	3.60	3.54	3.48	3.42	3.38	3.35	3.29	3.24	3.16	3.08	3.05
29	3.93	3.87	3.84	3.81	3.77	3.71	3.67	3.61	3.58	3.53	3.48	3.42	3.37	3.28	3.23	3.18	3.12	3.09	3.03
30	3.92	3.86	3.79	3.71	3.67	3.59	3.51	3.46	3.41	3.37	3.30	3.25	3.21	3.13	3.08	3.03	2.99	2.94	2.87
31	3.94	3.89	3.85	3.83	3.77	3.73	3.68	3.61	3.58	3.53	3.50	3.42	3.37	3.31	3.24	3.20	3.13	3.08	3.05
32	3.96	3.91	3.86	3.83	3.79	3.75	3.71	3.65	3.60	3.55	3.48	3.43	3.37	3.31	3.26	3.24	3.17	3.11	3.05
33	3.86	3.79	3.74	3.72	3.69	3.60	3.55	3.47	3.40	3.35	3.30	3.25	3.20	3.17	3.08	3.04	2.97	2.91	2.87
34	3.92	3.86	3.81	3.78	3.69	3.65	3.61	3.57	3.51	3.47	3.42	3.41	3.35	3.25	3.19	3.12	3.08	3.03	2.98
35	3.86	3.78	3.72	3.67	3.60	3.53	3.46	3.40	3.34	3.28	3.22	3.17	3.11	3.08	3.02	2.98	2.96	2.91	2.88
36	3.76	3.70	3.67	3.65	3.61	3.58	3.55	3.50	3.44	3.42	3.37	3.31	3.24	3.21	3.18	3.10	3.05	2.98	2.95

D r i p p e r N u m b e r

### APPENDIX – III

#### Weibull distribution theory for fitting temporal distribution of emitter clogging

Weibull distribution is a very widely used tool in engineering practice. This was originally proposed for the interpretation of fatigue, but now its use has been extended to many other engineering problems. The general expression of the weibull failure probability distribution function is given as (Weibull, 1951)

$$f(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\alpha} e^{-[(t-\gamma)^\beta]/\alpha} \quad \text{When } t > \gamma \quad \text{else } f(t) = 0$$

$\alpha$  = Scale parameter

$\beta$  = Shape parameter or Weibull slope

$\gamma$  = Location parameter or lower bound of life

The cumulative density function (CDF) for Weibull model can be obtained by integrating the probability distribution function.

$$F(t) = 1 - e^{-[(t-\gamma)^\beta]/\alpha}$$

Any nature of the failure can be fitted with this function by suitably estimating the parameters ( $\alpha$ ,  $\beta$ ,  $\gamma$ ) of the Weibull distribution. In some of the cases (machine parts) the failure starts as soon as the object starts working. But in case of drip emitter clogging the lower bound of life cannot be eliminated, as the drippers are not

subjected to sudden clogging. To estimate the Weibull parameters, data on number of failures versus time or time between failures are to be calculated.

There are many ways for estimating population parameters from sample data. A few of these are graphical procedures, matching selected points, method of moments, and least square technique. For the type of data that can be easily gathered on drip irrigation emitter clogging, the least square method is simple and reasonably precise. It gives estimates closer to other methods, which are very complicated in nature.

This Weibull distribution function is first converted into a linear form for applying least square technique in order to estimate the parameter values. Rearranging and taking natural logarithm twice on both sides of the function results in

$$\ln[-\ln[1-f(t)]] = \beta \ln(t - \gamma) - \ln(\alpha)$$

This is in the standard form of a linear equation  $Y = m X + C$ . Therefore least square technique can be applied by considering  $\ln[-\ln[1-f(t)]]$  as  $Y$  and  $\ln(t - \gamma)$  as  $X$ . After that, the slope ' $m$ ' and  $Y$ -axis interception ' $C$ ' can be equated with the corresponding terms in the linear form of Weibull cumulative function.

$$\beta = m \text{ and}$$

$$\alpha = \text{antilog}(C)$$

## Mean and standard deviation of Weibull model

The mean time for emitters to get clogged to a particular percentage can be calculated from the Weibull model as

$$\mu = \gamma + \alpha^{1/\beta} \Gamma\left(1 + \frac{1}{\beta}\right) \quad \Gamma \quad ?$$

and the variance of the model is calculated as

$$\sigma^2 = \alpha^{2/\beta} \left\{ \Gamma\left(1 + \frac{2}{\beta}\right) - \left[ \Gamma\left(1 + \frac{1}{\beta}\right) \right]^2 \right\}$$

By knowing the mean and variance of the Weibull model, the time to clog emitters can be predicted with some confidence of interval.

## Simulation of clogging time

The developed probability density functions can be used to generate the data on failure time of emitters by using Monte-Carlo simulation method. Random numbers that are generated using the developed probability density functions can be considered as time to clog that much percentage of total emitters. The cumulative distribution values are chosen from a uniform distribution. This is possible because of the fact that the cumulative probability function for any continuous variate is uniformly distributed over the interval of 0 to 1 (Hann, 1977). For the Weibull distribution the time to clog can be generated as follows

$$R_u = 1 - e^{-[(t-\gamma)^\beta]/\alpha}$$

$R_u$  is the random number ranging from 0 to 1 selected from uniform distribution. Computer routines for generating uniform random numbers are available with the computer languages. Solving for time between failure,  $t$

$$t = [\alpha(-\ln(1 - R_u))]^{1/\beta} + \gamma$$

This equation is solved for required number of times by substituting corresponding Weibull parameters and uniformly distributed random numbers generated using built-in function of C language. The procedure is repeated for different clogging levels of drip emitters (5%, 10%, 15% and 20%).

## APPENDIX - IV

### 'C' CODE TO ESTIMATE THE WEIBULL DISTRIBUTION PARAMETERS

```
# include<stdio.h>
#include<math.h>
#include<string.h>
#define e 2.7182818
main()
{
    int n,i;
    float u,l,s;
    float x;
    float F[300],t[300];
    char out[5]=".txt";
    char res[6]="i.txt";
    char fres[6]="r.txt";

    FILE *fp,*fr,*fr1;
    char fname[20],resfile[20],resfile1[20];
    float sx,sx2,sy,ssxy,spxy,ssx,c;
    float alpha,beta;
    clrscr();
    printf("\n Give the Input file name");
    scanf("%s",fname);
    strcpy(resfile,fname);
    strcpy(resfile1,fname);
    strcat(fname,out);
    printf("\n Input filename: %s\n",fname);
    strcat(resfile,res);
```

```
printf("\n Output(Alpha and Beta)filename: %s\n",resfile);
```

```
strcat(resfile1,fres);
```

```
printf("\n Output(Final table)filename: %s\n",resfile1);
```

```
fp=fopen(fname, "r");
```

```
fr=fopen(resfile,"w");
```

```
fr1=fopen(resfile1,"w");
```

```
printf("\n Give the number of data set in the file: ");
```

```
scanf("%d",&n);
```

```
for(i=0;i<n;i++)
```

```
{
```

```
    fscanf(fp,"%f %f",&t[i],&F[i]);
```

```
}
```

```
fclose(fp);
```

```
l=t[0];
```

```
u=t[n-1];
```

```
s=t[1]-t[0];
```

```
for(i=0;i<n;i++)
```

```
{
```

```
    F[i]=1-F[i];
```

```
    F[i]=(-1)*log(F[i]);
```

```
    F[i]=log(F[i]);
```

```
    t[i]=log(t[i]);
```

```
}
```

```
sx=0; sy=0; sx2=0; ssxy=0;
```

```

for (i=0;i<n;i++)
{
    sx=sx+t[i];
    sy=sy+F[i];
    sx2=sx2+t[i]*t[i];
    ssxy=ssxy+t[i]*F[i];
}
spxy=ssxy-sx*sy/n;
ssx=sx2-sx*sx/n;
beta=spxy/ssx;
c=(sy/n)-(beta*(sx/n));
c=-1*c;
alpha=pow(e,c);

printf("\n ALPHA= %f",alpha);
printf("\n BETA = %f\n",beta);
fprintf(fr,"%f\n",alpha);
fprintf(fr,"%f",beta);
fclose(fr);

```

```

for(i=l;i<=u;i=i+s)
{
    x=pow(i,beta);
    x=-x;
    x=x/alpha;
    x=pow(2.718,x);
    x=1-x;
    fprintf(fr1,"\n %d\t%f",i,x);
}
fclose(fr1);
getchar();
}

```

## APPENDIX - V

Details of the Farmer's fields selected for the drip irrigation clogging study

FIELD NO.	ADDRESS	Descriptin
F1	Dr. K. Dhandapani Doctor thottam Kalapalyam Coimbatore	Crop: Grapes Spacing: 2.5 x 0.75 m Dripper: 8 LPH Lateral size: 16 mm Pressure: 1-1.25 kg/m <sup>2</sup> Study: Impact of Emitter type and water quality on clogging
F2	Mr. Chinnadurai Goundar Near kallukkadai bus stop Thithipalayam Coimbatore	
F3	Mr. R. Duraisamy KUMARAN BRICK WORKS (KBW) Somayampalayam Coimbatore	
F4	Mr. R. M. Viswanathan Madampatti Coimbatore	

FIELD NO.	ADDRESS	Descriptin
1.	Mr. Maruthakutti Vadavalli Coimbatore	Crop: Arecanut Spacing: 2.2 x 2.2 m Dripper: 4 LPH Study: Temporal and Spatial distributions
2	Mr. Moorthy Thondamuthur Coimbatore	Crop: Banana Spacing: 2 x 2 m Dripper: 8 LPH Dripper Study: Impact of Fertigation on clogging

## APPENDIX - VI



**Emitter clogging studies in a grape field**



**Emitter clogging studies in a banana field**

**APPENDIX - VII**



**Filtration unit in a drip irrigation field**



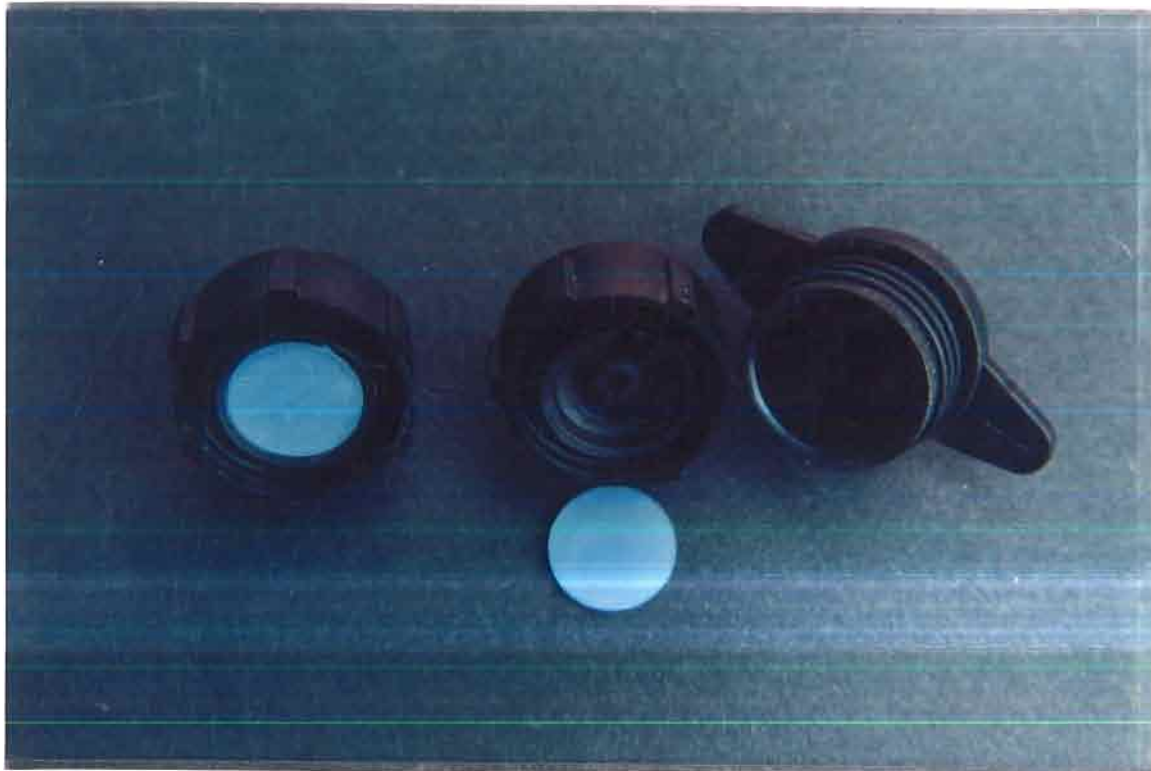
**Fertigation tank (blue) and filtration unit in a drip irrigation field**

## APPENDIX - VIII

Water quality parameters for the tested drip irrigation fields

S. No	Parameter	Field 1 (F1)	Field 2 (F2)	Field 3 (F3)	Field 4 (F4)
1	EC (dS/m)	0.9	1.4	2.2	3.0
2	pH	7.9	7.8	7.1	7.1
3	Ca (mg L <sup>-1</sup> )	167	195	253	328
4	Na (mg L <sup>-1</sup> )	168	173	213	245
5	K (mg L <sup>-1</sup> )	5.8	6.9	9.8	14.5
6	HCO <sub>3</sub> (mg L <sup>-1</sup> )	291	333	371	412
8	Cl <sub>2</sub> (mg L <sup>-1</sup> )	2.3	7.1	10.7	11.7
9	TDS (mg L <sup>-1</sup> )	641	678	753	837
10	TSS (mg L <sup>-1</sup> )	64	67	54	58

APPENDIX - IX



Dripper - A (Pressure compensation type)



Dripper - B (Helical long flow path type)



Dripper – C (Helical short flow path type)



Dripper – D (Screw flow path type)

## APPENDIX - X

### 'C' CODE FOR THE COMPUTER MODEL RANGEN

```
#include<stdio.h>
#include<math.h>
#include<stdlib.h>
#include<time.h>
main()
{
int i,tn;
float x,j,p,t,s;
float m,sd,rn;
char out[20];
FILE *fp;
printf("\n\n\n\n\n\n\n\n\n");
printf("\n *****DRIPCLOG*****");
printf("\n A Computer model for generating emitter discharge coefficients (K) and
clogging variations (P)");

getchar();
printf("\n Please enter to continue");
clrscr();

printf("\n Name the output file for saving:\t");
scanf("%s",out);
printf("\n How many numbers do you want ? =\t");
scanf("%d",&tn);
printf("\n Mean of the Distribution = ");
scanf("%f",&m);
printf("\n Standard Deviation of the Distribution = ");
```

```
scanf("%f",&sd);
fp=fopen(out,"w");
if(fp==NULL)
{
printf("Unable to open %s ",kval);
exit();
}
```

```
randomize();
```

```
for(i=0;i<tn;i++)
{
x=random(100);
x=x/100;
s=0;
for(j=-3;s<=x;j=j+0.01)
{
p=j*j/2;
t=exp(-p);
s=s+(0.39894*t*0.01);
}
rn=m+sd*j;
fprintf(fp,"%f\n",rn);
}
fclose(fp);
}
```

## APPENDIX - XI

### 'C' CODE FOR THE COMPUTER MODEL DRIPCLOG

```
#include<stdio.h>
#include<math.h>
float x;
main()
{
/* Variables declaration */
int i,j,m,n;
float l,ld,sd,mhf,ed,es,ls,lsl,msl;
float hmin;
float qq=0,oqq,cq=0;
float b,el,z,ha=10,flag=0;
float p[100][100],k[100][100];
char kval[20],pval[20],out[20];
float fl[100][100],h[100][100];
float flowc(float p,float k,float h);
float head(float qq,float ld,float es,float h,float z,float k,float p);
float ffactor(float q,float d);
float hloss(float f,float l,float q,float d);
float elength(float b,float d);
float fun(float h1,float h2,float q,float p,float z,float hf,float hm,float d,float k);
float secant(float x1,float q1,float p,float z,float hf,float hm,float d,float k);
float mainloss(float l,float q,float d);
/* File Pointers declaration */
FILE *fk,*fp,*fr;
/* End of declration */
clrscr();
printf("\n\n\n\n\n\n\n\n\n\n");
```

```

printf("\n *****DRIPCLOG*****");
printf("\n A Computer model for evaluating variations of hydraulic pressure and
and emitter discharge under manufacturing and clogging variations");

getchar();
printf("\n Please enter to continue");
clrscr();

/* Reading K and P values from text files created using RANGEN */
printf("\n Please enter the file names carefully");
printf("\n Name of the K value file = ");
scanf("%s",kval);

printf("\n Name of the P value file = ");
scanf("%s",pval);

printf("\n Name of the Output file = ");
scanf("%s",out);

fk=fopen(kval,"r");
if(fk==NULL)
{
printf("Unable to open %s ",kval);
exit();
}

fp=fopen(pval,"r");
if(fp==NULL)

```

```
{  
printf("Unable to open %s ",pval);  
exit();  
}
```

```
fr=fopen(out,"w");  
if(fr==NULL)  
{  
printf("Unable to open output file");  
exit();  
}  
/* Inputting system parameters */  
printf("\n Number of drippers = ");  
scanf("%d",&n);  
printf("\n Number of laterals = ");  
scanf("%d",&m);
```

```
for(i=1;i<=m;i++)  
for(j=1;j<=n;j++)  
{  
fscanf(fk,"%f",&k[i][j]);  
}  
fclose(fk);  
for(i=1;i<=m;i++)  
for(j=1;j<=n;j++)  
{  
fscanf(fp,"%f",&p[i][j]);  
}  
fclose(fp);
```

```

printf("\n Feed the drip system parameters\n");
printf("\n Length of the Lateral = ");
scanf("%f",&l);
printf("\n Diameter of the Lateral = ");
scanf("%f",&d);
printf("\n Diameter of the submain = ");
scanf("%f",&sd);
printf("\n Emitter Spacing = ");
scanf("%f",&es);
printf("\n Lateral Spacing = ");
scanf("%f",&ls);
printf("\n Slope along the lateral = ");
scanf("%f",&sl);
printf("\n Slope along the main(%) = ");
scanf("%f",&msl);
printf("\n Minimum Operating Pressure Required = ");
scanf("%f",&hmin);
hmin=10;
printf("\n Emitter Discharge Exponent(x) = ");
scanf("%f",&x);
printf("\n Constant of proportionality(k) = ");
scanf("%f",&k);
printf("\n Emitter Barb Diameter(b) = ");
scanf("%f",&b);
clrscr();

el=length(b,(ld*1000));          /* Eq. Length Calculation*/
es=es+el;                       /* Correction for Emitter barb*/
h[0][0]=hmin;                   /* Assigning Head for First Emitter*/
z=es*sl/100;                    /* Elevational loss/gain*/

```

```

ha=12;
h[1][1]=10;

for(i=1;i<=m;i++)
{
printf("\n Calculating for %d lateral",i);
flag=1;

while(flag==1)
{
for(j=1;j<=n;j++)
{
fl[i][j]=flowc(p[i][j],k[i][j],h[i][j]);
qq=qq+fl[i][j];
if(j!=n)
h[i][j+1]=head(qq,ld,es,h[i][j],z,k[i][j+1],p[i][j+1]);
}

if(fabs(h[i][n]-ha)>=0.01)
{
if(h[i][n]<ha)
h[i][1]=h[i][1]+0.001;
else
h[i][1]=h[i][1]-0.001;
flag=1;
qq=0;
}
else flag=0;
}
}

```

```

flag=0;
cq=cq+qq;
printf(" cq= %f",cq);
mhf=mainloss(ls,cq,sd);
ha=ha+mhf;
printf(" h= %f ",h[i][1]);
h[i+1][1]=h[i][1]+mhf;
}

for(j=n;j>=1;j--)
{
fprintf(fr,"\n");
for(i=1;i<=m;i++)
fprintf(fr,"%f\t%f",h[i][j],fl[i][j]);
}
} /* End of main*/

```

```

/* Pressure head calculation */

```

```

float head(float q,float ld,float es,float h,float z,float k,float p)
{
float f,hf,fh;
f=ffactor(q,ld);
hf=hloss(f,es,q,ld);
fh=secant(h,q,p,z,hf,0,ld,k);
return(fh);
}

```

```
/* Flow calculation */
```

```
float flowc(float p,float k,float h)
```

```
{
```

```
float fq;
```

```
fq=(1-p)*k*pow(h,x);
```

```
return(fq);
```

```
}
```

```
/*Friction factor calculation*/
```

```
float ffactor(float q,float d)
```

```
{
```

```
float t,re,ff;
```

```
t=(q/3600000)/(3.14*d*d/4);
```

```
re=1000*t*d/(8.3/100000);
```

```
d=d*1000;
```

```
ff=0.316/pow(re,0.25);
```

```
return(ff);
```

```
}
```

```
/* Head Loss Calculation*/
```

```
float hloss(float f,float l,float q,float d)
```

```
{
```

```
float fhf;
```

```
d=d*1000;
```

```
fhf=(6.3755*f*l*q*q)/pow(d,5);
```

```
return(fhf);
```

```
}
```

```
/* Head loss in submain pipe*/
```

```
float mainloss(float l,float q,float d)
```

```
{  
    float ml,f;  
    f=ffactor(q,d);  
    ml=hloss(f,l,q,d);  
    return(ml);  
}
```

```
/* Equivalent Length for Emitter barb*/
```

```
float elength(float b,float d)
```

```
{  
    float el;  
    el=0.25*b*19/pow(d,1.9);  
    return(el);  
}
```

```
/* Numerical solution for polinomial equation using secant method */
```

```
float secant(float h,float q,float p,float z,float hf,float hm,float d,float k)
```

```
{  
    float x1,x2;  
    float x3;  
    float e=1;  
    float fx1,fx2;  
    x1=h;  
    x2=x1+5;
```

```

while(e>0.0005)
{
    fx1=fun(x1,h,q,p,z,hf,hm,d,k);
    fx2=fun(x2,h,q,p,z,hf,hm,d,k);
    x3=x2-((fx2*(x2-x1))/(fx2-fx1));
    e=fabs((x3-x2)/x3);
    x1=x2;
    x2=x3;
}
return(x3);
}

```

/\* Calculation of function value \*/

```

float fun(float h1,float h2,float q1,float p,float z,float hf,
          float hm,float d,float k)
{
    float q2,qt,a,fv;
    q2=q1+(1-p)*k*pow(h1,x);
    q1=q1/(3.6e06);
    q2=q2/(3.6e06);
    a=3.1415*d*d/4;
    qt=((q1*q1)-(q2*q2))/(2*9.81*a);
    fv=h2+qt+z+hf+hm-h1;
    return(fv);
}

```

APPENDIX - XII



Laboratory scale drip irrigation layout



Segmental hydraulic gradient assessment using 'U' tube manometer

### APPENDIX - XIII

Generated K values for 100 emitters with 3 per cent  $CV_m$  using RANGEN

Emitter No.	K value	Emitter No.	K value	Emitter No.	K value	Emitter No.	K value
1	2.174	26	2.102	51	2.161	76	2.070
2	2.156	27	2.240	52	2.065	77	2.104
3	2.113	28	2.315	53	2.186	78	2.134
4	2.159	29	2.078	54	2.121	79	2.167
5	2.136	30	2.315	55	2.199	80	2.132
6	2.125	31	2.284	56	2.262	81	2.225
7	2.161	32	2.106	57	2.127	82	2.099
8	2.099	33	2.197	58	2.148	83	2.199
9	2.199	34	2.169	59	2.213	84	2.172
10	2.205	35	2.144	60	2.156	85	2.143
11	2.154	36	2.109	61	2.216	86	2.164
12	2.074	37	2.191	62	2.157	87	2.275
13	2.161	38	2.191	63	2.284	88	2.119
14	2.218	39	2.186	64	2.121	89	2.131
15	2.201	40	2.189	65	2.169	90	2.029
16	2.061	41	2.061	66	2.216	91	2.082
17	2.231	42	2.143	67	2.228	92	2.061
18	2.207	43	2.189	68	2.111	93	2.154
19	2.184	44	2.109	69	2.231	94	2.164
20	2.099	45	2.228	70	2.203	95	2.029
21	2.048	46	2.240	71	2.207	96	2.156
22	2.111	47	2.117	72	2.207	97	2.141
23	2.106	48	2.181	73	2.218	98	2.111
24	2.055	49	2.123	74	2.154	99	2.148
25	2.179	50	2.154	75	2.143	100	2.082

## APPENDIX - XIV

Generated clogging (P) values for the emitters having mean clogging of 10 per cent  
with 3 per cent CV<sub>c</sub> using DRIPCLOG

Emitter No.	P value	Emitter No.	P value	Emitter No.	P value	Emitter No.	P value
1	0.088	26	0.121	51	0.088	76	0.114
2	0.118	27	0.118	52	0.088	77	0.100
3	0.082	28	0.104	53	0.122	78	0.110
4	0.052	29	0.109	54	0.115	79	0.136
5	0.109	30	0.091	55	0.060	80	0.092
6	0.110	31	0.126	56	0.044	81	0.068
7	0.106	32	0.181	57	0.118	82	0.079
8	0.133	33	0.094	58	0.098	83	0.103
9	0.103	34	0.048	59	0.133	84	0.108
10	0.057	35	0.102	60	0.069	85	0.107
11	0.116	36	0.110	61	0.119	86	0.077
12	0.104	37	0.134	62	0.072	87	0.060
13	0.063	38	0.095	63	0.119	88	0.096
14	0.123	39	0.074	64	0.116	89	0.121
15	0.070	40	0.139	65	0.035	90	0.099
16	0.092	41	0.094	66	0.106	91	0.091
17	0.141	42	0.144	67	0.095	92	0.110
18	0.035	43	0.110	68	0.048	93	0.060
19	0.115	44	0.107	69	0.078	94	0.129
20	0.161	45	0.134	70	0.123	95	0.092
21	0.123	46	0.124	71	0.133	96	0.144
22	0.057	47	0.091	72	0.096	97	0.091
23	0.133	48	0.150	73	0.088	98	0.055
24	0.181	49	0.085	74	0.044	99	0.117
25	0.099	50	0.081	75	0.138	100	0.106

### APPENDIX - XV

Simulated pressure head and emitter flow for a  $CV_m$  of 3 per cent and clogging of 10 per cent with  $CV_c$  of 3 per cent using DRIPCLOG

Emitter No.	Pressure, m	Emitter flow, lph	Emitter No.	Pressure, m	Emitter flow, lph
1	12.009	7.482	26	10.327	6.831
2	11.924	7.598	27	10.278	7.596
3	11.840	7.961	28	10.229	7.438
4	11.758	7.741	29	10.183	7.319
5	11.677	7.311	30	10.137	7.002
6	11.598	7.267	31	10.092	7.048
7	11.521	7.411	32	10.049	7.491
8	11.445	7.933	33	10.007	7.295
9	11.371	7.156	34	9.966	7.308
10	11.298	7.353	35	9.926	7.165
11	11.226	7.083	36	9.887	7.548
12	11.157	7.228	37	9.849	6.749
13	11.088	7.372	38	9.813	7.225
14	11.021	8.204	39	9.777	7.181
15	10.956	7.634	40	9.743	6.988
16	10.892	7.285	41	9.709	7.167
17	10.829	7.358	42	9.677	6.842
18	10.768	7.465	43	9.646	6.896
19	10.708	7.296	44	9.615	6.665
20	10.650	7.802	45	9.586	7.672
21	10.593	7.258	46	9.557	7.321
22	10.537	7.003	47	9.530	6.637
23	10.483	7.081	48	9.503	6.769
24	10.430	7.038	49	9.477	6.634
25	10.378	6.800	50	9.453	6.934

Emitter No.	Pressure, m	Emitter flow, lph	Emitter No..	Pressure, m	Emitter flow, lph
51	9.429	6.958	76	9.068	6.748
52	9.406	6.818	77	9.061	5.785
53	9.383	6.495	78	9.055	6.274
54	9.362	6.732	79	9.049	6.831
55	9.341	6.856	80	9.044	6.163
56	9.321	6.735	81	9.039	6.041
57	9.302	6.564	82	9.035	6.633
58	9.284	6.786	83	9.031	7.299
59	9.266	6.383	84	9.027	6.569
60	9.249	6.493	85	9.024	6.413
61	9.233	6.541	86	9.021	7.012
62	9.218	7.023	87	9.018	6.663
63	9.203	6.873	88	9.016	6.934
64	9.189	6.570	89	9.014	6.369
65	9.175	6.494	90	9.013	6.522
66	9.163	6.654	91	9.011	7.118
67	9.150	7.131	92	9.010	6.755
68	9.139	6.871	93	9.009	6.235
69	9.128	5.953	94	9.008	6.617
70	9.118	6.878	95	9.008	6.476
71	9.108	7.248	96	9.007	6.516
72	9.099	6.376	97	9.007	7.010
73	9.090	7.136	98	9.007	6.642
74	9.082	6.799	99	9.007	6.513
75	9.075	6.356	100	9.007	6.787

### APPENDIX - XVI

Simulation result for a field scale drip system ( $CV_m$  of 3 per cent and clogging of 10 per cent with  $CV_c$  of 3 per cent) using DRIPCLOG

Emitter Number	Lateral number	Emitter flow, lph	Pressure, m
1	1	7.524	12.001
11	1	7.526	11.220
21	1	7.360	10.588
31	1	6.534	10.090
41	1	7.103	9.704
51	1	6.707	9.418
61	1	7.150	9.219
71	1	6.881	9.091
81	1	7.709	9.020
91	1	7.369	8.991
100	1	6.709	8.987
1	2	7.551	12.001
11	2	7.266	11.207
21	2	7.557	10.562
31	2	7.113	10.049
41	2	7.217	9.655
51	2	6.939	9.364
61	2	6.699	9.162
71	2	7.564	9.031
81	2	7.480	8.960
91	2	6.570	8.932
100	2	7.402	8.928
...	....	...	...
...	....	...	...
...	....	...	...